

# FY2021 ILAW Glass Ion-Exchange Rate Testing

Prepared for the U.S. Department of Energy  
Assistant Secretary for Environmental Management

Contractor for the U.S. Department of Energy  
Office of River Protection under Contract DE-AC27-08RV14800



**P.O. Box 850**  
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## FY2021 ILAW Glass Ion-Exchange Rate Testing

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*By Sarah Harrison at 12:24 pm, May 03, 2022*

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**Final Report**

**FY2021 ILAW Glass Ion-Exchange Rate Testing**

*prepared by*

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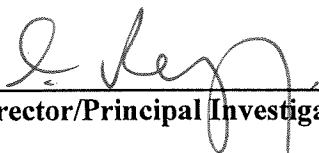
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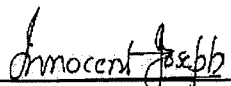
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**Completeness of Testing:**

This report describes the results of work and testing specified by WRPS. The work and any associated testing followed established quality assurance requirements. The descriptions provided in this test report are an accurate account of both the conduct of the work and the data collected. Results required by the test program are reported. Also reported are any unusual or anomalous occurrences that are different from the starting hypotheses. The test results and this report have been reviewed and verified.

I. L. Pegg:  Date: 9/30/21  
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### **List of Abbreviations**

|           |                                                                       |
|-----------|-----------------------------------------------------------------------|
| ANL-LRM   | Argonne National Laboratory – Low-Activity Waste Reference Material   |
| ASME      | American Society of Mechanical Engineers                              |
| ASTM      | American Society for Testing and Materials                            |
| CCC       | Canister Centerline Cooling                                           |
| CERCLA    | Comprehensive Environmental Response, Compensation, and Liability Act |
| CUA       | The Catholic University of America                                    |
| DOE       | Department of Energy                                                  |
| DWPF-WA   | Defense Waste Processing Facility – Environmental Assessment Glass    |
| EDS       | Energy Dispersive X-ray Spectroscopy                                  |
| HLW       | High Level Waste                                                      |
| ICP-AES   | Inductively Coupled Plasma-Atomic Emission Spectroscopy               |
| IDF       | Integrated Disposal Facility                                          |
| ILAW      | Immobilized Low Activity Waste                                        |
| IHLW      | Immobilized High Level Waste                                          |
| IEX       | Ion Exchange                                                          |
| LAW       | Low Activity Waste                                                    |
| LFRG      | Low-Level Waste Disposal Facility Federal Review Group                |
| NDR       | Normalized Dissolution Rate                                           |
| NIST      | National Institute of Standards and Technology                        |
| NQA       | Nuclear Quality Assurance                                             |
| ORP       | Office of River Protection                                            |
| PA        | Performance Assessment                                                |
| PCT       | Product Consistency Test                                              |
| PFT       | Pulsed-Flow Test                                                      |
| PUF       | Pressurized Unsaturated Flow                                          |
| QA        | Quality Assurance                                                     |
| QARD      | Quality Assurance Requirements and Description                        |
| RCRA      | Resource Conservation and Recovery Act                                |
| ROD       | Record of Decision                                                    |
| S/V       | Ratio of Surface Area to Solution Volume                              |
| SEM       | Scanning Electron Microscopy                                          |
| SPFT      | Single-Pass Flow-Through                                              |
| SRL-EA    | Savannah River Laboratory-Environmental Assessment                    |
| TC&WM EIS | Tank Closure & Waste Management Environmental Impact Statement        |
| Tris      | tris(hydroxymethyl)aminomethane                                       |
| TST       | Transition State Theory                                               |
| US        | United States                                                         |
| VHT       | Vapor Hydration Test                                                  |
| VSL       | Vitreous State Laboratory                                             |
| WRPS      | Washington River Protection <i>Solutions</i> , LLC                    |
| WTP       | Hanford Tank Waste Treatment and Immobilization Plant                 |
| XRF       | X-Ray Fluorescence                                                    |

## **SECTION 1.0 INTRODUCTION**

### **1.1 Background**

Approximately 54 to 56 million gallons of radioactive mixed waste is currently stored in underground tanks at The United States Department of Energy's (DOE's) Hanford site in the State of Washington. The Hanford Tank Waste Treatment and Immobilization Plant (WTP) will provide DOE's Office of River Protection (ORP) with a means of treating this waste by vitrification for subsequent disposal. The tank waste will be separated into low- and high-activity waste fractions, which will then be vitrified respectively into Immobilized Low Activity Waste (ILAW) and Immobilized High-Level Waste (IHLW) products. The ILAW product will be disposed of in an engineered facility – the Integrated Disposal Facility (IDF) – on the Hanford site, while the IHLW product will be directed to the national deep geological disposal facility for high-level nuclear waste. The ILAW and IHLW products must meet a variety of requirements with respect to protection of the environment before they can be accepted for disposal.

The Record of Decision (ROD) from the Tank Closure & Waste Management Environmental Impact Statement (TC&WM EIS) establishes the current waste streams to be disposed of at the IDF to be located in the 200 East Area which include ILAW, secondary waste associated with ILAW production, and other on-site Hanford non-Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) waste. In accordance with the DOE order on radioactive waste management (DOE Order 435.1), the IDF performance assessment is intended to analyze the long-term impacts on human health and the environment of the disposition of waste placed into the facility. Evaluation of the impact of disposed waste requires the ability to predict the long-term release of key radionuclides from the engineered system. In the case of the IDF, the engineered system includes a number of components including the proposed Resource Conservation and Recovery Act (RCRA) cap, back fill material, ILAW glass, leachate collection system, etc.

Since 1998, the IDF PA (formerly the ILAW PA) has been supported by a PA maintenance plan focused on collecting the critical data needed to predict long-term performance: site geology, recharge, hydrology, geochemistry (measurement of site specific  $K_d$  values for key contaminants of concern), and waste form release. The purpose of the PA maintenance plan is to allow PA revisions to reflect new scientific information that reduces the technical uncertainty associated with critical aspects of the PA. Although many of the components contained in the engineered system and addressed in previous IDF PAs are important in minimizing radionuclide release, arguably the most important, protective, and uncertain aspect of the engineered system is the long-term performance of the ILAW glass. The ILAW glass serves as a primary barrier for radionuclide release. Therefore, developing robust, scientifically defensible predictions of long-term glass

performance for the IDF PA is critical. The technical approach that is currently used to predict long-term release from ILAW glass for the IDF PA has gained acceptance from the Low-Level Waste Disposal Facility Federal Review Group (LFRG) and the international community evaluating the long-term corrosion of waste glass. It has also been peer reviewed and approved by a panel of independent experts during development of the 1998 IDF PA [1].

To support the early IDF PAs, much of the testing focused on three prototypic glasses developed by the Vitreous State Laboratory (VSL) of The Catholic University of America (CUA) that spanned the range of glass compositions expected to be produced by the WTP (LAWA44, LAWB45 and LAWC22); these glasses were selected based upon specific processing constraints and composition projections that were current at the time. However, subsequent work has expanded the range of glass compositions that may be produced at the WTP and this type of composition range expansion is likely to continue through the life of the project. Thus, while the basic technical approach is well developed, there is a need to expand the range of glasses tested in order to span the composition range expected to be disposed of in the IDF and to develop an understanding of the dependence of the underlying model parameters and reaction network on the ILAW glass composition. Consequently, more recent testing has been directed towards addressing that need. Results from that work have identified a number of areas for potential improvement of the glass corrosion model that has been developed to support the ILAW PA, including the need to better understand and quantitatively describe the alkali-hydrogen ion exchange (abbreviated as ion exchange or IEX). The need to link the quantified IEX properties to glass composition is also evident. In Fiscal Year (FY)19 and FY20, the team of Atkins/VSL completed a series of tests to evaluate the ability of a fed-batch type reactor system (termed a Pulsed-Flow Test, or PFT) to elucidate the time dependence of ILAW glass IEX [2, 3]. This work was important since many researchers believe that IEX is a diffusion limited process and will decrease with time. In contrast, the current IDF PA models IEX as a time-independent rate process. The Atkins/VSL tests were very successful and the work has resulted in a large volume of data representing some of the most detailed information on ion exchange for LAW glasses obtained to date.

To capitalize on the success of the FY19 and FY20 Atkins/VSL test results on six glasses, Washington River Protection *Solutions*, LLC (WRPS) has contracted with Atkins/VSL to collect IEX data on four more ILAW glasses using PFT, the results of which are the subject of the present report. The work described herein was performed according to a Test Plan [4] that is responsive to the corresponding WRPS scope of work [5].

The following sections provide a brief review of the current approach for modeling ILAW release; the alternative ion exchange modeling approach that was evaluated in the previous [2, 3] and present work; and an overview of the testing approach. Details and results are provided in the subsequent sections of this report.

## 1.2 ILAW Release Approach for the IDF PA

The technical approach that is currently used to predict long-term release from ILAW glass for the IDF PA has been developed, refined, and updated over the past decade or so. The approach and the supporting test data for ILAW glasses have been extensively documented [6 - 22]. A brief summary is presented in this section.

The underlying premise of the IDF PA is that the source term for radionuclide release is controlled by the long-term weathering of the glass matrix. This engineering-based approach has been used in previous PAs to provide the defense-in-depth required to defend the above premise and demonstrate through computer simulations that the proposed glass waste form will meet the regulatory requirements put forth by regulators and evaluated by the LFRG. The focus of this engineering-based approach is on estimating the model parameters and chemical reaction network needed to provide a robust simulation of glass weathering and the corresponding release of radionuclides over a period of approximately 10,000 years even though the DOE period of compliance is only 1000 years. The overall model incorporates the effects of chemical affinity and ion exchange. The model parameters  $\bar{k}_o$ ,  $\eta$ ,  $E_a$ , and  $K_g$  are used to populate a chemical affinity-based kinetic rate law that is based upon Transition State Theory (TST) [23]:

$$r = \bar{k}_o 10^{\eta pH} \exp\left(\frac{-E_a}{RT}\right) \left[1 - \left(\frac{Q}{K_g}\right)^\sigma\right] \quad (1.1)$$

where

- $r$  is the dissolution rate of the glass [ $\text{g}_{\text{glass}}/(\text{m}^2 \text{ d})$ ], which is estimated after normalizing the measured concentration of each dissolved glass component to its concentration in the glass (value dependent on component since glass dissolves incongruently<sup>1</sup>),
- $\bar{k}_o$  is the forward rate constant [ $\text{g}_{\text{glass}}/(\text{m}^2 \text{ d})$ ],
- $pH$  is the negative of the logarithm to base 10 of the hydrogen ion activity,
- $\eta$  is the power law coefficient, which is unitless,
- $E_a$  is the apparent activation energy (kJ/mol),
- $R$  is the gas constant [ $8.314 \cdot 10^{-3} \text{ kJ}/(\text{mol K})$ ],
- $T$  is the temperature (K),

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<sup>1</sup> If species are found in solution in proportion to their stoichiometry in the glass, dissolution is congruent. This is usually the case for boron for which the rate of release from the glass is proportional to the glass dissolution rate because it is typically not retained in any reaction product formed during leaching. However, to address the possible diffusive release of boron, molybdenum and rhenium spiked into the glass also are used as indicators of matrix dissolution. When alkali and boron in the leachate have similar normalized concentrations, their release is congruent.

- $Q$  is the ion activity product (unitless<sup>2</sup>),
- $K_g$  is the pseudo-equilibrium constant for the rate controlling phase or phases (unitless<sup>2</sup>), and
- $\sigma$  is the Temkin coefficient, which has been theoretically shown to equal one [24, 25].

Equation (1.1) relates the effect of: (1) pH, (2) temperature, and (3) the activities of species that affect the rate of glass dissolution via  $Q$ . Equation (1.1) is based on the kinetic rate equation developed by Åagaard and Helgeson [24], as applied to glass by Grambow [26] wherein orthosilicic acid ( $\text{H}_4\text{SiO}_4$ ) is the only rate controlling species in  $Q$ .

In addition to the dissolution rate equation, a term is included in the IDF PA calculations to represent the ion-exchange rate ( $r_{\text{IEX}}$ ) between sodium in the glass and hydrogen ions in the aqueous phase, as the glass-water reaction proceeds. In general, the ion exchange rate is a function of temperature, glass composition, and reaction progress (stage of the glass-water reaction), as well as solution pH [2, 3]. The potential importance of the contribution from ion exchange in the long-term corrosion mechanism had been emphasized previously by Feng and Pegg [27 - 29]. In previous glass testing work in support of the IDF PA, the standard approach to estimate this parameter has been that of McGrail et al. [8] and Pierce et al. [12] whereby  $r_{\text{IEX}}$  is obtained by subtraction of the boron dissolution rate from the sodium dissolution rate. Measurement of the temperature dependence of  $r_{\text{IEX}}$  also permits estimation of the activation energy  $E_{ad}$  of the Na ion exchange reaction, and thus a determination of  $r_{\text{IEX}}$  at the IDF nominal temperature of 15 °C. More recently, various issues with this approach have been identified [30, 31] including: (i) the reliability of this subtraction approach in view of the diffusive release of boron [16, 19]; (ii) an error in the calculation of  $r_{\text{IEX}}$  that has been propagated through previous work [31]; and (iii) the use of an  $r_{\text{IEX}}$  term that is independent of time and solution composition [30, 31]. In view of these issues, WRPS has commissioned studies of potential alternative approaches for incorporation of ion exchange into the rate law [30, 31].

The use of Equation (1.1) with suitably estimated parameters, together with  $r_{\text{IEX}}$ , solution speciation, and secondary phase formation, allows for the source-term to be estimated within a reactive chemical transport modeling framework that takes into account the coupled effects of fluid flow and glass-water reactions on the chemistry of fluids percolating through the disposal facility [32, 33]. Coupling the fluid chemistry with the kinetic rate equations allows the simulations to describe the response of the glass corrosion rate to changes in fluid composition as a function of time and space.

In previous work, the model parameters for Equation (1.1) have been obtained from the

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<sup>2</sup> Note that although  $Q$  and  $K_g$  are unitless, their values are dependent on the standard state that is used for the underlying activities (typically, a hypothetical ideal solution at a concentration of 1 mol per liter, which was used in this work). Consequently, their values are of no use unless these units are specified.

analysis of data produced using a variety of experimental techniques. The single-pass flow through (SPFT) test has been the primary technique used to estimate the coefficients of Equation (1.1). The results of recent work [2, 3] show that PFTs can also be used to obtain  $K_g$  and likely other parameters of Equation (1.1). Other tests used to evaluate glass durability are long-term high surface to volume ratio (S/V) product consistency test (PCT-B), vapor hydration test (VHT), and pressurized unsaturated flow (PUF) test. This suite of tests evaluates different aspects of the glass-water reaction over the course of the various regimes of glass weathering: the initial forward rate regime; the decreasing rate regime; the residual rate regime; and the alteration rate renewal regime. These regimes are described below.

The initial forward rate consists of both ion-exchange and hydrolysis reactions. In dilute to near-saturated solutions, the TST-based model (without the ion-exchange term) successfully accounts for silicate dissolution in terms of temperature, pH, and reactive surface area because hydrolysis is the controlling reaction. However, as the glass-water reaction proceeds and the concentrations of glass components (particularly the dissolved silicic acid concentration) increase in solution, the rate of dissolution decreases. For ILAW glasses tested under alkaline conditions, it has been observed that ion exchange becomes the dominant process controlling glass weathering under these near-saturated conditions [11], as predicted previously [29]. The data collected from SPFT experiments conducted as a function of pH, temperature, and silicic acid concentration are used to study these processes and to obtain the model parameters  $\bar{k}_o$ ,  $\eta$ ,  $E_a$ , and  $K_g$ .

As the glass continues to dissolve, the aqueous concentration of dissolved components approaches saturation with respect to the formation of a hydrated surface layer. The hydrated surface layer forms when relatively insoluble glass components (e.g., Al, Fe, and Si) accumulate in the bulk solution and condense at the glass-water interface. The rate of dissolution then continues at a relatively constant residual rate consistent with a process controlled by diffusion through the hydrated surface layer [34, 35]. The key alteration phase is often a clay mineral, such as a smectite or chlorite [16, 36, 37]. The precipitation kinetics associated with these phases can be complex, but in general the rate of secondary phase growth increases in response to an increase in the magnitude of supersaturation [38, 39]. In cases where an appreciable level of ion-exchange is present, the data collected from SPFT experiments conducted as a function of temperature and silicic acid concentration can be used to determine the model parameter  $r_{IEX}$ . Variable temperature experiments also permit extrapolation of  $r_{IEX}$  to a specific repository temperature.

Finally, depending on the type of alteration phases that form, the glass-water reaction can increase from the residual rate and return to an elevated rate. This type of behavior has been observed in accelerated testing of various glasses including US HLW glasses [36, 39-43], other HLW glasses [34, 35, 44-52], as well as Hanford low-activity waste (LAW) glasses [16, 42, 53-56].

The combined  $H^+/Na^+$  ion exchange and hydrolysis of the silicate network lead to the formation of a multi-layered reaction zone including a hydrated porous gel layer, and crystalline

phases that precipitate on the surface [46, 51]. Increasing the S/V (e.g., in PCT-B) is one method to explore higher reaction progresses and identify the secondary phases that are associated with resumption.

The data collected from VHT [16, 55], PCT-B [37, 42, 54-56], and PUF experiments [12] along with geochemical modeling and solid-phase characterization have been used to identify the key alteration phases formed as the glass weathers. The results from these tests provide the additional information needed to identify and constrain the appropriate chemical reaction network required for model simulations.

The above elements of the glass-water interactions are incorporated into the conceptual model that is used in the IDF PA to model glass dissolution, as described in more detail elsewhere [57].

### **1.3 Alternative Ion Exchange Approach**

As described above, the current approach for modeling the release of contaminants from glass dissolution in the IDF PA employs a chemical affinity-based kinetic rate law that is used in combination with a term ( $r_{IEX}$ ) that is intended to represent  $H^+/Na^+$  ion exchange, together with the formation of secondary solid phases. Historically, the ion-exchange term has been assumed to be a constant for any given glass and depends only on temperature. As in the previous FY19 and FY20 work [2, 3], the present work addresses the need for an improved methodology for including ion exchange and for measuring the relevant  $H^+$ /alkali ion exchange parameters. The approach follows the recommendations provided in reference [30], which are in turn based on the findings of Feng and Pegg [29]. Thus, specific features of the present approach include:

- Recognition that ion exchange is a diffusive process and therefore the rate is expected to decrease as the square root of time;
- Recognition that ion exchange involves the exchange of an alkali ion by a hydronium ion or a proton and therefore the rate is expected to depend on the concentration of those species in solution. In other words, the ion exchange rate is expected to depend on the solution pH and to decrease as the pH increases;
- Recognition that ion exchange involves an activation energy and the rate is therefore expected to show an Arrhenius dependence on temperature;
- Recognition that all alkalis are subject to ion exchange, not just sodium. While sodium is the major alkali in LAW glasses, lithium becomes increasingly important as the sulfur content in the waste increases since lithium (and other species such as vanadium and calcium) is added in increasing amounts to the glass formulations. Significant amounts of potassium are present in some wastes, which may also need to be considered.

As stated earlier, in comparison, the present approach used in the IDF PA employs an ion exchange rate that is constant with respect to time and solution composition, and for sodium only.

The approach of Feng and Pegg [29], together with the recognition that ion exchange and diffusive processes are expected to show an Arrhenius dependence on temperature, addresses all of the above issues and provides a rational basis for improvement of the manner in which ion exchange is incorporated into the IDF PA modeling. In that approach, release of alkalis by ion exchange is governed by the following rate equation [29]:

$$\frac{d[R^+]}{dt} = \frac{1}{2} k_d \frac{S}{V} \left( \frac{[H^+]}{[H^+]_0} \right)^\alpha t^{-1/2} \quad , \quad (1.2)$$

where  $[R^+]$  is the solution concentration of alkali  $R$  due to ion exchange,  $k_d$  is a rate constant,  $S$  is the glass surface area,  $V$  is the solution volume,  $[H^+]$  is the  $H^+$  concentration,  $[H^+]_0$  is a scaling factor,  $t$  is time, and  $\alpha$  is a constant (set equal to one half in [29] based on consistency with the data set analyzed in [29]). It should be noted that this provides a separate release mechanism for alkali above and beyond that provided by Equation (1.1).

Mathematically, both the time dependence and the pH dependence in Equation (1.2) are equivalent to those later described by Ojovan et al. [58] and subsequently implemented in the GRAAL model [59, 60], which together provide further underpinning of the basis for this approach. However, the interpretation is somewhat different in the GRAAL model (diffusion of all species through a protective layer in the GRAAL model [59, 60] versus diffusion-controlled release of alkali via ion exchange in [29] and [58]).

Finally, the temperature dependence is included by replacing  $k_d$  by  $k_d(T)$  and writing:

$$k_d(T) = k_{d0} \exp\left(-\frac{E_{ad}}{RT}\right) \quad (1.3)$$

where  $k_d(T)$  is the temperature dependent rate constant,  $k_{d0}$  is a constant,  $E_{ad}$  is an effective activation energy for ion exchange,  $R$  is the gas constant, and  $T$  is the absolute temperature. As noted previously [16, 30], if the ion exchange process is further interpreted in terms of the Doremus interdiffusion model [61], the rate constants are interpreted as diffusion coefficients and the term  $RT$  is replaced by  $2RT$  in Equation (1.3); as in previous work [2, 3], we adopt the rate constant approach and effective activation energy shown in Equation (1.3) for the present work.

As noted above, in the present IDF PA, sodium ion exchange is incorporated via an ion exchange rate that is assumed to be a constant (though sometimes temperature dependent) for any given glass. That rate,  $r_{IEX}$ , is expressed as moles of sodium released from the glass per unit time per unit glass surface area (typically  $\text{mol}_{\text{Na}} \text{m}^{-2} \text{s}^{-1}$ ). Clearly, that quantity can be obtained from

Equation (1.2) by simply dividing by S/V. Thus, combining all of these results, the proposed new ion exchange rate is given by:

$$r_{\text{IEX}} = \frac{1}{2} k_{d0} \exp\left(-\frac{E_{ad}}{RT}\right) \left(\frac{[H^+]}{[H^+]_0}\right)^\alpha t^{-\frac{1}{2}} \quad (1.4)$$

Setting  $[H^+]_0 = 1$  mol per liter and using  $\text{pH} = -\log a\{H^+\} \approx -\log [H^+]$ , where “log” denotes the logarithm to base ten, we obtain:

$$r_{\text{IEX}} = \frac{1}{2} k_{d0} \exp\left(-\frac{E_{ad}}{RT}\right) 10^{-\alpha \text{pH}} t^{-\frac{1}{2}} \quad (1.5)$$

and therefore:

$$\log r_{\text{IEX}} = A + \frac{B}{T} + C \text{pH} - \frac{1}{2} \log t \quad (1.6)$$

where  $A = \log(k_{d0}/2)$ ,  $B = -(E_{ad}/R) \log e$ , and  $C = -\alpha$ .

We can also generalize Equation (1.4) to allow for deviation from square-root-of-time behavior by writing:

$$r_{\text{IEX}} = \frac{1}{2} k_{d0} \exp\left(-\frac{E_{ad}}{RT}\right) \left(\frac{[H^+]}{[H^+]_0}\right)^\alpha t^{-\gamma} \quad (1.7)$$

which yields:

$$\log r_{\text{IEX}} = A + \frac{B}{T} + C \text{pH} + D \log t \quad (1.8)$$

where  $D = -\gamma$ .

Equations (1.6) and (1.8) were used for the regression analysis of the PFT data, as described in Section 5.

The above approach could potentially address many of the shortcomings in the present IDF PA rate law and should be relatively simple to implement. However, any such approach requires a supporting test program that is designed to determine, over the range of ILAW glass compositions of interest, the new model parameters that are introduced. The work described herein further demonstrates the viability of this approach, which was verified for three glasses in the FY19

work [2] and three more glasses in FY20 work [3], and expands the ion exchange data set to cover more of the LAW glass composition range.

It should be noted that ion exchange and matrix dissolution do not occur independently but are coupled processes that occur simultaneously, as described previously [29]. Thus, while in isolation, Equation (1.2) indicates that the ion exchange rate goes to zero as time goes to infinity, that is not the case when that process is coupled with matrix dissolution, described, for example, by Equation (1.1). Essentially, the velocity with which the diffusive alkali depletion front propagates into the glass is proportional to Equation (1.2) and that velocity decreases as that depletion layer increases in thickness. However, the glass is also being dissolved at the outer surface (the surface in contact with the solution) via matrix dissolution and, therefore, that surface propagates inwards at a velocity proportional to Equation (1.1); this process tends to thin the alkali depletion layer. This is a classic moving boundary problem, which has a steady-state solution wherein the two velocities become equal and the depletion layer moves inwards but with a constant thickness [29]. As a result, the time dependence will change from that typical for a diffusive system ( $t^{1/2}$ ) to a time independent system ( $t^0$ ). Finally, other processes, such as the evolution of the solution composition and secondary phase formation, also modify the overall reaction trajectory. Thus, in implementation, Equations (1.1) and (1.5) (or the corresponding version of (1.7)) are coupled through the solution chemistry and speciation and precipitation reactions, which are typically handled in a geochemical code that forms part of the overall model. In the original work of Feng and Pegg [29], this coupling of the solution chemistry (but not secondary phase formation) was performed explicitly for silicon species only. Furthermore, the moving boundary aspects of the problem were handled in an approximate fashion by noting that, within this model, the velocity of the ion exchange front cannot fall below the velocity of the matrix dissolution front; therefore, if the calculated velocity of the ion exchange front does fall below the velocity of the matrix dissolution front, the former should be replaced by the latter, which leads to corresponding criteria for the ion exchange rate and matrix dissolution rate. Feng and Pegg [29] describe the various regimes in this overall process as these two rates approach each other and, ultimately, become equal.

## **1.4 Test Overview**

Per the Test Plan [4] and WRPS work scope [5], this work addressed the measurement of ion exchange rates for selected LAW glasses using the PFT approach described in Section 1.3. The test conditions included variations in temperature, pH, and time in order to further test the alternative ion exchange model described in Section 1.3 and to determine the parameters in the ion exchange model for each glass.

As described in the glass selection document provided to WRPS for review [62] and subsequently approved by WRPS, four glasses were selected to address the ongoing objective of filling gaps in the compositions of glasses tested previously for ion exchange. The first three glasses were formulated using the WTP Baseline LAW Glass Correlation [63] and the fourth glass

was formulated using the Enhanced LAW Glass Correlation for high waste loading glasses [64]. These glasses, IDF21-1, IDF21-2, IDF21-3, and IDF21-4, were selected to address gaps in the existing ion exchange data [62]. The versions of these formulations used in the present work are labeled IDFIX21-1, IDFIX21-2 IDFIX21-3 and IDFIX21-4, respectively, in order to identify the particular batches of these formulations, including specific component spikes, used for the present testing.

The work included fabrication, heat treatment, and confirmation of the composition of the selected glasses followed by testing to determine ion exchange rates using the Pulsed-Flow method. The data were analyzed to test the applicability of the ion exchange model form proposed by Feng and Pegg [29], as described in Section 1.3. Tests were conducted at three temperatures (70°C, 40°C, and 23°C) and five different buffer compositions covering a pH range from 7 to 11 (at room temperature) with ten sampling times for each experiment. The leachants were spiked with silicic acid in order to decrease the rate of matrix dissolution so that the relative ion exchange contribution to the overall glass dissolution rate was enhanced.

## **SECTION 2.0 GLASS SELECTION AND FABRICATION**

### **2.1 Glass Selection**

The primary approach in glass selection for the present work was to fill gaps in the existing ion-exchange data from the perspective of the compositions of the glasses that have been tested previously and their coverage of the composition range. For convenience, a list of glasses previously tested by SPFT is included in Table 2.1 and prior PFT results are included in Table 2.2. The compositions of SPFT and PFT glasses are combined in Table 2.3. As seen in the table, determination of the sodium ion exchange rate was not possible using the SPFT for three glasses: LAWB45 [15], IDF3-F7 [16], and IDF7-E12 [18]. These three glasses have:

- The highest, second highest, and fourth highest concentrations of  $\text{Li}_2\text{O}$  of all the glasses tested for ion exchange rate to date;
- The lowest, second lowest, and fourth lowest concentrations of  $\text{Na}_2\text{O}$  of all the glasses tested for ion exchange rate to date;
- The highest, and second highest concentrations of  $\text{SO}_3$  of all the glasses tested for ion exchange rate to date;
- The highest concentration of  $\text{MgO}$  of all the glasses tested for ion exchange rate to date.

Consequently, the previous inability to obtain ion exchange data for these glasses leaves a significant gap in the glass composition space with ion exchange data.

Figure 2.1 shows a scatter-plot matrix of the compositions of the 18 glasses listed in Table 2.3, excluding the three glasses for which no ion exchange rate data are available. The nine glasses for which ion exchange data were obtained by SPFT are identified by red full circles [15, 16, 18-22, 50]; the three glasses tested by both SPFT and PFT are identified by black diamonds [2]; and the three glasses tested by PFT only are identified by blue triangles [3]. The gaps described above are evident in this plot, as are others, as discussed below.

The use of early Tank Farm Contractor Operations and Utilization Plan (TFCOUP) data [65] is responsible for some of the observed gaps. For example, this leads to high potassium in the tank waste being correlated with low sulfate, which is then reflected in the resulting glass composition coverage. However, feed make-up logistics could well lead to blends that deviate from this correlation. The  $\text{Li}_2\text{O}$ - $\text{K}_2\text{O}$  plot in Figure 2.1 shows a clear gap in the center because the two previous glasses tested in SPFT at high  $\text{K}_2\text{O}$  do not include any  $\text{Li}_2\text{O}$ . This is because, according to the WTP Baseline LAW Glass Formulation Correlation [63] and the Enhanced LAW

Glass Formulation Correlation [64] developed previously by VSL, lithium is added as a glass former only at higher  $\text{SO}_3$  waste contents. Furthermore, in the Enhanced LAW Glass Formulation Correlation for high waste loading glasses, higher  $\text{SO}_3$  also drives the addition of  $\text{V}_2\text{O}_5$  (and  $\text{CaO}$ ), which leads to visible gaps in the  $\text{V}_2\text{O}_5$ - $\text{K}_2\text{O}$  plot.

These considerations were used to inform the present selection of glasses for testing but this was balanced against the importance of the alkalis for ion exchange and the process control strategy for the WTP, which is based on the above-mentioned Correlations, and which will determine the range of compositions that are likely to be produced at the WTP.

The four glasses recommended for this work range in concentrations from 9.78 to 21.0 wt%  $\text{Na}_2\text{O}$  (Table 2.4), all include some  $\text{K}_2\text{O}$ , ranging from 0.75 wt% to 5.0 wt%, and two of the glasses include  $\text{Li}_2\text{O}$  at 2.35 wt% and 3.82 wt%, respectively, so that a significant quantity of all three major alkalis are present in these two glasses.

Three of the glasses recommended were formulated using the WTP Baseline LAW Glass Correlation [63], at 9.8, 13.8, and 21 wt%  $\text{Na}_2\text{O}$  and with respective potassium contents of 1.0, 2.0, and 0.75 wt%  $\text{K}_2\text{O}$ . As illustrated in Figure 2.2, these three glasses also further cover the ILAW compositional space of glasses tested by either SPFT or PFT. In particular, these three glasses lie on the WTP Baseline Correlation line and bracket the glass formulation for the DFLAW commissioning feed (AP107WDFL). The fourth glass was formulated using the high waste loading Enhanced LAW Glass Correlation [64] at 21 wt%  $\text{Na}_2\text{O}$ , 5 wt%  $\text{K}_2\text{O}$ , and higher  $\text{SO}_3$  content than formerly tested with high potassium glasses, thus requiring (by Correlation design) the addition of both  $\text{V}_2\text{O}_5$  and  $\text{SnO}_2$ . Because of the high  $\text{K}_2\text{O}$  content, the waste loading in this glass is not limited by the  $\text{Na}_2\text{O}$  content but, instead, is limited by  $\text{ALK} = \text{Na}_2\text{O} + 0.66 \times \text{K}_2\text{O} < 24.3$  wt%. In Figure 2.2, it lies between the two Correlation lines (WTP Baseline in blue and Enhanced in red), which is a region that has not been addressed previously.

Using the most recent glass property-composition models [66-69], PCT-B, PCT-Na, VHT, melt viscosity, and electrical conductivity (at 1100°C and 1150°C), K-3 neck corrosion, as well as sulfate solubility were calculated for the four recommended new glasses and are given in the lower section of Table 2.4. All properties are within contractual limits and the  $\text{SO}_3$  contents are below the respective estimated solubility limits.

As was the case in previous PFTs [2, 3], the recommended glass compositions also include spikes of rhenium and molybdenum as indicators of matrix dissolution, and cesium, which together with sodium, lithium, and potassium, allows for assessment and comparison of the behavior of all of the alkalis in LAW glasses. Rhenium is also a non-radioactive surrogate for technetium and its dissolution behavior, therefore, provides information regarding the long-term immobilization of technetium in LAW glasses.

The recommendations of the above glass compositions for testing [62] were reviewed and approved by WRPS before preparation, characterization, and testing of these glasses.

## **2.2 Glass Preparation**

The four glass compositions selected were prepared from reagent grade or higher purity chemicals according to VSL standard operating procedures. Briefly, an appropriate combination of well-mixed chemicals was melted at 1200°C for 75 minutes in a platinum-gold crucible. Mixing of the melt was accomplished with a platinum stirrer beginning 15 minutes after the start of melting and continuing for the next 60 minutes, until the end of melting. The melt batch included a rhenium spike targeted at 0.1 wt%  $\text{Re}_2\text{O}_7$ , if all of it were retained in the glass. Since rhenium is subject to significant volatile loss from the glass during melting, excess  $\text{Re}_2\text{O}_7$  was added to compensate, assuming an average retention of 53.5% based on extensive past testing [70]. This results in the addition of 0.93 g, instead of 0.50 g of  $\text{Re}_2\text{O}_7$ , to each batch targeting 500 g of glass. Spikes of  $\text{Cs}_2\text{O}$  and  $\text{MoO}_3$ , targeted at 0.15 wt% and 0.10 wt%, respectively, were not over-batched since any volatile losses, which are expected to be much smaller than that for rhenium, have not been as well quantified as that for rhenium.

The as-melted glass samples (before heat treatment) showed no visible sulfate layer. Glasses IDFIX21-1, IDFIX21-2, and IDFIX21-3 were dark brown in color due to their high  $\text{Fe}_2\text{O}_3$  content and IDFIX21-4 was emerald green, the coloration from chromium and vanadium being more visible because the iron content is very low. A portion (~50 to 60 g) of the as-melted glass was set aside for analysis and the remainder was subjected to canister centerline cooling (CCC) heat treatment according to the WTP LAW container cooling profile [71] shown in Figure 2.3. After CCC heat treatment, the sample was about 11 cm in diameter at the surface and about 2 cm thick and the four glasses remained translucent throughout (brown and emerald green, respectively – see Figure 2.4), indicating homogeneous crystal-free glasses. As expected from glass property-composition models, no sulfate layer was observed in any of the four glasses.

## **2.3 Glass Compositional Analysis**

The primary method used for glass composition analysis was X-ray fluorescence spectroscopy (XRF) on powdered glass samples. A PANalytical Axios<sup>mAX</sup>-Advanced XRF spectrometer was used for this purpose. The XRF is calibrated over a range of glass compositions using standard reference materials traceable to the National Institute of Standards and Technology (NIST), as well as waste glasses such as the Argonne National Laboratory – Low-Activity Waste Reference Material (ANL-LRM) [72] and the Defense Waste Processing Facility (DWPF) – Environmental Assessment Glass (EA) [73]. Since boron and lithium are not determined by this procedure, it is supplemented by acid digestion followed by solution analysis, as described below.

Glass samples for analysis by inductively coupled plasma atomic emission spectroscopy (ICP-AES) analysis are first subjected to microwave-assisted total acid dissolution in Teflon vessels according to VSL standard operating procedures. Twenty milliliters of a 1:5 mixture of concentrated  $\text{HF}:\text{HNO}_3$  is diluted to 50 ml and used for the dissolution. This procedure is similar

to the American Society for Testing and Materials (ASTM) Test Method C1412-99, which also employs a mixture of concentrated HF and HNO<sub>3</sub> in microwave digestion of pulverized glass samples; supplemental use of HCl/H<sub>3</sub>BO<sub>3</sub> is not included in the VSL procedure since boron is normally one of the analytes. The solutions resulting from the acid digestion are analyzed by ICP-AES.

The glass composition analyses were performed on replicate samples, including the as-melted glasses and the sample subjected to CCC, which were both analyzed separately for composition by XRF, and ICP-AES after total acid digestion. The samples are typically rejected when major oxides, with target concentrations of 3 wt% or more, show relative deviations from the target composition of greater than 10%. The results provided in Table 2.5 show that the glasses are on target for all of the major glass constituents. SO<sub>3</sub> is found to be slightly below target, with a loss of 0.01 to 0.19 wt% SO<sub>3</sub> from target and no significant differences observed between the as-melted glass and the sample subjected to CCC for the two lower sulfate formulations (<0.1 wt% loss). Cl is another volatile constituent, which shows a loss of ~0.05 to 0.14 wt%.

Rhenium was one of three spikes that were added for the specific purpose of estimating ion-exchange in glass during leaching. Rhenium was over-batched to compensate for volatile loss during melting; evaluation of 363 earlier crucible melts at a target Re<sub>2</sub>O<sub>7</sub> concentration of 0.1 wt% showed an average retention of 53.5% [70]. With this compensation, the rhenium content in the three glass samples subjected to CCC varies from 0.094 to 0.119 wt% Re<sub>2</sub>O<sub>7</sub>. Batching did not include any compensation for volatility of the other two spikes, cesium and molybdenum. The spike of 0.15 wt% Cs<sub>2</sub>O in all measured glass samples varies from 0.114 to 0.131 wt%. Molybdenum was batched at 0.1 wt% and was measured between 0.07 and 0.10 wt% MoO<sub>3</sub>, indicating a relatively small volatile loss during melting. Table 2.6 provides a description of the glass compositions, highlighting the species used to monitor matrix dissolution and the alkalis for which ion exchange rates were determined. The measured rhenium, cesium, and molybdenum concentrations (Table 2.6) for each glass were used in normalization of the leaching data presented in Section 4 and the target value was used for the main glass constituents.

## **2.4 Glass Evaluation and Preparation for Pulse-Flow Testing**

In addition to composition analysis, evaluation of the glass samples included scanning electron microscopy (SEM) imaging of cross-sectioned, polished and carbon-coated grains with energy dispersive X-ray spectroscopy (EDS) analysis. These methods were used to verify that samples IDFIX21-1CCC, IDFIX21-2CCC, IDFIX21-3CCC, and IDFIX21-4CCC were free of crystallization at microscopic scale. All samples were found to be free of crystallization. At large magnification, small spherical voids (0.1 to 1 µm in diameter) were observed in IDFIX21-4CCC, which are likely the remnants of minute sulfate inclusions in the glass.

Composition analysis by EDS of glass free of crystallization at the center of the crucible showed results consistent with the XRF analysis and the target glass composition.

Glass ground from each CCC heat treated sample was used for the PFTs. Prior to their use in the leach tests, the glass samples were crushed and sieved to 100-200 mesh (75-149  $\mu\text{m}$ ). The ground glass was washed (2 minutes in deionized water and 2 minutes in 99% absolute ethanol) and air-dried to remove fines, which tend to dissolve faster than glass grains during leach tests and, thus, interfere with the test results.

The measured densities of the four glasses are  $2.716 \text{ g.cm}^{-3}$  for IDFIX21-1CCC,  $2.722 \text{ g.cm}^{-3}$  for IDFIX21-2CCC,  $2.688 \text{ g.cm}^{-3}$  for IDFIX21-3CCC, and  $2.698 \text{ g.cm}^{-3}$  for IDFIX21-4CCC.

To simplify discussion in subsequent sections of this report, the four glasses are referred to as IDFIX21-1, IDFIX21-2, IDFIX21-3, and IDFIX21-4, or, equivalently, as IX21-1, IX21-2, IX21-3, and IX21-4, with the understanding that all of the samples that were tested were collected from the above described batches of CCC heat treated material.

## **SECTION 3.0 ION-EXCHANGE RATE TESTING**

### **3.1 Pulsed-Flow Test Matrix**

The four glasses were subjected to PFTs as a function of pH, temperature, and time at silicic acid saturation, according to a test matrix similar to that typically used for SPFT testing.

The standard SPFT test matrix on a single glass includes 48 tests that vary temperature, pH, silicic acid concentration, and test time. In the present work, which was focused on the determination of ion exchange rates, only the highest silicic acid concentrations (at each test condition) was used. Similar silicic acid spiking was used for tests at all five values of pH instead of at pH 9 only in the typical SPFT test matrix. In previous SPFT testing, the tests at pH 11 and 12 have employed LiOH/LiCl “buffers.” These solutions are not very effective at holding the pH but, more important for the present purpose, they introduce large (and artificial) concentrations of lithium, which can ion exchange with other alkalis (notably sodium) in the glass, thereby complicating data interpretation and preventing the measurement of lithium ion exchange all together. Therefore, alkali-containing buffers were avoided in the present work. Instead, as was successfully used in previous PFTs [2, 3], the amine buffer piperidine was used for pH 11; testing at pH 12 was not performed. In addition to the deletion of the pH 12 tests, it was necessary to reduce the number of temperature conditions from four to three due to funding limitations. In this manner, the ion exchange test matrix on a single glass could be completed with 15 tests, according to the matrix described in Table 3.1, which includes:

- Five values of  $\text{pH}_{\text{RT}}^3$  (7, 8, 9, 10, 11)
- Three values of temperature (23, 40, 70°C)
- All tests with silicon spiking ranging from 35 to 360 ppm
- All tests measure B, the alkali species Na, K, and Li, Al, and the three spikes Re, Mo, and Cs in solution
- All tests run for sufficient time to adequately define the time dependence (10 to 30 days) and a minimum of 10 samples for each experiment.

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<sup>3</sup> Subscript indicates pH values obtained from measurements at room temperature (RT).

### **3.2 Solution Preparation**

Glass leaching experiments at a  $\text{pH}_{\text{RT}}$  range from 7 to 10 were performed in 0.05 M tris(hydroxymethyl)aminomethane (Tris) solutions buffered to the target pH using concentrated  $\text{HNO}_3$ . Glass leaching experiments at  $\text{pH}_{\text{RT}}$  11 were performed in piperidine buffered with concentrated  $\text{HNO}_3$ . A small amount of piperidine was also required to adjust the  $\text{pH}_{\text{RT}}$  10 solutions. For a 0.05 M piperidine stock solution, 4.26 g piperidine (Aldrich, >99.5%,  $d = 0.862 \text{ g/mL}$ ,  $\text{pK}_a$  11.22) was removed with a syringe from the sealed bottle, added dropwise to a tared plastic bottle containing deionized water, and then diluted to one liter.

Leaching solutions containing varying amounts of Si were prepared by dissolving analytical grade silicic acid powder ( $\text{SiO}_2 \cdot \text{H}_2\text{O}$ ) in 0.05 M Tris or piperidine. Due to the low solubility of amorphous silica in aqueous solutions, Tris stock solutions containing at least 160 ppm [Si] were prepared, heated at  $90^\circ\text{C}$  for a period of time (typically a week), decanted carefully into fresh bottles to avoid transfer of precipitated solids, and analyzed by ICP-AES in order to determine the concentration of Si. As necessary, the stock solutions were diluted to the target [Si] and buffered to  $\text{pH}_{\text{RT}}$  7, 8, 9, or 10, as previously described. For the piperidine stock solution, the 2.5 g of silicic acid powder added to one liter of 0.05 M piperidine solution could not be completely dissolved even after a week at  $90^\circ\text{C}$ . After careful decantation and analysis ( $\sim 700 \text{ ppm Si}$ ) the solution was diluted with 0.05 M piperidine to the target [Si] and the pH was adjusted from about 11.6 to 11.0 using concentrated nitric acid. The silicic acid ( $\text{pK}_a \sim 9.9$ ) brings down the pH of the piperidine solution, so less  $\text{HNO}_3$  is needed to adjust the pH to 11. The pH of the piperidine-base 0.05 M stock solution was about 11.5. Concentrated nitric acid ( $\sim 500 \mu\text{L}$ ) was added to adjust the pH to 11 for one liter of buffer containing silica. Silicic acid also brings down the pH of the 0.05 M Tris solution, in the range of about 9.6 to 9.9, so that about 15 drops of piperidine per liter of buffer are needed to adjust the pH to 10.0 at 105 ppm [Si] ( $\sim 10$  drops at 90 ppm [Si] and  $\sim 23$  drops at 140 ppm [Si]).

The  $\text{pH}_T^4$  values of the buffer solutions, heated to the test temperature, were measured using a temperature-compensated pH meter. Determination of  $\text{pH}_T$  was necessary for the calculation of model parameters using Equation (1.1) and the pH dependence of ion exchange in Equations 1.6 and 1.8. The pH values are provided in Table 3.2, showing good agreement with those of solutions used in previous tests [2, 3, 18, 20, 22].

### **3.3 Description of Pulsed-Flow Experimental Setup**

The rationale for flow-through tests such as the SPFT is to achieve steady state with respect to species in solution in order to control the affinity term in the rate law. Frequently, that steady

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<sup>4</sup> Subscript indicates pH values measured at the test temperature  $T$ .

state corresponds to essentially very dilute conditions wherein the affinity term is equal to one. This condition is favored by higher flow rate, but then the concentrations in solution become very small and therefore a practical compromise must be reached. Typical volumetric flow rates employed in SPFT tests on LAW glasses have been in the range of about 7 to 50  $\mu\text{L}/\text{min}$ , which corresponds to about 10 to 72  $\text{mL}/\text{day}$ .

An often simpler approach to flow-through testing is to employ pulsed flow instead of continuous flow, wherein a portion of the leachate solution is replaced by fresh leachant at regular intervals to achieve the same average flow rate. This type of partial replenishment test was developed and employed extensively by VSL beginning in the 1980s for the HLW glass development and testing program and was called the “Pulsed-Flow Test.” VSL has hundreds of such tests still in progress that have been running for many decades [39, 41, 74, 75].

The present tests were designed with a periodic replacement of 50% of the leachate with fresh leachant in a 50-ml stainless steel vessel. The replacements were set at intervals of 1-day at 70 °C and 3-days at 40 °C and 23 °C. The quantity of glass was adjusted so that its surface area would approach the linear flow rate<sup>5</sup>,  $q/S$ , and residence time values employed in previous SPFT tests on Hanford LAW glasses, as shown in Table 3.1. From each of the 25-ml samples collected, an aliquot of 5 ml was pipetted and reserved for pH measurement and the remaining 20 ml was sampled for analysis after acidification.

### **3.4 Sample Analysis**

The pH was measured on each sample collected from the flow-tests. The measured pH values were found to remain at the target buffer values with less than 1% relative deviation for all buffers for glasses IDFIX21-1, IDFIX21-2, and IDFIX21-3. With the higher waste loading glass IDFIX21-4, the deviation is also less than 1% relative in most experiments, except for the  $\text{pH}_{\text{RT}} 7$  buffer at 70 °C (+6% relative on average) and at 40 °C (+4%).

Collected samples designated for solution analysis were acidified with a small amount of concentrated  $\text{HNO}_3$  or 1:5 mixture  $\text{HF}/\text{HNO}_3$  for the  $\text{pH}_{\text{RT}} 11$  buffer highest in Si, and analyzed by ICP-AES for B, Al, Li, K, and Na. Analyses of Mo, Re, and Cs were conducted by inductively coupled plasma – mass spectroscopy (ICP-MS).

A total of 60 PFTs were performed yielding, with the buffer blanks and standard mix controls, 725 individual samples analyzed for solution chemistry. The nomenclature used for PFT samples was “IX21-glass number-Buffer ID-Dx” where x is the sequential number of sampling,

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<sup>5</sup> The linear flow rate is calculated as the volumetric flow rate divided by the total surface area of glass in the test vessel.

from 1 to 10; note that sampling 10, for example, is at 10 days for 70°C but it is at 30 days for 23°C and 40°C. Buffer identifications are given in Table 3.2. Two samples were found to be contaminated (IX21-2-E3D10, IX21-3-D3D10 ) and a few data points were identified as possible outliers in modeling. However, only the two contaminated samples were removed from the model set. At the end of the experiment, the altered glasses were collected, water-washed gently, and air dried. The altered glass samples were archived for potential future characterization.

### 3.5 Data Reduction

To the extent possible, the guidelines for SPFT data analysis in the ASTM standard [76] were adapted for the Pulsed-Flow data, as described in this section. The more substantive changes that are required are described in Sections 3.5.1 and 3.5.2.

For the SPFT, if a glass specimen having a known surface area is contacted by a solution that flows continuously at a known flow rate and at a constant temperature, the concentration of the  $i$ -th soluble glass component in the effluent solution exiting the reactor vessel can be used to calculate the amount of glass that has dissolved. The flow rate is determined by dividing the mass of solution that is collected for analysis by the duration over which it was collected. The dissolution rate of the glass ( $\text{g m}^{-2} \text{ day}^{-1}$ ) is then calculated as [68]:

$$(\text{rate}) = \frac{[C_i - C_i^o] \cdot \left( \frac{F}{S^o} \right)}{f_i} \quad (3.1)$$

where:

$C_i$  - is the steady-state concentration of component  $i$  measured in the effluent solution (g/L)

$C_i^o$  - is the background concentration of component  $i$  in the influent solution as measured in a blank test (g/L)

$F$  - is the solution flow rate (L/day)

$S^o$  - is the initial surface area of the glass sample that is exposed to solution ( $\text{m}^2$ ), and

$f_i$  - is the mass fraction of component  $i$  in the glass (g/g).

Several samples of the effluent solution are collected during the SPFT test to determine the steady-state concentrations of dissolved glass components at a particular solution flow rate.

When testing a crushed glass sample, its surface area ( $S^o$ ) is calculated as the product of the specific surface area and the mass of glass ( $m_g$ ) used in the test. The specific surface area is approximated based on the mesh size of the fraction used in the test and the density of the glass. The particles of glass are presumed to be spherical with diameter ( $d$ ) equal to the arithmetic average

of the openings of the sieves used to prepare the material ( $d = 5.625 \times 10^{-5}$  m for the -100 to +200 mesh fraction). The specific surface area ( $S_p$ ) of a glass having a density  $\rho$  is [76]:

$$S_p = \frac{6}{\rho \cdot d} \quad (3.2)$$

thus, 
$$S^o = S_p \cdot m_g \quad (3.3)$$

The specific areas calculated using this approach are all very close for the four glasses:  $1.963 \times 10^{-2} \text{ m}^2 \cdot \text{g}^{-1}$  for IDFIX21-1 ( $\rho = 2.716 \text{ g} \cdot \text{cm}^{-3}$ ),  $1.960 \times 10^{-2} \text{ m}^2 \cdot \text{g}^{-1}$  for IDFIX21-2 ( $\rho = 2.722 \text{ g} \cdot \text{cm}^{-3}$ ),  $1.984 \times 10^{-2} \text{ m}^2 \cdot \text{g}^{-1}$  for IDFIX21-3 ( $\rho = 2.688 \text{ g} \cdot \text{cm}^{-3}$ ), and  $1.976 \times 10^{-2} \text{ m}^2 \cdot \text{g}^{-1}$  for IDFIX21-4 ( $\rho = 2.698 \text{ g} \cdot \text{cm}^{-3}$ ).

In the SPFT, the volumetric flow rate ( $F$ ) is calculated by dividing the mass of solution that is collected by the time for its collection and its density (which can be assumed to be  $1 \text{ g/cm}^3$  in most cases).

During glass dissolution, the mass and surface area of the glass sample are expected to change over time as material is dissolved. The surface area  $S_j$  at time  $j$  during a SPFT test is calculated from the following expression [76]:

$$S_j = \frac{3}{\rho r_o} m_o^{1/3} m_j^{2/3} \quad (3.4)$$

where  $r_o$  is the radius of the glass particle and  $m_j$  is the sample mass at time  $j$ . The value of  $m_j$  is estimated by the equation [77]:

$$m_j = m_o - \frac{1}{f_i} \left[ \sum_{n=1}^{j-1} F_n C_{n,i} \Delta t_n + F_j C_{j,i} \frac{\Delta t_j}{2} \right], j \geq 1 \quad (3.5)$$

where  $i$  is an element representative of the extent of glass dissolution such as boron, which was used for this purpose in the present work. Here it should be noted that Equation (3.5) inherently assumes uniform dissolution during SPFT testing and the absence of any surface alterations such as cracking.

To determine the steady-state concentration ( $C_i$ ), the measured concentration of the  $i$ -th component is plotted as a function of time in order to visually identify the data to be used. Data that precede the attainment of steady-state conditions are excluded before calculating the mean and standard deviation of the remainder. The relative standard deviation (the standard deviation divided by the mean) of the calculated steady state concentration must be less than 0.15 for the SPFT test results to be valid [76]. Soluble components monitored in this fashion typically include silicon, aluminum, sodium, and boron. The parameters of Equation (1.1) are typically estimated

using normalized dissolution rate (NDR) of boron.

*Estimation of  $K_g$ .* For SPFT data,  $K_g$  is estimated from the NDR values obtained at steady state when the glass is leached in the presence of different concentrations of Si and at specific pH and  $T$ . To determine the parameter  $K_g$  at a given  $T$ , NDR values are plotted as a function of the activity of orthosilicic acid ( $a[\text{H}_4\text{SiO}_4]$ ) present in the effluent solutions at steady state (Equation (1.1)) and a linear regression on the data is performed. A similar approach was used for the PFT data. Values of  $a[\text{H}_4\text{SiO}_4]$  were determined from the corresponding solution chemistry using the geochemical code PHREEQC (database Phreeqc.dat 2010). According to Equation (1.1),  $K_g$  is given by the value of  $a[\text{H}_4\text{SiO}_4]$  at  $\text{NDR} = 0$  [10]. To determine the  $K_g$  value at the presumed repository temperature of 15 °C, the natural logarithm of the measured  $K_g$  values is plotted against the reciprocal of the absolute temperature and a linear regression is performed on the data [11].

*Estimation of ion exchange parameters.*  $r_{\text{IEX}}$  and  $E_{\text{ad}}$  for Na, Li, K, and Cs: Alkali ion exchange rates were obtained by subtracting the normalized PFT dissolution rates of either Mo, Re, or B from the normalized dissolution rate of the alkali and converting the result to moles of the specific alkali per unit glass surface area per unit time (*not* moles of *glass* per unit area per unit time). The activation energy  $E_{\text{ad}}$  of each alkali can be evaluated by performing a linear regression of the natural logarithm of the measured  $r_{\text{IEX}}$  values versus the reciprocal of the absolute temperature for a constant value of time and pH. The slope of each regression provides  $-E_{\text{ad}}/R$  according to Equation (1.3). The results from the regression can then be used to extrapolate the  $r_{\text{IEX}}$  values of each alkali to the presumed repository temperature of 15 °C. However, it is preferable to perform regression analysis on the entire data set (time, temperature, and pH) to extract the best estimates of all of the model parameters simultaneously, as described in Section 5.

The leachant flow in the SPFT is continuous, whereas in the PFT it is pulsed, and therefore discrete. Consequently, extraction of leach rates from the pulsed flow data requires a different approach from that used for the SPFT data per ASTM C 1662. Before describing the pulsed-flow case, it is instructive to describe first the derivation of the rate equation for the continuous case.

### 3.5.1 Continuous Flow Case

We consider a sample of glass with surface area  $S$  in a reactor of volume  $V$  that is filled with leachant that flows through the reactor continuously at a constant volumetric flow rate  $F$ . The rate of release of species  $i$  from the glass at time  $t$  is  $r_i(t)$  (mass of species  $i$  released into the leachant per unit surface area of glass per unit time). The mass of species  $i$  in solution in the reactor at time  $t$  is  $m_i(t)$  and the concentration is  $c_i(t) = m_i(t)/V$ . That mass increases as a result of release from the glass and decreases as a result of the leachant flow, such that its rate of change is given by:

$$\frac{dm_i(t)}{dt} = r_i(t)S - c_i(t)F \quad (3.6)$$

and therefore:

$$\frac{dc_i(t)}{dt} = r_i(t) \frac{S}{V} - c_i(t) \frac{F}{V} \quad (3.7)$$

At steady state,  $dc_i(t)/dt = 0$ , so:

$$r_i = c_i(t) \frac{F}{S} \quad (3.8)$$

To obtain the rate of glass dissolution,  $r_g$ , we normalize by dividing by  $f_i$ , the mass fraction of species  $i$  in the glass to obtain:

$$r_g = c_i(t) \frac{F}{S f_i}, \quad (3.9)$$

which, except for blank subtraction, is exactly the result given in Eq. 3.1 for analysis of SPFT data.

### 3.5.2 Pulsed-Flow Case

In the PFT, after each time interval  $\Delta t$ , a sample of the leachate of volume  $\Delta V$  is withdrawn from the vessel for analysis and a volume  $\Delta V$  of fresh leachant is added to the vessel. Considering the  $n^{\text{th}}$  and  $(n+1)^{\text{th}}$  samplings, we denote the concentrations of species  $i$  at each point in this process as follows:

$c_{i,n}$  = the concentration of species  $i$  at the  $n^{\text{th}}$  sampling before replacement

$c_{i,n,s}$  = the concentration of species  $i$  at the  $n^{\text{th}}$  sampling after replacement (i.e., at the start of the next leaching interval)

$c_{i,n+1}$  = the concentration of species  $i$  at the  $(n+1)^{\text{th}}$  sampling before replacement (i.e., at the end of that leaching interval).

The mass of species  $i$  in the leachant in the vessel after sampling is equal to the mass before sampling minus the mass removed; this quantity divided by the volume gives the concentration at the start of the interval:

$$c_{i,n,s} = (c_{i,n}V - c_{i,n}\Delta V) / V = c_{i,n} \left( 1 - \frac{\Delta V}{V} \right) \quad (3.10)$$

Over the interval  $\Delta t$ , the mass of species  $i$  added to the solution in the reactor is  $r_i S \Delta t$ ; it is also equal to the change in the concentration multiplied by the leachate volume:

$$(c_{i,n+1} - c_{i,n,s})V = \left[ c_{i,n+1} - c_{i,n} \left( 1 - \frac{\Delta V}{V} \right) \right] V \quad (3.11)$$

Setting these equal we obtain:

$$r_i(t) = \frac{c_{i,n+1} - c_{i,n} \left[ 1 - \frac{\Delta V}{V} \right]}{\Delta t \frac{S}{V}} \quad (3.12)$$

As before, the rate of glass dissolution,  $r_g(t)$ , is obtained through normalization by dividing by  $f_i$ , the mass fraction of species  $i$  in the glass:

$$r_g(t) = \frac{c_{i,n+1} - c_{i,n} \left[ 1 - \frac{\Delta V}{V} \right]}{\Delta t \frac{S}{V} f_i} \quad (3.13)$$

This is identical to the equation used previously at VSL to extract normalized glass dissolution rates from PFT data (see, for example [41]).

At steady state,  $c_{i,n+1} = c_{i,n}$  and, identifying  $\Delta V / \Delta t$  as the effective flow rate  $F_{PFT}$ , therefore:

$$r_g = c_{i,n} \frac{\Delta V}{\Delta t} \frac{1}{S f_i} = c_{i,n} \frac{F_{PFT}}{S f_i}, \quad (3.14)$$

which agrees with the continuous case above (Equation (3.9)).

In the present work, Equation (3.13) was applied to PFT data for each of the alkalis (Li, Na, K, and Cs) and also to the data for the species used to measure release via matrix dissolution (B, Mo, and Re). Note that the concentration values in Equation 3.13 ( $c_{i,n}$  and  $c_{i,n+1}$ ) were obtained by first subtracting the background concentrations  $c_i^o$  from the corresponding measured concentrations, where:

$c_i^\circ$  = is the background concentration of component  $i$  in the influent solution as measured in a blank test (Appendix A, Table A0).

Alkali ion exchange rates were then obtained by subtracting the normalized dissolution rates of either Mo, Re, or B from the normalized dissolution rate of the alkali and converting the result to moles of the specific alkali per unit glass surface area per unit time (*not* moles of *glass* per unit area per unit time). Thus, for alkali  $R$  ( $R = \text{Li, Na, K, Cs}$ ) and matrix dissolution indicator  $M$  ( $M = \text{B, Mo, Re}$ ),  $r_{\text{IEX}}$  is given by:

$$r_{\text{IEX},R} = (r_{g,R} - r_{g,M}) \frac{f_R}{W_R}, \quad (3.15)$$

where  $W_R$  is the atomic mass of  $R$ . Since  $r_g$  is typically stated in units of  $\text{g m}^{-2} \text{d}^{-1}$  whereas  $r_{\text{IEX}}$  is typically stated in units of  $\text{mol m}^{-2} \text{s}^{-1}$ , the result in Equation (3.15) is then further divided by the number of seconds per day.

## **SECTION 4.0 PULSED-FLOW TEST RESULTS**

This section provides a discussion of the results from the PFTs on glasses IDFIX21-1, IDFIX21-2, IDFIX21-3, and IDFIX21-4. The results from regression analysis of the data in terms of the model described in Section 1.3 are presented in Section 5.

### **4.1 General Observations**

Effluent solution analytical results for ten successive samples (daily at 70 °C and every 3 days at 40 °C and 23 °C) are provided in Appendix A, Tables A1, to A12, for analyses conducted by DCP-AES, and Tables A13 to A24, for analyses conducted by ICP-MS. The steady-state concentrations of dissolved glass components were calculated as the average of the concentrations of the last few samples in each experiment (samples identified in boldface in Appendix A); they are presented in Tables 4.1 to 4.4 for IDFIX21-1, IDFIX21-2, IDFIX21-3, and IDFIX21-4, respectively. The steady-state concentrations were identified visually (see Appendix B) with attention to minimizing the percent relative standard deviation (%RSD) of the dataset averaged, eliminating from the average any negative values if one sample was measured slightly lower than the previous step or due to blank subtraction (values eliminated from the average are noted in italics in Appendix A). The normalized dissolution rate values were calculated according to the data analysis method described in Section 3.5 and accounting for the surface area correction, which, in keeping with long-standing convention, is based on the boron concentration in the leachates.

Sodium dissolution rates are nearly congruent with those of boron, particularly in the acidic range for glasses IX21-1, IX21-2, and IX21-3 ( $\text{pH}_{\text{RT}}$  values of 7 and 8 are 6.0 and 7.0, respectively, at 70 °C; a  $\text{pH}_{\text{RT}}$  of 7 is 6.6 at 40 °C). Near-congruence of boron and sodium is evident at all pH values in the case of the high alkali glass IX21-4. Lithium, present in IDFIX21-1 and IDFIX21-2, dissolves also nearly congruently to sodium. Potassium dissolution rates are generally lower than that of sodium in all four glasses. In many cases, alkali dissolution rates fall below that of boron, such that subtracting the boron dissolution rate from that of the alkali is clearly not a viable method to determine the ion-exchange rate.

The present data show clearly that rhenium and molybdenum are valuable, and perhaps preferable, markers of glass matrix dissolution and for that reason, they were used throughout this data analysis in preference to boron in the estimation of ion-exchange rates (though all are reported). The Na ion-exchange rate was estimated by subtracting from the sodium dissolution rate the dissolution rate of either Re or Mo, in a manner similar to previous data analysis [2, 3, 15-22]. The ion-exchange rate values obtained from subtracting the dissolution rate for Re and Mo from

those for the alkali components are in good agreement with each other. In the rest of the discussion below, the ion-exchange rate values are the average ion exchange rates calculated based on Re and Mo dissolution rates<sup>6</sup>, and in the few instances where values based on either one could not be estimated, the value based on only the other is used. The Na ion-exchange rate was also estimated based on boron dissolution rate but, as noted above, was frequently not measurable because the boron dissolution rate is high at low pH and equal to or greater than the dissolution rates for alkalis.

Plots of Na ion exchange rates calculated using Mo, Re, and B as tracers for bulk glass dissolution as functions of time are presented in Appendix C. From the plots it can be seen that ion exchange rates are highest at the early times and reach steady values at longer times. These steady values of the ion exchange rates (average of the last two to five points, no negative values included) calculated from the average of rates calculated using Mo and Re as tracers are listed in Table 4.5.

Ion exchange rates for Li and K, which can be significant contributors to the overall effect of ion exchange, are also reported here. Lithium is a glass modifier added in IDFIX21-1 and IDFIX21-2, where it represents a significant fraction of the total alkali in the glass, about 24% and 43%, respectively (Table 2.6); potassium is also present in all four glasses tested, originating from the LAW, ranging from 2 to 14% of the total alkali in the glass. Potassium concentrations in the leachates are low and often close to that of the blank in IDFIX21-2 and IDFIX21-3, for which potassium normalized dissolution rates and ion exchange rates were often not reportable. The situation is somewhat better for IDFIX21-1 and IDFIX21-4 where the potassium content in the glass is higher. Ion exchange rates for both Li and K were evaluated by difference of their normalized dissolution rates from those for Mo and Re and, when possible, from the normalized dissolution rate of B. Li and K ion exchange rates (average of the last two to five points, as for Na described above) calculated from the average of the rates calculated from Mo and Re as tracers, are provided in Table 4.5.

The third spike included in the present study is cesium, which was added to evaluate its leach rate in comparison to the other alkalis. As expected, its leach rate is generally higher than that of Mo and Re and clearly higher in the acidic range where the ion exchange rate is higher. As discussed below, cesium shows an ion exchange rate that is about three orders of magnitude lower than that of sodium, in agreement with previous observations [2, 3, 70].

## **4.2 Variation of Pulsed-Flow Test Results with Glass Composition**

IDFIX21-1, IDFIX21-2, and IDFIX21-3 are the glasses formulated according to the WTP baseline LAW Glass Correlation [63] whereas IDFIX21-4 is an enhanced high waste loading glass formulation [64]. Therefore, IDFIX21-1, IDFIX21-2, and IDFIX21-3 have lower waste loadings

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<sup>6</sup> That is, the average of the ion exchange rate using Re-subtraction and the ion exchange rate using Mo-subtraction.

(total of 18.9 to 23.3 mol% alkali oxides) and are expected to display lower dissolution rates than IDFIX21-4. IDFIX21-2 is the glass with the lowest total alkali content of 18.9 mol% and contains four alkalis (Li, Na, K, and a Cs spike of 0.15 wt%) with sodium representing 53.2% of the total glass alkali content (10.07 mol% Na<sub>2</sub>O), lithium 43.1% of the alkali (8.2 mol% Li<sub>2</sub>O), plus a small amount of K (0.68 mol% K<sub>2</sub>O). IDFIX21-1 ranks second in terms of total alkali at 21.1 mol% total of Na+Li+K+Cs, of which Na represent 69% of the total, with Li and K at 24% and 7%, respectively. IDFIX21-3 contains 23.3 mol% alkali and does not include Li; sodium represents 97.6% of the total and potassium represents 2.3% of total alkalis. IDFIX21-4 is the highest potassium glass with a total alkali content of 27.4 mol%, of which, 86.3% is Na and 13.5% is K. Cesium is the least abundant alkali at around 0.03 mol% Cs<sub>2</sub>O in all of the glasses. The cesium concentration in the leachate was analyzed by ICP-MS along with Mo and Re. K was analyzed by DCP-AES along with all of the other main glass constituents in the leachate. However, the K concentration was too low to yield meaningful ion-exchange data in about 20% of the samples of glasses IDFIX21-1, IDFIX21-2, and IDFIX21-3; this was much less of an issue for IDFIX21-4.

Steady state dissolution rates for B, Li, K, Na, Cs, Mo, and Re are shown in Figures 4.1 to 4.3 where the four glasses are compared at each temperature. It is evident from these plots (note the differences in scale) that IDFIX21-2, the glass formulated at nominal waste loading and at the lowest total alkali content, shows much lower dissolution rates than the other three. The much lower dissolution rate is very evident at 70 °C (Figure 4.1). The general trends with pH are similar at all temperatures except for glass IDFIX21-2 at 23 °C (and to some extent at 40 °C) for the pH 11 buffer, where the dissolution rates are significantly higher than the trend; this may be due to the tenth sample of the series being eliminated from the average (IX21-2-E3D10 was contaminated). As expected, next in order of dissolution rates are IDFIX21-1 and IDFIX21-3, with IDFIX21-4, the enhanced high waste loading glass formulation, the highest.

### 4.3 Time Dependence of Ion-Exchange

The time dependence of the sodium ion exchange rates estimated from fourteen of fifteen experiments with glass IDFIX21-1 fit reasonably well to the  $t^{-1/2}$  relationship ( $R^2$  greater than 0.7 with the exception of data at pH<sub>T</sub> 6.9 and 10 at 70 °C), as shown in the plots of Figure 4.4. One experiment not shown is at 23 °C for pH 11.1 because too few points were reportable. The fitted data follow the inverse square root of time dependence given in Equation (1.2). Similar time dependence of the sodium ion exchange rates are obtained for the other two glass compositions designed at the nominal WTP waste loading, IDFIX21-2 and IDFIX21-3 (Figures 4.5 and 4.6, respectively). Some of the experiments on glass IDFIX21-2 (lowest in sodium) do not include all 10 points (e.g., only seven are reportable at 23 °C for pH 11.1) and the linear fits to  $t^{-1/2}$  have a lower  $R^2$ . Results for IDFIX21-3, with the highest Na<sub>2</sub>O content of 21 wt%, are much improved (Figure 4.6). Although the intention was to plot averages of sodium ion exchange rates estimated by difference of dissolution rate to both Re and Mo, this is not possible when NDR<sub>Mo</sub> is not reportable; the figure legends indicate these cases.

For the fourth composition IDFIX21-4, selected to represent formulations designed using the Enhanced LAW Glass Correlation (at the high sodium limit of 23.66 mol% Na<sub>2</sub>O and with high potassium of 3.71 mol% K<sub>2</sub>O), the normalized leach rates are higher for the alkalis, as expected. The time dependence of the sodium ion exchange rates for all fifteen experiments with this glass fits well to the  $t^{-1/2}$  relationship ( $R^2$  in the range of 0.61 to 0.97), as shown in the plots of Figure 4.7.

Lithium ion exchange rates show a similar trend, as shown in Figures 4.8 and 4.9, for IDFIX21-1 and IDFIX21-2, respectively, which both contain lithium; the calculated ion exchange rates for lithium in the figures are based only on Re as the tracer for glass matrix dissolution when Mo is not reportable. In most cases, the decrease of ion exchange rate over time fits well to the  $t^{-1/2}$  time dependence ( $R^2$  greater than 0.7 with the exception of data at pH<sub>T</sub> 6.9 and 10 at 70 °C); the data are more sparse for the higher pH buffers, which include slightly higher lithium impurities based on blank analyses.

The four glasses also contain various amounts of potassium (0.53 to 3.71 mol% K<sub>2</sub>O) and the same spike of 0.03 mol% Cs<sub>2</sub>O. The leach rates for these two components are generally lower than for the other alkalis, up to four times lower than that of sodium (see Tables 4.1-4.4) and in most cases lower than the normalized rate for boron. Therefore, neither potassium nor cesium ion exchange rates could be estimated based on boron. However, they could be estimated using either Re or Mo as the tracer for matrix dissolution by using results from the late samplings (typically, 7 to 10 days at 70 °C, beyond 20 days at 40 °C and 23 °C). The paucity of data did not permit generation of a time dependence plot but were sufficient to compare K and Cs ion exchange rate values to the rates for other alkalis (Table 4.5) and to construct the models described in Section 5.

#### **4.4 pH Dependence of Ion Exchange**

The logarithm of the sodium, lithium, potassium, and cesium ion exchange rates (average steady-state values) are plotted as a function of pH<sub>T</sub> in Figures 4.10 to 4.13 for the four glasses. Unless noted, the ion exchange rate values are based on dissolution rates of Mo and Re; in some of the plots, the dotted lines show the trend if boron is used as the basis, demonstrating how the acidic region biases the ion exchange rate estimation based on boron.

As shown in the figures, the logarithms of the ion exchange rates of Na, Li, K and Cs decrease linearly as pH increases. Fit  $R^2$  values for Na, Li, and K for IDFIX21-1 and for Na and K for IDFIX21-3 and IDFIX21-4, range from 0.73 to 0.97, in general accord with the model described in Section 1.3. For the low sodium glass, IDFIX21-2, the fits are not as good since dissolution rates were lower and the concentrations are sometimes close to the blank concentrations.

In general, ion-exchange is highest for Na, closely followed by Li, then K, and Cs always 2 to 3 orders of magnitude lower (3 log units lower in the plots of Figures 4.10 to 4.13 ) [78]. It is expected that  $\text{Li}^+$  diffuses at a slower rate than  $\text{Na}^+$  through the glass because, although it is smaller in size, it possesses a larger field strength [10, 79]. A comparison of the respective  $\text{Na}^+$  and  $\text{Li}^+$  ion exchange rates for all temperatures and pH conditions used in PFTs shows on average a factor of 3 difference between the two rates for IDFIX21-1 (top plot in Figure 4.14). Since the lithium content in glass IDFIX21-1 is 3 times lower than the Na content, the lithium ion exchange rate in this glass is evidently similar to that of sodium once adjusted for the respective molar fractions in the glass, as indicated from the near congruence observed in their release rates. In IDFIX21-2, the respective amounts of Na and Li are much closer, resulting in the very close  $\text{Na}^+$  and  $\text{Li}^+$  ion exchange rates (lower plot in Figure 4.14).

Because of the low K concentration in glass IDFIX21-2, there are fewer data above the detection limit for potassium for this glass. The fits are generally better for the other glasses and, as expected, the best fits for K are obtained from test results for glass IDFIX21-4, which includes 3.71 mol%  $\text{K}_2\text{O}$  (Figure 4.13). As can be seen in Figure 4.15, the K ion exchange rate is about one to two orders of magnitude lower than that for sodium (between 12 to 100 times lower). Because of its larger size,  $\text{K}^+$  is expected to diffuse through the glass at a slower rate than  $\text{Na}^+$ . After accounting for the respective concentrations of  $\text{Na}^+$  and  $\text{K}^+$  in the various glasses, the  $\text{K}^+$  ion exchange rate is about half that of  $\text{Na}^+$ .

$\text{Cs}^+$  has been reported to exhibit a diffusion coefficient that is 10 times lower than that for  $\text{Na}^+$  and to possess a diffusion activation energy that is higher than that of  $\text{Na}^+$  by a factor of 2 [78] because heavier cations such as  $\text{Cs}^+$  favor stabilization of terminal NBOs [80]. As with  $\text{Li}^+$  and  $\text{K}^+$ , ion exchange rates for  $\text{Na}^+$  and  $\text{Cs}^+$  were compared for all temperatures and pH conditions tested in PFT. It is not surprising to find the highest sodium ion exchange rates for IDFIX21-4 and IDFIX21-3, the glasses with the highest sodium contents. Cesium release, however, shows a larger deviation from congruence to sodium in these two glasses than in IDFIX21-1 or IDFIX21-2. As shown in Figure 4.16, there is a factor of 800 to 3000 difference between the ion exchange rates of  $\text{Na}^+$  and  $\text{Cs}^+$ ; since the cesium contents are 350 to 840 times lower than the Na contents, the  $\text{Cs}^+$  ion exchange rates are 2 to 5 times lower than those for  $\text{Na}^+$  once adjusted for the respective molar fractions in each glass.

#### 4.5 Estimation of $K_g$ for IDFIX21-1, IDFIX21-2, IDFIX21-3, and IDFIX21-4

As noted above, determination of  $K_g$  was not an objective of the present work and the test matrix was focused instead on ion exchange. However, the available data from the PFTs were assessed to estimate the  $K_g$  parameter for the four glasses. The results from previous tests [2, 3] showed that the  $K_g$  values determined from PFT method showed good agreement with those obtained using the SPFT tests and, therefore, the PFT provides a potential alternative test method for determination of this parameter. As described earlier [2, 3], estimation of the  $K_g$  value requires a linear regression of the steady state NDR vs.  $a[\text{H}_4\text{SiO}_4]$ . This regression is conducted here using

two parallel approaches: using  $NDR_B$  and using  $NDR_{Re}$ . In view of the limitation in using boron as a matrix dissolution indicator in the acidic region (discussed above), the  $NDR_B$  regressions often excluded the data at  $pH_T = 6.00$  ( $pH_{RT} = 7$  at  $70^\circ C$ ).  $H_4SiO_4$  activities were calculated using the code PHREEQC with solution input descriptions corresponding to the leachates from the tests (Table 3.2). The data at  $pH_{RT} = 11$  did not comport to the trends expected according to Equation (1.1) and were therefore mostly excluded from this analysis.

The results of regressions at the four experimental temperatures for both  $NDR_B$  and  $NDR_{Re}$  are given in Figures 4.17, 4.18, 4.19, and 4.20 for IDFIX21-1, IDFIX21-2, IDFIX21-3, and IDFIX21-4, respectively. Plots of the NDR values for boron and rhenium as functions of orthosilicic acid activity and the various fitted equations are given in each figure.

$K_g$  is the value of  $a[H_4SiO_4]$  at a dissolution rate of zero ( $NDR = 0$  for  $Q/K_g$  equal to one in Equation (1.1)). From the linear fits, six  $K_g$  values were calculated for each glass: at three temperatures, each using  $NDR_B$  and  $NDR_{Re}$ .

Results of the above analysis, given in Table 4.6 and Figure 4.21, provide the data necessary to plot these estimated  $K_g$  values as a function of  $1/T$  ( $K^{-1}$ ) to estimate the value of  $K_g$  at the presumed repository temperature of  $15^\circ C$ , as listed in Table 4.6 and summarized in Table 4.7. As is evident from Table 4.7, the various  $K_g$  values are remarkably similar for the first three glasses. The lower value for IDFIX21-4 may be due to fits including  $pH_{RT} = 11$ . Overall,  $K_g$  values are close to the values obtained previously for the six other glasses subjected to PFT testing [2, 3], which averaged  $1.68 \times 10^{-3} \text{ mol L}^{-1}$ . Furthermore, these values are quite consistent with the values obtained for other LAW glasses, listed in Table 2.1.

## **SECTION 5.0 MODELING OF PULSED-FLOW TEST DATA**

### **5.1 Data Modeling**

The alkali ion exchange rate data obtained from PFTs for all four glasses were analyzed according to the model described in Section 1.3. It should be noted that whereas the results described in Section 4 were obtained by assessing the variation of the ion exchange rates separately with respect to each of the independent variables (time, temperature, and pH<sub>T</sub>), the results in this section were obtained by instead performing regression analysis of the entire data set against the models described in Section 1.3.

The analysis was performed using JMP® Pro Version 15.0. For each alkali for each glass, the test matrix (10 time intervals, 5 pH values, and 3 temperatures) provides up to 150 data points for each case. However, this number was reduced somewhat by cases in which the rate subtraction yielded negative values, in addition to two contaminated samples identified earlier. Whenever possible, which was the vast majority of the cases, the average of the ion exchange rates obtained by subtracting the Re and Mo NDRs from the alkali NDRs were used in the fit; in other cases only one or the other was available, but all non-negative values were used in the model.

Two forms of the model described in Section 1.3 were used: one in which a square-root-of-time dependence was used and another in which a power law in time was used in which the exponent was a fitted parameter (as opposed to being fixed at a value of  $-1/2$ ). Thus, the data were analyzed according to Equation (1.6) and also according to Equation (1.8).

Data for four alkalis (Na, K, Li, Cs) were analyzed for IX21-1 and IX21-2, and for three alkalis (Na, K, Cs) for IX21-3 and IX21-4. Thus, 28 models were developed. As noted in Section 4, models for potassium are provided even though its concentrations in some of the glasses are low, which leads to noisier and fewer data for modeling and poorer quality models.

Table 5.1 presents the regression statistics, fitted parameters, and uncertainties in the fitted parameters for all alkalis and all four glasses for the square-root-of-time model in Equation (1.6). Predicted versus measured plots for each case are shown in Figures 5.1 – 5.14. Overall, these three-parameter fits of data sets containing between 118 and 150 points are good. For sodium, the  $R^2$  values are between 0.781 and 0.970; values for cesium are between 0.688 and 0.889. The potassium and lithium values range from 0.718 to 0.963 and 0.857 to 0.859, respectively. The slightly lower values for the potassium models are due to the low concentrations in the glass and therefore in the leachate, the lower sensitivity of DCP-AES versus ICP-MS, and trace amounts in the blanks. Similarly, the lower values for cesium likely reflect the greater uncertainty in the data as a result of the very low cesium concentrations in the glass and therefore in the leachates, although this is partially compensated by the higher sensitivity of the measurements by ICP-MS.

Note that a few outliers were identified in JMP®, using the studentized residuals analyses, which detects outliers by assessing the equal variance assumption of model residuals. This, for example is clearly visible in the Cs-model plot in Figure 5.22 with the outlier identified with the red circle; however, none of the model outliers were removed from the model data set because doing so did not yield significant difference in the resulting fitted parameters and none were separately experimentally justifiable. In the case of the point identified above for the Cs-model, for example, removal of the outlier improved  $R^2$  (from 0.688 to 0.766), as expected, but the fitted parameters remained within the range of the standard error:  $E_{ad}$  (Cs in IX21-2) changes from 31.9 to 36.0, a change well within the error of  $\pm 4.4 \text{ kJ mol}^{-1}$ . The activation energies are consistent with the general range found in previous measurements on LAW glasses. The pH exponent  $\alpha$  is reasonably consistent across all of the fits. The mean value across all fits is 0.201; the mean value for sodium is 0.187 and the mean value for cesium is 0.222; the values for potassium and lithium are 0.234 and 0.161, respectively. The values of  $\alpha$  for Na show a rough trend with the amount of alkali in the glass: the lowest  $\alpha$  value of 0.075 corresponds to lowest concentration of  $\text{Na}_2\text{O}$  (9.78 wt% in IX21-2 glass); the next highest  $\alpha$  value of 0.187 corresponds to the next highest  $\text{Na}_2\text{O}$  concentration (13.78 wt% for IX21-1); and the highest values of 0.199 and 0.286 are for IX21-3 and IX21-4, respectively, which have the highest  $\text{Na}_2\text{O}$  content (21 wt%).

Since there was a slight drift in the pH for samples collected for glass IX21-4, the effect of using the measured, rather than the nominal pH values was investigated. Minimal changes were found in the parameter values when they were instead obtained from a new fit using the pH measured at each sample collection (measured at room temperature but recalculated to test temperatures). For example,  $R^2$  for the sodium model increased from 0.970 to 0.972 and  $E_{ad}$  changed from 73.0 to 72.8  $\text{kJ mol}^{-1}$ , a change well within the standard error of  $\pm 1.4 \text{ kJ mol}^{-1}$ .

Table 5.2 presents the regression statistics, fitted parameters, and uncertainties in the fitted parameters for all alkalis and all four glasses for the power-of-time model in Equation (1.8), where the time exponent is now a fitted parameter instead of being fixed at a value of  $\frac{1}{2}$ . Predicted versus measured plots for each case are shown in Figures 5.15 – 5.28. Again, overall, these four-parameter fits of data sets containing between 118 and 150 points are good. For sodium, the  $R^2$  values for sodium are between 0.792 and 0.972; values for cesium are between 0.688 and 0.897, while the potassium and lithium values are between 0.721 and 0.972. Again, the lower values for cesium and potassium, likely reflect the greater uncertainty in the data as a result of the low concentrations of these species in the glass and therefore the leachates. All of the fits with Equation (1.8) are slightly better than those obtained using Equation (1.6); this is still true when comparing the  $R^2_{adj}$ , which is intended to account for the effect of the difference in the number of fitting parameters. However, the difference is not great. The activation energies are generally very close to those determined from the fits to Equation (1.6) and are consistent with the general range found in previous measurements on LAW glasses [2, 3].

The pH exponent  $\alpha$  is reasonably consistent across all of the fits and in good agreement with the results from the fits to Equation (1.6). The mean value across all fits is 0.189; the mean value for sodium is 0.187 and the mean value for cesium is 0.225; the values for potassium and

lithium are 0.236 and 0.161, respectively. The  $\alpha$  values for Na show the same rough trend with  $\text{Na}_2\text{O}$  concentration in the glass. The additional parameter  $\gamma$  is reasonably consistent across all of the fits with a minimum value of 0.194 for the potassium ion exchange rate of IX21-4 and a maximum of 0.764 for sodium ion exchange rate for glass IX21-1. The mean value of  $\gamma$  across all fits is 0.512; the mean value for sodium is 0.647, the mean for lithium is 0.812, the mean value for potassium is 0.288, and the mean value for cesium is 0.300. Overall, therefore, the present data set suggest that the parameter  $\gamma$  is close to  $\frac{1}{2}$  but can be slightly higher or lower. Deviations from a value of  $\frac{1}{2}$  could be a reflection of departures from simple diffusion behavior such as the effects of concentration and spatially dependent diffusion coefficients, which would not be unlikely in the altered glass reaction zone. However, in view of the very small differences in  $R^2$  values between corresponding fits to Equations (1.6) and (1.8), these apparent departures from a value of  $\frac{1}{2}$  may not be significant.

Figures 5.29 and 5.30 show predicted versus measured plots for sodium ion exchange for all four glasses for the fits to Equation (1.6) and (1.8), respectively. Figure 5.31 compares the predicted effects of temperature and pH on the sodium ion exchanges rate at 15 °C calculated from the fits to Equation (1.6).

## 5.2 Activation Energies and Ion Exchange Rates at 15 °C

Table 5.3 and Figure 5.32 compare the values of ion exchange activation energy  $E_{ad}$  for Na, Li, K, and Cs obtained from models applied to PFTs on IX21-1, IX21-2, IX21-3, and IX21-4 glasses in the present work. Within the experimental errors,  $E_{ad}$  values based on fits using Eq. 1.6) are very comparable for each glass composition and appear to depend more on the glass composition than the type of alkali; the average values with standard errors over all alkali types for both models, for a given glass are:

$$\begin{aligned}E_{ad} \text{ IX21-1} &= 51.1 \pm 1.5 \text{ kJ mol}^{-1}, \\E_{ad} \text{ IX21-2} &= 41.8 \pm 3.7 \text{ kJ mol}^{-1}, \\E_{ad} \text{ IX21-3} &= 59.0 \pm 2.9 \text{ kJ mol}^{-1}, \text{ and} \\E_{ad} \text{ IX21-4} &= 73.2 \pm 1.5 \text{ kJ mol}^{-1}.\end{aligned}$$

$E_{ad}$  is higher for the higher waste loading IX21-4 glass, which has higher amounts of  $\text{Na}_2\text{O}$  (21.00 wt.%) and  $\text{K}_2\text{O}$  (5.00 wt.%); it is lowest for IX21-2, which has the lowest sodium and potassium content (9.78 wt.% of  $\text{Na}_2\text{O}$  and 1.00 wt. % of  $\text{K}_2\text{O}$ ). A similar observation was made earlier in [2, 3]. Overall,  $E_{ad}$  for glasses formulated using the WTP Baseline LAW Glass Correlation [63] range from 39 to 59  $\text{kJ mol}^{-1}$ , while for glasses formulated using the Enhanced LAW Glass Correlation for high waste loading glasses [64],  $E_{ad}$  ranges from 63 to 73  $\text{kJ mol}^{-1}$ .

The fitted models can be used to calculate the ion exchange rates at the presumed repository temperature of 15 °C. Table 5.4 lists ion exchange rates for Na, Li, K, and Cs obtained from the two models, extrapolated to 15°C, at 30 days and pH in the range of 7 to 11.

The observed variation in  $r_{IEX}$  (15 °C) in units of  $\text{mol m}^{-2} \text{s}^{-1}$  includes the effect of variations of the concentrations of the various alkalis in the four glasses, which differ significantly. In order to compare the intrinsic ion exchanges rates for each alkali for each glass, it is therefore useful to first normalize  $r_{IEX}$  for a given alkali by the molar concentration of that alkali in the glass. It is convenient to then consider the ratio of the normalized  $r_{IEX}$  for sodium to the normalized  $r_{IEX}$  for any other alkali. Doing so, we obtain the following average ratios:

|                |     |
|----------------|-----|
| Li for IX21-1: | 0.9 |
| Li for IX21-2: | 0.7 |
| K for IX21-1:  | 1.9 |
| K for IX21-2:  | 1.4 |
| K for IX21-3:  | 4.3 |
| K for IX21-4:  | 1.9 |
| Cs for IX21-1: | 2.1 |
| Cs for IX21-2: | 1.4 |
| Cs for IX21-3: | 4.9 |
| Cs for IX21-4: | 3.2 |

These trends for the ratios of normalized  $r_{IEX}$  (15 °C) values for lithium, potassium, and cesium are in general agreement with dissolution rates and the results from analysis of data at all temperatures and pH values shown in Figures 4.14 - 4.16 discussed above. For example, the dissolution rate plots in Figures B1 and B2 (Appendix B) demonstrate close congruency between Na and Li, which is in agreement with close ion exchange rates normalized to the glass composition. They are also in qualitative agreement with expectations based on the increasing size of K and Cs compared to Na and effects of the higher field strength of Li compared to Na.

With the results from FY19 on three glasses [2], three more in FY20 [3], plus four in the present work, we now have ten glasses for which ion exchange rates have been estimated using the PFT method. The extrapolated sodium ion exchange rates ( $r_{IEX \text{ Na}}$  (15°C), pH<sub>15°C</sub> 9) for these ten glasses are compared in Figure 5.33a, which shows a clear trend with sodium content. Regression analysis shows a simple exponential dependence of the sodium ion exchange rate on the Na<sub>2</sub>O content of the glass, as shown in Figure 5.33b, with an R<sup>2</sup> of 0.96. Clearly, other glass composition variables will also influence the ion exchange rate but, despite the small dataset, this result suggests that sodium content is the most important factor for these ten glasses. If such a result holds up as more data are added, this could provide a simple means for including the effect of glass composition in the ion exchange model used in the ILAW PA. Data from previous measurements using the SFPT test and boron as the indicator for matrix dissolution, listed in Table 2.1, are also plotted in Figure 5.33b (but were not included in the regression). These data show

similar general order of magnitude but considerable scatter and no obvious trend. It is possible that this behavior is a result of the use of boron as an indicator of matrix dissolution in the extraction of the ion exchange rates as compared to the use of rhenium and molybdenum for the PFT data. Consequently, it may be useful to re-test some of these glasses using the present methodology.

## **SECTION 6.0 COMPARISON OF RESULTS, SUMMARY, AND CONCLUSIONS**

The present work builds on the results from FY19 and FY20 work [2, 3], which collectively addressed the need for:

- 1) An improved methodology for including ion exchange in the model for ILAW corrosion;
- 2) An improved method for measuring the relevant ion exchange parameters that is ideally more reliable, efficient, and cost effective than the past approach that employed the SPFT test; and
- 3) An improved understanding of the variation of ion exchange rates with glass composition.

Thus, this work focused on the alternative ion exchange modeling approach described in Section 1.3 and the use of the PFT as a potential alternative to the SPFT for determining ion exchange rate parameters. Ion exchange rates for selected LAW glasses were measured using the PFT. The test conditions included variations in temperature, pH, and time in order to test the proposed alternative ion exchange model.

The glasses selected for this work were IDFIX21-1, IDFIX21-2, IDFIX21-3, and IDFIX21-4. These formulations were selected because they are important to the near-term DFLAW operations since they are designed for the LAW from the likely commissioning tank AP-107. IDFIX21-1, IDFIX21-2, and IDFIX21-3 were formulated using the WTP Baseline LAW Glass Correlation [63] and IDFIX21-4 was formulated using the Enhanced LAW Glass Correlation for high waste loading glasses [64].

The four selected glasses were fabricated to also include three spikes: Mo and Re as potential alternatives to boron as indicators of glass matrix dissolution and Cs to evaluate its ion exchange rate in comparison to other alkalis. An extensive set of leaching data was collected using the PFT method, which provides a simpler means of performing flow-through testing.

The data collected were analyzed to extract the various model parameters with particular emphasis on ion exchange. Although not a primary objective of the present work, the available data also permitted estimation of the  $K_g$  parameter for the four new glasses.

Overall, the measured ion exchange data are in general accord with expectations based on the ion exchange model described in Section 1.3:

- The measured ion exchanges rates follow the predicted linear dependence on the reciprocal of the square root of time reasonably well.
- The measured ion exchanges rates follow the predicted dependence on pH, with the logarithms of the ion exchange rates decreasing linearly as the pH increases.
- The measured ion exchanges rates follow the predicted Arrhenius dependence on temperature, with the logarithms of the ion exchange rates decreasing linearly with the reciprocal of the absolute temperature.
- Na, Li, K, and Cs all follow the above behavior reasonably well but with rate constants that depend on the alkali in the order  $\text{Na} \approx \text{Li} > \text{K} > \text{Cs}$ .

Based on these findings, the alkali ion exchange rate data obtained from PFTs were subjected to regression analysis to extract the parameters of the model described in Section 1.3. It should be noted that whereas the results described in Section 4 were obtained by assessing the variation of the ion exchange rates separately with respect to each of the independent variables (time, temperature, and pH), the results presented in Section 5 were obtained by performing regression analysis of the entire data set against the models described in Section 1.3. The analysis was performed using JMP® Pro Version 15.0.

Two forms of the model described in Section 1.3 were used: one in which a square-root-of-time dependence was used and another in which a power-law-in-time dependence was used in which the exponent was a fitted parameter (as opposed to being fixed at a value of  $-1/2$ ). Thus, the data were analyzed according to Equation (1.6) and also according to Equation (1.8). Data for four alkalis (Na, Li, K, Cs) were analyzed for IDFIX21-1, four alkalis for IDFIX21-2 (Na, Li, K, Cs), and three alkalis for IDFIX21-3 (Na, K, Cs), and IDFIX21-4 (Na, K, Cs). Thus, 28 models were developed. Due to the low total alkalis and low concentrations of potassium in IDFIX21-2, even though the resulting ion exchange parameters were evaluated, greater uncertainties are expected for K and Cs evaluation in this glass.

Overall, the three-parameter fits of Equation (1.6) to the data sets containing between 118 and 150 points are good. For sodium, the  $R^2$  values are between 0.781 and 0.970; values for cesium are between 0.688 and 0.889, with the lowest value in both cases being for glass IDFIX21-1. The potassium and lithium values range from 0.718 to 0.963 and 0.857 to 0.859, respectively. The lower values for the four models in glass IDIX21-2 are due to the low concentrations of these species in the glass and therefore in the leachate, the lower sensitivity of DCP-AES versus ICP-MS, and trace amounts (particularly K) in the blanks. Additionally, the lower values for cesium likely reflect the greater uncertainty in the data as a result of the very low cesium concentrations in the glasses and therefore in the leachates, although this is partially compensated by the higher sensitivity of the measurements by ICP-MS. The activation energies are consistent with the general range found in previous measurements on LAW glasses. The pH exponent  $\alpha$  is reasonably consistent across all of the fits. The mean value across all fits is 0.201; the mean value for sodium

is 0.187 and the mean value for cesium is 0.222; the mean values for potassium and lithium are 0.234 and 0.161, respectively.

Similarly, four-parameter fits of Equation (1.8) to the same data sets are also good, with slight improvement to the statistics when allowing the additional time parameter  $\gamma$  to vary. Again, we find the best statistics with glass IDFIX21-4 and the worst for glass IDFIX21-2. For sodium, the  $R^2$  values are between 0.792 and 0.972; values for cesium are between 0.688 and 0.897, while the potassium and lithium values are between 0.721 and 0.972. Again, the lower values for cesium and potassium likely reflect the greater uncertainty in the data as a result of the low concentrations of these species in the glass and therefore in the leachates. All of the fits with Equation (1.8) are slightly better than those obtained using Equation (1.6); this is still true when comparing the  $R^2_{\text{adj}}$ , which is intended to account for the effect of the difference in the number of fitting parameters, except for the Cs fit of IX21-2. However, the difference is not great. The activation energies are generally very close to those determined from the fits to Equation (1.6) and are consistent with the general range found in previous measurements on LAW glasses.

The additional parameter  $\gamma$  is reasonably consistent across all of the fits with a minimum value of 0.194 for potassium ion exchange rate of IX21-4 and a maximum of 0.764 for sodium ion exchange rate for glass IX21-1. The mean value of  $\gamma$  across all fits is 0.512; the mean value for sodium is 0.647, the mean for lithium is 0.812, the mean for potassium is 0.288, and the mean value for cesium is 0.300. Overall, therefore, the present data set suggest that the parameter  $\gamma$  is close to  $\frac{1}{2}$  but can be slightly higher or lower. Deviations from a value of  $\frac{1}{2}$  could be a reflection of departures from simple diffusion behavior such as the effects of concentration and spatially dependent diffusion coefficients, which would not be unlikely in the altered glass reaction zone. However, in view of the very small differences in  $R^2$  values between corresponding fits to Equations (1.6) and (1.8), these apparent departures from a value of  $\frac{1}{2}$  may not be significant.

The pH exponent  $\alpha$  is reasonably consistent across all of the fits and in very good agreement with the results from the fits to Equation (1.6). The mean value across all fits is 0.189; the mean value for sodium is 0.187 and the mean value for cesium is 0.225; the values for potassium and lithium are 0.236 and 0.161, respectively.

As in previous work, attempts were made to estimate the ion exchange rate by subtraction of the normalized boron dissolution rate from that of each of the alkalis; however, positive values were obtained only for sodium. As noted above, this approach assumes that boron is released solely by matrix dissolution whereas its release appears to follow diffusive kinetics. This issue was resolved by including spikes of rhenium and molybdenum, which provided excellent alternative indicators of matrix dissolution with results that were generally in very close agreement with each other. Thus, while parameters were extracted using the conventional boron-based approach wherever possible, as well as using the Mo- and Re-based approaches, the data indicate that the Mo/Re approach is to be preferred. Unlike boron, molybdate and perrhenate, which are the dominant Mo and Re species in the glass and which are isomorphous (and also isomorphous with sulfate and chromate), are insignificant participants in the glass matrix, instead residing

interstitially [81-85]. They are relatively large and therefore diffusive release should be insignificant. Thus, their release relies upon the dissolution of the surrounding glass matrix. Both species form very soluble anions and can be spiked and analyzed reliably at low concentrations such that they do not participate significantly in secondary phase formation, particularly in the case of rhenium. Overall, therefore, we consider these species to be good candidates for alternative markers of matrix dissolution.

The use of new buffer chemistry (using piperidine instead of LiOH) developed in previous work [2, 3], permitted the reliable measurement of Li ion exchange, in addition to Na, K, and Cs, even in glasses with low total alkali content and therefore low dissolution rates. Notably, the use of the PFT method allowed the measurement of ion exchange for Na, Li, K, and Cs in two glasses with 9.78 and 13.78 wt% Na<sub>2</sub>O that are in a composition range where the SPFT standard procedure failed to provide any ion exchange parameters, even for sodium [15, 16, 18].

Tests on glass IX21-4, formulated with the enhanced LAW Glass Correlation for high waste loading glasses [64], provided the largest dataset since the measured release rates were farther above detection limits and not affected by the subtraction of minor contaminations in the buffer blanks. Estimates of the ion exchange rates for Na, K, and Cs fit well into the overall set of data, indicating that the use of the two new glass former additives vanadium and tin in the enhanced glass formulations developed at VSL do not have significant impacts on alkali ion exchange.

As shown previously [3], the Na<sub>2</sub>O content of the glass dominates the observed glass composition effects on sodium ion exchange rate, which shows a simple exponential dependence on the Na<sub>2</sub>O content, despite other significant variations in glass composition. These results are sustained after the addition of data for the four new glasses studied in the present work and over the full composition range studied so far in PFT of 9.78 to 25 wt% Na<sub>2</sub>O. As the PFT data set grows, more detailed evaluations of glass composition effects will be possible for sodium as well as for the other alkalis.

The current ILAW glass corrosion model considers only Na<sup>+</sup>-H<sup>+</sup> ion exchange. However, the growing dataset from PFT measurements shows that the contributions of other alkalis can be substantial in comparison to sodium. In particular, depending on the glass composition, consideration should be given to including the contributions from ion exchange involving lithium, for which  $r_{\text{IEX}}$  can be of the same order of magnitude as sodium, and potassium for glasses made from high-potassium LAW compositions.

## **SECTION 7.0 QUALITY ASSURANCE**

This work was conducted under a quality assurance (QA) program compliant with the applicable criteria of 10 CFR 830.120; the American Society of Mechanical Engineers (ASME) Nuclear Quality Assurance (NQA)-1-2008 including NQA-1a-2009 addenda; and DOE Order 414.1D, Quality Assurance. These QA requirements are implemented through a Quality Assurance Project Plan for WRPS work [86] that is conducted at VSL. Test and procedure requirements by which the testing activities are planned and controlled are also defined in that plan. The program is supported by VSL standard operating procedures were used for this work [87]. This is LAW work and is not subject to the requirements of DOE/RW-0333P, Office of Civilian Waste Management Quality Assurance Requirements and Description (QARD).

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**Table 2.1. Summary of Kinetic Parameters Determined by SPFT on Various LAW Glasses.**

| Glass Name           | $k_0$<br>g-glass m <sup>-2</sup> d <sup>-1</sup> | $\eta$    | $E_a$<br>kJ mol <sup>-1</sup> | $K_g(15^\circ\text{C})^a$<br>mol L <sup>-1</sup> | $r_{\text{IEX}}(15^\circ\text{C})^*$<br>mol-Na m <sup>-2</sup> s <sup>-1</sup> | Source                |
|----------------------|--------------------------------------------------|-----------|-------------------------------|--------------------------------------------------|--------------------------------------------------------------------------------|-----------------------|
| ORLEC46              | 2.9x10 <sup>4</sup>                              | 0.39±0.06 | 58±3                          | (1.2 x 10 <sup>-3</sup> )                        | 1.4 x 10 <sup>-10</sup> **                                                     | VSL-18R4510-2         |
| ORLEC52              | 2.0x10 <sup>6</sup>                              | 0.43±0.04 | 72±4                          | (5.7 x 10 <sup>-4</sup> )                        | 2.6 x 10 <sup>-11</sup> **                                                     | VSL-18R4510-2         |
| ORLEC28 <sup>b</sup> | 2.7x10 <sup>6</sup>                              | 0.55±0.02 | 79±2                          | (1.3 x 10 <sup>-4</sup> )                        | 2.7 x 10 <sup>-11</sup> **                                                     | PNNL-27098, Rev 0     |
| ORLEC33              | 3.8x10 <sup>6</sup>                              | 0.56±0.02 | 81±2                          | (1.1 x 10 <sup>-4</sup> )                        | 3.3 x 10 <sup>-11</sup> **                                                     | PNNL-27098, Rev 0     |
| ORLEC14              | 2.7x10 <sup>6</sup>                              | 0.48±0.04 | 76±2                          | (6.75 x 10 <sup>-4</sup> )                       | 7.4 x 10 <sup>-11</sup> **                                                     | VSL-17R4320-1, Rev. 0 |
| IDF18-A161           | 5.9x10 <sup>6</sup>                              | 0.28±0.06 | 61±6                          | (2.3 x 10 <sup>-4</sup> )                        | 7.6 x 10 <sup>-11</sup>                                                        | PNNL-26169, Rev 0     |
| ORPLG9               | 2.5x10 <sup>8</sup>                              | 0.36±0.07 | 81±7                          | (log $K_g$ = 100)                                | 5.3 x 10 <sup>-11</sup>                                                        | PNNL-26169, Rev. 0    |
| IDF7-E12             | 5.7x10 <sup>4</sup>                              | 0.32±0.03 | 55±5                          | 1.87x10 <sup>-3</sup>                            | <1x10 <sup>-10</sup>                                                           | VSL-17R3860-1, Rev. 0 |
| LAWA44               | 1.3x10 <sup>4</sup>                              | 0.49±0.08 | 60±7                          | 1.87x10 <sup>-3</sup> ***                        | 5.3x10 <sup>-11</sup>                                                          | PNNL-24615, Rev. 0    |
| LAWB45               | 1.6x10 <sup>4</sup>                              | 0.34±0.03 | 53±3                          | 1.79x10 <sup>-3</sup> ***                        | 0                                                                              | PNNL-24615, Rev. 0    |
| LAWC22 <sup>b</sup>  | 1.0x10 <sup>5</sup>                              | 0.42±0.02 | 64±2                          | 1.80x10 <sup>-3</sup> ***                        | 1.2 x 10 <sup>-10</sup>                                                        | PNNL-24615, , Rev. 0  |
|                      |                                                  |           |                               |                                                  | 1.28 x 10 <sup>-11</sup> **                                                    | Corrected value       |
| IDF1-B2 <sup>b</sup> | 4.6x10 <sup>4</sup>                              | 0.49±0.05 | 64±4                          | 1.70x10 <sup>-3</sup>                            | 3.4 x 10 <sup>-10</sup>                                                        | VSL-11R2270-1, Rev. 0 |
|                      |                                                  |           |                               |                                                  | 6.21 x 10 <sup>-11</sup> **                                                    | Corrected value       |
| LAWABP1              | 3.4x10 <sup>6</sup>                              | 0.35±0.03 | 68±3                          | 4.90x10 <sup>-4</sup>                            | 3.4x10 <sup>-11</sup>                                                          | PNNL-24615, Rev. 0    |

\* As-reported values; uncorrected except where indicated (see Section 4.4 of [20]).

\*\* Corrected value, see [31]

\*\*\* Corrected value, see [16]

<sup>a</sup> Questionable values are shown in parentheses - Kinetic rate law does not model glass dissolution under saturating conditions.

<sup>b</sup> Glasses evaluated by PFT in FY 2019[2].

**Table 2.2. Comparison of Activation Energies and Extrapolated Ion Exchange Rates Previously Determined at VSL [2,3].**

| Method                     | Element | Glass ID   | $E_{ad}^{\&}$<br>kJ/mol  | $r_{\text{IEX}}(15\text{ }^{\circ}\text{C})^{\&}$<br>mol m <sup>-2</sup> s <sup>-1</sup> |
|----------------------------|---------|------------|--------------------------|------------------------------------------------------------------------------------------|
|                            |         |            | All pH                   | pH <sub>15°C</sub> 9                                                                     |
| SPFT (Mo&Re ) <sup>§</sup> | Na      | LAWC22     | 56 ± 7 (47) <sup>*</sup> | 8.7 × 10 <sup>-12</sup>                                                                  |
| PFT (Mo&Re )               | Na      | LAWC22     | 53 ± 7                   | 1.2 × 10 <sup>-11</sup>                                                                  |
| PFT (Mo&Re )               | Na      | ORLEC28    | 73 ± 8                   | 7.2 × 10 <sup>-11</sup>                                                                  |
| PFT (Mo&Re )               | Na      | IDF1B2     | 55 ± 6                   | 1.4 × 10 <sup>-10</sup>                                                                  |
| PFT (Mo&Re )               | Na      | AP107WDFL  | 41 ± 2.8                 | 1.8 × 10 <sup>-11</sup>                                                                  |
| PFT (Mo&Re )               | Na      | ORLECAP107 | 66 ± 1.8                 | 9.8 × 10 <sup>-11</sup>                                                                  |
| PFT (Mo&Re )               | Na      | ORLEC44    | 55 ± 2.4                 | 5.0 × 10 <sup>-11</sup>                                                                  |
| SPFT (Mo&Re and B)         | Li      | LAWC22     | 46 ± 10                  | 2.7 × 10 <sup>-12</sup>                                                                  |
| PFT (Mo&Re )               | Li      | LAWC22     | 37 ± 12                  | 4.0 × 10 <sup>-12</sup>                                                                  |
| PFT (Mo&Re )               | Li      | AP107WDFL  | 42 ± 3.8                 | 2.2 × 10 <sup>-12</sup>                                                                  |
| PFT (Mo&Re )               | Li      | ORLEC44    | 58 ± 3                   | 5.3 × 10 <sup>-12</sup>                                                                  |
| PFT (Mo&Re )               | K       | ORLEC28    | 78 ± 9                   | 3.4 × 10 <sup>-12</sup>                                                                  |
| PFT (Mo&Re )               | K       | ORLECAP107 | 66 ± 2                   | 1.3 × 10 <sup>-12</sup>                                                                  |
| PFT (Mo&Re )               | K       | ORLEC44    | 68 ± 4                   | 7.3 × 10 <sup>-13</sup>                                                                  |
| SPFT (Mo&Re )              | Cs      | LAWC22     | 56 ± 28                  | 3.6 × 10 <sup>-15</sup>                                                                  |
| PFT (Mo&Re )               | Cs      | LAWC22     | 50 ± 12                  | 5.3 × 10 <sup>-15</sup>                                                                  |
| PFT (Mo&Re )               | Cs      | ORLEC28    | 71 ± 9                   | 3.1 × 10 <sup>-14</sup>                                                                  |
| PFT (Mo&Re )               | Cs      | IDF1B2     | 62 ± 8                   | 7.8 × 10 <sup>-15</sup>                                                                  |
| PFT (Mo&Re )               | Cs      | AP107WDFL  | 34 ± 4                   | 1.2 × 10 <sup>-14</sup>                                                                  |
| PFT (Mo&Re )               | Cs      | ORLECAP107 | 58 ± 3                   | 2.5 × 10 <sup>-14</sup>                                                                  |
| PFT (Mo&Re )               | Cs      | ORLEC44    | 71 ± 4                   | 2.7 × 10 <sup>-14</sup>                                                                  |

<sup>&</sup>For PFT, fit using Eq. 1.8

<sup>\*</sup>Lowest pH measurement at 70 °C has been omitted for this value in parentheses

<sup>§</sup>Calculation of ion exchange rates employed the normalized dissolution rates of the elements shown in parentheses to represent the matrix dissolution rates

**Table 2.3. Sodium Ion-Exchange Rates ( $\text{mol m}^{-2} \text{s}^{-1}$ ) Determined from SPFT or PFT Tests on LAW Glasses and Corresponding Glass Compositions (wt%).**

| Glass Oxides                   | LD6-5412 | LAW A BP1 | LAW A44  | LAW B45 | IDF2 -G9 | IDF3 -F7 | IDF7 -E12 | IDF18 -A161 | ORLE C14 | ORLE C33 | ORLE C46 | ORLE C52 | LAW C22  | IDF1 -B2 | ORLE C28 | AP107 WDF L | ORLE C- AP107 | ORLE C44 |
|--------------------------------|----------|-----------|----------|---------|----------|----------|-----------|-------------|----------|----------|----------|----------|----------|----------|----------|-------------|---------------|----------|
| Al <sub>2</sub> O <sub>3</sub> | 12.00    | 10.00     | 6.20     | 6.13    | 6.76     | 8.65     | 7.58      | 10.04       | 10.000   | 9.227    | 7.600    | 9.92     | 6.08     | 10       | 10.00    | 6.10        | 9.00          | 7.600    |
| B <sub>2</sub> O <sub>3</sub>  | 5.00     | 9.25      | 8.90     | 12.34   | 8.51     | 9.53     | 9.82      | 13.51       | 10.000   | 11.000   | 11.000   | 11.0     | 10.06    | 7.3      | 10.00    | 10.00       | 11.00         | 11.000   |
| CaO                            | 4.00     | NI        | 1.99     | 6.63    | 2.7      | 9.77     | 10.02     | 7.9         | 1.950    | 2.500    | 6.940    | 1.95     | 5.12     | 1.1      | 1.95     | 3.94        | 1.95          | 5.488    |
| Cr <sub>2</sub> O <sub>3</sub> | 0.04     | 0.02      | 0.02     | 0.07    | 0.59     | 0.56     | 0.5       | 0.02        | 0.342    | 0.080    | 0.080    | 0.20     | 0.02     | 0.52     | 0.44     | 0.08        | 0.34          | 0.080    |
| Fe <sub>2</sub> O <sub>3</sub> | 0.00     | 2.50      | 6.98     | 5.26    | 0.2      | 0.23     | 0.24      | 0.99        | 0.335    | 0.200    | 0.200    | 0.2      | 5.43     | 1.1      | 0.60     | 5.50        | 0.34          | 0.200    |
| K <sub>2</sub> O               | 1.46     | 2.20      | 0.50     | 0.26    | 5.76     | 0.5      | 0.55      | 0.44        | 0.500    | 0.500    | 0.500    | 0.5      | 0.10     | 0.12     | 3.36     | 0.38        | 0.54          | 0.500    |
| La <sub>2</sub> O <sub>3</sub> | 0.00     | 2.00      | 0.00     | 0.00    | 0.00     | 0.00     | 0.00      | 0.00        | 0.00     | 0.00     | 0.00     | 0.00     | 0.00     | 0.00     | 0.00     | 0.00        | 0.00          | 0.00     |
| Li <sub>2</sub> O              | 0.00     | 0.00      | 0.00     | 4.62    | 0.00     | 4.37     | 2.49      | 0.00        | 0.000    | 0.000    | 1.864    | 0.00     | 2.51     | 0.00     | 0.00     | 0.89        | 0.00          | 0.993    |
| MgO                            | 0.00     | 1.00      | 1.99     | 2.97    | 0.96     | 0.98     | 1.04      | 0.99        | 1.000    | 1.000    | 1.000    | 1.0      | 1.51     | 1.1      | 1.00     | 1.48        | 1.00          | 1.000    |
| Na <sub>2</sub> O              | 20.00    | 20.00     | 20.00    | 6.50    | 21       | 12       | 16        | 20.66       | 24.000   | 23.000   | 18.000   | 23.80    | 14.40    | 25       | 22.11    | 17.20       | 24.00         | 20.000   |
| SiO <sub>2</sub>               | 55.91    | 41.89     | 44.55    | 47.86   | 40.82    | 42.38    | 41.19     | 36.05       | 38.808   | 40.943   | 42.028   | 38.61    | 46.67    | 39.88    | 37.76    | 45.50       | 39.35         | 42.527   |
| SnO <sub>2</sub>               | 0.00     | 0.00      | 0.00     | 0.00    | 2.84     | 0.00     | 0.00      | 0.00        | 2.330    | 0.000    | 0.000    | 0.80     | 0.00     | 1.08     | 2.33     | 0.00        | 1.02          | 0.000    |
| TiO <sub>2</sub>               | 0.00     | 2.49      | 1.99     | 0.00    | 0.00     | 0.00     | 0.00      | 0.00        | 0.335    | 0.000    | 0.000    | 0.00     | 1.14     | 0.00     | 0.60     | 1.40        | 0.34          | 0.000    |
| V <sub>2</sub> O <sub>5</sub>  | 0.00     | 0.00      | 0.00     | 0.00    | 0.00     | 2.5      | 1.74      | 0.99        | 0.350    | 2.100    | 2.498    | 1.88     | 0.00     | 2.00     | 0.00     | 0.00        | 1.55          | 2.443    |
| ZnO                            | 0.00     | 2.60      | 2.96     | 3.15    | 3.4      | 2.92     | 3.21      | 2.95        | 3.000    | 3.000    | 3.000    | 3.0      | 3.07     | 3.65     | 3.00     | 3.50        | 3.00          | 3.000    |
| ZrO <sub>2</sub>               | 0.00     | 5.25      | 2.99     | 3.15    | 5.68     | 3.92     | 3.53      | 2.95        | 6.030    | 5.030    | 3.500    | 5.83     | 3.03     | 5.44     | 6.03     | 3.00        | 5.55          | 3.500    |
| SO <sub>3</sub>                | 0.21     | 0.10      | 0.10     | 0.84    | 0.2      | 1.5      | 1.5       | 1.1         | 0.60     | 1.0      | 1.370    | 0.90     | 0.36     | 0.52     | 0.40     | 0.439       | 0.60          | 1.249    |
| Others                         | 1.38     | 0.70      | 0.83     | 0.22    | 0.58     | 0.19     | 0.59      | 1.41        |          |          |          |          | 0.52     | 1.19     | 0.42     | 0.590       | 0.42          | 0.42     |
| SUM                            | 100.00   | 100.00    | 100.00   | 100.00  | 100.00   | 100.00   | 100.00    | 100.00      | 100.00   | 100.00   | 100.00   | 100.00   | 100.02   | 100.00   | 100.00   | 100.42      | 100.00        | 100.00   |
| $r_{IX}$                       | 1.74E-11 | 3.40E-11  | 5.30E-11 | 0       | 5.30E-11 | 0        | <1E-10    | 7.60E-11    | 7.40E-11 | 3.30E-11 | 1.40E-10 | 2.60E-11 | 1.28E-11 | 6.21E-11 | 2.70E-11 | No data     |               |          |
| Ref. SPFT                      | [7]      | [7]       | [15]     | [15]    | [19]     | [16]     | [18]      | [19]        | [20]     | [21]     | [22]     | [22]     | [15]     | [16]     | [21]     |             |               |          |
| PFT IX Na (pH 9) [2, 3]        | No data  |           |          |         |          |          |           |             |          |          |          |          | 1.20E-11 | 1.45E-10 | 7.20E-11 | 1.75E-11    | 9.75E-11      | 4.98E-11 |

**Table 2.4. Target Compositions (wt%) of Glasses Selected for Ion-Exchange Testing.**

| Glass ID                                   | IDFIX21-1 | IDFIX21-2 | IDFIX21-3 | IDFIX21-4 |
|--------------------------------------------|-----------|-----------|-----------|-----------|
| Al <sub>2</sub> O <sub>3</sub>             | 6.10      | 6.10      | 6.10      | 9.00      |
| B <sub>2</sub> O <sub>3</sub>              | 10.00     | 10.00     | 10.00     | 11.00     |
| CaO                                        | 5.47      | 6.80      | 2.03      | 1.95      |
| Cr <sub>2</sub> O <sub>3</sub>             | 0.07      | 0.07      | 0.07      | 0.32      |
| Cs <sub>2</sub> O                          | 0.15      | 0.15      | 0.15      | 0.15      |
| Fe <sub>2</sub> O <sub>3</sub>             | 5.50      | 5.50      | 5.50      | 0.27      |
| K <sub>2</sub> O                           | 2.00      | 1.00      | 0.75      | 5.00      |
| Li <sub>2</sub> O                          | 2.35      | 3.82      | 0.00      | 0.00      |
| MgO                                        | 1.48      | 1.77      | 1.48      | 1.00      |
| MoO <sub>3</sub>                           | 0.10      | 0.10      | 0.10      | 0.10      |
| Na <sub>2</sub> O                          | 13.78     | 9.78      | 21.00     | 21.00     |
| NiO                                        | 0.00      | 0.00      | 0.00      | 0.01      |
| PbO                                        | 0.00      | 0.00      | 0.00      | 0.01      |
| SiO <sub>2</sub>                           | 43.96     | 45.78     | 43.95     | 36.02     |
| SnO <sub>2</sub>                           | 0.00      | 0.00      | 0.00      | 2.15      |
| TiO <sub>2</sub>                           | 1.40      | 1.40      | 1.40      | 0.27      |
| V <sub>2</sub> O <sub>5</sub>              | 0.00      | 0.00      | 0.00      | 1.69      |
| ZnO                                        | 3.50      | 3.50      | 3.50      | 3.00      |
| ZrO <sub>2</sub>                           | 3.00      | 3.00      | 3.00      | 5.95      |
| Cl                                         | 0.36      | 0.36      | 0.36      | 0.20      |
| F                                          | 0.04      | 0.04      | 0.04      | 0.08      |
| P <sub>2</sub> O <sub>5</sub>              | 0.12      | 0.12      | 0.12      | 0.12      |
| SO <sub>3</sub>                            | 0.52      | 0.61      | 0.35      | 0.62      |
| Re <sub>2</sub> O <sub>7</sub>             | 0.10      | 0.10      | 0.10      | 0.10      |
| Total                                      | 100.00    | 100.00    | 100.00    | 100.00    |
| <b>Predicted Properties</b>                |           |           |           |           |
| SO <sub>3</sub> -Sat                       | 0.64      | 0.83      | 0.50      | 0.63      |
| K-3 Neck (inch)                            | 0.029     | 0.019     | 0.032     | 0.017     |
| Viscosity (P) at 1100°C                    | 54        | 55        | 86        | 75        |
| Viscosity (P) at 1150°C                    | 34        | 34        | 53        | 44        |
| Conductivity (S/m)<br>at 1100°C            | 0.274     | 0.243     | 0.506     | 0.526     |
| Conductivity (S/m)<br>at 1150°C            | 0.336     | 0.303     | 0.426     | 0.444     |
| B-PCT (g/L)                                | 1.00      | 0.76      | 1.32      | 2.01      |
| Na-PCT (g/L)                               | 0.97      | 0.72      | 1.16      | 1.40      |
| VHT (g/m <sup>2</sup> /day)<br>24-day rate | 3         | 2         | 5         | 36        |

**Table 2.5. Target and Analyzed Compositions (wt%) of Glasses Selected for Ion-Exchange Testing.**

| Glass ID                       | IDFIX21-1 | IDFIX21-1             | IDFIX21-1CCC          | IDFIX21-2 | IDFIX21-2         | IDFIX21-2CCC      | IDFIX21-3 | IDFIX21-3             | IDFIX21-3CCC      | IDFIX21-4 | IDFIX21-4         | IDFIX21-4CCC      |
|--------------------------------|-----------|-----------------------|-----------------------|-----------|-------------------|-------------------|-----------|-----------------------|-------------------|-----------|-------------------|-------------------|
|                                | Target    | Analyzed*             | Analyzed*             | Target    | Analyzed*         | Analyzed*         | Target    | Analyzed*             | Analyzed*         | Target    | Analyzed*         | Analyzed*         |
| Al <sub>2</sub> O <sub>3</sub> | 6.10      | 6.14                  | 6.21                  | 6.10      | 6.25              | 6.16              | 6.10      | 6.12                  | 6.16              | 9.00      | 9.03              | 8.99              |
| B <sub>2</sub> O <sub>3</sub>  | 10.00     | 9.10                  | 9.55                  | 10.00     | 9.36              | 9.45              | 10.00     | 9.29                  | 9.32              | 11.00     | 10.25             | 9.95              |
| CaO                            | 5.47      | 5.64                  | 5.68                  | 6.80      | 6.85              | 6.98              | 2.03      | 2.11                  | 2.15              | 1.95      | 2.02              | 2.00              |
| Cr <sub>2</sub> O <sub>3</sub> | 0.07      | 0.07                  | 0.08                  | 0.07      | 0.07              | 0.08              | 0.07      | 0.06                  | 0.06              | 0.32      | 0.40              | 0.46              |
| Cs <sub>2</sub> O              | 0.15      | 0.10                  | 0.13                  | 0.15      | 0.14              | 0.13              | 0.15      | 0.14                  | 0.11              | 0.15      | 0.12              | 0.14              |
| Fe <sub>2</sub> O <sub>3</sub> | 5.50      | 5.84                  | 5.74                  | 5.50      | 5.76              | 5.95              | 5.50      | 5.94                  | 5.72              | 0.27      | 0.35              | 0.33              |
| K <sub>2</sub> O               | 2.00      | 1.87                  | 1.96                  | 1.00      | 0.97              | 1.01              | 0.75      | 0.73                  | 0.71              | 5.00      | 4.84              | 4.75              |
| Li <sub>2</sub> O              | 2.35      | 2.27                  | 2.16                  | 3.82      | 3.58              | 3.50              | 0.00      | 0.00                  | 0.00              | 0.00      | 0.00              | 0.00              |
| MgO                            | 1.48      | 1.44                  | 1.42                  | 1.77      | 1.72              | 1.71              | 1.48      | 1.41                  | 1.48              | 1.00      | 0.99              | 0.94              |
| MoO <sub>3</sub>               | 0.10      | 0.07                  | 0.08                  | 0.10      | 0.07              | 0.07              | 0.10      | 0.08                  | 0.07              | 0.10      | 0.08              | 0.11              |
| Na <sub>2</sub> O              | 13.78     | 13.73                 | 13.45                 | 9.78      | 9.51              | 9.47              | 21.00     | 20.79                 | 21.55             | 21.00     | 21.47             | 21.26             |
| NiO                            | 0.00      | 0.00                  | 0.01                  | 0.00      | 0.00              | 0.00              | 0.00      | 0.00                  | 0.00              | 0.01      | 0.01              | 0.01              |
| PbO                            | 0.00      | 0.00                  | 0.00                  | 0.00      | 0.00              | 0.00              | 0.00      | 0.00                  | 0.00              | 0.01      | 0.00              | 0.00              |
| SiO <sub>2</sub>               | 43.96     | 43.82                 | 43.91                 | 45.78     | 45.93             | 45.73             | 43.95     | 43.54                 | 43.51             | 36.02     | 36.34             | 36.37             |
| SnO <sub>2</sub>               | 0.00      | 0.00                  | 0.00                  | 0.00      | 0.00              | 0.00              | 0.00      | 0.00                  | 0.00              | 2.15      | 1.65              | 1.90              |
| TiO <sub>2</sub>               | 1.40      | 1.57 <sup>&amp;</sup> | 1.52 <sup>&amp;</sup> | 1.40      | 1.51              | 1.52              | 1.40      | 1.59 <sup>&amp;</sup> | 1.49              | 0.27      | 0.29              | 0.29              |
| V <sub>2</sub> O <sub>5</sub>  | 0.00      | 0.00                  | 0.00                  | 0.00      | 0.00              | 0.00              | 0.00      | 0.00                  | 0.00              | 1.69      | 1.77              | 1.81              |
| ZnO                            | 3.50      | 3.51                  | 3.50                  | 3.50      | 3.39              | 3.47              | 3.50      | 3.51                  | 3.33              | 3.00      | 2.91              | 2.86              |
| ZrO <sub>2</sub>               | 3.00      | 2.84                  | 2.96                  | 3.00      | 2.91              | 2.92              | 3.00      | 3.00                  | 2.78              | 5.95      | 5.68              | 5.74              |
| Cl                             | 0.36      | 0.23                  | 0.22                  | 0.36      | 0.26              | 0.22              | 0.36      | 0.30                  | 0.24              | 0.20      | 0.16              | 0.14              |
| F                              | 0.04      | 0.04 <sup>§</sup>     | 0.04 <sup>§</sup>     | 0.04      | 0.04 <sup>§</sup> | 0.04 <sup>§</sup> | 0.04      | 0.04 <sup>§</sup>     | 0.04 <sup>§</sup> | 0.08      | 0.08 <sup>§</sup> | 0.08 <sup>§</sup> |
| P <sub>2</sub> O <sub>5</sub>  | 0.12      | 0.15                  | 0.13                  | 0.12      | 0.15              | 0.14              | 0.12      | 0.13                  | 0.14              | 0.12      | 0.14              | 0.14              |
| SO <sub>3</sub>                | 0.52      | 0.42                  | 0.44                  | 0.61      | 0.47              | 0.42              | 0.35      | 0.34                  | 0.32              | 0.62      | 0.55              | 0.55              |
| Re <sub>2</sub> O <sub>7</sub> | 0.10      | 0.13                  | 0.12                  | 0.10      | 0.14              | 0.11              | 0.10      | 0.13                  | 0.09              | 0.10      | 0.11              | 0.09              |
| Total                          | 100.0     | 98.9                  | 99.3                  | 100.0     | 99.0              | 99.0              | 100.0     | 99.2                  | 99.2              | 100.0     | 99.1              | 98.8              |

\*Analyzed by XRF except for boron and lithium, which were measured by DCP-AES.

<sup>§</sup> Target concentration.

<sup>&</sup>TiO<sub>2</sub> measured by DCP was 1.37 wt%.

**Table 2.6. Alkali Content and Species Used to Monitor Matrix Dissolution in Four LAW Glasses**  
(target values unless noted).

|                    | Glass ID, wt%                  | IDFIX21-1CCC | IDFIX21-2CCC | IDFIX21-3CCC | IDFIX21-4CCC | Notes                                      |
|--------------------|--------------------------------|--------------|--------------|--------------|--------------|--------------------------------------------|
| Composition (wt%)  | Na <sub>2</sub> O              | 13.78        | 9.78         | 21.00        | 21.00        | Alkali species undergoing ion exchange     |
|                    | K <sub>2</sub> O               | 2.00         | 1.00         | 0.75         | 5.00         |                                            |
|                    | Li <sub>2</sub> O              | 2.35         | 3.82         | 0.00         | 0.00         |                                            |
|                    | Cs <sub>2</sub> O              | 0.131*       | 0.129*       | 0.114*       | 0.143*       |                                            |
|                    | B <sub>2</sub> O <sub>3</sub>  | 10.00        | 10.00        | 10.00        | 11.00        | Species used to monitor matrix dissolution |
|                    | MoO <sub>3</sub>               | 0.076*       | 0.070*       | 0.069*       | 0.100*       |                                            |
|                    | Re <sub>2</sub> O <sub>7</sub> | 0.119*       | 0.106*       | 0.094*       | 0.094*       |                                            |
| Composition (mol%) | Na <sub>2</sub> O              | 14.52        | 10.07        | 22.70        | 23.66        | Alkali species undergoing ion exchange     |
|                    | K <sub>2</sub> O               | 1.39         | 0.68         | 0.53         | 3.71         |                                            |
|                    | Li <sub>2</sub> O              | 5.14         | 8.16         | 0.00         | 0.00         |                                            |
|                    | Cs <sub>2</sub> O              | 0.030        | 0.029        | 0.027        | 0.035        |                                            |
|                    | B <sub>2</sub> O <sub>3</sub>  | 9.38         | 9.17         | 9.62         | 11.03        | Species used to monitor matrix dissolution |
|                    | MoO <sub>3</sub>               | 0.034        | 0.031        | 0.032        | 0.048        |                                            |
|                    | Re <sub>2</sub> O <sub>7</sub> | 0.016        | 0.014        | 0.013        | 0.014        |                                            |

\*Analyzed by XRF

**Table 3.1. Pulsed-Flow Test Matrix.**

| Temperature [°C] | Pulsed-Flow Test (cell volume 50 ml) |                                |                |                  |                |                |                 |        |                      |                                     |                           |
|------------------|--------------------------------------|--------------------------------|----------------|------------------|----------------|----------------|-----------------|--------|----------------------|-------------------------------------|---------------------------|
|                  | Target<br>[Si] <sub>in</sub>         | Measured<br>[Si] <sub>in</sub> | Target<br>Flow | pH <sub>RT</sub> | m <sub>g</sub> | S*             | S/V             | RT     | Sampling<br>Interval | Replacement<br>volume <sup>\$</sup> | q/S                       |
|                  | [ppm]                                | [ppm]                          | [μl/min]       |                  | [g]            | m <sup>2</sup> | m <sup>-1</sup> | (days) | (days)               | cc/day                              | 10 <sup>-8</sup><br>m/sec |
| 23               | 35                                   | 34.0                           | 7              | 7                | 3.278          | 0.065          | 1306            | 6.0    | 3                    | 8.3                                 | 0.15                      |
|                  | 40                                   | 38.9                           | 7              | 8                | 3.278          | 0.065          | 1306            | 6.0    | 3                    | 8.3                                 | 0.15                      |
|                  | 52.5                                 | 53.7                           | 7              | 9                | 3.278          | 0.065          | 1306            | 6.0    | 3                    | 8.3                                 | 0.15                      |
|                  | 90                                   | 83.6                           | 7              | 10               | 1.639          | 0.033          | 653             | 6.0    | 3                    | 8.3                                 | 0.30                      |
|                  | 230                                  | 229.1                          | 7              | 11               | 1.639          | 0.033          | 653             | 6.0    | 3                    | 8.3                                 | 0.30                      |
| 40               | 40                                   | 38.3                           | 7              | 7                | 1.650          | 0.033          | 658             | 6.0    | 3                    | 8.3                                 | 0.29                      |
|                  | 45                                   | 43.6                           | 7              | 8                | 1.650          | 0.033          | 658             | 6.0    | 3                    | 8.3                                 | 0.29                      |
|                  | 60                                   | 61.4                           | 7              | 9                | 1.650          | 0.033          | 658             | 6.0    | 3                    | 8.3                                 | 0.29                      |
|                  | 105                                  | 100.5                          | 7              | 10               | 0.826          | 0.016          | 329             | 6.0    | 3                    | 8.3                                 | 0.59                      |
|                  | 270                                  | 284.6                          | 7              | 11               | 0.826          | 0.016          | 329             | 6.0    | 3                    | 8.3                                 | 0.59                      |
| 70               | 55                                   | 56.4                           | 35             | 7                | 0.770          | 0.015          | 307             | 2.0    | 1                    | 25.0                                | 1.89                      |
|                  | 60                                   | 62.4                           | 35             | 8                | 0.770          | 0.015          | 307             | 2.0    | 1                    | 25.0                                | 1.89                      |
|                  | 80                                   | 78.4                           | 35             | 9                | 0.770          | 0.015          | 307             | 2.0    | 1                    | 25.0                                | 1.89                      |
|                  | 140                                  | 133.4                          | 35             | 10               | 0.495          | 0.010          | 197             | 2.0    | 1                    | 25.0                                | 2.93                      |
|                  | 360                                  | 360.0                          | 35             | 11               | 0.495          | 0.010          | 197             | 2.0    | 1                    | 25.0                                | 2.93                      |

\*The above values are calculated using a glass density of 2.68 g/cm<sup>3</sup>.

\$ The replacement volume is 25 cc/day at 70 °C and 25 cc every three days at 23 °C and 40 °C.

**Table 3.2. Measured Room Temperature ( $pH_{RT}$ ), *in Situ* pH ( $pH_T$ ) and Associated Silicic Acid Activity of Influent Solutions.**

| Buffer                         | Buffers 23 °C |                     |                           | Buffers 40 °C |           |                   |                           | Buffers 70 °C |           |                   |                           |
|--------------------------------|---------------|---------------------|---------------------------|---------------|-----------|-------------------|---------------------------|---------------|-----------|-------------------|---------------------------|
| Description                    | ID            | * $pH_{23^\circ C}$ | $a[H_4SiO_4] \times 10^3$ | ID            | $pH_{RT}$ | $pH_{40^\circ C}$ | $a[H_4SiO_4] \times 10^3$ | ID            | $pH_{RT}$ | $pH_{70^\circ C}$ | $a[H_4SiO_4] \times 10^3$ |
| Tris – $HNO_3$                 | A3            | <b>7.01</b>         | 1.2450                    | A2            | 7.00      | <b>6.61</b>       | 1.4230                    | A1            | 7.03      | <b>6.00</b>       | 1.9580                    |
| Tris – $HNO_3$                 | B3            | <b>8.11</b>         | 1.3990                    | B2            | 8.10      | <b>7.72</b>       | 1.5830                    | B1            | 7.98      | <b>6.96</b>       | 2.1270                    |
| Tris – $HNO_3$                 | C3            | <b>9.09</b>         | 1.5950                    | C2            | 9.07      | <b>8.70</b>       | 1.9070                    | C1            | 9.00      | <b>7.98</b>       | 2.7210                    |
| Tris – Piperidine – $H_4SiO_4$ | D3            | <b>9.97</b>         | 1.3760                    | D2            | 10.04     | <b>9.69</b>       | 1.6940                    | D1            | 9.95      | <b>8.94</b>       | 3.4650                    |
| Piperidine – $HNO_3$           | E3            | <b>11.06</b>        | 0.4527                    | E2            | 11.08     | <b>10.75</b>      | 0.6153                    | E1            | 10.98     | <b>9.97</b>       | 2.1310                    |

\* $pH_{23^\circ C} = pH_{RT}$

**Table 4.1. Glass Dissolution Rates based on B, Li, K, Na, Cs, Mo, and Re (average of the final few sampling times) from Pulsed-Flow Tests with IDFIX21-1CCC at 70 °C, 40 °C, and 23 °C.**

| Temperature | [Si] <sub>in</sub> | pH <sub>T</sub> | NDR <sub>B</sub> ,<br>g-glass m <sup>-2</sup> d <sup>-1</sup> | NDR <sub>Li</sub> ,<br>g-glass m <sup>-2</sup> d <sup>-1</sup> | NDR <sub>Na</sub> ,<br>g-glass m <sup>-2</sup> d <sup>-1</sup> | NDR <sub>K</sub> ,<br>g-glass m <sup>-2</sup> d <sup>-1</sup> | NDR <sub>Mo</sub> ,<br>g-glass m <sup>-2</sup> d <sup>-1</sup> | NDR <sub>Cs</sub> ,<br>g-glass m <sup>-2</sup> d <sup>-1</sup> | NDR <sub>Re</sub> ,<br>g-glass m <sup>-2</sup> d <sup>-1</sup> |
|-------------|--------------------|-----------------|---------------------------------------------------------------|----------------------------------------------------------------|----------------------------------------------------------------|---------------------------------------------------------------|----------------------------------------------------------------|----------------------------------------------------------------|----------------------------------------------------------------|
| 70°C        | 55                 | 6.0             | 0.1118±0.00502                                                | 0.1167±0.00531                                                 | 0.1182±0.00497                                                 | 0.1076±0.00143                                                | 0.0062±0.00044                                                 | 0.0901±0.00259                                                 | 0.0255±0.00114                                                 |
|             | 60                 | 7.0             | 0.0418±0.00515                                                | 0.0445±0.00537                                                 | 0.0416±0.00482                                                 | 0.0403±0.00308                                                | 0.0033±0.00109                                                 | 0.0301±0.00525                                                 | 0.01±0.0015                                                    |
|             | 80                 | 8.0             | 0.014±0.00157                                                 | 0.014±0.00096                                                  | 0.0144±0.00105                                                 | 0.0135±0.00079                                                | 0.0082±0.00431                                                 | 0.0184±0.00155                                                 | 0.0099±0.00072                                                 |
|             | 140                | 8.9             | 0.0036±0.00114                                                | 0.0064±0.00058                                                 | 0.0065±0.00104                                                 | 0.0045±0.00106                                                | 0.0026±0.00028                                                 | 0.0012±0.00054                                                 | not reportable                                                 |
|             | 360                | 10.0            | 0.0003±0.0002                                                 | 0.011±0.00094                                                  | 0.0036±0.0014                                                  | not reportable                                                | 0.0112±0.00216                                                 | 0.0005±0.00067                                                 | 0.0056±0.00225                                                 |
| 40°C        | 40                 | 6.6             | 0.0055±0.00023                                                | 0.00571±0.00029                                                | 0.00553±0.00025                                                | 0.00539±0.00167                                               | 0.00078±0.00026                                                | 0.00346±0.00019                                                | 0.00202±0.00033                                                |
|             | 45                 | 7.7             | 0.00151±0.00015                                               | 0.0019±0.00017                                                 | 0.0019±0.00016                                                 | 0.00166±0.00025                                               | 0.00059±0.00022                                                | 0.0013±0.00033                                                 | 0.0007±0.00045                                                 |
|             | 60                 | 8.7             | 0.00053±0.00003                                               | 0.00093±0.0001                                                 | 0.00099±0.00009                                                | 0.00074±0.00003                                               | 0.00033±0.00034                                                | 0.0007±0.00004                                                 | 0.00058±0.00043                                                |
|             | 105                | 9.7             | 0.00038±0.00014                                               | 0.00079±0.00019                                                | 0.00091±0.00027                                                | 0.00086±0.00043                                               | not reportable                                                 | 0.00067±0.00019                                                | 0.00055±0.0002                                                 |
|             | 270                | 10.8            | 0.00090±0.0002                                                | 0.00135±0.0001                                                 | 0.00179±0.00009                                                | 0.00091±0.00017                                               | not reportable                                                 | 0.00099±0.00027                                                | 0.00118±0.00012                                                |
| 23°C        | 35                 | 7.0             | 0.0008±0.00014                                                | 0.001±0.00013                                                  | 0.0009±0.00014                                                 | 0.0007±0.00014                                                | 0.0004±0.00034                                                 | 0.0007±0.00022                                                 | 0.0005±0.00021                                                 |
|             | 40                 | 8.1             | 0.0003±0.00011                                                | 0.0005±0.00012                                                 | 0.00040±0.00010                                                | 0.0003±0.00015                                                | 0.0003±0.00012                                                 | 0.0004±0.00013                                                 | 0.0002±0.00019                                                 |
|             | 52.5               | 9.1             | 0.0002±0.00000                                                | 0.0004±0.00001                                                 | 0.0003±0.0000                                                  | not reportable                                                | not reportable                                                 | 0.0002±0.00002                                                 | 0.0002±0.00009                                                 |
|             | 90                 | 10.0            | 0.0003±0.00003                                                | 0.0004±0.00012                                                 | 0.0004±0.0001                                                  | 0.0004±0.00014                                                | 0.0004±0.00017                                                 | 0.0005±0.00008                                                 | 0.0002±0.00008                                                 |
|             | 230                | 11.1            | 0.0006±0.00023                                                | 0.0007±0.0001                                                  | 0.0007±0.00011                                                 | 0.0008±0.00014                                                | not reportable                                                 | 0.0007±0.00003                                                 | 0.0006±0.00025                                                 |

Notes: In the rate units, “g-glass” represents the mass of glass dissolved as calculated based on the indicated species, as described in Section 3.7.  
The means and standard deviations listed are calculated from the last two to four time points.

**Table 4.2. Glass Dissolution Rates based on B, Li, K, Na, Cs, Mo, and Re (average of the final few sampling times) from Pulsed-Flow Tests with IDFIX21-2CCC at 70 °C, 40 °C, and 23 °C.**

| Temperature | [Si] <sub>in</sub> | pH <sub>T</sub> | NDR <sub>B</sub> ,<br>g-glass m <sup>-2</sup> d <sup>-1</sup> | NDR <sub>Li</sub> ,<br>g-glass m <sup>-2</sup> d <sup>-1</sup> | NDR <sub>Na</sub> ,<br>g-glass m <sup>-2</sup> d <sup>-1</sup> | NDR <sub>K</sub> ,<br>g-glass m <sup>-2</sup> d <sup>-1</sup> | NDR <sub>Mo</sub> ,<br>g-glass m <sup>-2</sup> d <sup>-1</sup> | NDR <sub>Cs</sub> ,<br>g-glass m <sup>-2</sup> d <sup>-1</sup> | NDR <sub>Re</sub> ,<br>g-glass m <sup>-2</sup> d <sup>-1</sup> |
|-------------|--------------------|-----------------|---------------------------------------------------------------|----------------------------------------------------------------|----------------------------------------------------------------|---------------------------------------------------------------|----------------------------------------------------------------|----------------------------------------------------------------|----------------------------------------------------------------|
| 70°C        | 55                 | 6.0             | 0.0341±0.00008                                                | 0.0343±0.0005                                                  | 0.033±0.00085                                                  | 0.0099±0.00042                                                | 0.0037±0.00138                                                 | 0.0313±0.00111                                                 | 0.0083±0.00114                                                 |
|             | 60                 | 7.0             | 0.0121±0.00158                                                | 0.0134±0.00167                                                 | 0.0131±0.00144                                                 | 0.0106±0.00132                                                | 0.0063±0.00082                                                 | 0.0114±0.00221                                                 | 0.0039±0.00178                                                 |
|             | 80                 | 8.0             | 0.0138±0.00203                                                | 0.0159±0.00259                                                 | 0.0156±0.00287                                                 | 0.0166±0.00579                                                | 0.0126±0.00579                                                 | 0.013±0.00207                                                  | 0.0098±0.00094                                                 |
|             | 140                | 8.9             | 0.0008±0.00059                                                | 0.0038±0.00076                                                 | 0.0023±0.0001                                                  | not reportable                                                | not reportable                                                 | not reportable                                                 | not reportable                                                 |
|             | 360                | 10.0            | not reportable                                                | 0.0056±0.00047                                                 | 0.0072±0.00171                                                 | 0.0018±0.00045                                                | 0.004±0.00062                                                  | not reportable                                                 | 0.0026±0.00113                                                 |
| 40°C        | 40                 | 6.6             | 0.00129±0.00021                                               | 0.00143±0.00022                                                | 0.00136±0.00022                                                | 0.0013±0.00019                                                | not reportable                                                 | 0.00115±0.00016                                                | 0.0003±0.00026                                                 |
|             | 45                 | 7.7             | 0.00069±0.0001                                                | 0.00108±0.00012                                                | 0.00107±0.00008                                                | 0.001±0.00016                                                 | 0.00021±0.00012                                                | 0.0008±0.00005                                                 | 0.00024±0.00003                                                |
|             | 60                 | 8.7             | 0.00034±0.00001                                               | 0.00071±0.00003                                                | 0.00073±0.00004                                                | 0.00061±0.00035                                               | 0.00016±0.00006                                                | 0.00053±0.00008                                                | 0.00034±0.00006                                                |
|             | 105                | 9.7             | 0.00002±0.00004                                               | 0.00056±0.00006                                                | 0.00052±0.00008                                                | 0.00045±0.00011                                               | 0.00001±0.00004                                                | 0.00044±0.00007                                                | 0.00029±0.00007                                                |
|             | 270                | 10.8            | 0.00129±0.00019                                               | 0.00182±0.00014                                                | 0.0026±0.00007                                                 | not reportable                                                | 0.00133±0.00041                                                | 0.00116±0.00018                                                | 0.00083±0.00013                                                |
| 23°C        | 35                 | 7.0             | 0.0003±0.00004                                                | 0.0005±0.00004                                                 | 0.0004±0.00001                                                 | 0.0003±0.00008                                                | 0.0001±0.0001                                                  | 0.0003±0.00006                                                 | 0.0002±0.00003                                                 |
|             | 40                 | 8.1             | 0.0002±0.00006                                                | 0.0004±0.0001                                                  | 0.0003±0.00008                                                 | 0.0001±0.00008                                                | 0.0004±0.00026                                                 | 0.0003±0.00008                                                 | 0.0003±0.00021                                                 |
|             | 52.5               | 9.1             | 0.0002±0.00001                                                | 0.0003±0.00004                                                 | 0.0002±0.00002                                                 | not reportable                                                | 0.0002±0.00008                                                 | 0.0002±0.00013                                                 | 0.0002±0.00011                                                 |
|             | 90                 | 10.0            | 0.0001±0.00005                                                | 0.0003±0.00006                                                 | 0.0002±0.00005                                                 | 0.0003±0.00008                                                | 0.0006±0.00013                                                 | 0.0003±0.00005                                                 | 0.0001±0.00004                                                 |
|             | 230                | 11.1            | 0.0007±0.00009                                                | 0.0007±0.00012                                                 | 0.001±0.00007                                                  | 0.0006±0.00032                                                | 0.001±0.00023                                                  | 0.0009±0.00008                                                 | 0.0007±0.00031                                                 |

Notes: In the rate units, “g-glass” represents the mass of glass dissolved as calculated based on the indicated species, as described in Section 3.7.  
The means and standard deviations listed are calculated from the last two to four time points.

**Table 4.3. Glass Dissolution Rates Based on B, Li, K, Na, Cs, Mo, and Re (average of the final few sampling times) from Pulsed-Flow Tests with IDFIX21-3CCC at 70 °C, 40 °C, and 23 °C.**

| Temperature | [Si] <sub>in</sub> | pH <sub>T</sub> | NDR <sub>B</sub> ,<br>g-glass m <sup>-2</sup> d <sup>-1</sup> | NDR <sub>Na</sub> ,<br>g-glass m <sup>-2</sup> d <sup>-1</sup> | NDR <sub>K</sub> ,<br>g-glass m <sup>-2</sup> d <sup>-1</sup> | NDR <sub>Mo</sub> ,<br>g-glass m <sup>-2</sup> d <sup>-1</sup> | NDR <sub>Cs</sub> ,<br>g-glass m <sup>-2</sup> d <sup>-1</sup> | NDR <sub>Re</sub> ,<br>g-glass m <sup>-2</sup> d <sup>-1</sup> |
|-------------|--------------------|-----------------|---------------------------------------------------------------|----------------------------------------------------------------|---------------------------------------------------------------|----------------------------------------------------------------|----------------------------------------------------------------|----------------------------------------------------------------|
| 70°C        | 55                 | 6.0             | 0.2365±0.01898                                                | 0.2339±0.0203                                                  | 0.2318±0.02262                                                | 0.0094±0.00226                                                 | 0.1597±0.0192                                                  | 0.0338±0.00477                                                 |
|             | 60                 | 7.0             | 0.0931±0.00726                                                | 0.0892±0.00764                                                 | 0.0858±0.00159                                                | 0.0041±0.00255                                                 | 0.0562±0.00347                                                 | 0.0171±0.00288                                                 |
|             | 80                 | 8.0             | 0.0301±0.00328                                                | 0.0327±0.00355                                                 | 0.0298±0.00729                                                | 0.0029±0.0023                                                  | 0.0213±0.00197                                                 | 0.0094±0.00104                                                 |
|             | 140                | 8.9             | 0.0197±0.00129                                                | 0.0238±0.00084                                                 | 0.0075±0.00142                                                | not reportable                                                 | 0.0087±0.00257                                                 | 0.002±0.0014                                                   |
|             | 360                | 10.0            | 0.001±0.00035                                                 | 0.012±0.00031                                                  | not reportable                                                | not reportable                                                 | 0.0028±0.00057                                                 | 0.0025±0.00053                                                 |
| 40°C        | 40                 | 6.6             | 0.01176±0.00055                                               | 0.01188±0.00074                                                | 0.01053±0.00041                                               | 0.00054±0.00029                                                | 0.00604±0.0002                                                 | 0.00385±0.00045                                                |
|             | 45                 | 7.7             | 0.00332±0.00014                                               | 0.00397±0.00011                                                | 0.00293±0.00011                                               | 0.00034±0.00028                                                | 0.00197±0.00005                                                | 0.00129±0.00063                                                |
|             | 60                 | 8.7             | 0.00129±0.00006                                               | 0.0025±0.0001                                                  | 0.00128±0.00028                                               | 0.00035±0.00006                                                | 0.00108±0.00011                                                | 0.00093±0.00007                                                |
|             | 105                | 9.7             | 0.00044±0.0001                                                | 0.00189±0.00012                                                | 0.00078±0.00012                                               | not reportable                                                 | 0.00075±0.00018                                                | 0.00047±0.00014                                                |
|             | 270                | 10.8            | 0.00115±0.00025                                               | 0.00271±0.00047                                                | not reportable                                                | 0.00107±0.00044                                                | 0.00146±0.00027                                                | 0.00123±0.00025                                                |
| 23°C        | 35                 | 7.0             | 0.0017±0.00023                                                | 0.0018±0.00022                                                 | 0.0013±0.00021                                                | 0.0002±0.00013                                                 | 0.001±0.00017                                                  | 0.0008±0.00012                                                 |
|             | 40                 | 8.1             | 0.0004±0.00008                                                | 0.001±0.00013                                                  | 0.0004±0.00019                                                | 0.0001±0.00006                                                 | 0.0004±0.00008                                                 | 0.0003±0.00009                                                 |
|             | 52.5               | 9.1             | 0.0002±0.00003                                                | 0.0007±0.00003                                                 | not reportable                                                | not reportable                                                 | 0.0003±0.00004                                                 | 0.0002±0.00005                                                 |
|             | 90                 | 10.0            | 0.0003±0.00001                                                | 0.0007±0.00003                                                 | 0.0006±0.00027                                                | not reportable                                                 | 0.0005±0.00009                                                 | 0.0002±0.00009                                                 |
|             | 230                | 11.1            | 0.0005±0.00019                                                | 0.0008±0.00004                                                 | not reportable                                                | 0.0006±0.00041                                                 | 0.0007±0.00004                                                 | 0.0007±0.00004                                                 |

Notes: In the rate units, “g-glass” represents the mass of glass dissolved as calculated based on the indicated species, as described in Section 3.7. The means and standard deviations listed are calculated from the last two to four time points.

**Table 4.4. Glass Dissolution Rates Based on B, Li, K, Na, Cs, Mo, and Re (average of the final few sampling times) from Pulsed-Flow Tests with IDFIX21-4CCC at 70 °C, 40 °C, and 23 °C.**

| Temperature | [Si] <sub>in</sub> | pH <sub>T</sub> | NDR <sub>B</sub> ,<br>g-glass m <sup>-2</sup> d <sup>-1</sup> | NDR <sub>Na</sub> ,<br>g-glass m <sup>-2</sup> d <sup>-1</sup> | NDR <sub>K</sub> ,<br>g-glass m <sup>-2</sup> d <sup>-1</sup> | NDR <sub>Mo</sub> ,<br>g-glass m <sup>-2</sup> d <sup>-1</sup> | NDR <sub>Cs</sub> ,<br>g-glass m <sup>-2</sup> d <sup>-1</sup> | NDR <sub>Re</sub> ,<br>g-glass m <sup>-2</sup> d <sup>-1</sup> |
|-------------|--------------------|-----------------|---------------------------------------------------------------|----------------------------------------------------------------|---------------------------------------------------------------|----------------------------------------------------------------|----------------------------------------------------------------|----------------------------------------------------------------|
| 70°C        | 55                 | 6.0             | 0.9546±0.10195                                                | 0.8989±0.10118                                                 | 0.7441±0.08915                                                | 0.0105±0.00236                                                 | 0.3472±0.08204                                                 | 0.0402±0.00407                                                 |
|             | 60                 | 7.0             | 0.6013±0.05836                                                | 0.6416±0.08414                                                 | 0.4412±0.03714                                                | 0.0054±0.00144                                                 | 0.1705±0.00623                                                 | 0.0267±0.0028                                                  |
|             | 80                 | 8.0             | 0.3679±0.02835                                                | 0.3683±0.01074                                                 | 0.2137±0.00577                                                | 0.0064±0.00549                                                 | 0.0815±0.00371                                                 | 0.0117±0.00499                                                 |
|             | 140                | 8.9             | 0.3118±0.02267                                                | 0.2985±0.02212                                                 | 0.1616±0.01442                                                | not reportable                                                 | 0.0555±0.0109                                                  | 0.0148±0.00729                                                 |
|             | 360                | 10.0            | 0.058±0.00573                                                 | 0.0649±0.00588                                                 | 0.038±0.00241                                                 | not reportable                                                 | 0.0133±0.00213                                                 | not reportable                                                 |
| 40°C        | 40                 | 6.6             | 0.08536±0.00138                                               | 0.0817±0.0034                                                  | 0.05663±0.00128                                               | 0.00036±0.00017                                                | 0.02828±0.00211                                                | 0.01414±0.0008                                                 |
|             | 45                 | 7.7             | 0.0472±0.00069                                                | 0.0477±0.00059                                                 | 0.02838±0.00023                                               | 0.0002±0.00011                                                 | 0.00853±0.00046                                                | 0.00604±0.00037                                                |
|             | 60                 | 8.7             | 0.02874±0.00069                                               | 0.02866±0.0007                                                 | 0.01549±0.00035                                               | 0.00012±0.00009                                                | 0.00458±0.00027                                                | 0.00417±0.00018                                                |
|             | 105                | 9.7             | 0.01867±0.00019                                               | 0.01732±0.00013                                                | 0.0088±0.00013                                                | not reportable                                                 | 0.00265±0.00016                                                | 0.00242±0.00068                                                |
|             | 270                | 10.8            | 0.00643±0.00055                                               | 0.00361±0.00019                                                | not reportable                                                | not reportable                                                 | 0.00324±0.00042                                                | 0.00044±0.00021                                                |
| 23°C        | 35                 | 7.0             | 0.0137±0.00137                                                | 0.0135±0.00084                                                 | 0.0095±0.00118                                                | 0.0002±0.00003                                                 | 0.0048±0.00058                                                 | 0.0033±0.00038                                                 |
|             | 40                 | 8.1             | 0.0043±0.00048                                                | 0.0043±0.00027                                                 | 0.0027±0.00034                                                | 0.0001±0.00004                                                 | 0.001±0.00017                                                  | 0.001±0.00027                                                  |
|             | 52.5               | 9.1             | 0.0023±0.00033                                                | 0.0024±0.00027                                                 | 0.0009±0.00021                                                | not reportable                                                 | 0.0005±0.00008                                                 | 0.0008±0.0001                                                  |
|             | 90                 | 10.0            | 0.0019±0.00034                                                | 0.0021±0.00024                                                 | 0.0012±0.00014                                                | not reportable                                                 | 0.0006±0.00009                                                 | 0.0006±0.00054                                                 |
|             | 230                | 11.1            | 0.0006±0.00034                                                | 0.0008±0.00027                                                 | 0.0005±0.00019                                                | not reportable                                                 | 0.001±0.00034                                                  | 0.0002±0.00008                                                 |

Notes: In the rate units, “g-glass” represents the mass of glass dissolved as calculated based on the indicated species, as described in Section 3.7. The means and standard deviations listed are calculated from the last two to four time points.

**Table 4.5. Alkali Ion Exchange Rates (in  $\text{mol m}^{-2} \text{s}^{-1}$ )<sup>(a)</sup> from Pulsed-Flow Tests Performed on IDFIX21-1, IDFIX21-2, IDFIX21-3, and IDFIX21-4 (average of the final few sampling times).**

| Glass ID                |                        |                           | IDFIX21-1                                                            |                                                                      |                                                                        |                                                                         | IDFIX21-2                                                            |                                                                      |                                                                     |                                                                         |
|-------------------------|------------------------|---------------------------|----------------------------------------------------------------------|----------------------------------------------------------------------|------------------------------------------------------------------------|-------------------------------------------------------------------------|----------------------------------------------------------------------|----------------------------------------------------------------------|---------------------------------------------------------------------|-------------------------------------------------------------------------|
| $\text{pH}_{\text{RT}}$ | $\text{pH}_{\text{T}}$ | $[\text{Si}]_{\text{in}}$ | $r_{\text{IEX Na,}}^{\text{I}}$<br>$\text{mol m}^{-2} \text{s}^{-1}$ | $r_{\text{IEX Li,}}^{\text{I}}$<br>$\text{mol m}^{-2} \text{s}^{-1}$ | $r_{\text{IEX K,}}^{\text{I(b)}}$<br>$\text{mol m}^{-2} \text{s}^{-1}$ | $r_{\text{IEX Cs,}}^{\text{I(c)}}$<br>$\text{mol m}^{-2} \text{s}^{-1}$ | $r_{\text{IEX Na,}}^{\text{I}}$<br>$\text{mol m}^{-2} \text{s}^{-1}$ | $r_{\text{IEX Li,}}^{\text{I}}$<br>$\text{mol m}^{-2} \text{s}^{-1}$ | $r_{\text{IEX K,}}^{\text{I}}$<br>$\text{mol m}^{-2} \text{s}^{-1}$ | $r_{\text{IEX Cs,}}^{\text{I(b)}}$<br>$\text{mol m}^{-2} \text{s}^{-1}$ |
| <b>70°C Experiments</b> |                        |                           |                                                                      |                                                                      |                                                                        |                                                                         |                                                                      |                                                                      |                                                                     |                                                                         |
| 7                       | 6.0                    | 55                        | 5.31E-09                                                             | 1.84E-09                                                             | 4.56E-10                                                               | 8.08E-12                                                                | 1.01E-09                                                             | 8.51E-10                                                             | 1.09E-11                                                            | 2.87E-12                                                                |
| 8                       | 7.0                    | 60                        | 1.69E-09                                                             | 6.38E-10                                                             | 1.55E-10                                                               | 2.52E-12                                                                | 2.83E-10                                                             | 2.43E-10                                                             | 2.40E-11                                                            | 6.63E-13                                                                |
| 9                       | 8.0                    | 80                        | 3.26E-10                                                             | 6.64E-11                                                             | 3.32E-11                                                               | 1.14E-12                                                                | 2.62E-10                                                             | 6.74E-11                                                             | 5.34E-12                                                            | 1.51E-13 <sup>(b)</sup>                                                 |
| 10                      | 8.9                    | 140                       | 3.26E-10                                                             | 1.08E-10                                                             | 3.74E-11                                                               | 1.28E-13                                                                | 1.28E-10                                                             | 1.31E-10                                                             | 4.48E-12                                                            | 5.05E-14 <sup>(b)</sup>                                                 |
| 11                      | 10.0                   | 360                       | Not reportable                                                       | 7.20E-11 <sup>(b)</sup>                                              | Not reportable                                                         | Not reportable                                                          | 2.25E-10                                                             | 1.05E-10                                                             | Not reportable                                                      | Not reportable                                                          |
| <b>40°C Experiments</b> |                        |                           |                                                                      |                                                                      |                                                                        |                                                                         |                                                                      |                                                                      |                                                                     |                                                                         |
| 7                       | 6.6                    | 40                        | 2.15E-10                                                             | 7.89E-11                                                             | 2.01E-11                                                               | 2.20E-13                                                                | 4.39E-11                                                             | 3.73E-11                                                             | 2.80E-12                                                            | 1.05E-13                                                                |
| 8                       | 7.7                    | 45                        | 6.44E-11                                                             | 2.27E-11                                                             | 5.00E-12                                                               | 7.58E-14                                                                | 3.90E-11                                                             | 3.09E-11                                                             | 2.47E-12                                                            | 6.35E-14                                                                |
| 9                       | 8.7                    | 60                        | 3.14E-11                                                             | 9.96E-12                                                             | 1.80E-12                                                               | 5.03E-14                                                                | 1.94E-11                                                             | 1.33E-11                                                             | 1.03E-12                                                            | 3.57E-14                                                                |
| 10                      | 9.7                    | 105                       | 2.24E-11                                                             | 7.74E-12                                                             | 2.12E-12                                                               | 3.41E-14                                                                | 1.36E-11                                                             | 1.17E-11                                                             | 3.06E-12                                                            | 3.20E-14                                                                |
| 11                      | 10.8                   | 270                       | 5.05E-11                                                             | 1.28E-11                                                             | Not reportable                                                         | 1.74E-14                                                                | 4.25E-11                                                             | 1.54E-11                                                             | Not reportable                                                      | 2.02E-14 <sup>(b)</sup>                                                 |
| <b>23°C Experiments</b> |                        |                           |                                                                      |                                                                      |                                                                        |                                                                         |                                                                      |                                                                      |                                                                     |                                                                         |
| 7                       | 7.0                    | 35                        | 2.09E-11                                                             | 1.17E-11                                                             | 1.92E-12                                                               | 3.53E-14                                                                | 8.88E-12                                                             | 9.71E-12                                                             | 4.64E-13                                                            | 2.15E-14                                                                |
| 8                       | 8.1                    | 40                        | 9.84E-12                                                             | 4.56E-12                                                             | 6.00E-13                                                               | 1.95E-14                                                                | 3.51E-12 <sup>(b)</sup>                                              | 6.24E-12 <sup>(b)</sup>                                              | Not reportable                                                      | 7.21E-15 <sup>(b)</sup>                                                 |
| 9                       | 9.1                    | 52.5                      | 1.18E-11                                                             | 3.52E-12 <sup>(b)</sup>                                              | Not reportable                                                         | 1.13E-14 <sup>(b)</sup>                                                 | 4.26E-12                                                             | 4.93E-12                                                             | Not reportable                                                      | 1.53E-14                                                                |
| 10                      | 10.0                   | 90                        | 8.06E-12 <sup>(b)</sup>                                              | 2.93E-12 <sup>(b)</sup>                                              | 8.57E-13 <sup>(b)</sup>                                                | 1.72E-14 <sup>(b)</sup>                                                 | 4.13E-12                                                             | 5.82E-12 <sup>(b)</sup>                                              | 4.52E-13 <sup>(b)</sup>                                             | 2.04E-14 <sup>(b)</sup>                                                 |
| 11                      | 11.1                   | 230                       | 2.63E-11                                                             | 6.15E-12 <sup>(b)</sup>                                              | Not reportable                                                         | 4.46E-14                                                                | 2.20E-11                                                             | 5.91E-12 <sup>(b)</sup>                                              | Not reportable                                                      | 1.51E-14 <sup>(b)</sup>                                                 |

<sup>(a)</sup>“mol” in the  $r_{\text{IEX}}$  units refers to moles of the indicated alkali element released by ion exchange.

<sup>(b)</sup>  $r_{\text{IEX}}$  was calculated by difference to Re only when the Mo data were not reportable.

**Table 4.5. Alkali Ion Exchange Rates (in  $\text{mol m}^{-2} \text{s}^{-1}$ )<sup>(a)</sup> from Pulsed-Flow Tests Performed on IDFIX21-1, IDFIX21-2, IDFIX21-3, and IDFIX21-4 (average of the final few sampling times) (cont'd).**

| Glass ID                |                 |                    | IDFIX21-3                                                |                                                         |                                                          | IDFIX21-4                                                |                                                         |                                                                         |
|-------------------------|-----------------|--------------------|----------------------------------------------------------|---------------------------------------------------------|----------------------------------------------------------|----------------------------------------------------------|---------------------------------------------------------|-------------------------------------------------------------------------|
| pH <sub>RT</sub>        | pH <sub>T</sub> | [Si] <sub>in</sub> | r <sub>IE</sub> Na,<br>$\text{mol m}^{-2} \text{s}^{-1}$ | r <sub>IE</sub> K,<br>$\text{mol m}^{-2} \text{s}^{-1}$ | r <sub>IE</sub> Cs,<br>$\text{mol m}^{-2} \text{s}^{-1}$ | r <sub>IE</sub> Na,<br>$\text{mol m}^{-2} \text{s}^{-1}$ | r <sub>IE</sub> K,<br>$\text{mol m}^{-2} \text{s}^{-1}$ | r <sub>IE</sub> Cs, <sup>(b)</sup><br>$\text{mol m}^{-2} \text{s}^{-1}$ |
| <b>70°C Experiments</b> |                 |                    |                                                          |                                                         |                                                          |                                                          |                                                         |                                                                         |
| 7                       | 6.0             | 55                 | 1.67E-08                                                 | 3.84E-10                                                | 1.29E-11                                                 | 6.85E-08                                                 | 9.01E-09                                                | 3.77E-11                                                                |
| 8                       | 7.0             | 60                 | 6.15E-09                                                 | 1.40E-10                                                | 4.34E-12                                                 | 5.02E-08                                                 | 5.41E-09                                                | 1.81E-11                                                                |
| 9                       | 8.0             | 80                 | 2.13E-09                                                 | 4.11E-11                                                | 1.48E-12                                                 | 2.83E-08                                                 | 2.54E-09                                                | 8.69E-12                                                                |
| 10                      | 8.9             | 140                | 1.80E-09                                                 | 1.94E-11                                                | 7.39E-13                                                 | 2.22E-08 <sup>(b)</sup>                                  | 1.97E-09 <sup>(b)</sup>                                 | 4.78E-12 <sup>(b)</sup>                                                 |
| 11                      | 10.0            | 360                | 9.18E-10 <sup>(b)</sup>                                  | Not reportable                                          | 1.71E-13 <sup>(b)</sup>                                  | 5.19E-09                                                 | 4.83E-10 <sup>(b)</sup>                                 | 1.71E-12                                                                |
| <b>40°C Experiments</b> |                 |                    |                                                          |                                                         |                                                          |                                                          |                                                         |                                                                         |
| 7                       | 6.6             | 40                 | 7.59E-10                                                 | 1.54E-11                                                | 3.58E-13                                                 | 5.84E-09                                                 | 6.09E-10                                                | 2.48E-12                                                                |
| 8                       | 7.7             | 45                 | 2.52E-10                                                 | 4.06E-12                                                | 1.16E-13                                                 | 3.50E-09                                                 | 3.12E-10                                                | 6.43E-13                                                                |
| 9                       | 8.7             | 60                 | 1.43E-10                                                 | 9.91E-13                                                | 3.02E-14                                                 | 2.08E-09                                                 | 1.64E-10                                                | 2.87E-13                                                                |
| 10                      | 9.7             | 105                | 1.16E-10                                                 | 5.99E-13                                                | 2.88E-14                                                 | 1.17E-09                                                 | 7.85E-11 <sup>(b)</sup>                                 | 2.70E-14 <sup>(b)</sup>                                                 |
| 11                      | 10.8            | 270                | 1.30E-10                                                 | 2.50E-12 <sup>(b)</sup>                                 | 7.00E-14                                                 | 2.44E-10                                                 | 1.93E-11                                                | 3.23E-13                                                                |
| <b>23°C Experiments</b> |                 |                    |                                                          |                                                         |                                                          |                                                          |                                                         |                                                                         |
| 7                       | 7.0             | 35                 | 1.04E-10                                                 | 1.46E-12                                                | 4.39E-14                                                 | 9.21E-10                                                 | 9.53E-11                                                | 3.57E-13                                                                |
| 8                       | 8.1             | 40                 | 4.80E-11                                                 | 6.20E-14                                                | 1.72E-14                                                 | 2.91E-10                                                 | 2.59E-11                                                | 5.43E-14                                                                |
| 9                       | 9.1             | 52.5               | 4.72E-11                                                 | Not reportable                                          | 1.74E-14                                                 | 1.63E-10                                                 | 7.07E-12                                                | 6.56E-14 <sup>(c)</sup>                                                 |
| 10                      | 10.0            | 90                 | 4.44E-11                                                 | Not reportable                                          | 2.51E-14 <sup>(b)</sup>                                  | 1.56E-10                                                 | 1.39E-11                                                | 5.59E-14                                                                |
| 11                      | 11.1            | 230                | 2.92E-11                                                 | Not reportable                                          | 8.53E-15 <sup>(b)</sup>                                  | 4.28E-11 <sup>(b)</sup>                                  | 2.63E-12 <sup>(b)</sup>                                 | 9.06E-14 <sup>(b)</sup>                                                 |

<sup>(a)</sup>“mol” in the r<sub>ie</sub> units refers to moles of the indicated alkali element released by ion exchange.

<sup>(b)</sup> r<sub>IE</sub> was calculated by difference to Re only when the Mo data were not reportable.

<sup>(c)</sup> r<sub>IE</sub> was calculated by difference to Mo only when the Re data were not reportable.

**Table 4.6. Regression Results to Obtain  $K_g$  from Pulsed-Flow Test Data for IDFIX21-1, IDFIX21-2, IDFIX21-3, and IDFIX21-4.**

| -                                                              | Temperature   | NDR element | $K_g(\text{mol L}^{-1})$ |
|----------------------------------------------------------------|---------------|-------------|--------------------------|
| IDFIX21-1CC                                                    | 70°C          | B           | $3.30 \times 10^{-3}$    |
|                                                                | Linear fit    | Re          | $3.34 \times 10^{-3}$    |
|                                                                | 40°C          | B           | $2.04 \times 10^{-3}$    |
|                                                                | Linear fit    | Re          | $2.95 \times 10^{-3}$    |
|                                                                | 23°C          | B           | $2.15 \times 10^{-3}$    |
|                                                                | Linear fit    | Re          | $2.09 \times 10^{-3}$    |
|                                                                | 15°C          | B           | $1.79 \times 10^{-3}$    |
|                                                                | extrapolation | Re          | $2.03 \times 10^{-3}$    |
| IDFIX21-1 average of B and Re 15°C $K_g = 1.91 \times 10^{-3}$ |               |             |                          |
| IDFIX21-2CC                                                    | 70°C          | B           | $3.80 \times 10^{-3}$    |
|                                                                | Linear fit    | Re          | $2.24 \times 10^{-3}$    |
|                                                                | 40°C          | B           | $2.14 \times 10^{-3}$    |
|                                                                | Linear fit    | Re          | $2.35 \times 10^{-3}$    |
|                                                                | 23°C          | B           | $1.81 \times 10^{-3}$    |
|                                                                | Linear fit    | Re          | $1.83 \times 10^{-3}$    |
|                                                                | 15°C          | B           | $1.44 \times 10^{-3}$    |
|                                                                | extrapolation | Re          | $1.61 \times 10^{-3}$    |
| IDFIX21-2 average of B and Re 15°C $K_g = 1.52 \times 10^{-3}$ |               |             |                          |
| IDFIX21-2CC                                                    | 70°C          | B           | $3.67 \times 10^{-3}$    |
|                                                                | Linear fit    | Re          | $3.63 \times 10^{-3}$    |
|                                                                | 40°C          | B           | $2.06 \times 10^{-3}$    |
|                                                                | Linear fit    | Re          | $3.08 \times 10^{-3}$    |
|                                                                | 23°C          | B           | $1.99 \times 10^{-3}$    |
|                                                                | Linear fit    | Re          | $2.09 \times 10^{-3}$    |
|                                                                | 15°C          | B           | $1.61 \times 10^{-3}$    |
|                                                                | extrapolation | Re          | $2.00 \times 10^{-3}$    |
| IDFIX21-3 average of B and Re 15°C $K_g = 1.81 \times 10^{-3}$ |               |             |                          |
| IDFIX21-3IXCC                                                  | 70°C          | B           | $4.09 \times 10^{-3}$    |
|                                                                | Linear fit    | Re          | $4.10 \times 10^{-3}$    |
|                                                                | 40°C          | B           | $2.03 \times 10^{-3}$    |
|                                                                | Linear fit    | Re          | $1.99 \times 10^{-3}$    |
|                                                                | 23°C          | B           | $1.60 \times 10^{-3}$    |
|                                                                | Linear fit    | Re          | $1.63 \times 10^{-3}$    |
|                                                                | 15°C          | B           | $1.25 \times 10^{-3}$    |
|                                                                | extrapolation | Re          | $1.26 \times 10^{-3}$    |
| IDFIX21-4 average of B and Re 15°C $K_g = 1.25 \times 10^{-3}$ |               |             |                          |

**Table 4.7. Values of the Parameter  $K_g$  (mol L<sup>-1</sup>) at 15 °C for Glasses IDFIX21-1, IDFIX21-2, IDFIX21-3, and IDFIX21-4 from Pulsed-Flow Tests.**

| <b>Basis</b>        | <b>IDFIX21-1</b>      | <b>IDFIX21-2</b>            | <b>IDFIX21-3</b>            | <b>IDFIX21-4</b>            |
|---------------------|-----------------------|-----------------------------|-----------------------------|-----------------------------|
| Based on $NDR_B$    | $1.79 \times 10^{-3}$ | $1.44 \times 10^{-3}$       | $1.61 \times 10^{-3}$       | $1.25 \times 10^{-3}$       |
| Based on $NDR_{Re}$ | $2.03 \times 10^{-3}$ | $1.61 \times 10^{-3}$       | $2.00 \times 10^{-3}$       | $1.26 \times 10^{-3}$       |
| Average             | $1.91 \times 10^{-3}$ | $K_g = 1.52 \times 10^{-3}$ | $K_g = 1.81 \times 10^{-3}$ | $K_g = 1.25 \times 10^{-3}$ |

**Table 5.1. Summary of Regression Statistics and Model Parameters in Equation 1.6; Uncertainties in Parentheses.**

| Glass ID                                                                           | IX21-1             | IX21-1             | IX21-1             | IX21-1             | IX21-2             | IX21-2             | IX21-2             | IX21-2             |
|------------------------------------------------------------------------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|
| Element                                                                            | Na                 | Li                 | K                  | Cs                 | Na                 | Li                 | K                  | Cs                 |
| R <sup>2</sup>                                                                     | 0.810              | 0.859              | 0.794              | 0.754              | 0.781              | 0.857              | 0.718              | 0.688              |
| R <sup>2</sup> <sub>Adj</sub>                                                      | 0.808              | 0.857              | 0.791              | 0.750              | 0.778              | 0.855              | 0.713              | 0.683              |
| Root Mean Square Error                                                             | 0.368              | 0.309              | 0.418              | 0.444              | 0.357              | 0.263              | 0.386              | 0.444              |
| Mean of Response<br>(Log <sub>10</sub> <i>r</i> <sub>EX</sub> )                    | -9.930             | -10.342            | -11.083            | -12.903            | -10.267            | -10.317            | -11.645            | -13.149            |
| Number of Observations                                                             | 147                | 148                | 122                | 125                | 146                | 147                | 118                | 128                |
| <b>Model Terms: Log (<i>r</i><sub>EX</sub>) = A + (B/T) + C× pH - (1/2)×log(t)</b> |                    |                    |                    |                    |                    |                    |                    |                    |
| A (Intercept)                                                                      | 0.22 (0.51)        | -0.22 (0.42)       | 0.19 (0.65)        | -2.24 (0.66)       | -1.05 (0.49)       | -1.97 (0.36)       | -2.85 (0.62)       | -5.49 (0.67)       |
| B (1/Temp, K)                                                                      | -2552.0<br>(166.8) | -2518.8<br>(138.9) | -2855.4<br>(218.1) | -2749.9<br>(225.0) | -2563.2<br>(162.0) | -2150.7<br>(119.0) | -2357.1<br>(210.1) | -1665.5<br>(231.7) |
| C (pH)                                                                             | -0.187<br>(0.022)  | -0.196<br>(0.018)  | -0.215<br>(0.027)  | -0.174<br>(0.028)  | -0.075<br>(0.021)  | -0.126<br>(0.015)  | -0.106<br>(0.025)  | -0.223<br>(0.028)  |
| <b>Parameters in Equation 1.6:</b>                                                 |                    |                    |                    |                    |                    |                    |                    |                    |
| Log (k <sub>d0</sub> , mol m <sup>-2</sup> s <sup>-1/2</sup> )                     | 3.0 (0.5)          | 2.5 (0.4)          | 2.95 (0.65)        | 0.53 (0.66)        | 1.7 (0.5)          | 0.8 (0.4)          | -0.1 (0.6)         | -2.7 (0.7)         |
| E <sub>ad</sub> , kJ mol <sup>-1</sup>                                             | 48.9 (3.2)         | 48.2 (2.7)         | 54.7 (4.2)         | 52.6 (4.3)         | 49.1 (3.1)         | 41.2 (2.3)         | 45.1 (4.0)         | 31.9 (4.4)         |
| α                                                                                  | 0.187<br>(0.022)   | 0.196<br>(0.018)   | 0.215<br>(0.027)   | 0.174<br>(0.028)   | 0.075<br>(0.021)   | 0.126<br>(0.015)   | 0.106<br>(0.025)   | 0.223<br>(0.028)   |

**Table 5.1. Summary of Regression Statistics and Model Parameters in Equation 1.6; Uncertainties in Parentheses (cont'd).**

| Glass ID                                                                             | IX21-3           | IX21-3           | IX21-3           | IX21-4           | IX21-4           | IX21-4           |
|--------------------------------------------------------------------------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| Element                                                                              | Na               | K                | Cs               | Na               | K                | Cs               |
| R <sup>2</sup>                                                                       | 0.918            | 0.818            | 0.852            | 0.970            | 0.963            | 0.889            |
| R <sup>2</sup> <sub>Adj</sub>                                                        | 0.917            | 0.815            | 0.850            | 0.970            | 0.963            | 0.887            |
| Root Mean Square Error                                                               | 0.239            | 0.447            | 0.388            | 0.168            | -9.343           | 0.309            |
| Mean of Response (Log <sub>10</sub> <i>r</i> <sub>IEX</sub> )                        | -9.315           | -11.186          | -12.731          | -8.590           | -9.672           | 0.897            |
| Number of Observations                                                               | 147              | 120              | 127              | 150              | 148              | 145              |
| <b>Model Terms: Log (<i>r</i><sub>IEX</sub>) = A + (B/T) + C× pH - (1/2) ×log(t)</b> |                  |                  |                  |                  |                  |                  |
| A (Intercept)                                                                        | 1.68 (0.33)      | 2.17 (0.69)      | -0.10 (0.57)     | 6.25 (0.23)      | 5.86 (0.27)      | 1.89 (0.43)      |
| B (1/Temp, K)                                                                        | -2792.8 (107.9)  | -3317.2 (225.6)  | -3136.7 (185)    | -3813.5 (75.1)   | -3962.6 (87.5)   | -3699.1 (141.6)  |
| C (pH)                                                                               | -0.199 (0.014)   | -0.303 (0.029)   | -0.27 (0.025)    | -0.286 (0.01)    | -0.314 (0.011)   | -0.222 (0.018)   |
| <b>Parameters in Equation 1.6:</b>                                                   |                  |                  |                  |                  |                  |                  |
| Log (k <sub>d0</sub> , mol m <sup>-2</sup> s <sup>-1/2</sup> )                       | 4.5 (0.3)        | 4.9 (0.7)        | 2.7 (0.6)        | 9.0 (0.2)        | 8.6 (0.3)        | 4.7 (0.4)        |
| E <sub>ad</sub> , kJ mol <sup>-1</sup>                                               | 53.5 (2.1)       | 63.5 (4.3)       | 60 (3.5)         | 73.0 (1.4)       | 75.9 (1.7)       | 70.8 (2.7)       |
| α                                                                                    | 0.199<br>(0.014) | 0.303<br>(0.029) | 0.270<br>(0.025) | 0.286<br>(0.010) | 0.314<br>(0.011) | 0.222<br>(0.018) |

**Table 5.2. Summary of Regression Statistics and Model Parameters in Equation 1.8; Uncertainties in Parentheses.**

| Glass ID                                                                                      | IX21-1          | IX21-1          | IX21-1          | IX21-1          | IX21-2          | IX21-2          | IX21-2          | IX21-2              |
|-----------------------------------------------------------------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|---------------------|
| Element                                                                                       | Na              | Li              | K               | Cs              | Na              | Li              | K               | Cs                  |
| R <sup>2</sup>                                                                                | 0.820           | 0.872           | 0.796           | 0.760           | 0.792           | 0.879           | 0.721           | 0.688               |
| R <sup>2</sup> <sub>Adj</sub>                                                                 | 0.816           | 0.869           | 0.791           | 0.755           | 0.788           | 0.877           | 0.714           | 0.681               |
| Root Mean Square Error                                                                        | 0.360           | 0.296           | 0.418           | 0.440           | 0.348           | 0.242           | 0.385           | 0.446               |
| Mean of Response (Log <sub>10</sub> <i>r</i> <sub>IEX</sub> )                                 | -9.930          | -10.342         | -11.083         | -12.903         | -10.267         | -10.317         | -11.645         | -13.149             |
| Number of Observations                                                                        | 147             | 148             | 122             | 125             | 146             | 147             | 118             | 128                 |
| <b>Model Terms:</b> $\text{Log}(r_{IEX}) = A + (B/T) + C \times \text{pH} + D \times \log(t)$ |                 |                 |                 |                 |                 |                 |                 |                     |
| A (Intercept)*                                                                                | -0.43 (0.55)    | -0.94 (0.45)    | 0.51 (0.71)     | -1.54 (0.76)    | -1.66 (0.53)    | -2.77 (0.37)    | -2.46 (0.69)    | -5.45 (0.78)        |
| B (1/Temp, K)                                                                                 | -2264.2 (192.4) | -2200.3 (156.6) | -2995.3 (253.5) | -3053.1 (278.4) | -2292.5 (185.5) | -1798.6 (128.8) | -2525.1 (248.6) | -1681.241 (287.559) |
| C (pH)                                                                                        | -0.187 (0.021)  | -0.196 (0.017)  | -0.216 (0.027)  | -0.174 (0.028)  | -0.075 (0.02)   | -0.125 (0.014)  | -0.105 (0.025)  | -0.2 (0)            |
| D (log(t))                                                                                    | -0.764 (0.094)  | -0.796 (0.077)  | -0.371 (0.119)  | -0.246 (0.14)   | -0.755 (0.091)  | -0.828 (0.063)  | -0.355 (0.115)  | -0.488 (0.133)      |
| <b>Parameters in Equation 1.8:</b>                                                            |                 |                 |                 |                 |                 |                 |                 |                     |
| Log (k <sub>d0</sub> , mol m <sup>-2</sup> s <sup>(γ-1)</sup> )                               | 3.64 (0.72)     | 3.29 (0.45)     | 2.64 (0.92)     | -0.02 (1.03)    | 2.36 (0.7)      | 1.62 (0.48)     | -0.41 (0.9)     | -2.74 (1.02)        |
| E <sub>ad</sub> , kJ mol <sup>-1</sup>                                                        | 43.3 (3.7)      | 42.1 (3)        | 57.3 (4.9)      | 58.4 (5.3)      | 43.9 (3.6)      | 34.4 (2.5)      | 48.3 (4.8)      | 32.2 (5.5)          |
| α                                                                                             | 0.187 (0.021)   | 0.196 (0.017)   | 0.216 (0.027)   | 0.174 (0.028)   | 0.075 (0.02)    | 0.125 (0.014)   | 0.105 (0.025)   | 0.223 (0.029)       |
| γ                                                                                             | 0.764 (0.094)   | 0.796 (0.077)   | 0.371 (0.119)   | 0.246 (0.14)    | 0.755 (0.091)   | 0.828 (0.063)   | 0.355 (0.115)   | 0.488 (0.133)       |

**Table 5.2. Summary of Regression Statistics and Model Parameters in Equation 1.8; Uncertainties in Parentheses (cont'd).**

| Glass ID                                                                                      | IX21-3           | IX21-3           | IX21-3           | IX21-4           | IX21-4           | IX21-4           |
|-----------------------------------------------------------------------------------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| Element                                                                                       | Na               | K                | Cs               | Na               | K                | Cs               |
| R <sup>2</sup>                                                                                | 0.925            | 0.825            | 0.856            | 0.972            | 0.972            | 0.897            |
| R <sup>2</sup> <sub>Adj</sub>                                                                 | 0.923            | 0.820            | 0.853            | 0.972            | 0.971            | 0.895            |
| Root Mean Square Error                                                                        | 0.231            | 0.440            | 0.384            | 0.163            | 0.172            | 0.298            |
| Mean of Response (Log <sub>10</sub> <i>r</i> <sub>IEX</sub> )                                 | -9.315           | -11.186          | -12.731          | -8.590           | -9.672           | -12.037          |
| Number of Observations                                                                        | 147              | 120              | 127              | 150              | 148              | 145              |
| <b>Model Terms:</b> $\text{Log}(r_{IEX}) = A + (B/T) + C \times \text{pH} + D \times \log(t)$ |                  |                  |                  |                  |                  |                  |
| A (Intercept)                                                                                 | 1.17 (0.35)      | 2.97 (0.78)      | 0.64 (0.7)       | 6.16 (0.22)      | 5.66 (0.24)      | 1.73 (0.42)      |
| B (1/Temp, K)                                                                                 | -2568.2 (122.9)  | -3640.7 (271)    | -3431.1 (245.7)  | -3813.5 (72.9)   | -3959.8 (77.4)   | -3704.7 (136.5)  |
| C (pH)                                                                                        | -0.198 (0.013)   | -0.308 (0.029)   | -0.277 (0.025)   | -0.286 (0.009)   | -0.315 (0.01)    | -0.224 (0.017)   |
| D (log(t))                                                                                    | -0.707 (0.06)    | -0.23 (0.129)    | -0.264 (0.131)   | -0.361 (0.044)   | -0.194 (0.047)   | -0.204 (0.086)   |
| <b>Parameters in Equation 1.8:</b>                                                            |                  |                  |                  |                  |                  |                  |
| Log (k <sub>d0</sub> , mol m <sup>-2</sup> s <sup>(γ-1)</sup> )                               | 4.96 (0.46)      | 4.4 (1.01)       | 2.24 (0.95)      | 8.24 (0.31)      | 6.92 (0.33)      | 3.03 (0.6)       |
| E <sub>ad</sub> , kJ mol <sup>-1</sup>                                                        | 49.2 (2.4)       | 69.7 (5.2)       | 65.7 (4.7)       | 73.0 (1.4)       | 75.8 (1.5)       | 70.9 (2.6)       |
| α                                                                                             | 0.198<br>(0.013) | 0.308<br>(0.029) | 0.277<br>(0.025) | 0.286<br>(0.009) | 0.315<br>(0.01)  | 0.224<br>(0.017) |
| γ                                                                                             | 0.707<br>(0.06)  | 0.230<br>(0.129) | 0.264<br>(0.131) | 0.361<br>(0.044) | 0.194<br>(0.047) | 0.204<br>(0.086) |

**Table 5.3. Comparison of Activation Energies Determined for Na, K, Li, and Cs for Glasses IX21-1, IX21-2, IX21-3, and IX21-4.**

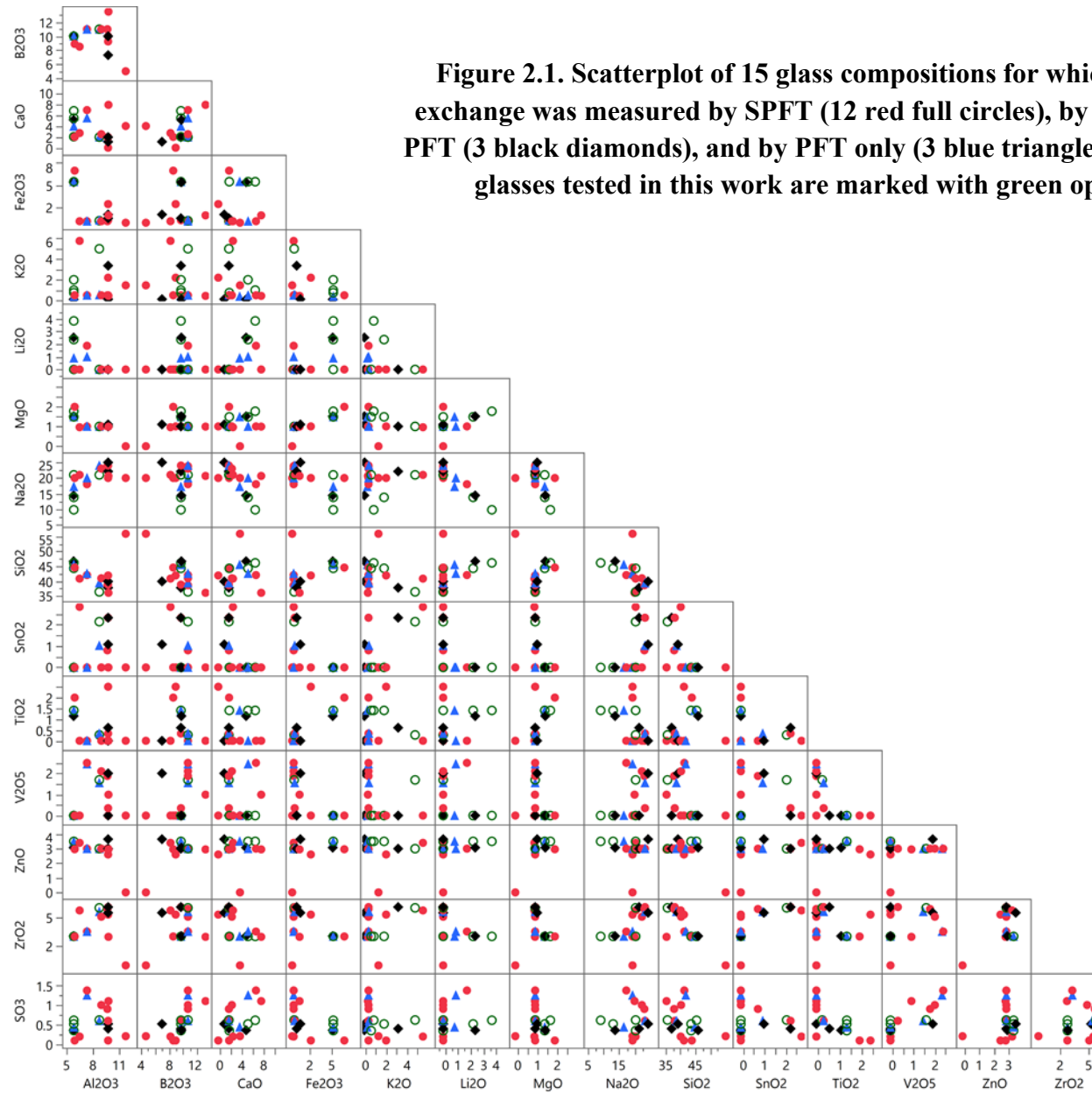
| Element | Glass ID | E <sub>ad</sub> , kJ/mol |              |
|---------|----------|--------------------------|--------------|
|         |          | Equation 1.6             | Equation 1.8 |
| Na      | IX21-1   | 48.9                     | 43.3         |
| Na      | IX21-2   | 49.1                     | 43.9         |
| Na      | IX21-3   | 53.5                     | 49.2         |
| Na      | IX21-4   | 73.0                     | 73.0         |
| Li      | IX21-1   | 48.2                     | 42.1         |
| Li      | IX21-2   | 41.2                     | 34.4         |
| K       | IX21-1   | 54.7                     | 57.3         |
| K       | IX21-2   | 45.1                     | 48.3         |
| K       | IX21-3   | 63.5                     | 69.7         |
| K       | IX21-4   | 75.9                     | 73.0         |
| Cs      | IX21-1   | 52.6                     | 58.4         |
| Cs      | IX21-2   | 31.9                     | 32.2         |
| Cs      | IX21-3   | 60.0                     | 65.7         |
| Cs      | IX21-4   | 70.8                     | 70.9         |

**Table 5.4. Comparison of Extrapolated Ion Exchange Rates Determined for Na, Li, K, and Cs for Glasses IX21-1, IX21-2, IX21-3, and IX21-4.**

| IEX Rate at 15 °C and 30 days from Eq. 1.6 (mol m <sup>-2</sup> s <sup>-1</sup> ) |          |          |          |          |          |          |          |          |
|-----------------------------------------------------------------------------------|----------|----------|----------|----------|----------|----------|----------|----------|
| Glass ID                                                                          | IX21-1   | IX21-1   | IX21-1   | IX21-1   | IX21-2   | IX21-2   | IX21-2   | IX21-2   |
| pH <sub>T</sub>                                                                   | Na       | Li       | K        | Cs       | Na       | Li       | K        | Cs       |
| 7                                                                                 | 2.04E-11 | 8.30E-12 | 1.07E-12 | 1.80E-14 | 6.07E-12 | 8.82E-12 | 3.10E-13 | 2.69E-14 |
| 8                                                                                 | 1.33E-11 | 5.28E-12 | 6.53E-13 | 1.21E-14 | 5.10E-12 | 6.60E-12 | 2.43E-13 | 1.61E-14 |
| 9                                                                                 | 8.62E-12 | 3.36E-12 | 3.99E-13 | 8.09E-15 | 4.29E-12 | 4.94E-12 | 1.91E-13 | 9.63E-15 |
| 10                                                                                | 5.61E-12 | 2.14E-12 | 2.43E-13 | 5.42E-15 | 3.61E-12 | 3.70E-12 | 1.50E-13 | 5.76E-15 |
| 11                                                                                | 3.65E-12 | 1.36E-12 | 1.48E-13 | 3.63E-15 | 3.03E-12 | 2.77E-12 | 1.17E-13 | 3.45E-15 |
| IEX Rate at 15 °C and 30 days from Eq. 1.8 (mol m <sup>-2</sup> s <sup>-1</sup> ) |          |          |          |          |          |          |          |          |
| Glass ID                                                                          | IX21-1   | IX21-1   | IX21-1   | IX21-1   | IX21-2   | IX21-2   | IX21-2   | IX21-2   |
| pH <sub>T</sub>                                                                   | Na       | Li       | K        | Cs       | Na       | Li       | K        | Cs       |
| 7                                                                                 | 1.84E-11 | 7.38E-12 | 1.12E-12 | 1.89E-14 | 5.46E-12 | 7.72E-12 | 3.23E-13 | 2.70E-14 |
| 8                                                                                 | 1.20E-11 | 4.70E-12 | 6.84E-13 | 1.26E-14 | 4.60E-12 | 5.79E-12 | 2.53E-13 | 1.61E-14 |
| 9                                                                                 | 7.76E-12 | 2.99E-12 | 4.17E-13 | 8.45E-15 | 3.87E-12 | 4.34E-12 | 1.99E-13 | 9.66E-15 |
| 10                                                                                | 5.04E-12 | 1.90E-12 | 2.54E-13 | 5.65E-15 | 3.26E-12 | 3.26E-12 | 1.56E-13 | 5.78E-15 |
| 11                                                                                | 3.27E-12 | 1.21E-12 | 1.54E-13 | 3.78E-15 | 2.74E-12 | 2.44E-12 | 1.22E-13 | 3.46E-15 |

**Table 5.4. Comparison of Extrapolated Ion Exchange Rates Determined for Na, Li, K and Cs for Glasses IX21-1, IX21-2, IX21-3, and IX21-4 (cont'd).**

| IEX Rate at 15 °C and 30 days from Eq. 1.6 (mol m <sup>-2</sup> s <sup>-1</sup> ) |          |          |          |          |          |          |
|-----------------------------------------------------------------------------------|----------|----------|----------|----------|----------|----------|
| Glass ID                                                                          | IX21-3   | IX21-3   | IX21-3   | IX21-4   | IX21-4   | IX21-4   |
| pH <sub>T</sub>                                                                   | Na       | K        | Cs       | Na       | K        | Cs       |
| 7                                                                                 | 7.16E-11 | 6.29E-13 | 2.39E-14 | 1.84E-10 | 1.46E-11 | 5.69E-14 |
| 8                                                                                 | 4.53E-11 | 3.13E-13 | 1.28E-14 | 9.52E-11 | 7.09E-12 | 3.41E-14 |
| 9                                                                                 | 2.87E-11 | 1.56E-13 | 6.88E-15 | 4.93E-11 | 3.44E-12 | 2.05E-14 |
| 10                                                                                | 1.82E-11 | 7.78E-14 | 3.69E-15 | 2.55E-11 | 1.67E-12 | 1.23E-14 |
| 11                                                                                | 1.15E-11 | 3.87E-14 | 1.98E-15 | 1.32E-11 | 8.10E-13 | 7.37E-15 |
| IEX Rate at 15 °C and 30 days from Eq. 1.8 (mol m <sup>-2</sup> s <sup>-1</sup> ) |          |          |          |          |          |          |
| Glass ID                                                                          | IX21-3   | IX21-3   | IX21-3   | IX21-4   | IX21-4   | IX21-4   |
| pH <sub>T</sub>                                                                   | Na       | K        | Cs       | Na       | K        | Cs       |
| 7                                                                                 | 6.60E-11 | 6.81E-13 | 2.50E-14 | 2.40E-10 | 2.62E-11 | 9.86E-14 |
| 8                                                                                 | 4.18E-11 | 3.35E-13 | 1.32E-14 | 1.24E-10 | 1.27E-11 | 5.89E-14 |
| 9                                                                                 | 2.65E-11 | 1.65E-13 | 6.98E-15 | 6.41E-11 | 6.12E-12 | 3.52E-14 |
| 10                                                                                | 1.68E-11 | 8.13E-14 | 3.69E-15 | 3.31E-11 | 2.96E-12 | 2.10E-14 |
| 11                                                                                | 1.07E-11 | 4.00E-14 | 1.95E-15 | 1.71E-11 | 1.43E-12 | 1.26E-14 |



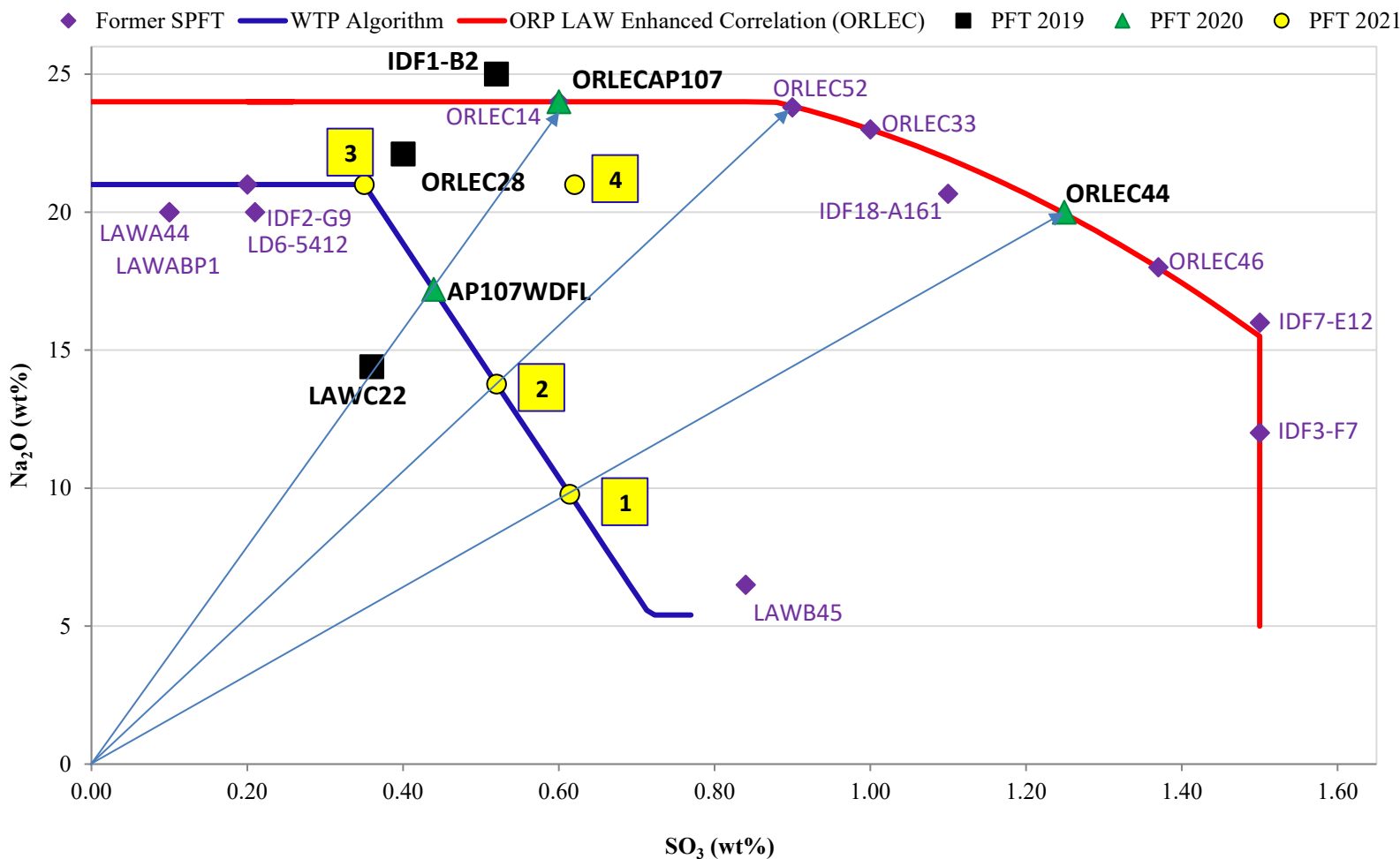
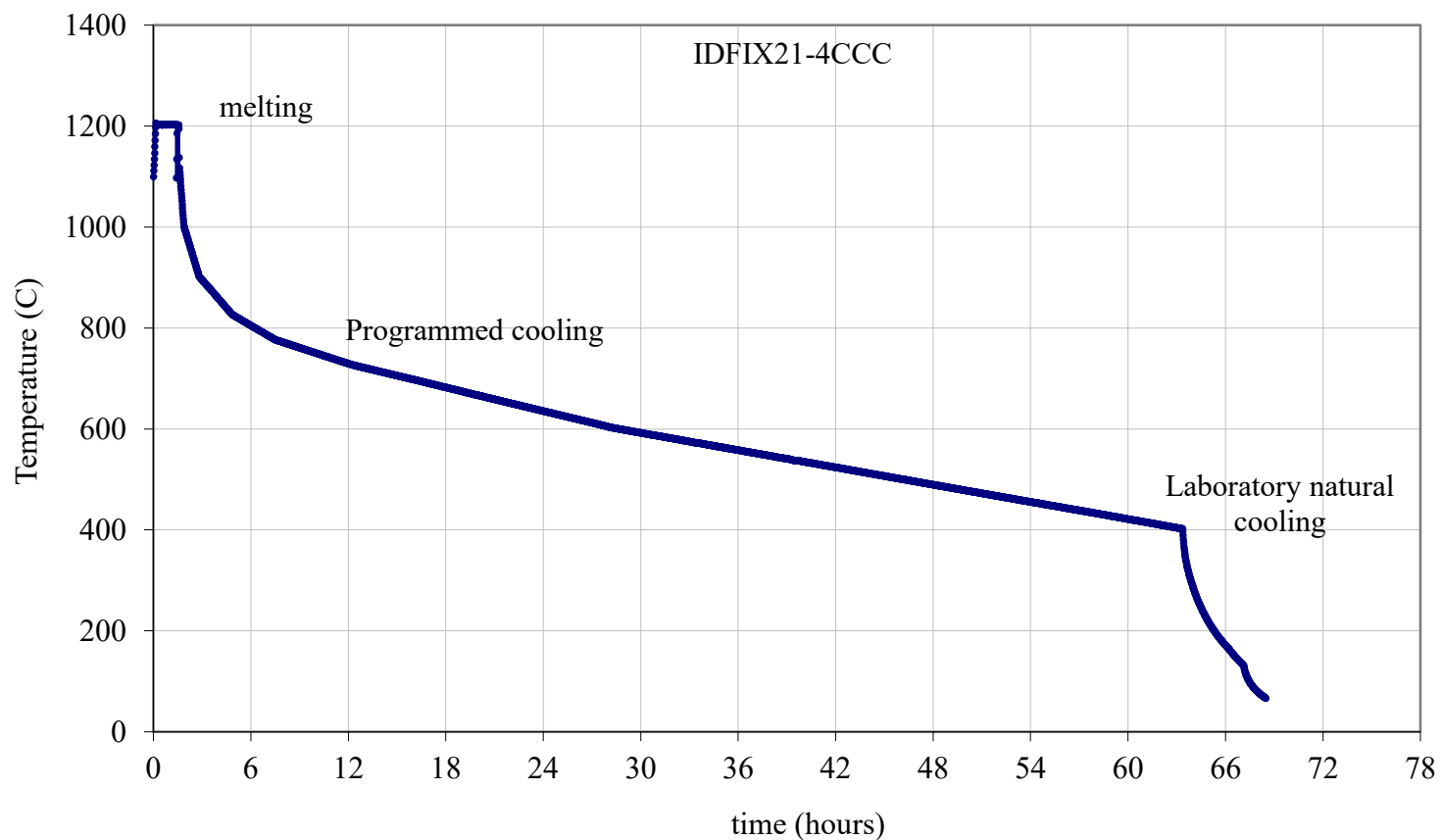
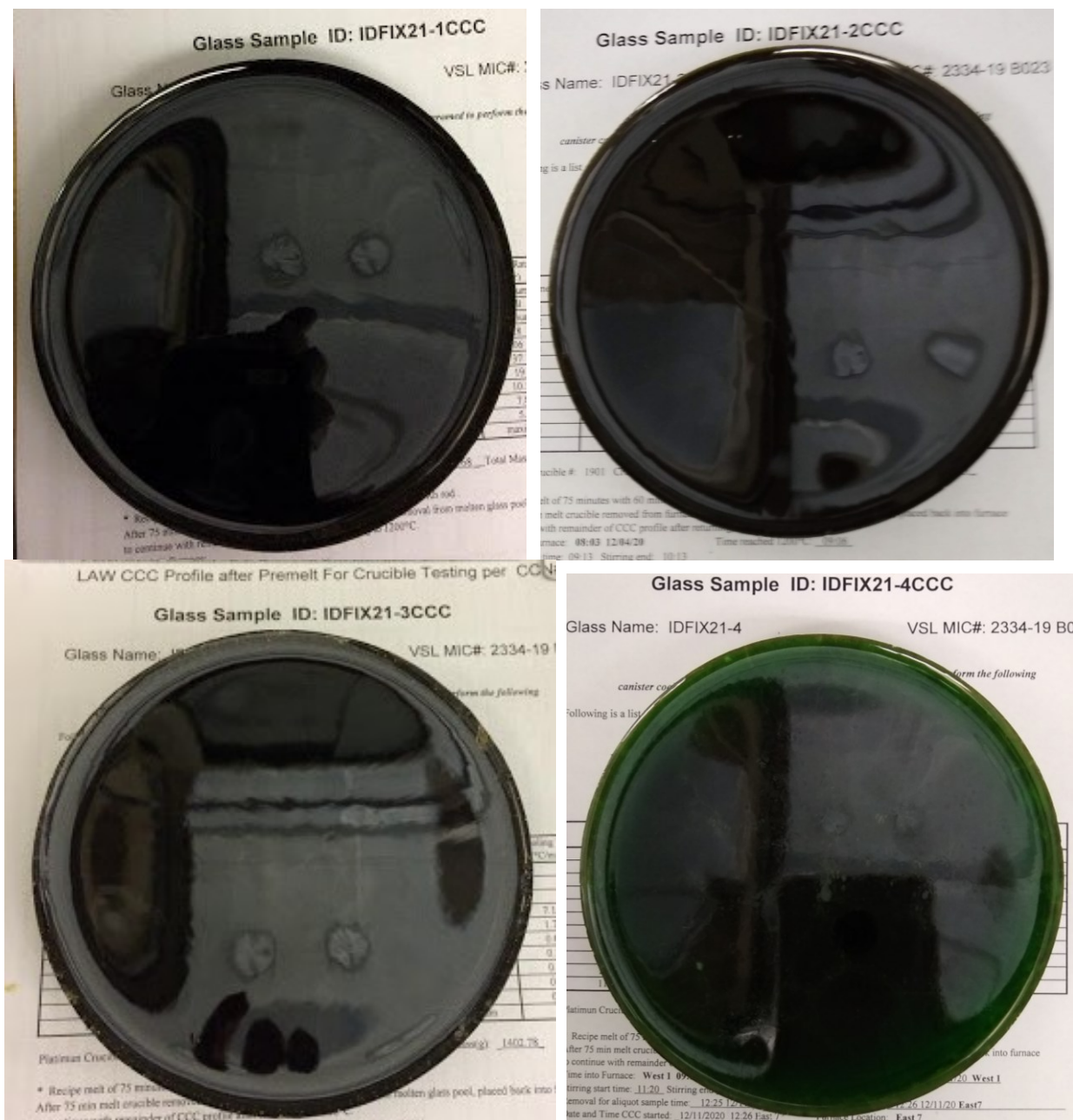


Figure 2.2. Na<sub>2</sub>O and SO<sub>3</sub> concentrations for the IDF glasses tested by SPFT (purple diamonds), by PFT in FY19 (black squares), and by PFT in FY20 (green triangles) compared to the four FY21 selected glasses for ion exchange testing by PFT (yellow circles); the blue lines show the waste loading increase from WTP Baseline to Enhanced correlation. Note that ion exchange data were not obtained for glasses LAWB45, IDF3-F7, and IDF7-E12.



**Figure 2.3. Canister centerline cooling profile recorded in preparation of IDFIX-4CCC.**



**Figure 2.4. Photographs of IDFIX21-1CCC, IDFIX21-2CCC, IDFIX21-3CCC, and IDFIX21-4CCC as collected from CCC heat treatment in platinum crucible.**

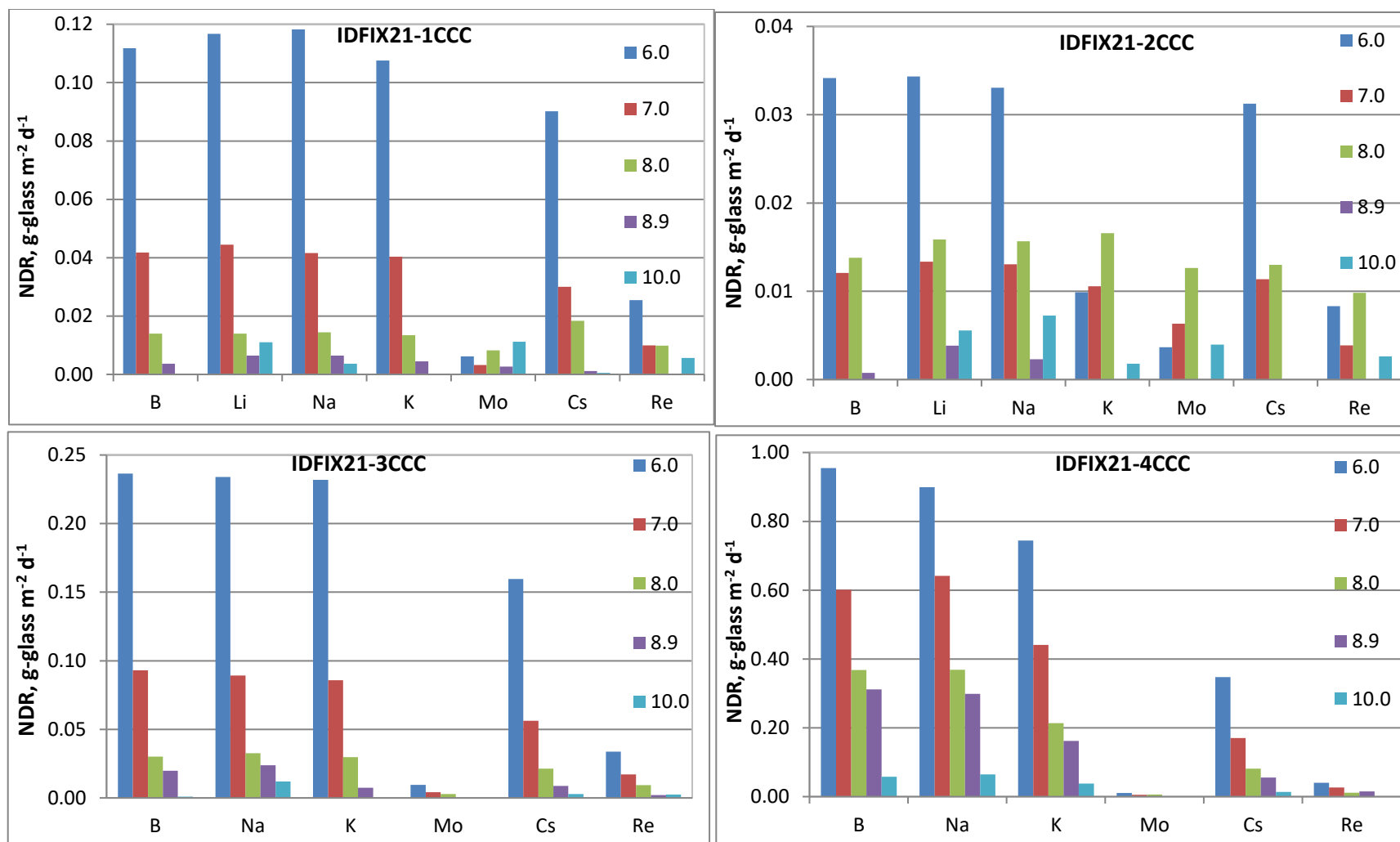


Figure 4.1. Dissolution rates of B, Li, K, Na, Cs, Mo, and Re from Pulsed-Flow tests for the four glasses at 70 °C and five pH values (labels show pH<sub>T</sub>).

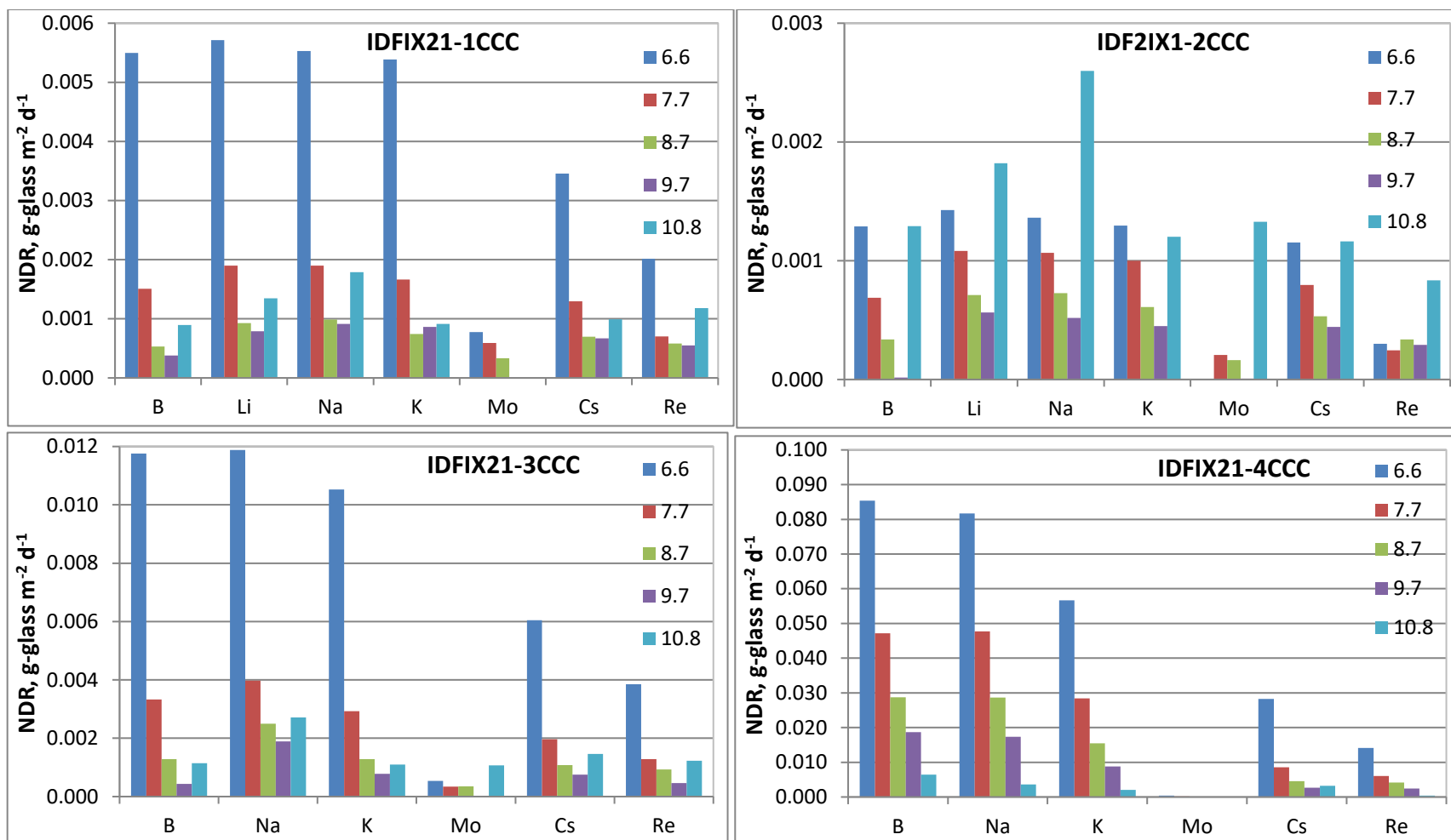


Figure 4.2. Dissolution rates of B, Li, K, Na, Cs, Mo, and Re from Pulsed-Flow tests for the four glasses at 40 °C and five pH values (labels show pH<sub>T</sub>).

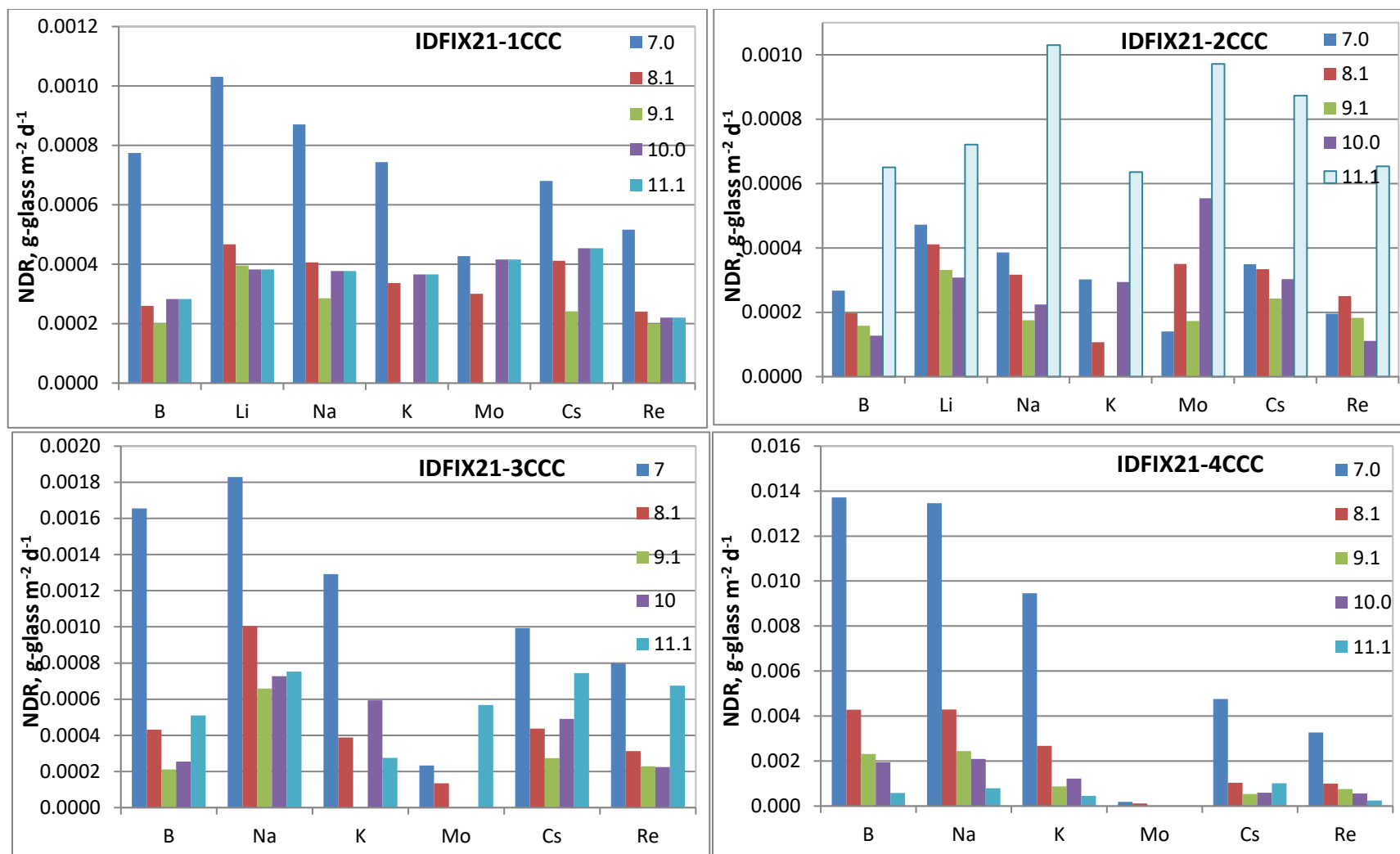
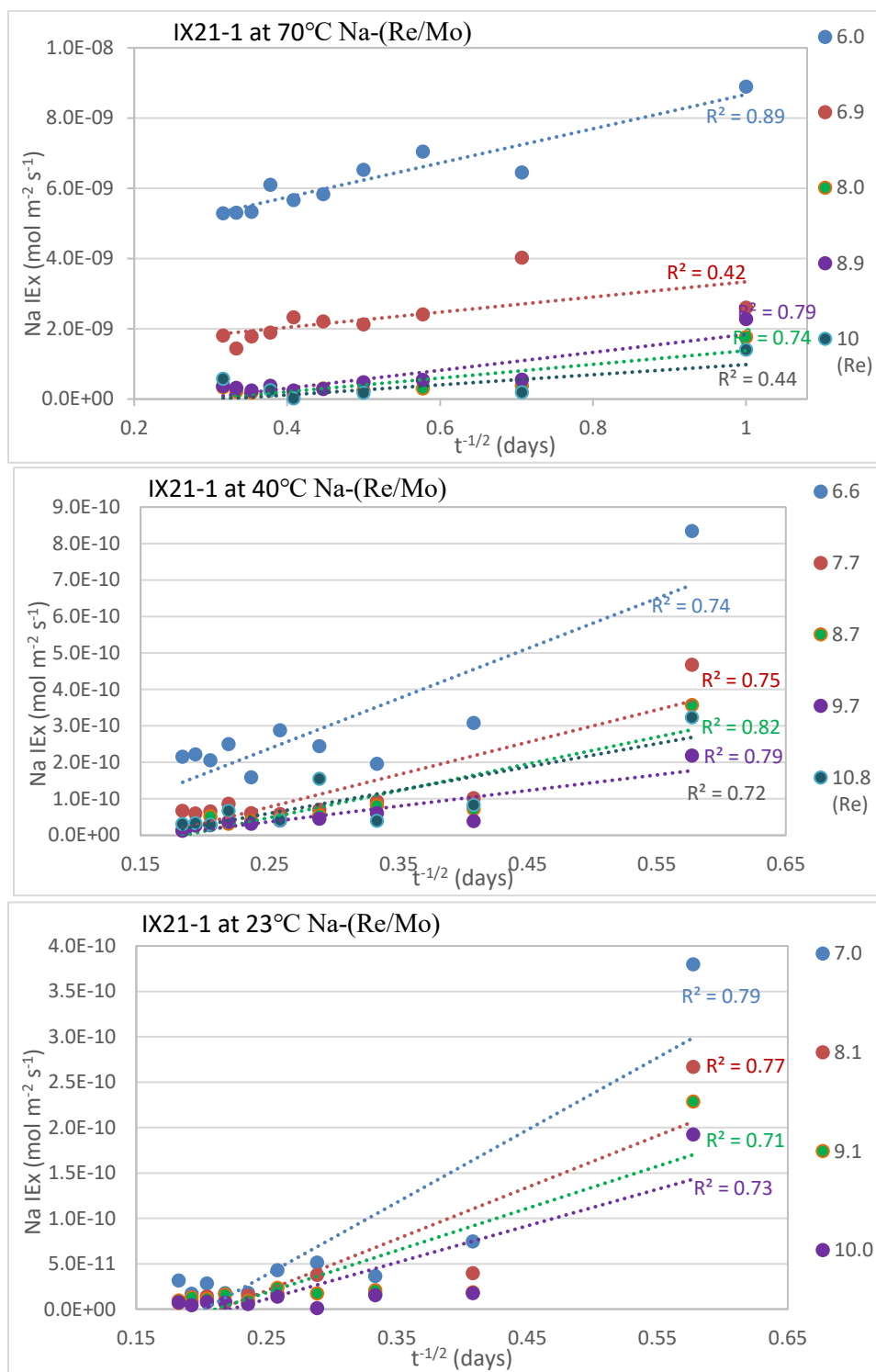
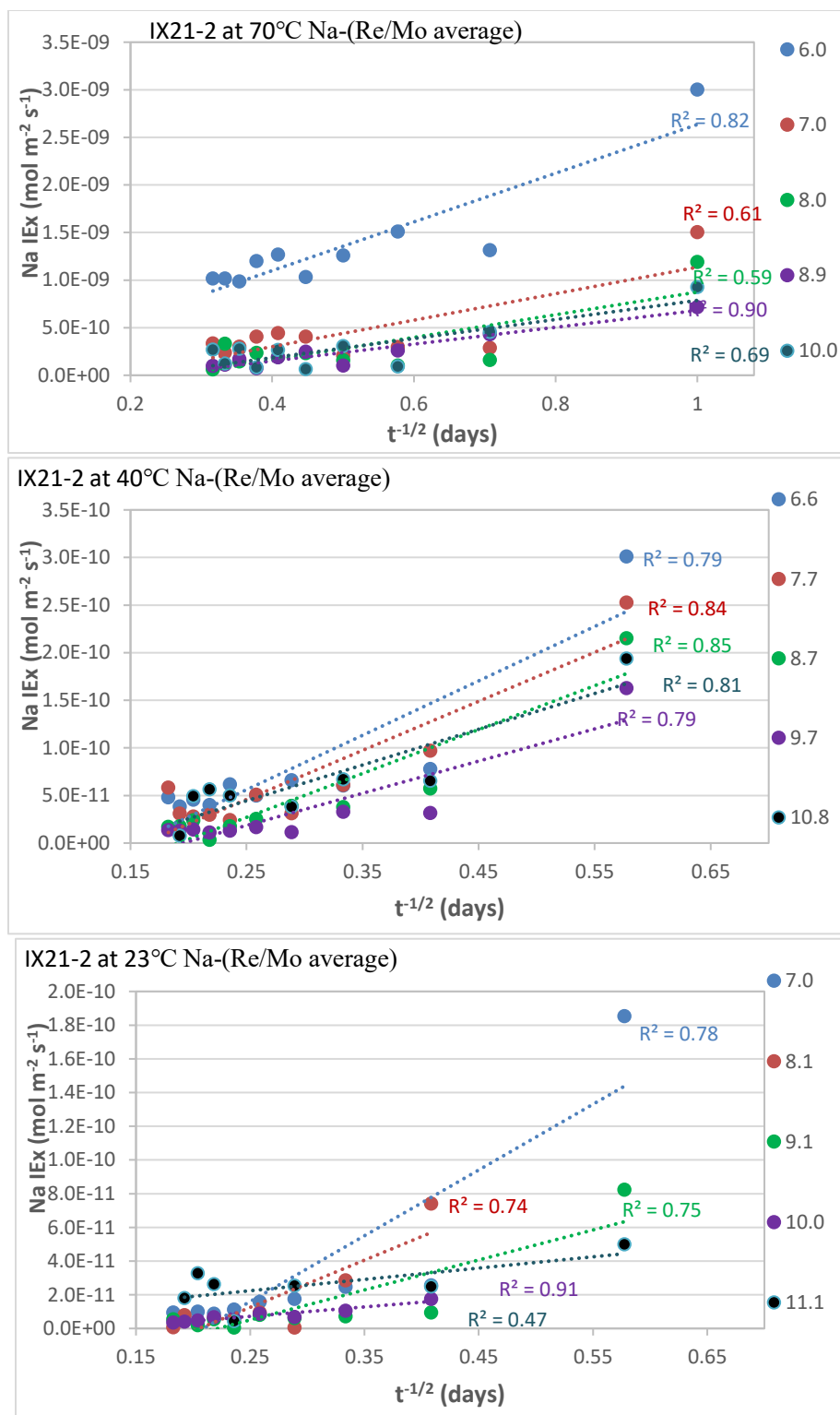


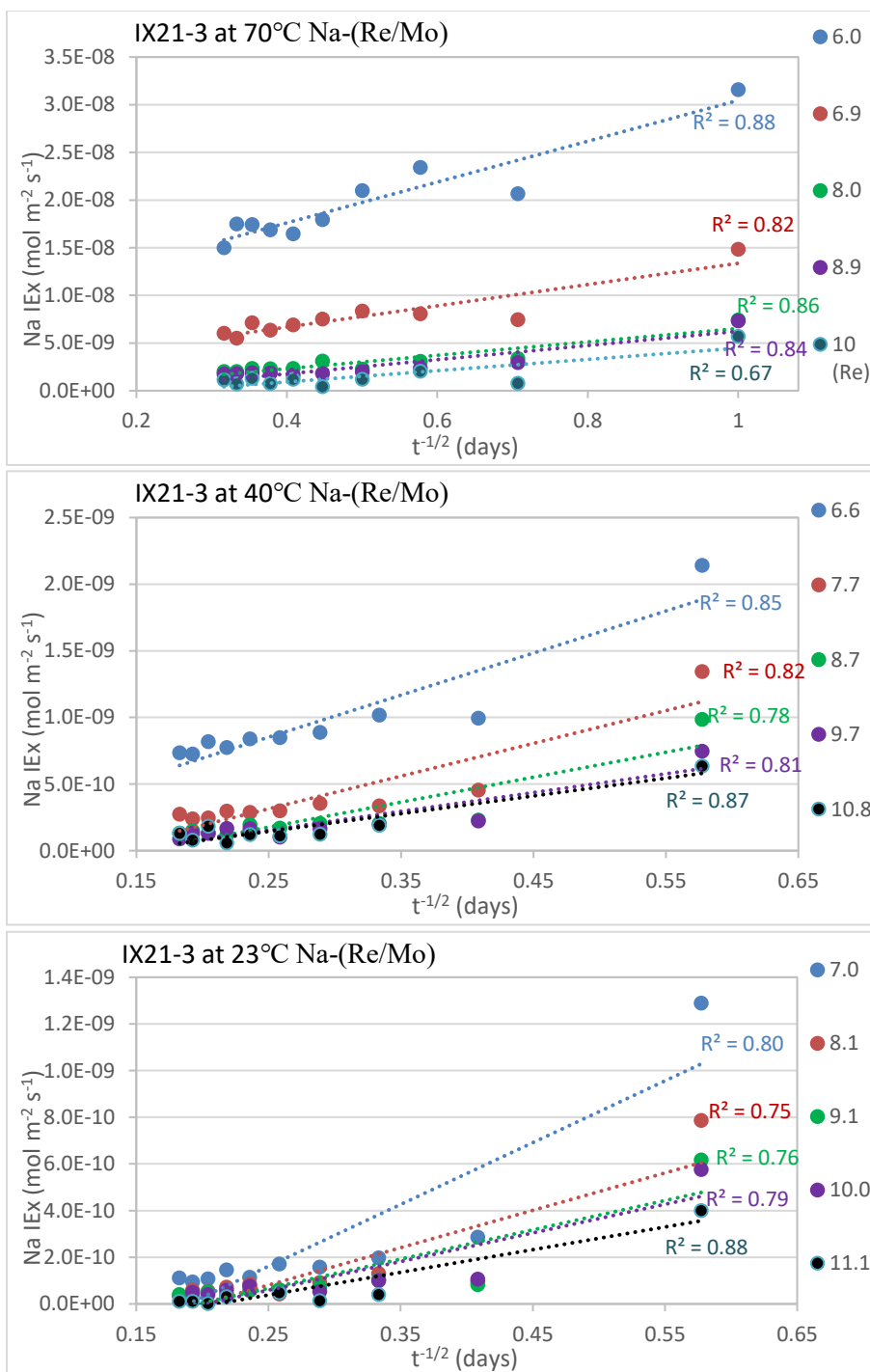
Figure 4.3. Dissolution rates of B, Li, K, Na, Cs, Mo, and Re from Pulsed-Flow tests for the four glasses at 23 °C and five pH values (labels show pH<sub>RT</sub>).



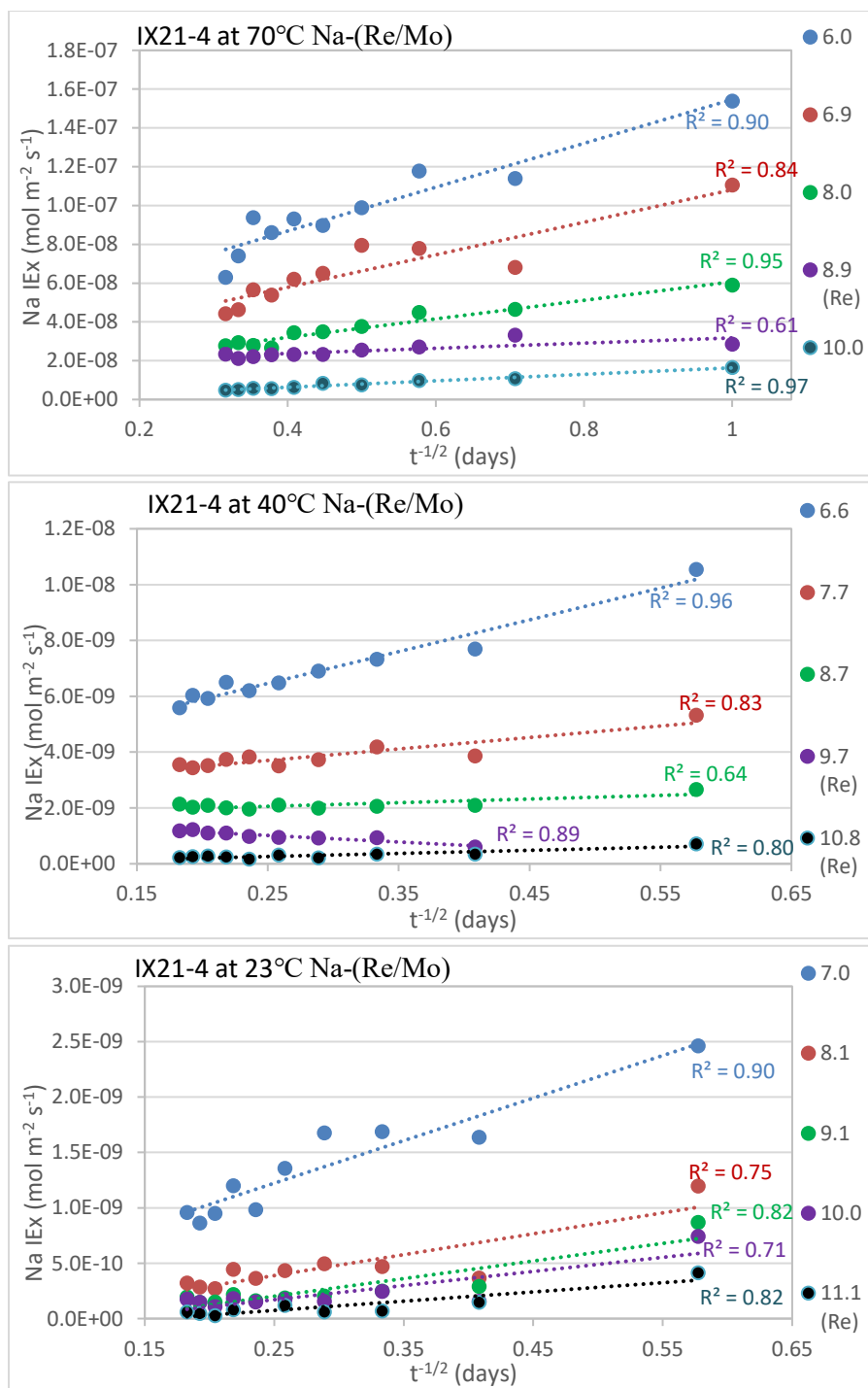
**Figure 4.4. Plots of sodium ion exchange rate as a function of square root of time (in days) from Pulsed-Flow tests conducted at 70 °C, 40 °C, and 23 °C with IDFIX21-1.**



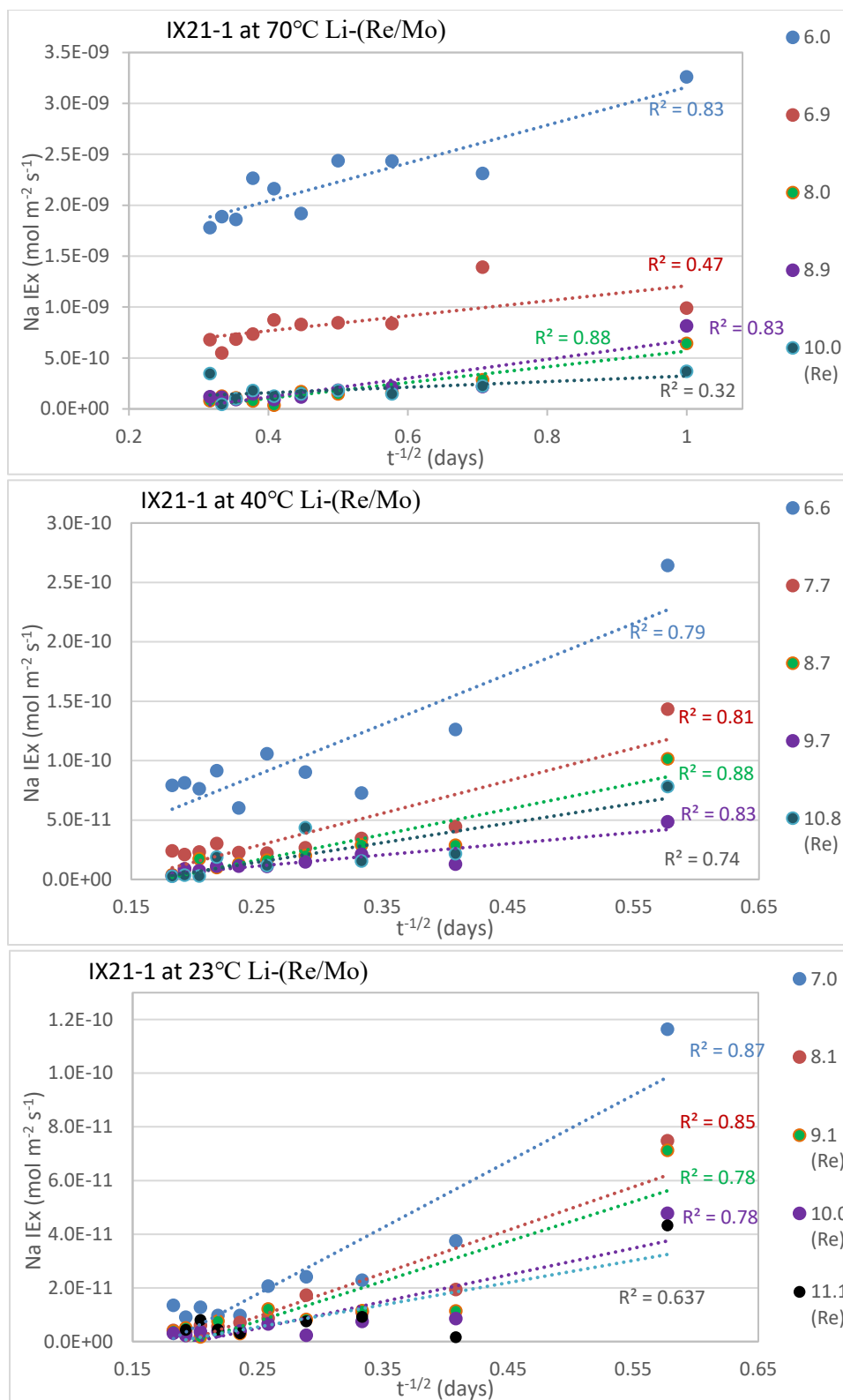
**Figure 4.5. Plots of sodium ion exchange rate as a function of square root of time from Pulsed-Flow tests conducted at 70 °C, 40 °C, and 23 °C with IDFIX21-2.**



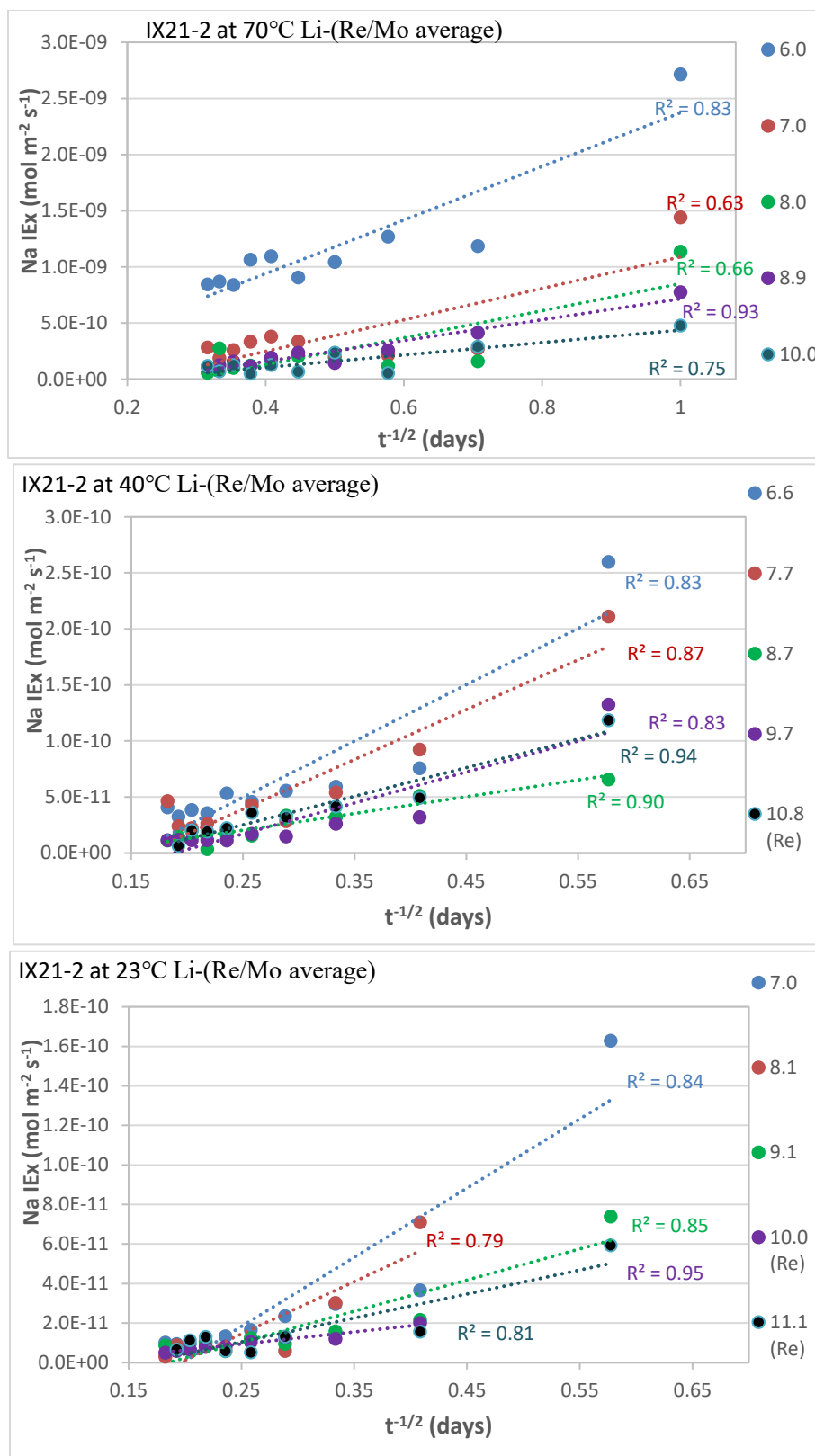
**Figure 4.6. Plots of sodium ion exchange rate as a function of square root of time from Pulsed-Flow tests conducted at 70 °C, 40 °C, and 23 °C with IDFIX21-3.**



**Figure 4.7. Plots of sodium ion exchange rate as a function of square root of time from Pulsed-Flow tests conducted at 70 °C, 40 °C, and 23 °C with IDFIX21-4.**



**Figure 4.8. Plots of lithium ion exchange rate as a function of square root of time from Pulsed-Flow tests conducted at 70 °C, 40 °C, and 23 °C with IDFIX21-1.**



**Figure 4.9. Plots of lithium ion exchange rate as a function of square root of time from Pulsed-Flow tests conducted at 70 °C, 40 °C, and 23 °C with IDFIX21-2.**

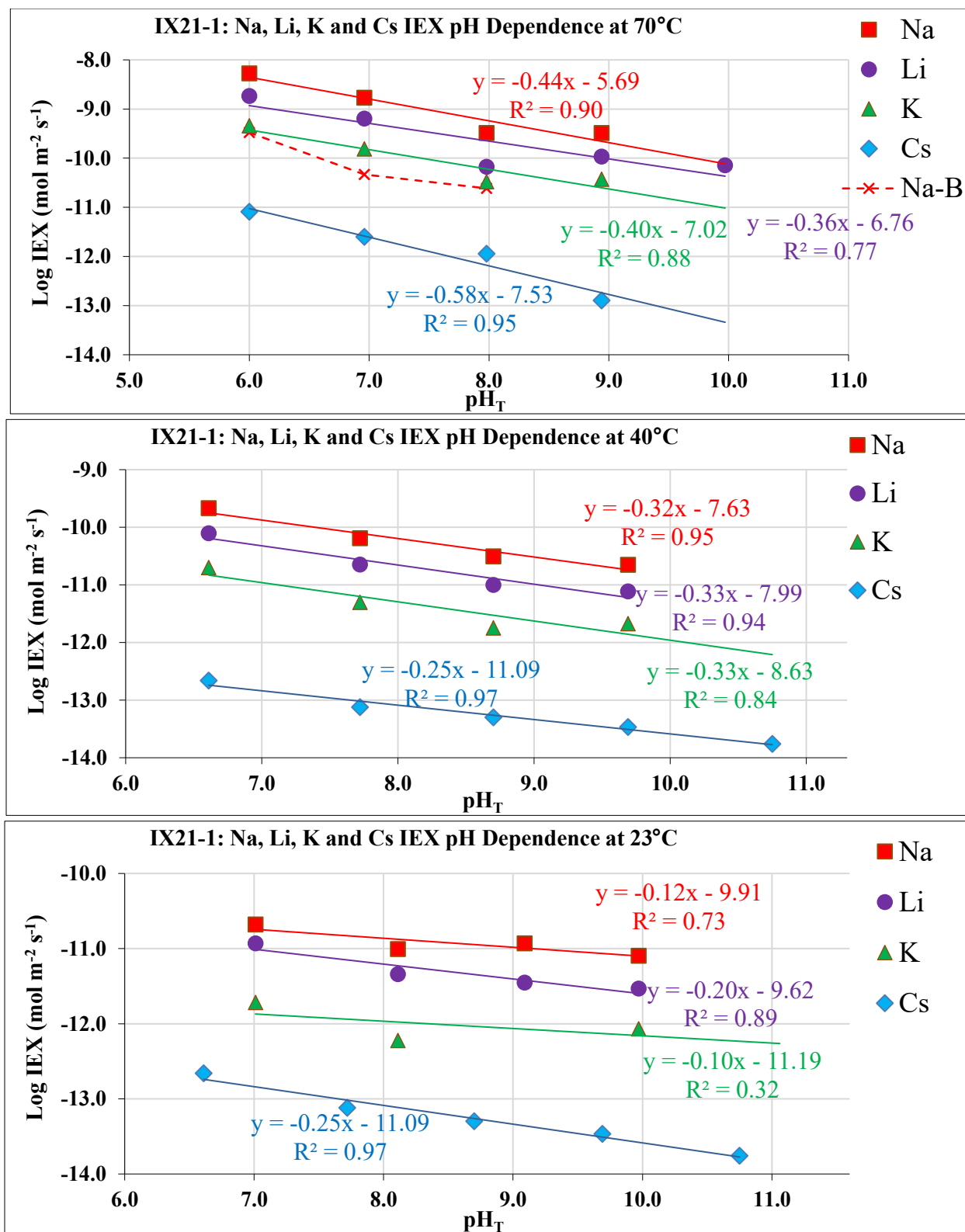


Figure 4.10. Plots of sodium, lithium, potassium, and cesium ion exchange rates as a function of pH for IDFIX21-1.

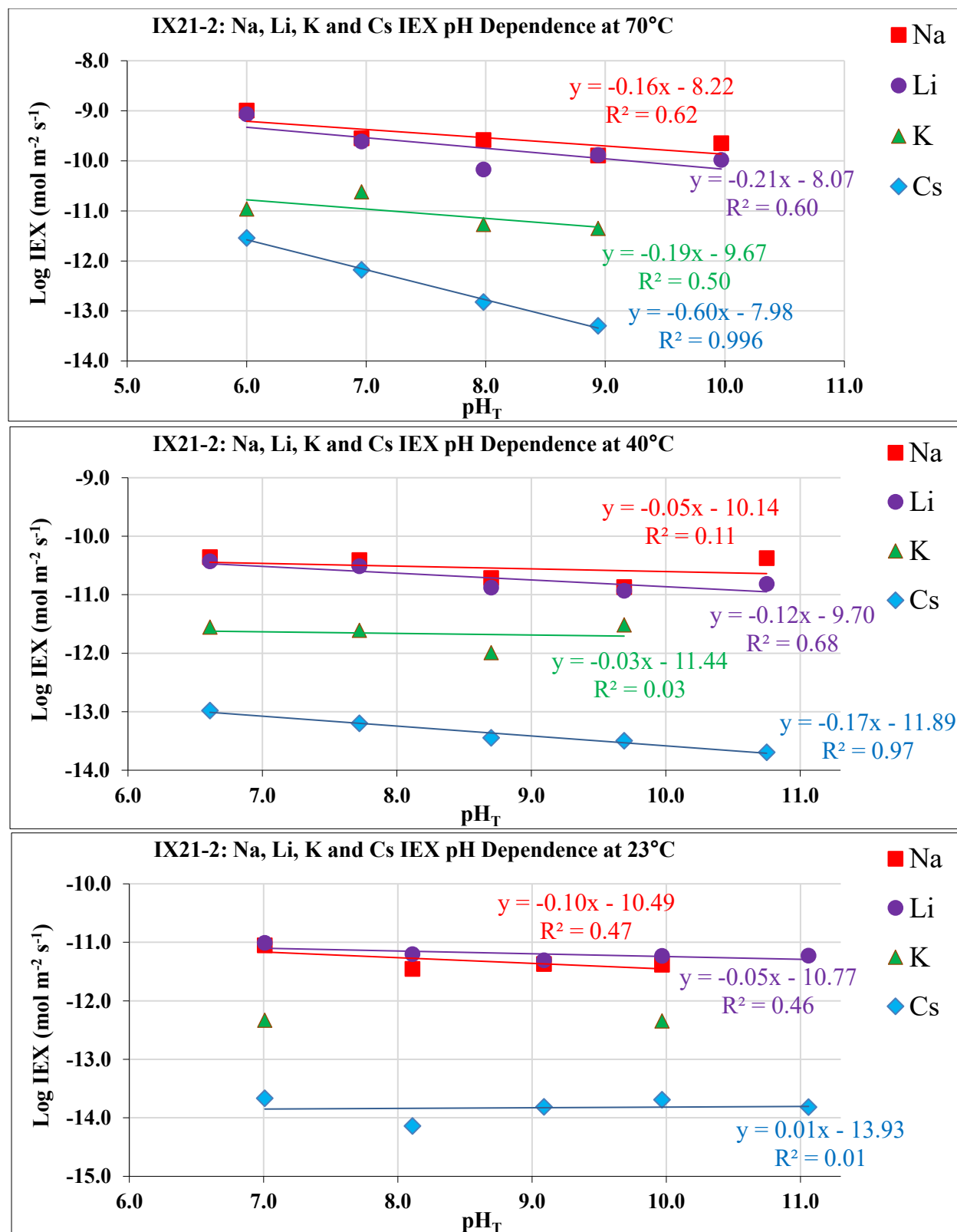


Figure 4.11. Plots of sodium, lithium, potassium, and cesium ion exchange rates as a function of pH for IDFIX21-2.

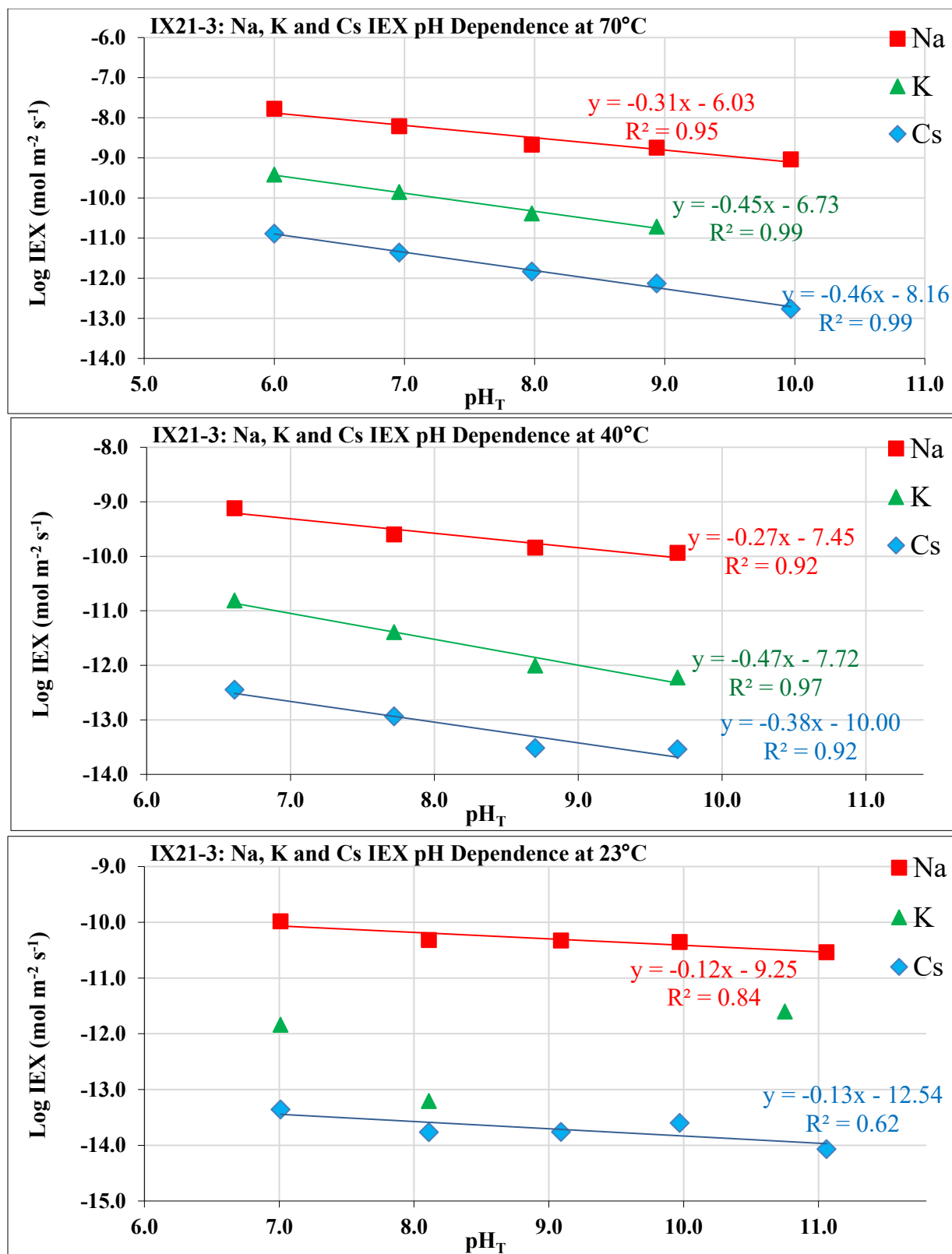


Figure 4.12. Plots of sodium, potassium and cesium ion exchange rates as a function of pH for IDFIX21-3.

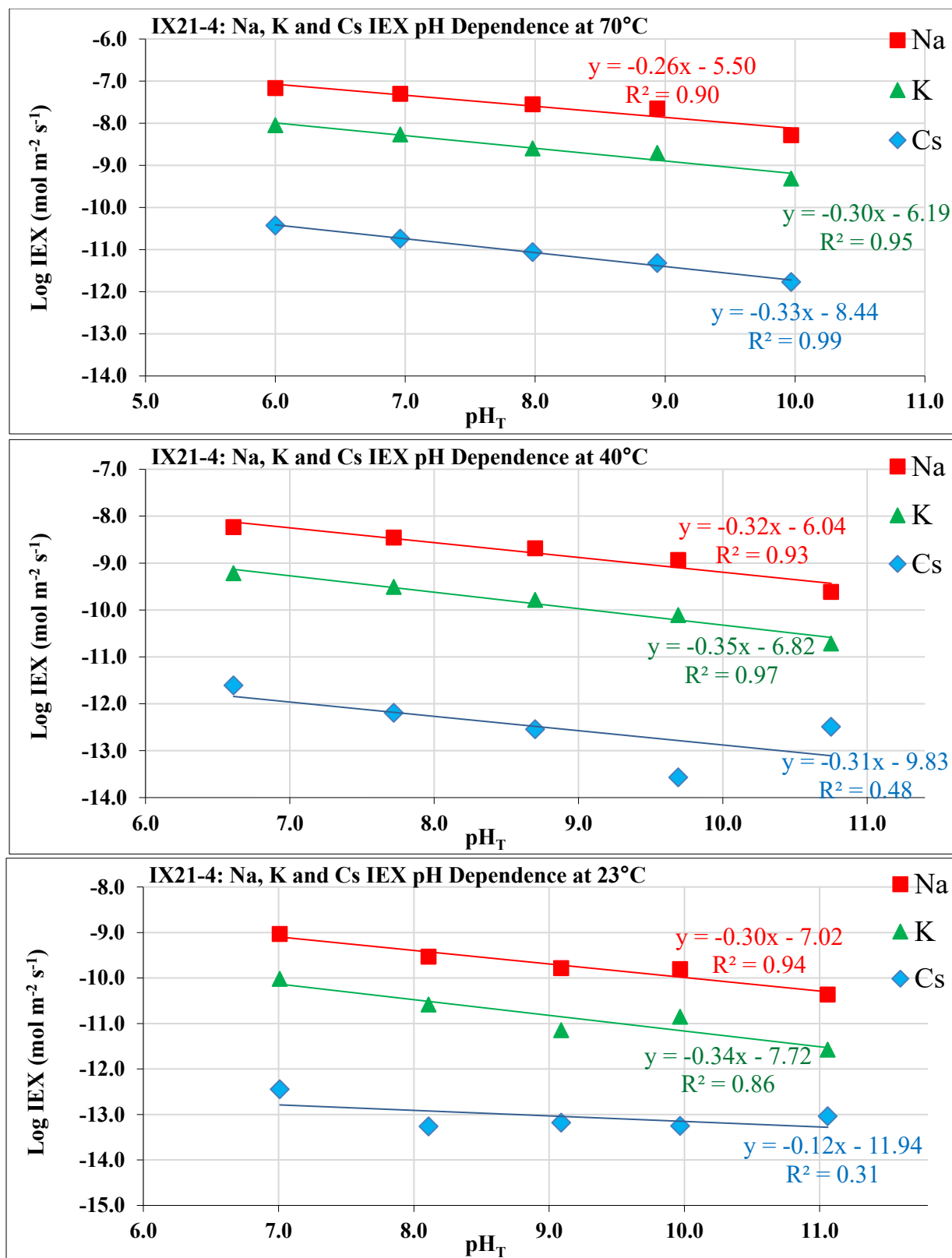
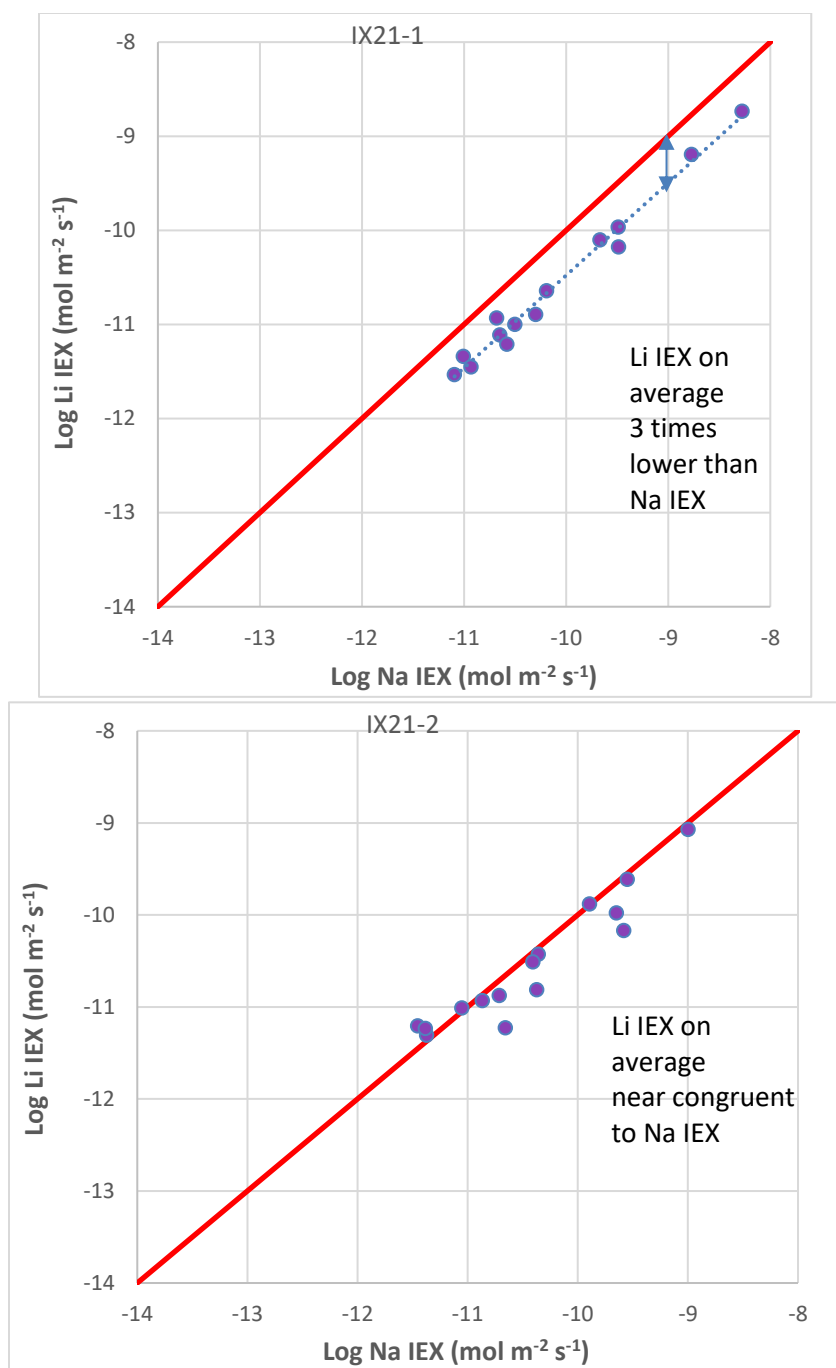
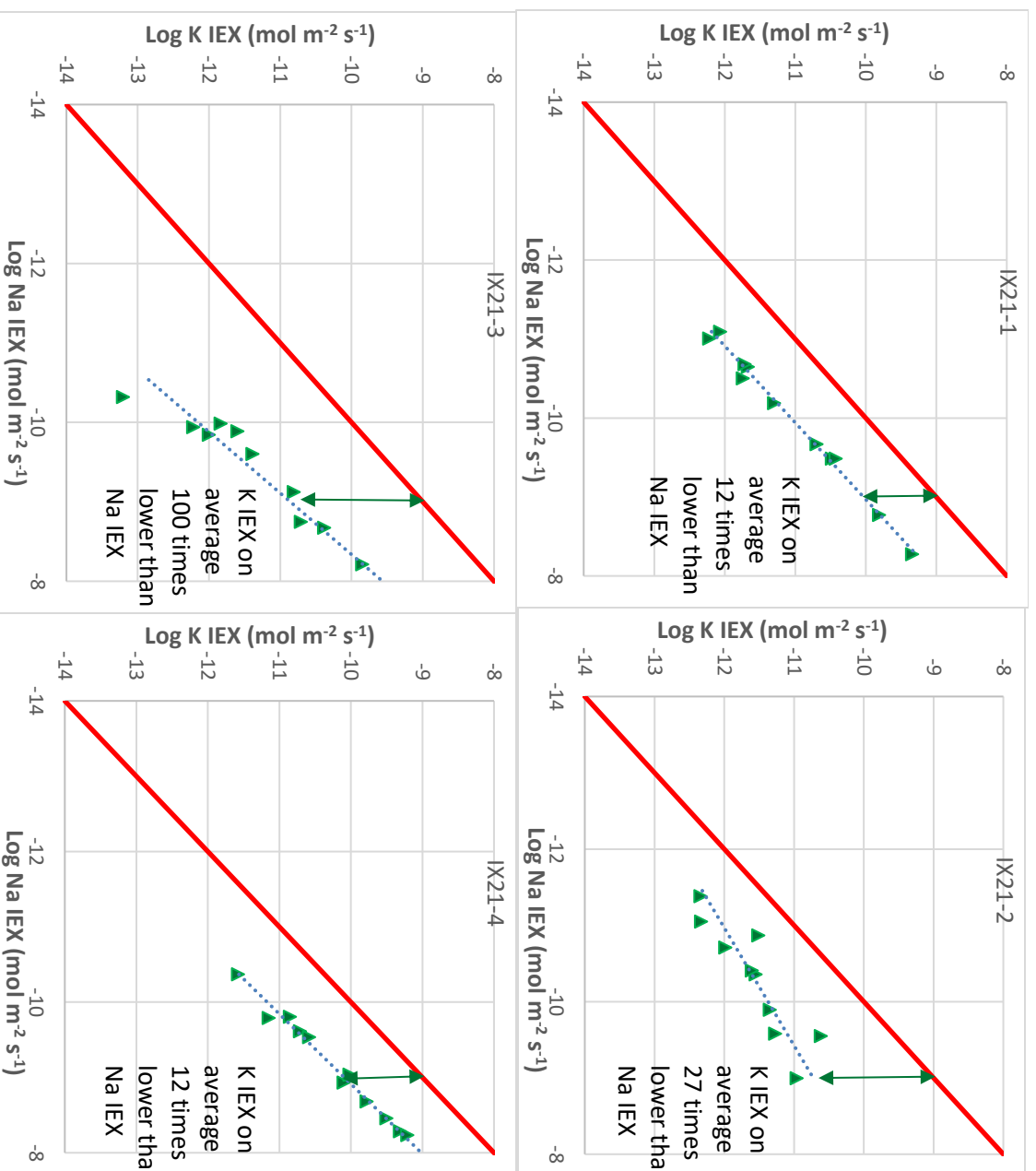


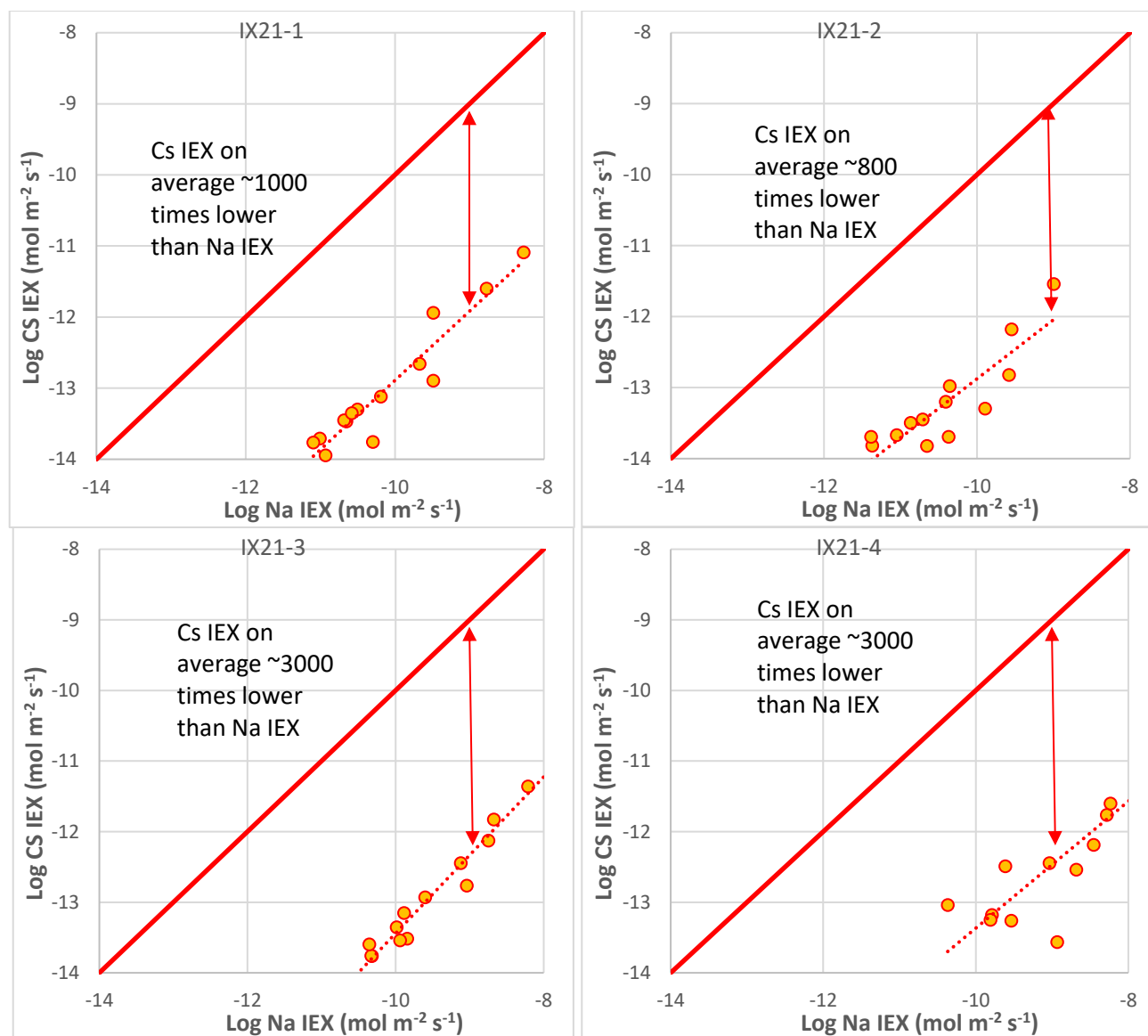
Figure 4.13. Plots of sodium, potassium and cesium ion exchange rates as a function of pH for IDFIX21-4.



**Figure 4.14. Plots of lithium ion exchange rate as a function of sodium ion exchange rate at all pH and temperature values for IDFIX21-1 and IDFIX21-2. The red line denotes equality of the alkali ion exchange rates; the Li data fall near or slightly below Na.**



**Figure 4.15. Plots of potassium ion exchange rate as a function of sodium ion exchange rate at all pH and temperature values for four glasses. The red line denotes equality of the alkali ion exchange rates; the K data fall well below Na.**



**Figure 4.16. Plots of cesium ion exchange rate as a function of sodium ion exchange rate at all pH and temperature values for four glasses. The red line denotes equality of the alkali ion exchange rates; the Cs data fall well below Na.**

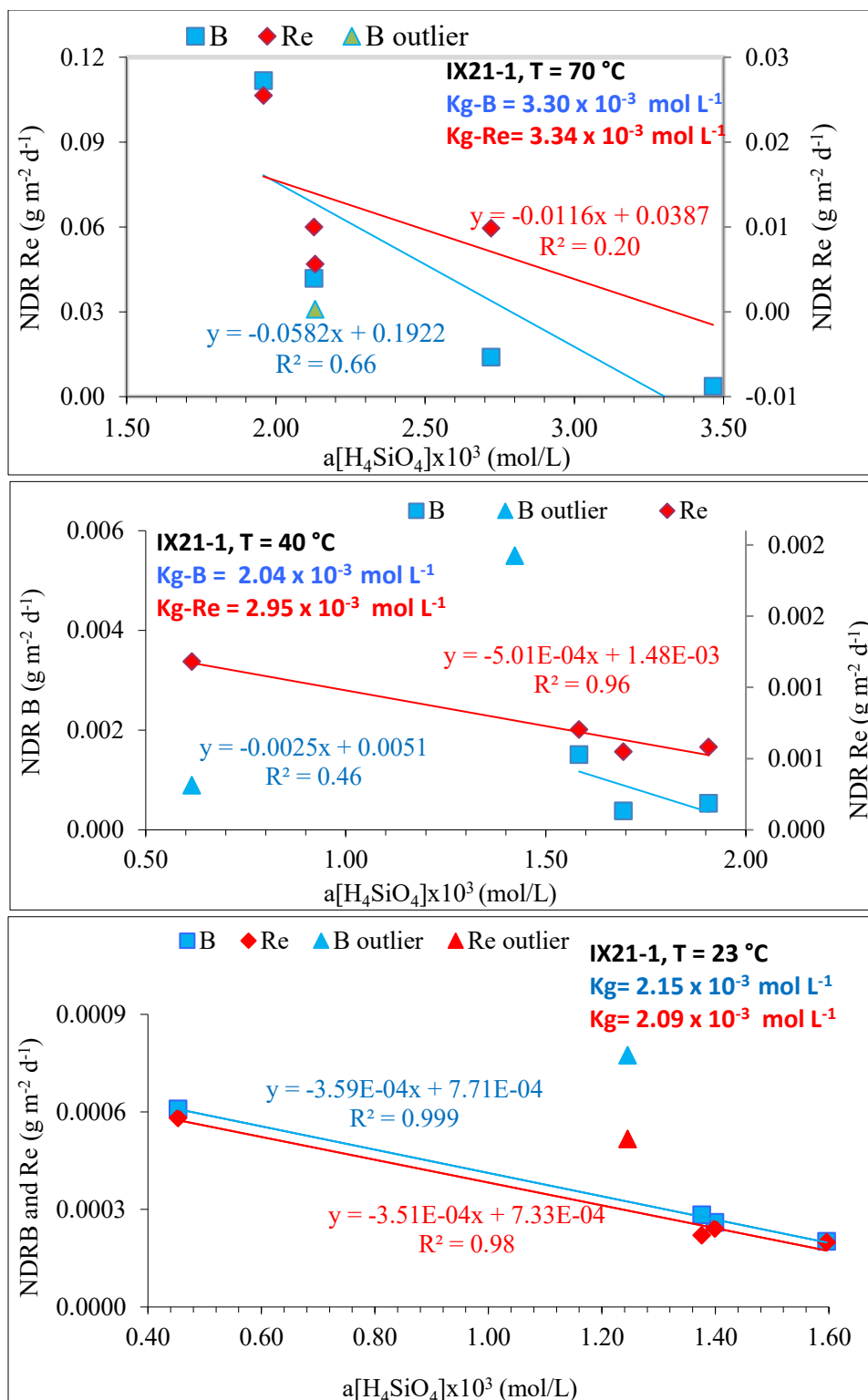


Figure 4.17. Linear regressions of boron and rhenium steady state NDR as a function of  $[\text{H}_4\text{SiO}_4]$  to assess  $K_g$  for IDFIX21-1.

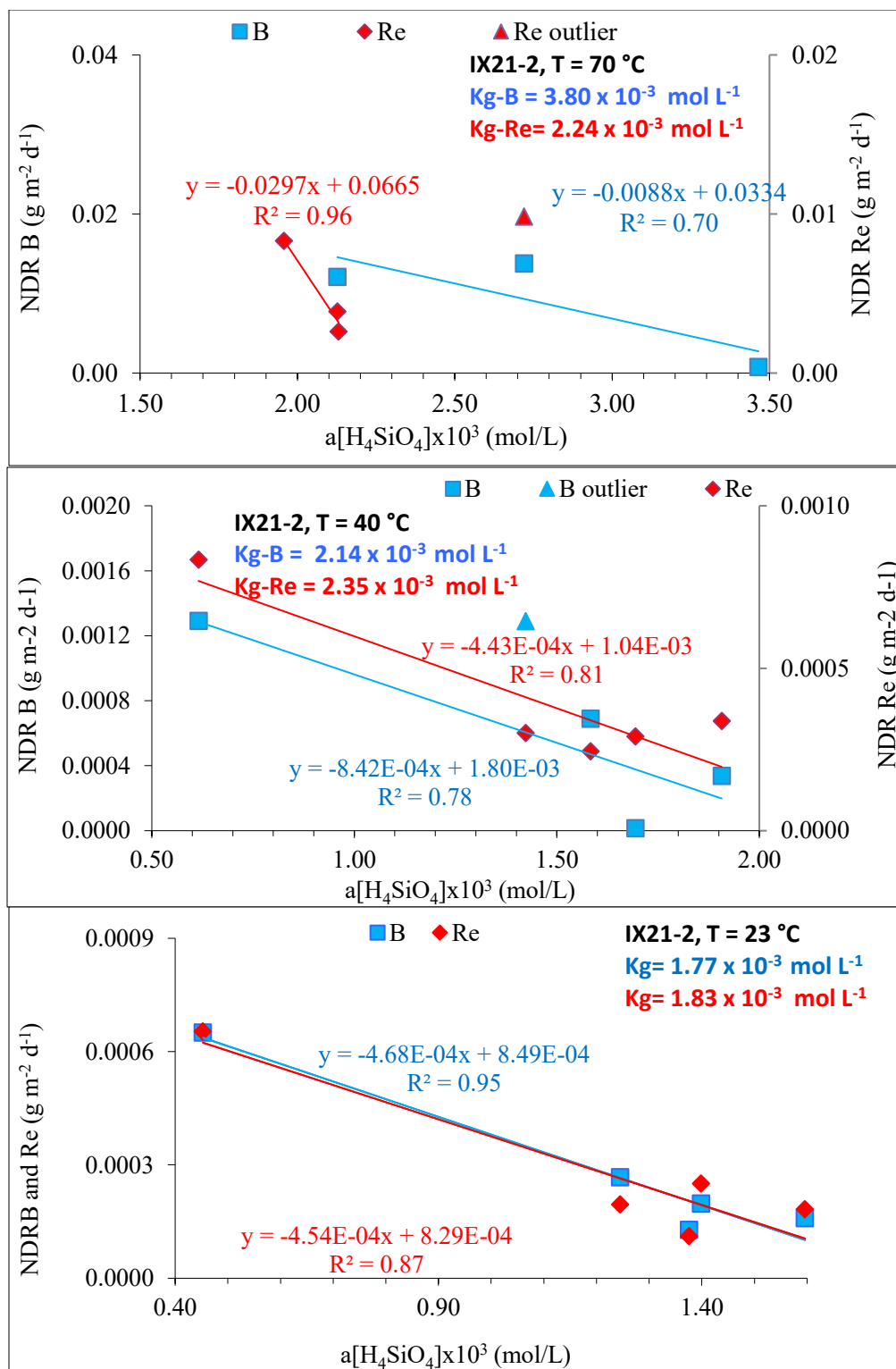


Figure 4.18. Linear regressions of boron and rhenium steady state NDR as a function of  $[\text{H}_4\text{SiO}_4]$  to assess  $K_g$  for IDFIX21-2.

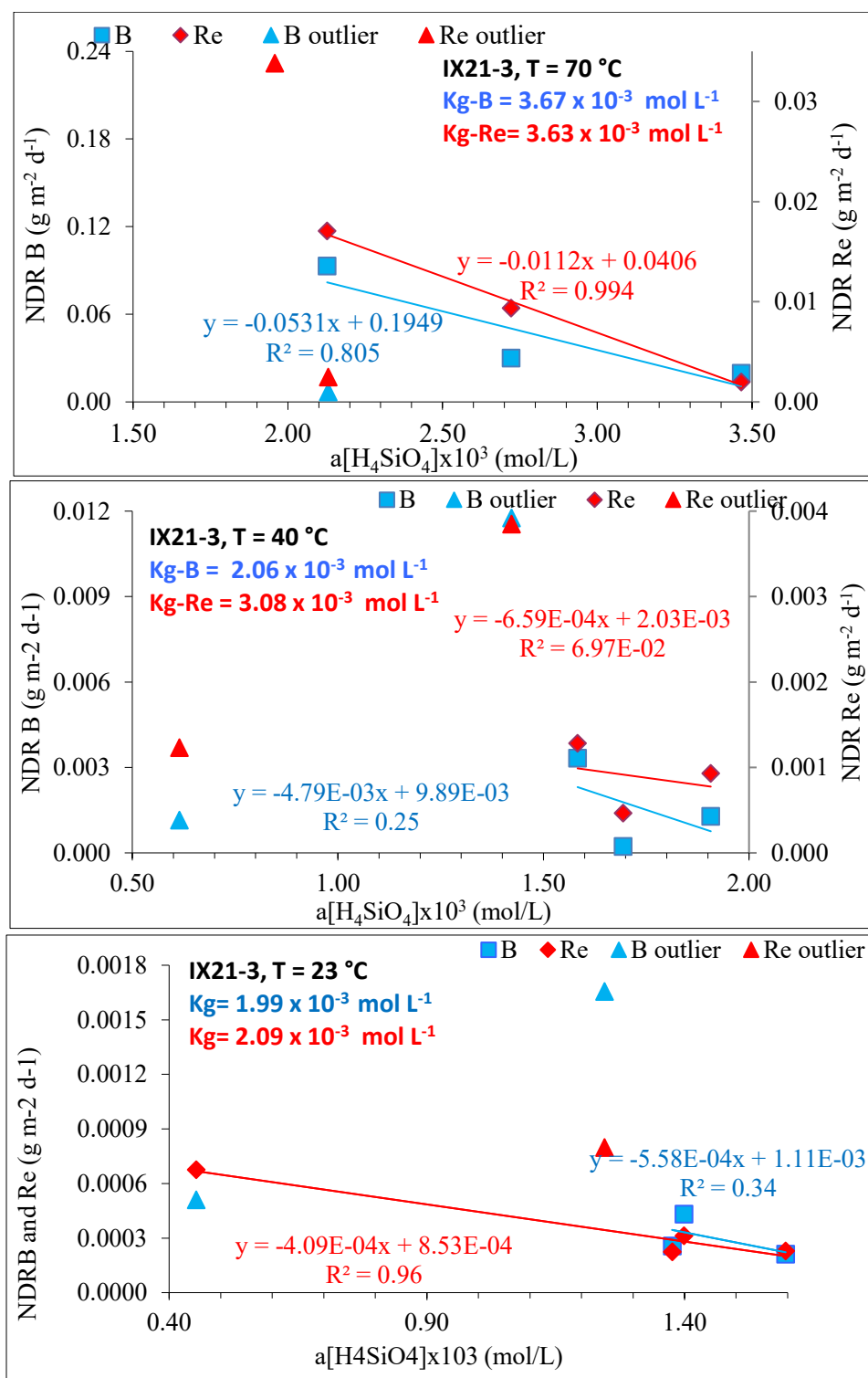


Figure 4.19. Linear regressions of boron and rhenium steady state NDR as a function of  $[\text{H}_4\text{SiO}_4]$  to assess  $K_g$  for IDFIX21-3.

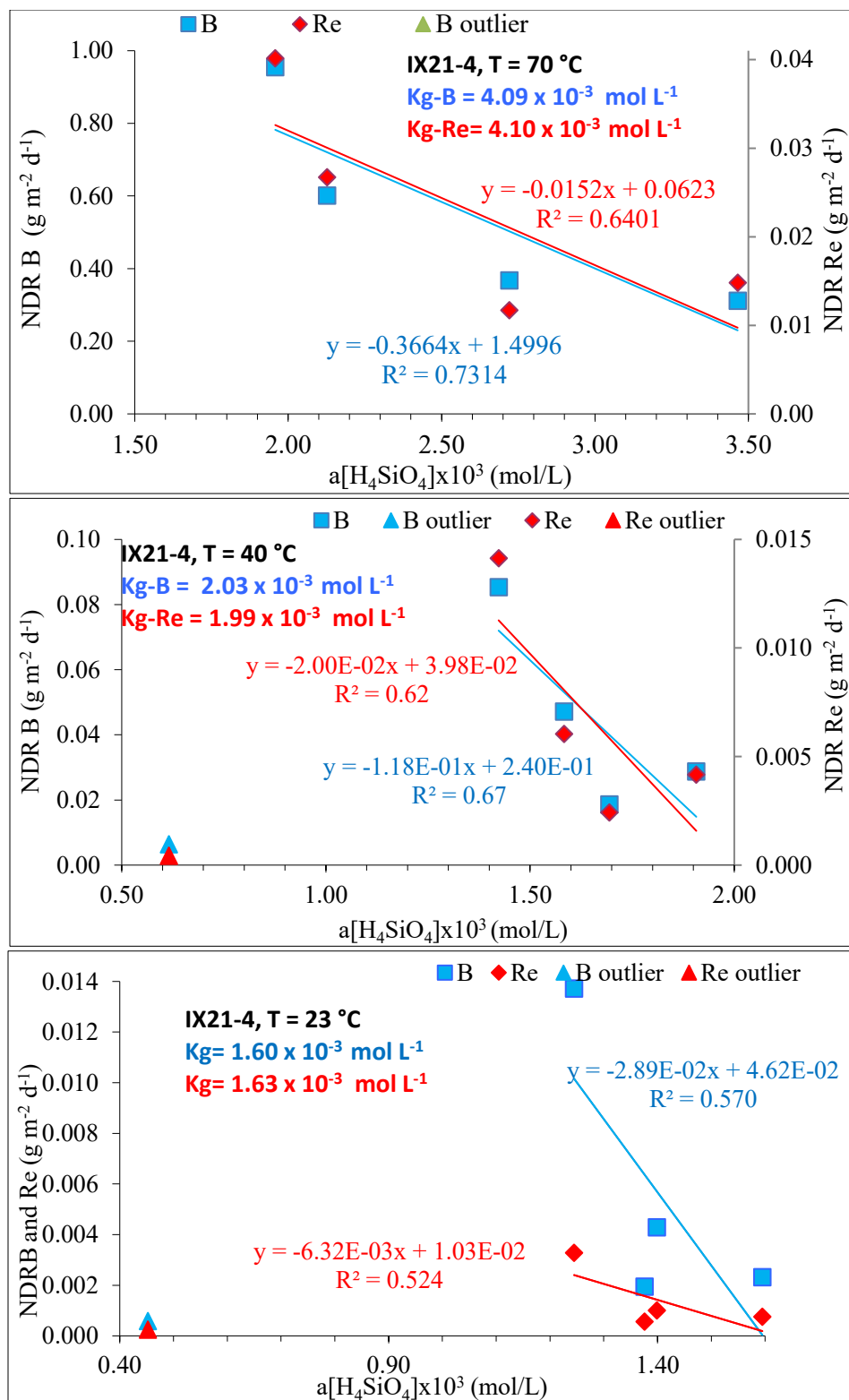


Figure 4.20. Linear regressions of boron and rhenium steady state NDR as a function of  $[\text{H}_4\text{SiO}_4]$  to assess  $K_g$  for IDFIX21-4.

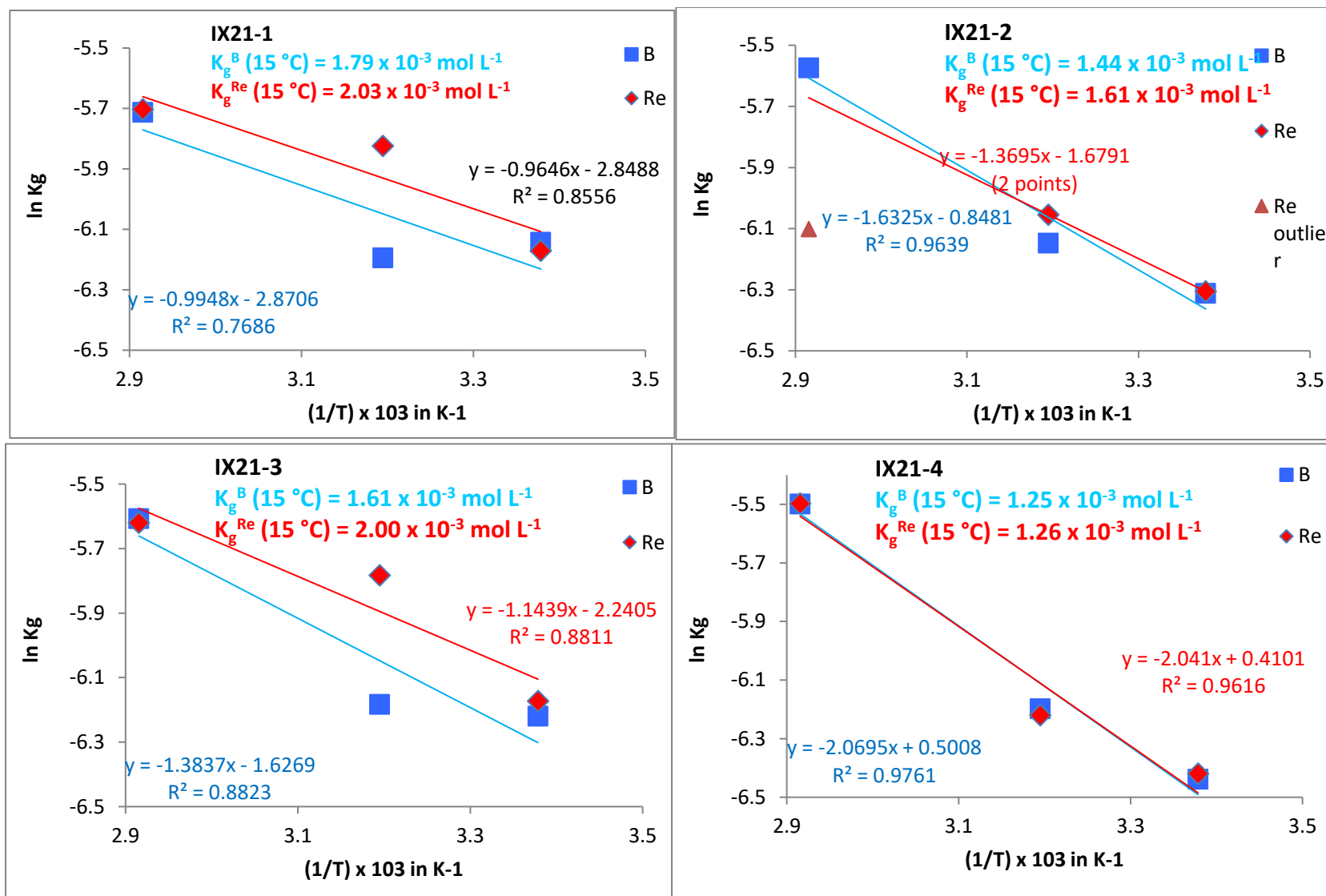
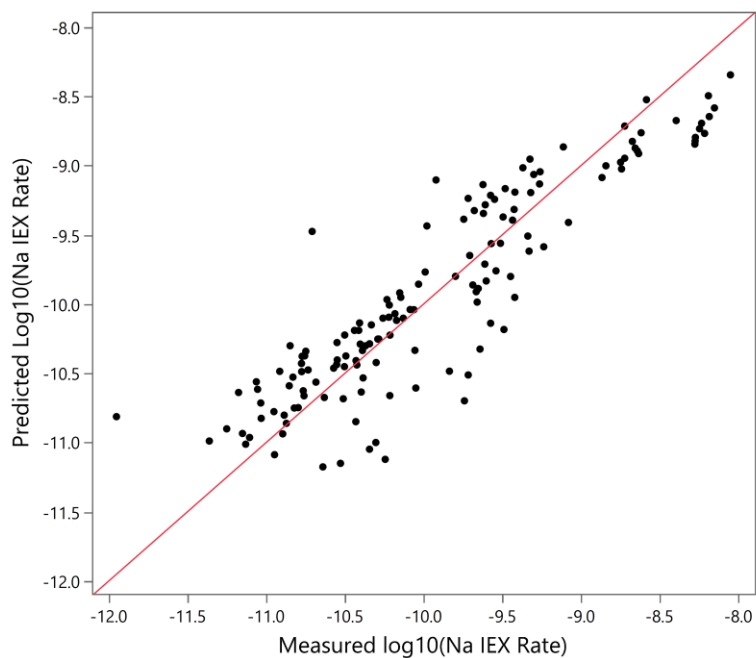
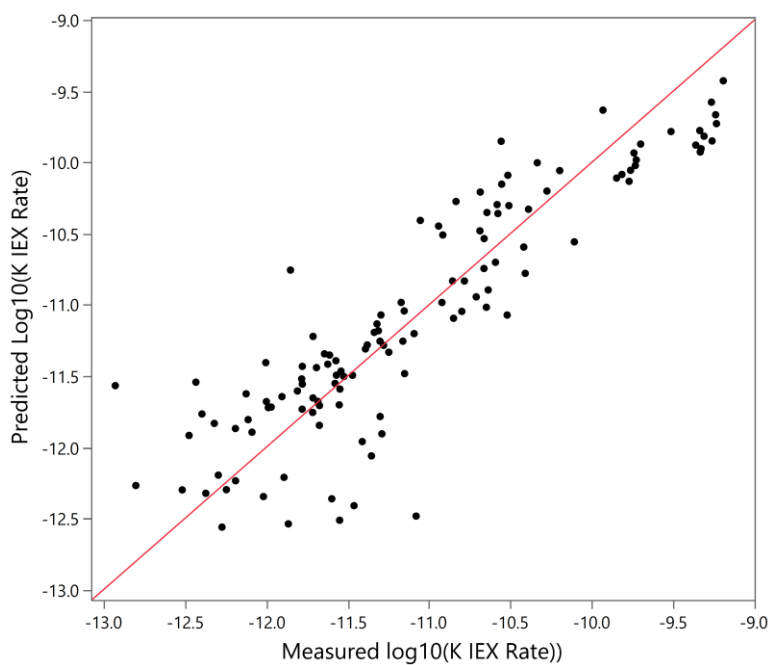


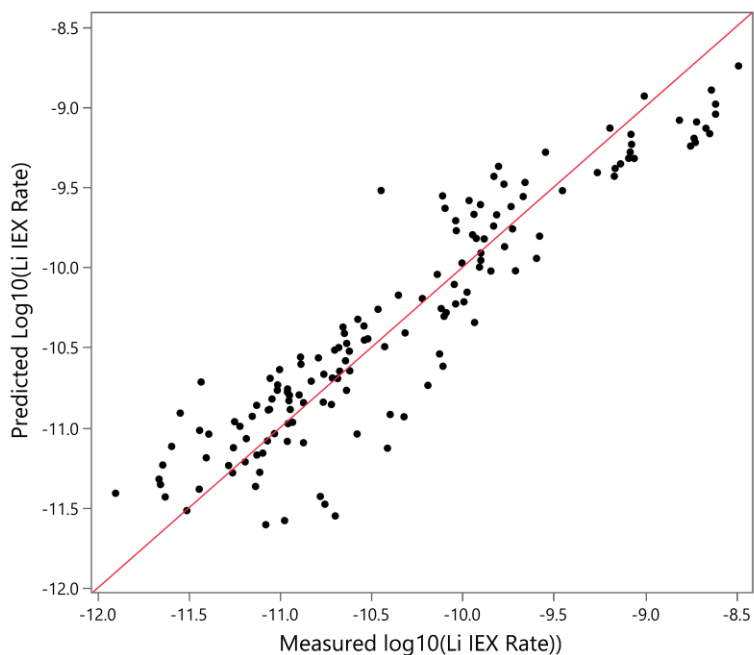
Figure 4.21.  $\ln K_g$  values for the four IDFIX21 glasses obtained from linear regression as a function of  $1/T$  ( $\text{K}^{-1}$ ) to estimate  $K_g$  at  $15^\circ\text{C}$ .



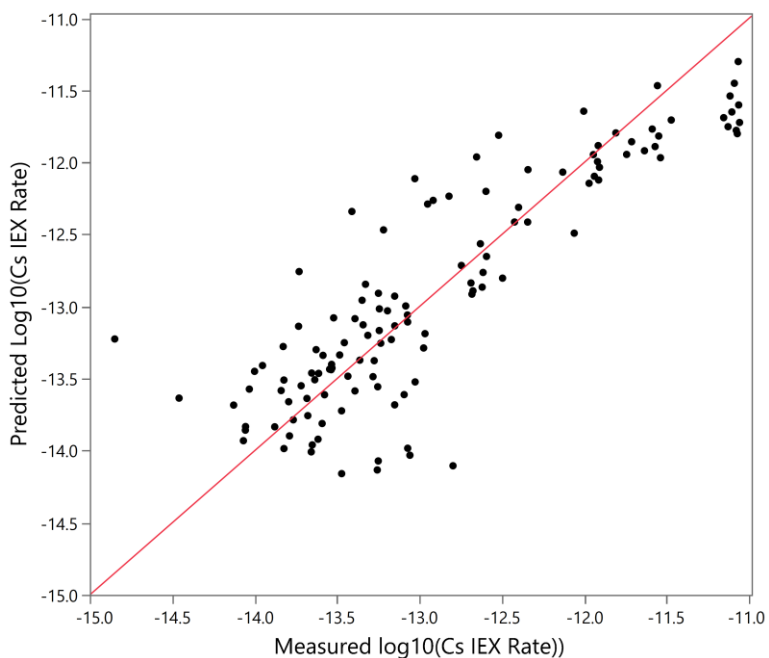
**Figure 5.1. Predicted vs. measured plot for sodium ion exchange rate for IX21-1 (Equation 1.6).**



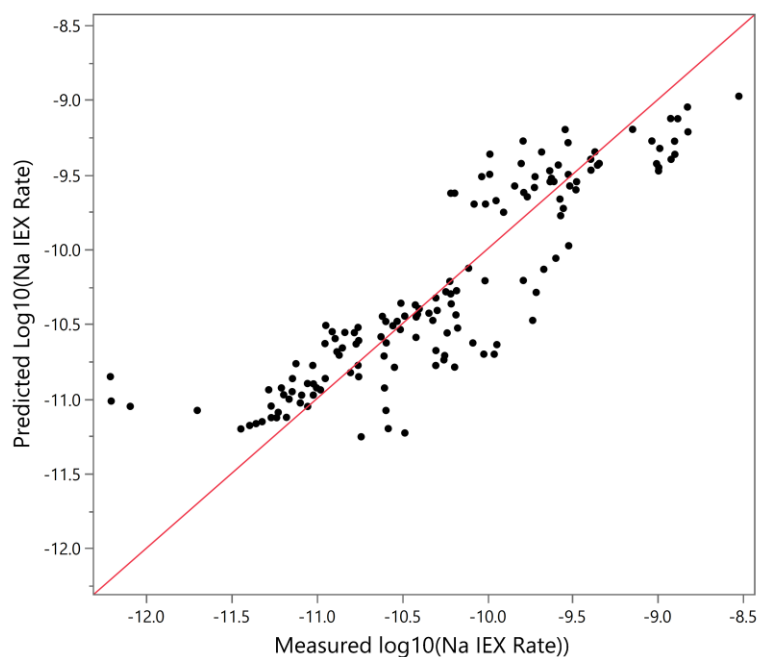
**Figure 5.2. Predicted vs. measured plot for potassium ion exchange rate for IX21-1 (Equation 1.6).**



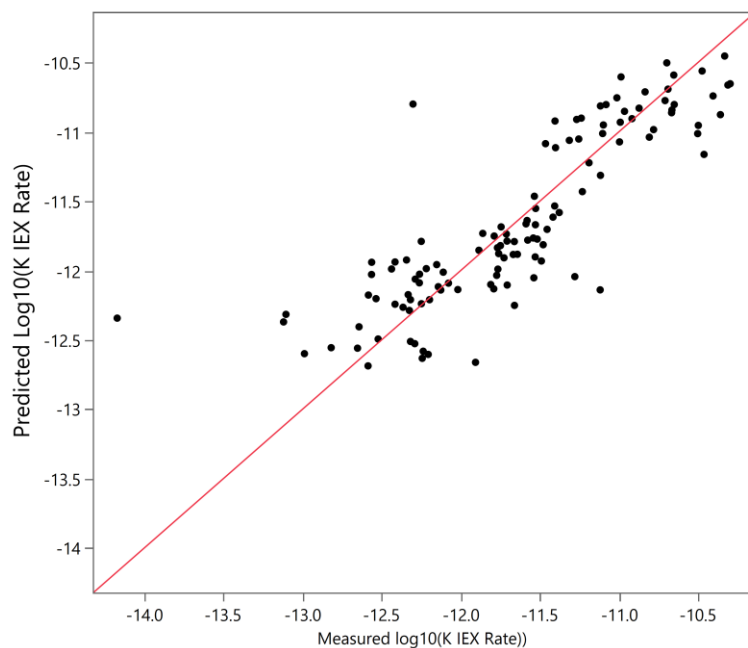
**Figure 5.3. Predicted vs. measured plot for lithium ion exchange rate for IX21-1 (Equation 1.6).**



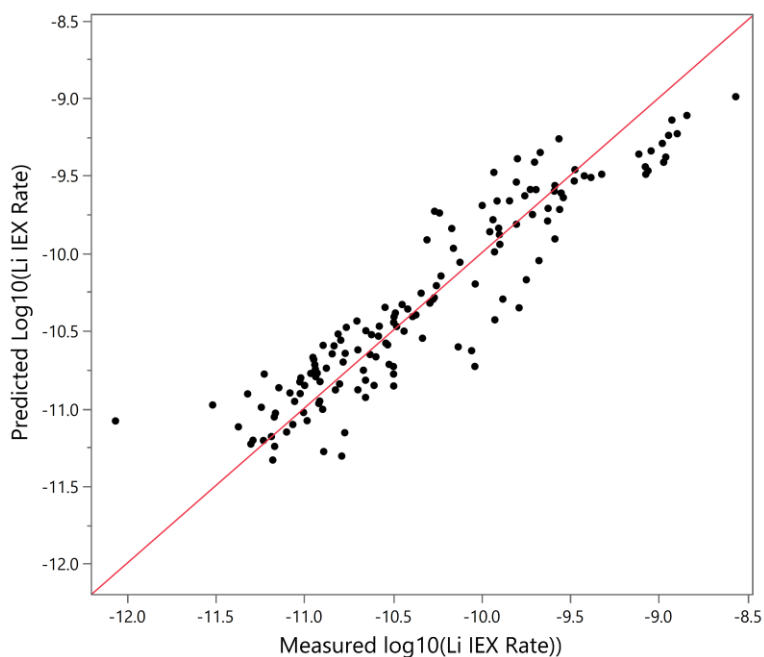
**Figure 5.4. Predicted vs. measured plot for cesium ion exchange rate for IX21-1 (Equation 1.6).**



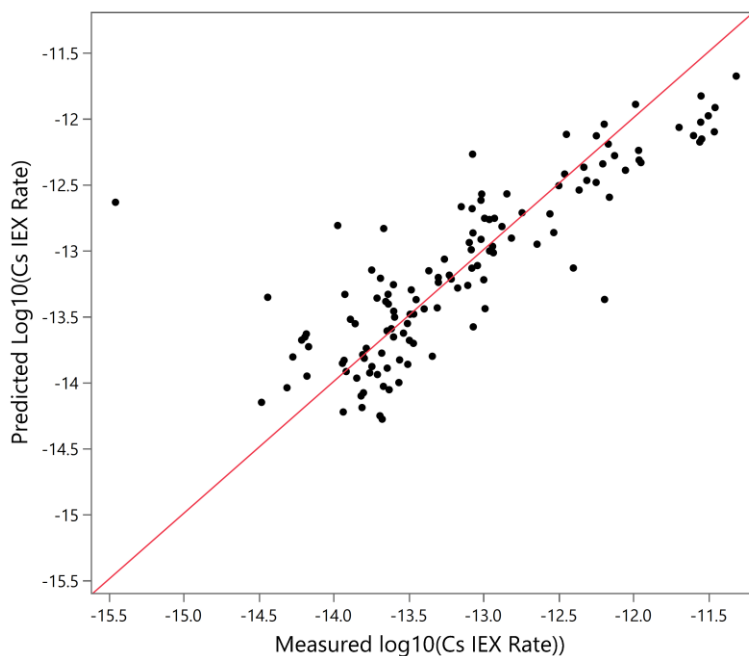
**Figure 5.5. Predicted vs. measured plot for sodium ion exchange rate for IX21-2 (Equation 1.6).**



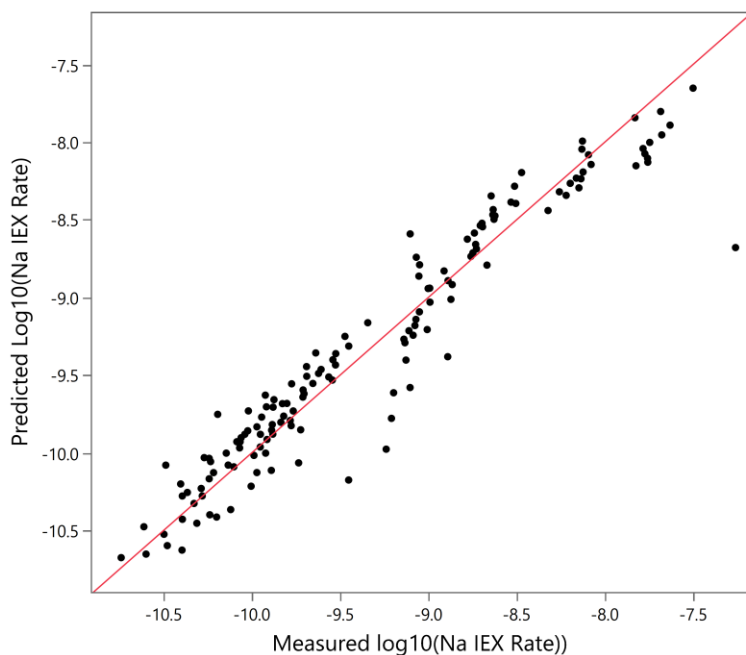
**Figure 5.6. Predicted vs. measured plot for potassium ion exchange rate for IX21-2 (Equation 1.6).**



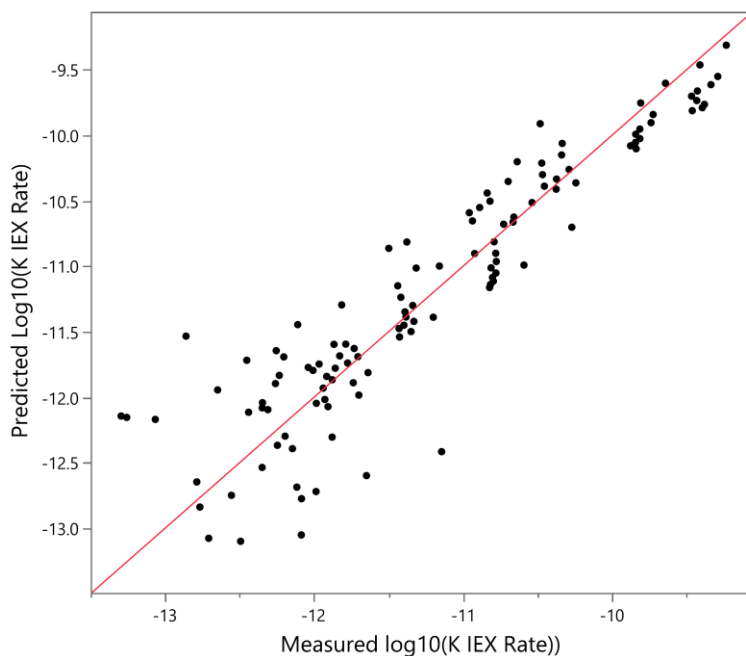
**Figure 5.7. Predicted vs. measured plot for lithium ion exchange rate for IX21-2 (Equation 1.6).**



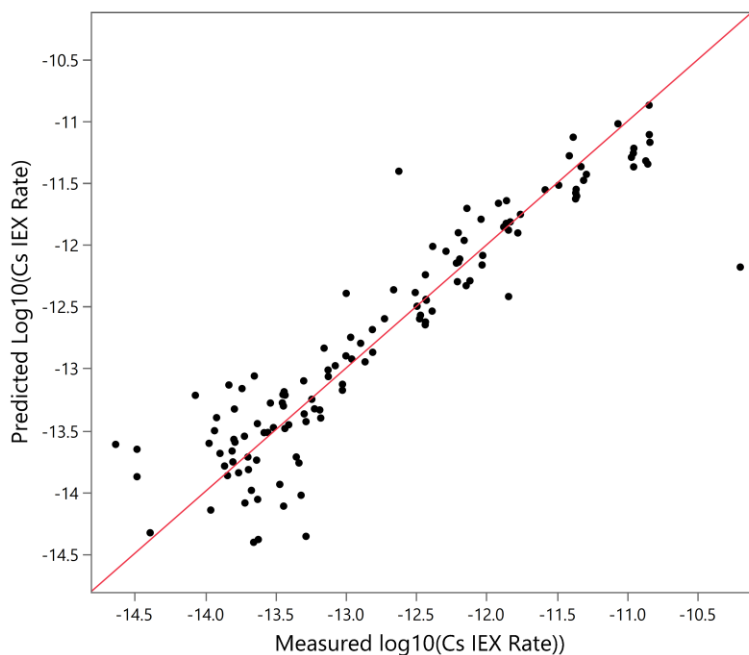
**Figure 5.8. Predicted vs. measured plot for cesium ion exchange rate for IX21-2 (Equation 1.6).**



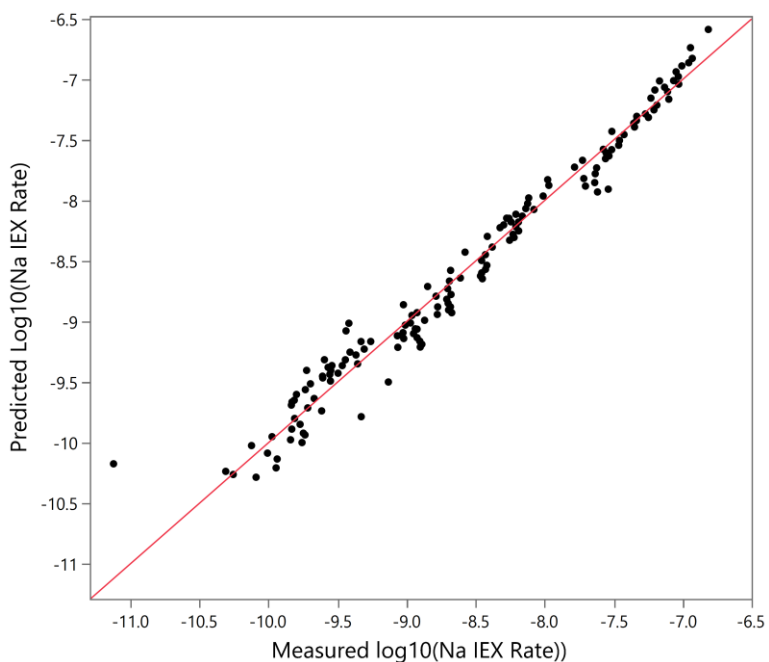
**Figure 5.9. Predicted vs. measured plot for sodium ion exchange rate for IX21-3 (Equation 1.6).**



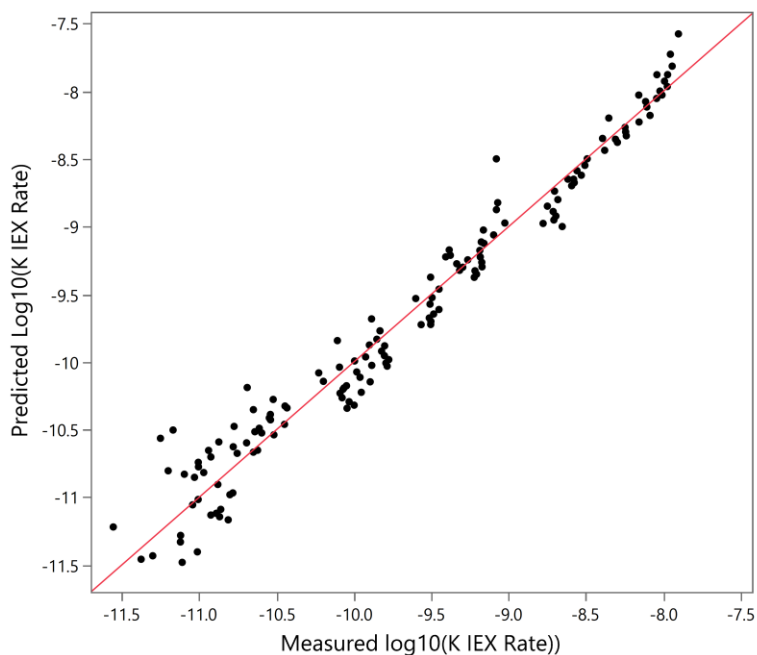
**Figure 5.10. Predicted vs. measured plot for potassium ion exchange rate for IX21-3 (Equation 1.6).**



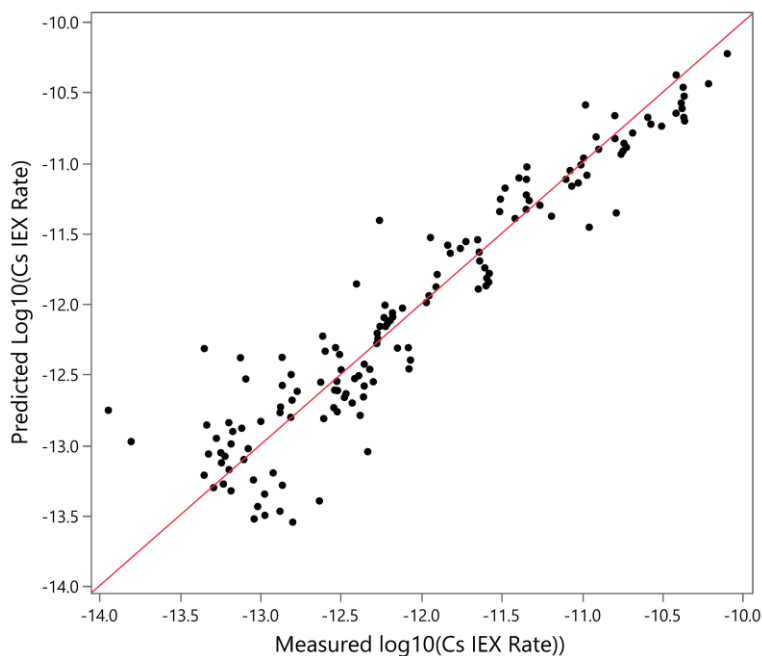
**Figure 5.11. Predicted vs. measured plot for cesium ion exchange rate for IX21-3 (Equation 1.6).**



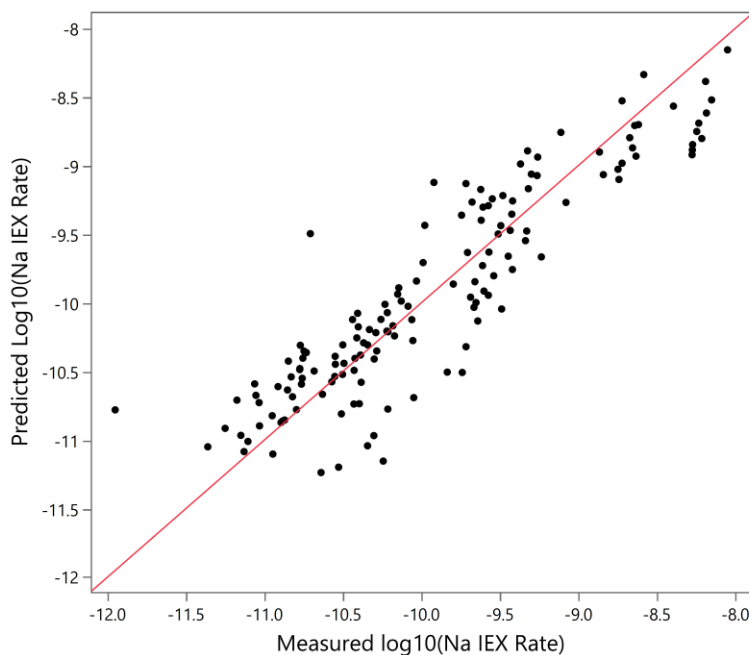
**Figure 5.12. Predicted vs. measured plot for sodium ion exchange rate for IX21-4 (Equation 1.6).**



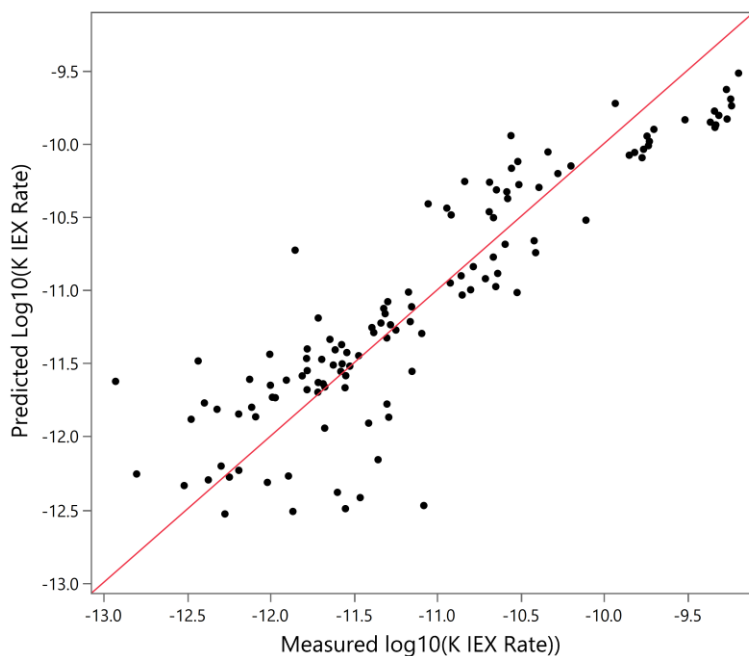
**Figure 5.13. Predicted vs. measured plot for potassium ion exchange rate for IX21-4 (Equation 1.6).**



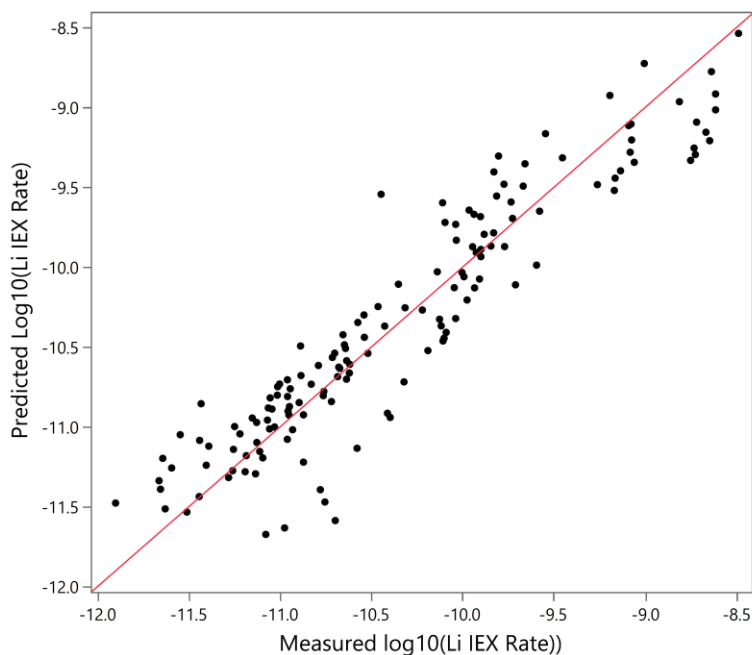
**Figure 5.14. Predicted vs. measured plot for cesium ion exchange rate for IX21-4 (Equation 1.6).**



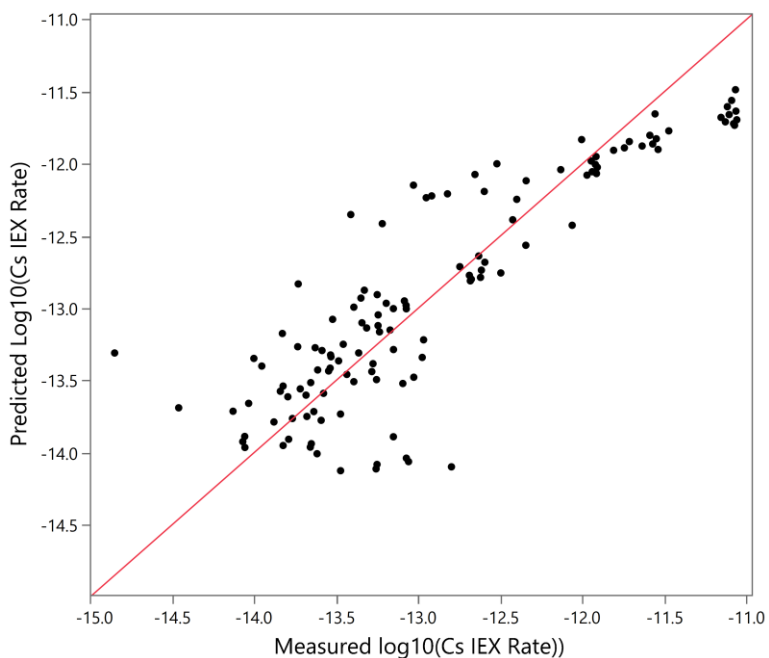
**Figure 5.15. Predicted vs. measured plot for sodium ion exchange rate for IX21-1 (Equation 1.8).**



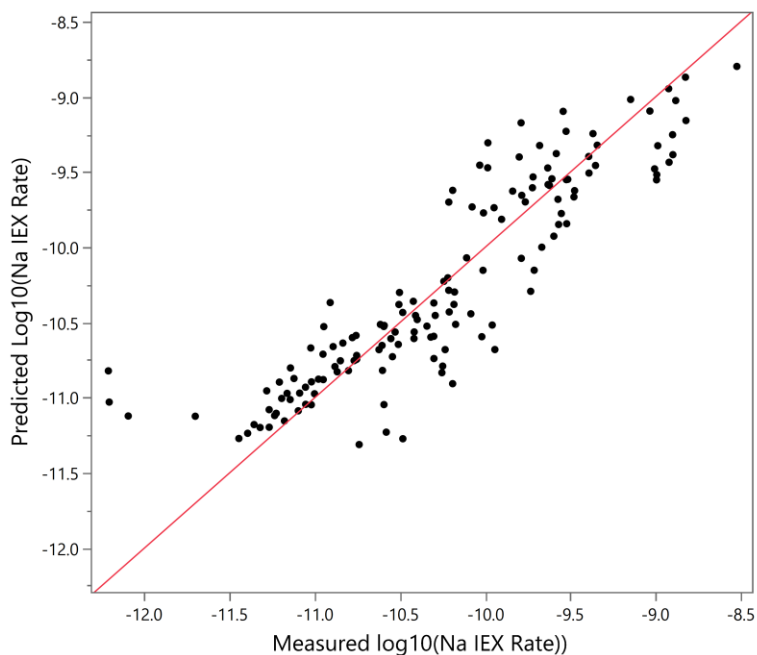
**Figure 5.16. Predicted vs. measured plot for potassium ion exchange rate for IX21-1 (Equation 1.8).**



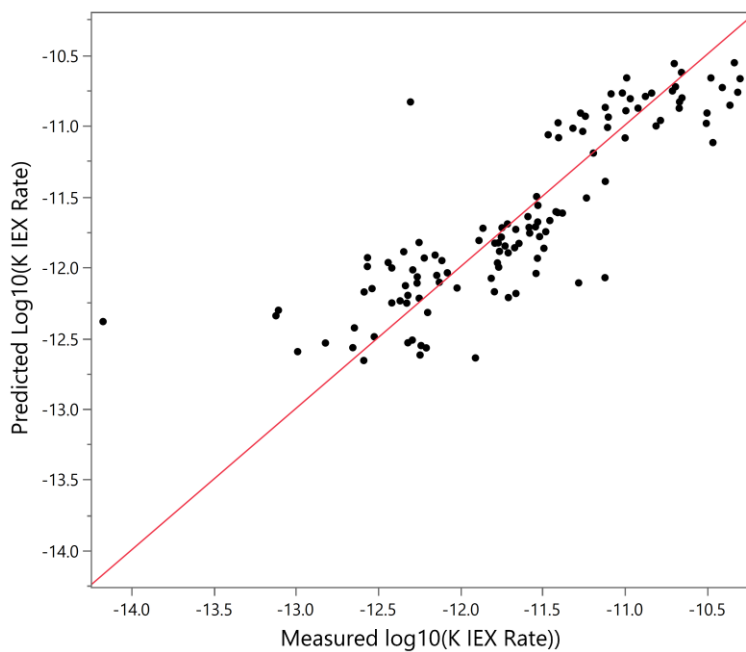
**Figure 5.17. Predicted vs. measured plot for lithium ion exchange rate for IX21-1 (Equation 1.8).**



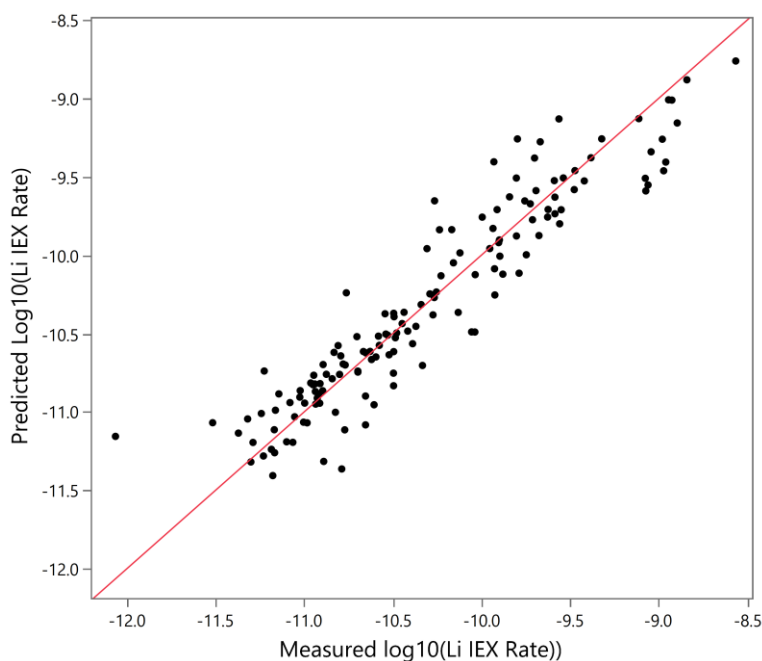
**Figure 5.18. Predicted vs. measured plot for cesium ion exchange rate for IX21-1 (Equation 1.8).**



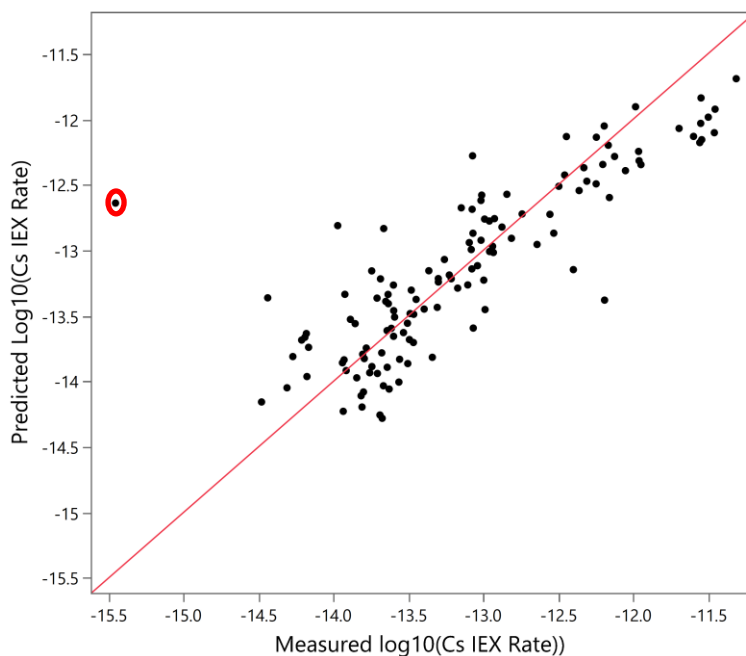
**Figure 5.19. Predicted vs. measured plot for sodium ion exchange rate for IX21-2 (Equation 1.8).**



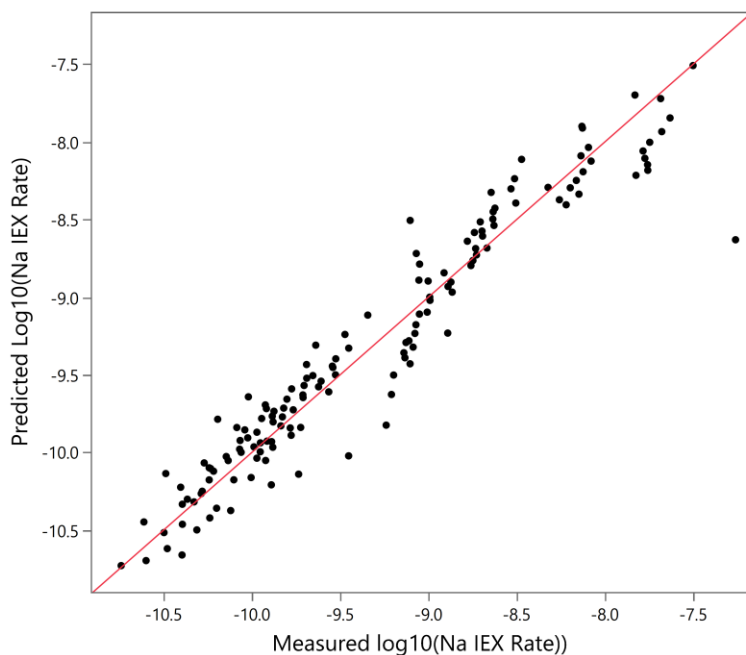
**Figure 5.20. Predicted vs. measured plot for potassium ion exchange rate for IX21-2 (Equation 1.8).**



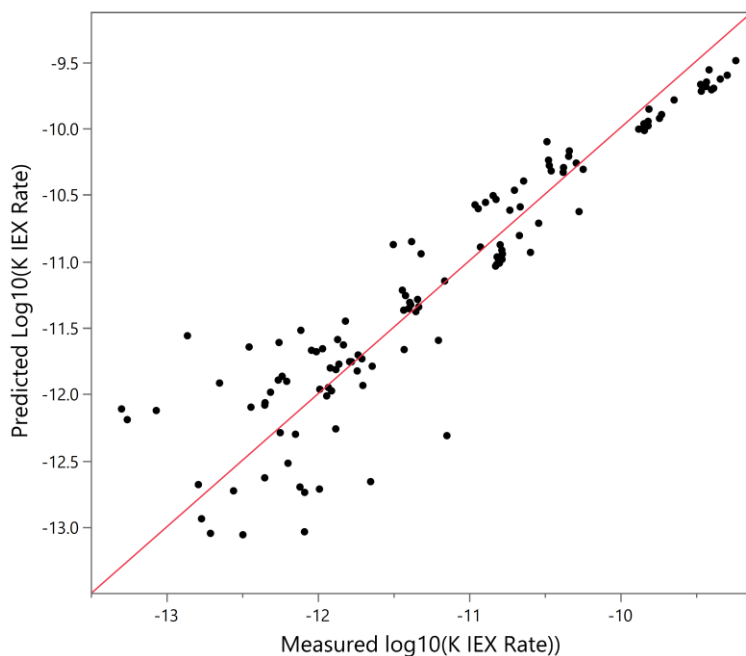
**Figure 5.21. Predicted vs. measured plot for lithium ion exchange rate for IX21-2 (Equation 1.8).**



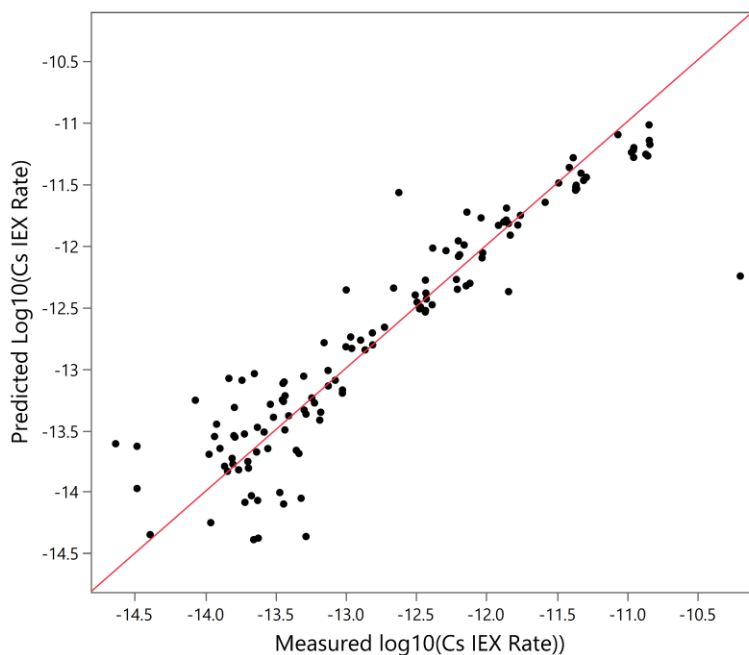
**Figure 5.22. Predicted vs. measured plot for cesium ion exchange rate for IX21-2 (Equation 1.8).** One outlier identified using the studentized residual analysis is circled in red – that outlier was not removed from the population as it did not significantly change the resulting model parameters.



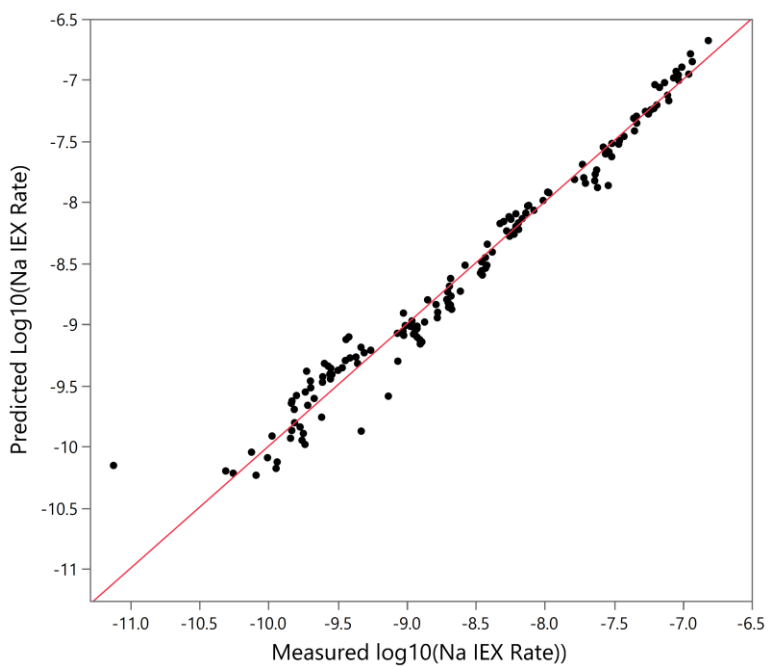
**Figure 5.23. Predicted vs. measured plot for sodium ion exchange rate for IX21-3 (Equation 1.8).**



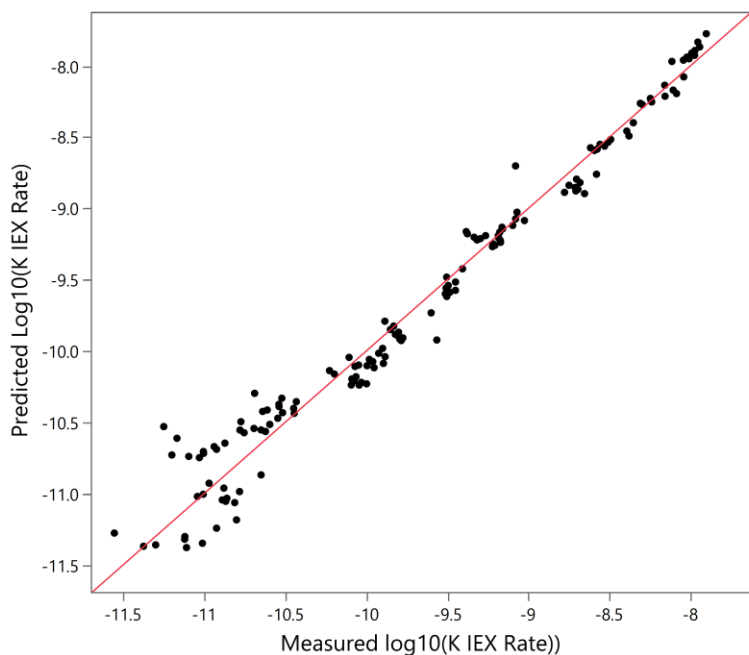
**Figure 5.24. Predicted vs. measured plot for potassium ion exchange rate for IX21-3 (Equation 1.8).**



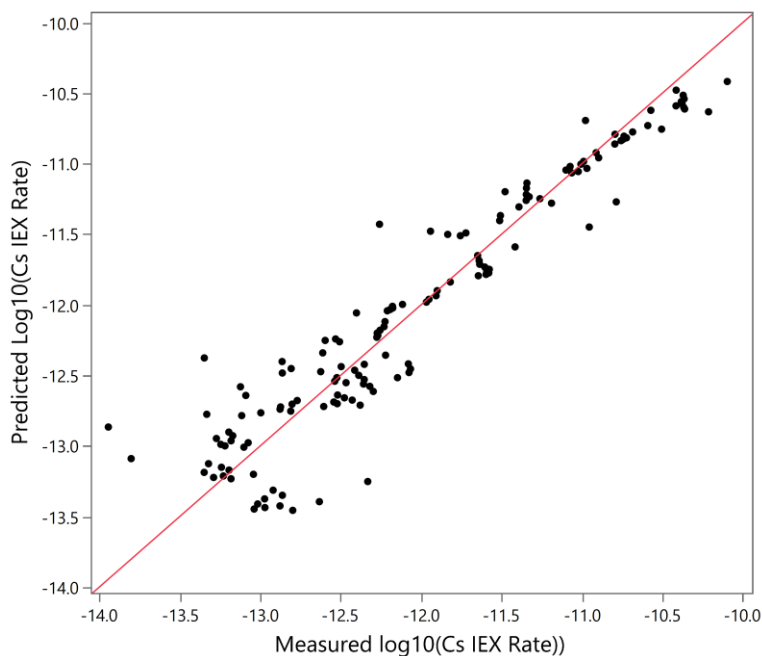
**Figure 5.25. Predicted vs. measured plot for cesium ion exchange rate for IX21-3 (Equation 1.8).**



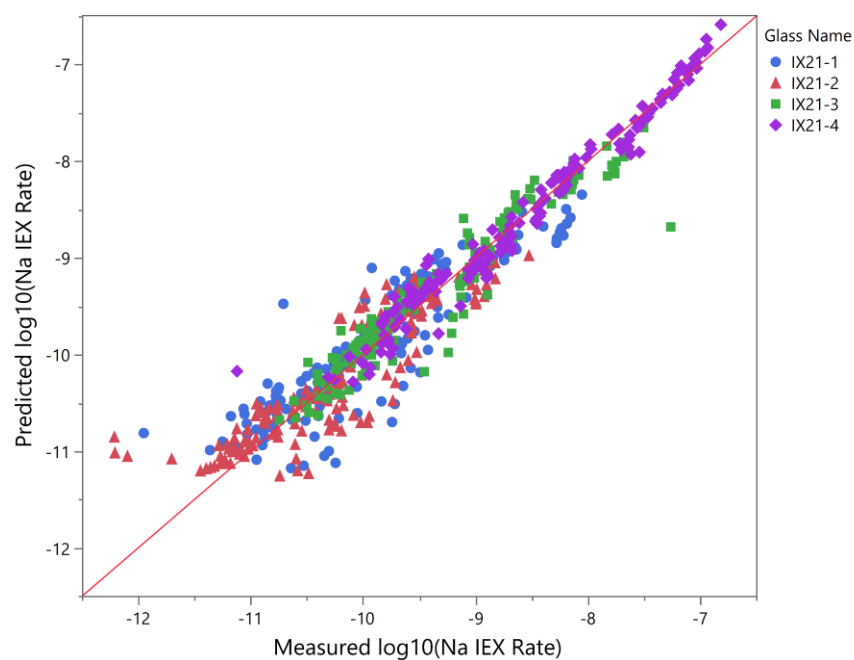
**Figure 5.26. Predicted vs. measured plot for sodium ion exchange rate for IX21-4 (Equation 1.8).**



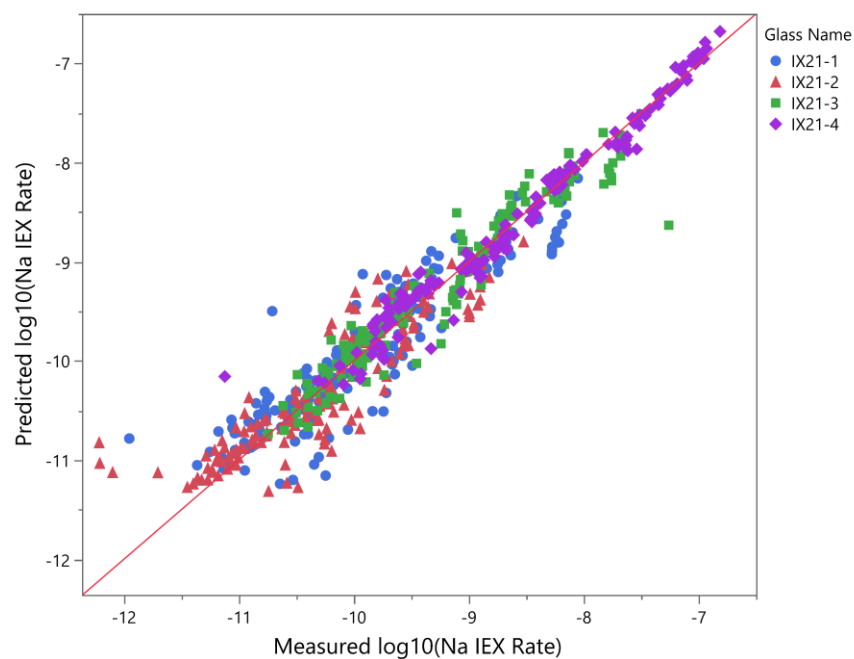
**Figure 5.27. Predicted vs. measured plot for potassium ion exchange rate for IX21-4 (Equation 1.8).**



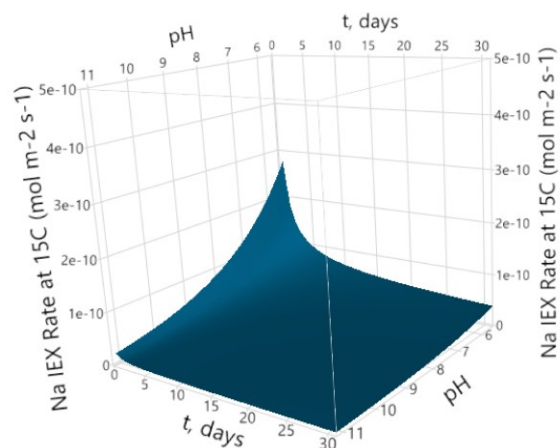
**Figure 5.28. Predicted vs. measured plot for cesium ion exchange rate for IX21-4 (Equation 1.8).**



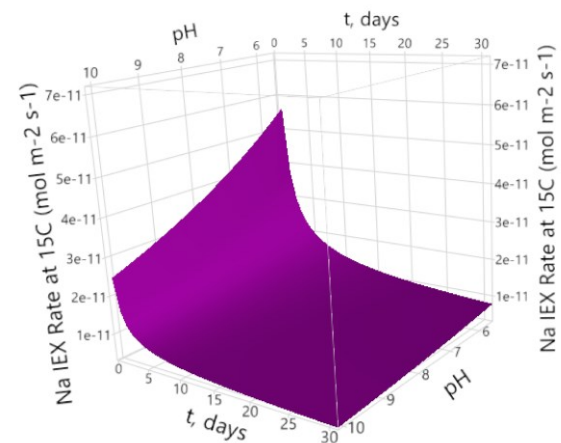
**Figure 5.29. Predicted vs. measured plot for sodium ion exchange rate for all four glasses using models given by Equation 1.6.**



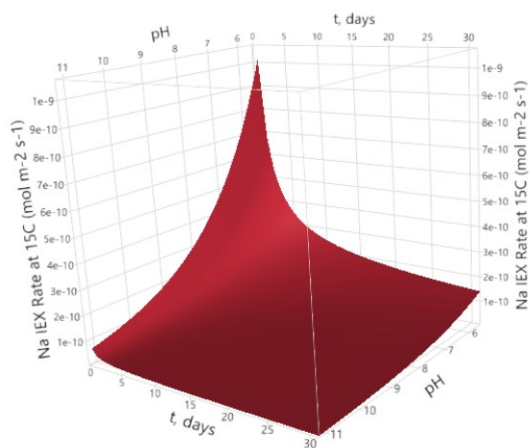
**Figure 5.30. Predicted vs. measured plot for sodium ion exchange rate for all four glasses using models given by Equation 1.8.**



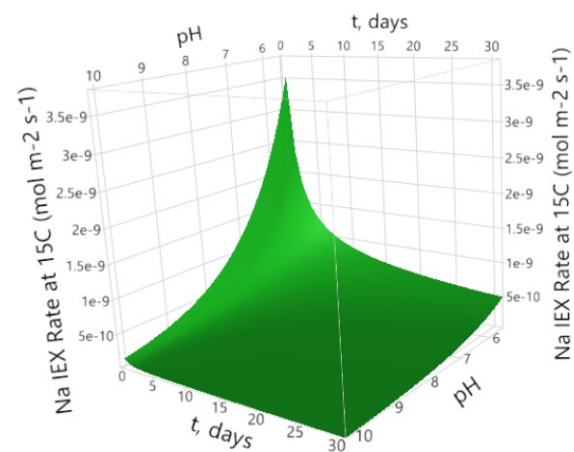
IX21-1



IX21-2



IX21-3



IX21-4

Figure 5.31. Predicted sodium ion exchange rate at 15°C as a function of pH and time for the four glasses (using Equation 1.6).

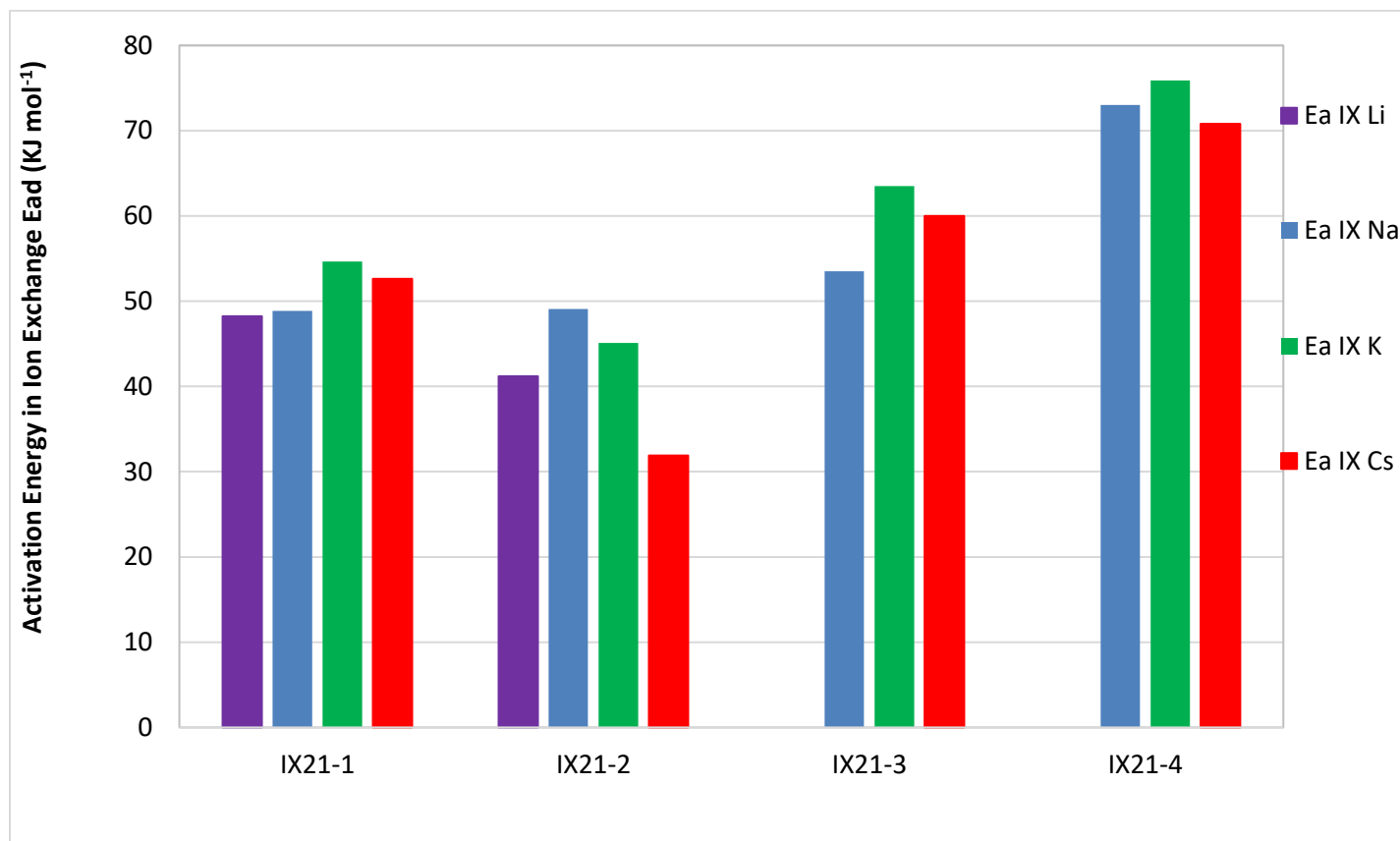
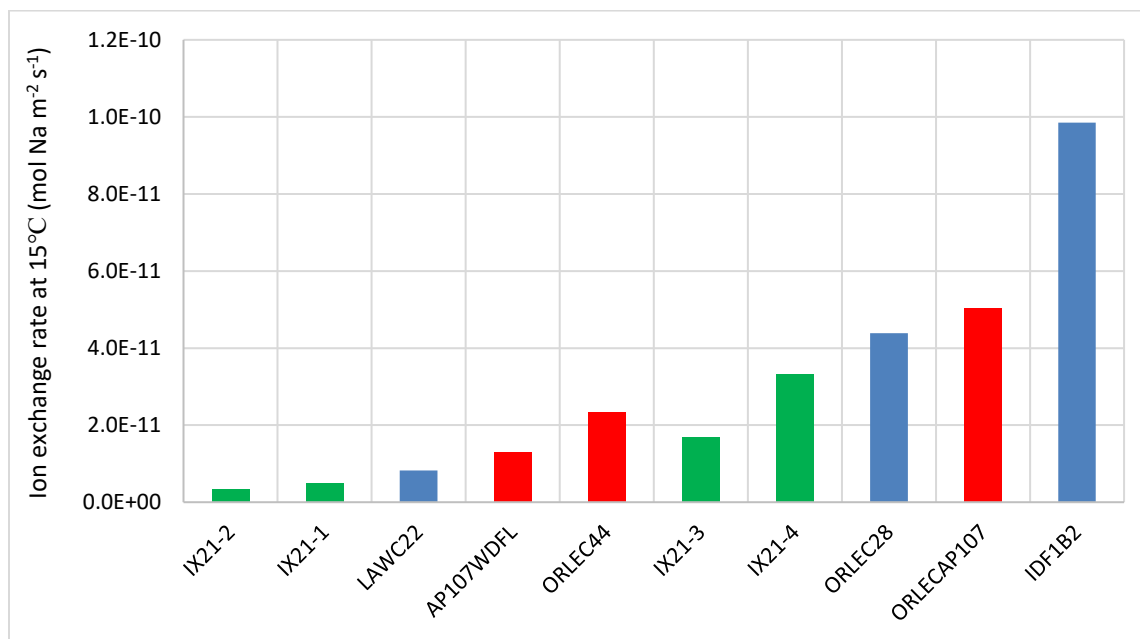
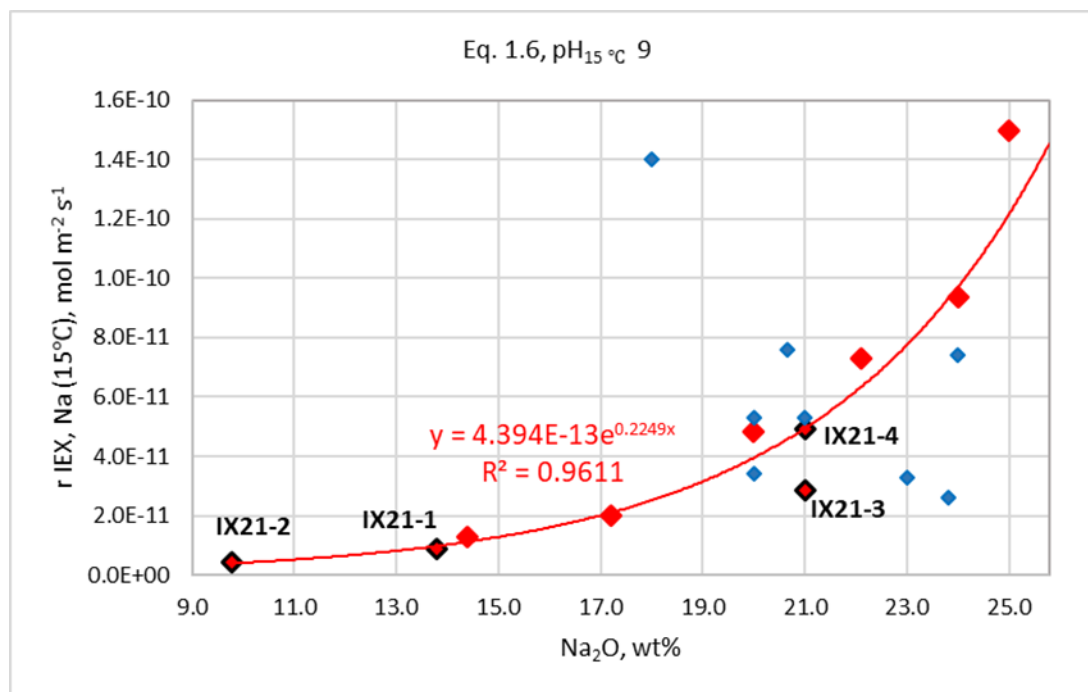


Figure 5.32. Plots of ion exchange activation energy  $E_{ad}$  for IDFIX21-1, IDFIX21-2, IDFIX21-3, and IDFIX21-4.



**Figure 5.33a.** Plot of sodium ion exchange rates at 15 °C ( $\text{pH}_{15^\circ\text{C}} 9$ ) for ten glasses tested by Pulsed-Flow tests. The sodium content in the glasses increases from left to right. Blue bars are from the FY19 work [2], red bars are from the FY20 work [3], green bars are from the present work.



**Figure 5.33b.** Plot of sodium ion exchange rates at 15 °C ( $\text{pH}_{15^\circ\text{C}} 9$ ) versus  $\text{Na}_2\text{O}$  content for ten glasses tested by Pulsed-Flow tests (red diamonds) and fitted regression line. Data from SPFT tests (Table 2.1) are also shown (blue squares) but these were not included in the fit.

## **APPENDIX A**

### **PULSED-FLOW TEST DATA FOR LAW GLASSES IDFIX21-1, IDFIX21-2, IDFIX21-3 and IDFIX21-4**

**Table A0. DCP-AES and ICPMS concentration analyses (ppm) for the fifteen buffers.**

| For test<br>Temperature<br>°C. | Sample ID | Target<br>[Si] <sub>Inf</sub><br>ppm | pH<br>23°C | pH <sub>T</sub> | [B] <sup>(a)</sup><br>ppm | [Li] <sup>(a)</sup><br>ppm | [Na]<br>ppm | [K]<br>ppm | [Al]<br>ppm | [Mo]<br>ppm | [Cs]<br>ppm | [Re]<br>ppm |
|--------------------------------|-----------|--------------------------------------|------------|-----------------|---------------------------|----------------------------|-------------|------------|-------------|-------------|-------------|-------------|
| <b>70</b>                      | BLKA1     | 55                                   | 7.0        | 6.0             | 0.0034                    | 0.0007                     | 0.1223      | 0.0260     | 0.0229      | 0.00020     | 0.00016     | 0.00018     |
|                                | BLKB1     | 60                                   | 8.0        | 7.0             | 0.0034                    | 0.0006                     | 0.1229      | 0.0166     | 0.0262      | 0.00026     | 0.00022     | 0.00010     |
|                                | BLKC1     | 80                                   | 9.0        | 8.0             | 0.0034                    | 0.0004                     | 0.1369      | 0.0095     | 0.0330      | 0.00005     | 0.00010     | 0.00008     |
|                                | BLKD1     | 140                                  | 10.0       | 8.9             | 0.0034                    | 0.0012                     | 0.2710      | 0.0238     | 0.0588      | 0.00027     | 0.00212     | 0.00121     |
|                                | BLKE1     | 360                                  | 11.0       | 10.0            | 0.0034                    | 0.0182                     | 0.9086      | 0.0453     | 0.1168      | 0.00029     | 0.00047     | 0.00090     |
| <b>40</b>                      | Blank A2  | 40                                   | 7.0        | 6.6             | 0.0034                    | 0.0035                     | 0.0837      | 0.0103     | 0.0213      | 0.00133     | 0.00015     | 0.00074     |
|                                | Blank B2  | 45                                   | 8.1        | 7.7             | 0.0034                    | 0.0035                     | 0.0825      | 0.0075     | 0.0188      | 0.00043     | 0.00010     | 0.00046     |
|                                | Blank C2  | 60                                   | 9.1        | 8.7             | 0.0034                    | 0.0035                     | 0.1058      | 0.0043     | 0.0260      | 0.00023     | 0.00002     | 0.00008     |
|                                | Blank D2  | 105                                  | 10.0       | 9.7             | 0.0034                    | 0.0035                     | 0.1875      | 0.0078     | 0.0468      | 0.00039     | 0.00000     | 0.00121     |
|                                | Blank E2  | 270                                  | 11.1       | 10.8            | 0.0034                    | 0.0038                     | 0.6480      | 0.0213     | 0.0895      | 0.00022     | 0.00003     | 0.00090     |
| <b>23</b>                      | BLKA3     | 35                                   | 7.0        | 7.0             | 0.0034                    | 0.0035                     | 0.0778      | 0.0180     | 0.0220      | 0.000755    | 0.000343    | 0.000134    |
|                                | BLKB3     | 40                                   | 8.1        | 8.1             | 0.0034                    | 0.0035                     | 0.0843      | 0.0185     | 0.0208      | 0.000740    | 0.000098    | 0.000461    |
|                                | BLKC3     | 52.5                                 | 9.1        | 9.1             | 0.0034                    | 0.0035                     | 0.1518      | 0.1670     | 0.0280      | 0.001143    | 0.000001    | 0.000002    |
|                                | BLKD3     | 90                                   | 10.0       | 10.0            | 0.0034                    | 0.0035                     | 0.1938      | 0.0113     | 0.0458      | 0.000412    | 0.000001    | 0.000260    |
|                                | BLKE3     | 230                                  | 11.1       | 11.1            | 0.0034                    | 0.0030                     | 0.5978      | 0.0180     | 0.1145      | 0.001427    | 0.000036    | 0.000434    |

<sup>(a)</sup> Detection limits for [B] = 0.0034 ppm and [Li] = 0.0035 used when none detectable in the blanks.

**Table A1. DCP-AES Analysis Results from Dissolution of Glass IDFIX21-1at 70°C: leachate concentration (ppm) and NDR<sub>i</sub> (g m<sup>-2</sup> d<sup>-1</sup>).**

| Exp. | Sample ID    | Target [Si] <sub>inf</sub> ppm | T °C | Flow Rate, m <sup>3</sup> /d | Time, days | pH 23°C | Glass Mass g | SA m <sup>2</sup> | [B] ppm | B Rate g <sub>-glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [Li] ppm | Li Rate g <sub>-glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [Na] ppm | Na Rate g <sub>-glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [K] ppm | K Rate g <sub>-glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [Al] ppm | Al Rate g <sub>-glass</sub> m <sup>-2</sup> d <sup>-1</sup> |
|------|--------------|--------------------------------|------|------------------------------|------------|---------|--------------|-------------------|---------|------------------------------------------------------------|----------|-------------------------------------------------------------|----------|-------------------------------------------------------------|---------|------------------------------------------------------------|----------|-------------------------------------------------------------|
| 1    | IX21-1-A1D1  | 55                             | 70   | 2.50E-05                     | 1          | 7       | 0.77         | 0.01511           | 2.125   | 0.2261                                                     | 0.8960   | 0.2702                                                      | 8.2572   | 0.2634                                                      | 1.1331  | 0.2208                                                     | 0.0530   | 0.0031                                                      |
|      | IX21-1-A1D2  | 55                             | 70   | 2.50E-05                     | 2          | 7       | 0.77         | 0.01508           | 2.504   | 0.1537                                                     | 0.9739   | 0.1589                                                      | 9.0248   | 0.1568                                                      | 1.2884  | 0.1416                                                     | 0.0694   | 0.0032                                                      |
|      | IX21-1-A1D3  | 55                             | 70   | 2.50E-05                     | 3          | 7       | 0.77         | 0.01505           | 2.731   | 0.1580                                                     | 1.0269   | 0.1634                                                      | 9.6851   | 0.1660                                                      | 1.3867  | 0.1460                                                     | 0.0787   | 0.0034                                                      |
|      | IX21-1-A1D4  | 55                             | 70   | 2.50E-05                     | 4          | 7       | 0.77         | 0.01503           | 2.792   | 0.1527                                                     | 1.0388   | 0.1593                                                      | 9.5673   | 0.1518                                                      | 1.4210  | 0.1433                                                     | 0.0905   | 0.0041                                                      |
|      | IX21-1-A1D5  | 55                             | 70   | 2.50E-05                     | 5          | 7       | 0.77         | 0.01500           | 2.507   | 0.1191                                                     | 0.9309   | 0.1250                                                      | 8.9093   | 0.1325                                                      | 1.2840  | 0.1126                                                     | 0.0791   | 0.0023                                                      |
|      | IX21-1-A1D6  | 55                             | 70   | 2.50E-05                     | 6          | 7       | 0.77         | 0.01497           | 2.473   | 0.1310                                                     | 0.9182   | 0.1378                                                      | 8.4534   | 0.1286                                                      | 1.2405  | 0.1178                                                     | 0.0866   | 0.0037                                                      |
|      | IX21-1-A1D7  | 55                             | 70   | 2.50E-05                     | 7          | 7       | 0.77         | 0.01495           | 2.462   | 0.1318                                                     | 0.9169   | 0.1396                                                      | 8.3570   | 0.1332                                                      | 1.2577  | 0.1259                                                     | 0.0830   | <b>0.0029</b>                                               |
|      | IX21-1-A1D8  | 55                             | 70   | 2.50E-05                     | 8          | 7       | 0.77         | 0.01492           | 2.321   | <b>0.1174</b>                                              | 0.8602   | <b>0.1227</b>                                               | 8.0116   | <b>0.1236</b>                                               | 1.1780  | <b>0.1083</b>                                              | 0.0822   | <b>0.0030</b>                                               |
|      | IX21-1-A1D9  | 55                             | 70   | 2.50E-05                     | 9          | 7       | 0.77         | 0.01490           | 2.180   | <b>0.1100</b>                                              | 0.8055   | <b>0.1148</b>                                               | 7.5352   | <b>0.1139</b>                                               | 1.1258  | <b>0.1059</b>                                              | 0.0796   | <b>0.0028</b>                                               |
|      | IX21-1-A1D10 | 55                             | 70   | 2.50E-05                     | 10         | 7       | 0.77         | 0.01487           | 2.088   | <b>0.1078</b>                                              | 0.7703   | <b>0.1126</b>                                               | 7.3931   | <b>0.1172</b>                                               | 1.1117  | <b>0.1085</b>                                              | 0.0770   | <b>0.0027</b>                                               |
| 2    | IX21-1-B1D1  | 60                             | 70   | 2.50E-05                     | 1          | 8       | 0.77         | 0.01511           | 0.772   | 0.0819                                                     | 0.3760   | 0.1133                                                      | 3.4999   | 0.1093                                                      | 0.4298  | 0.0824                                                     | 0.1495   | 0.0126                                                      |
|      | IX21-1-B1D2  | 60                             | 70   | 2.50E-05                     | 2          | 8       | 0.77         | 0.01510           | 1.205   | 0.0871                                                     | 0.5481   | 0.1086                                                      | 4.9494   | 0.1016                                                      | 0.6517  | 0.0855                                                     | 0.1203   | 0.0033                                                      |
|      | IX21-1-B1D3  | 60                             | 70   | 2.50E-05                     | 3          | 8       | 0.77         | 0.01509           | 1.164   | 0.0597                                                     | 0.4868   | 0.0642                                                      | 4.5352   | 0.0648                                                      | 0.6268  | 0.0584                                                     | 0.1311   | 0.0059                                                      |
|      | IX21-1-B1D4  | 60                             | 70   | 2.50E-05                     | 4          | 8       | 0.77         | 0.01508           | 1.087   | 0.0537                                                     | 0.4394   | 0.0592                                                      | 3.9879   | 0.0538                                                      | 0.5691  | 0.0494                                                     | 0.1276   | 0.0050                                                      |
|      | IX21-1-B1D5  | 60                             | 70   | 2.50E-05                     | 5          | 8       | 0.77         | 0.01507           | 1.033   | 0.0522                                                     | 0.4054   | 0.0561                                                      | 3.6959   | 0.0532                                                      | 0.5346  | 0.0483                                                     | 0.1244   | 0.0049                                                      |
|      | IX21-1-B1D6  | 60                             | 70   | 2.50E-05                     | 6          | 8       | 0.77         | 0.01506           | 1.000   | 0.0515                                                     | 0.3877   | 0.0559                                                      | 3.5383   | 0.0529                                                      | 0.5022  | 0.0453                                                     | 0.1221   | 0.0048                                                      |
|      | IX21-1-B1D7  | 60                             | 70   | 2.50E-05                     | 7          | 8       | 0.77         | 0.01505           | 0.924   | <b>0.0452</b>                                              | 0.3506   | <b>0.0474</b>                                               | 3.1728   | <b>0.0436</b>                                               | 0.4692  | <b>0.0420</b>                                              | 0.0721   | -0.0002                                                     |
|      | IX21-1-B1D8  | 60                             | 70   | 2.50E-05                     | 8          | 8       | 0.77         | 0.01504           | 0.889   | <b>0.0455</b>                                              | 0.3397   | <b>0.0497</b>                                               | 3.0798   | <b>0.0466</b>                                               | 0.4573  | <b>0.0430</b>                                              | 0.1237   | <b>0.0077</b>                                               |
|      | IX21-1-B1D9  | 60                             | 70   | 2.50E-05                     | 9          | 8       | 0.77         | 0.01503           | 0.768   | <b>0.0344</b>                                              | 0.2937   | <b>0.0375</b>                                               | 2.6838   | <b>0.0352</b>                                               | 0.4165  | <b>0.0360</b>                                              | 0.0913   | <b>0.0017</b>                                               |
|      | IX21-1-B1D10 | 60                             | 70   | 2.50E-05                     | 10         | 8       | 0.77         | 0.01502           | 0.777   | <b>0.0420</b>                                              | 0.2900   | <b>0.0434</b>                                               | 2.6632   | <b>0.0410</b>                                               | 0.4174  | <b>0.0403</b>                                              | 0.0984   | <b>0.0041</b>                                               |
| 3    | IX21-1-C1D1  | 80                             | 70   | 2.50E-05                     | 1          | 9       | 0.77         | 0.01512           | 0.455   | 0.0481                                                     | 0.2598   | 0.0782                                                      | 2.6002   | 0.0797                                                      | 0.2525  | 0.0484                                                     | 0.1140   | 0.0083                                                      |
|      | IX21-1-C1D2  | 80                             | 70   | 2.50E-05                     | 2          | 9       | 0.77         | 0.01511           | 0.373   | 0.0153                                                     | 0.2032   | 0.0220                                                      | 2.0291   | 0.0214                                                      | 0.2098  | 0.0157                                                     | 0.0935   | 0.0020                                                      |
|      | IX21-1-C1D3  | 80                             | 70   | 2.50E-05                     | 3          | 9       | 0.77         | 0.01511           | 0.347   | 0.0169                                                     | 0.1729   | 0.0214                                                      | 1.7604   | 0.0219                                                      | 0.1875  | 0.0155                                                     | 0.1358   | 0.0074                                                      |
|      | IX21-1-C1D4  | 80                             | 70   | 2.50E-05                     | 4          | 9       | 0.77         | 0.01510           | 0.334   | 0.0169                                                     | 0.1524   | 0.0198                                                      | 1.5640   | 0.0199                                                      | 0.1852  | 0.0173                                                     | 0.1086   | 0.0025                                                      |
|      | IX21-1-C1D5  | 80                             | 70   | 2.50E-05                     | 5          | 9       | 0.77         | 0.01510           | 0.299   | 0.0139                                                     | 0.1227   | 0.0139                                                      | 1.2946   | 0.0144                                                      | 0.1746  | 0.0154                                                     | 0.1167   | 0.0047                                                      |
|      | IX21-1-C1D6  | 80                             | 70   | 2.50E-05                     | 6          | 9       | 0.77         | 0.01510           | 0.277   | <b>0.0135</b>                                              | 0.1064   | <b>0.0135</b>                                               | 1.1438   | <b>0.0139</b>                                               | 0.1451  | <b>0.0106</b>                                              | 0.1254   | <b>0.0052</b>                                               |
|      | IX21-1-C1D7  | 80                             | 70   | 2.50E-05                     | 7          | 9       | 0.77         | 0.01509           | 0.278   | <b>0.0146</b>                                              | 0.1026   | <b>0.0148</b>                                               | 1.1086   | <b>0.0152</b>                                               | 0.1450  | <b>0.0135</b>                                              | 0.1219   | <b>0.0044</b>                                               |
|      | IX21-1-C1D8  | 80                             | 70   | 2.50E-05                     | 8          | 9       | 0.77         | 0.01509           | 0.263   | <b>0.0131</b>                                              | 0.097    | <b>0.0136</b>                                               | 1.057    | <b>0.0141</b>                                               | 0.147   | <b>0.0139</b>                                              | 0.115    | <b>0.0038</b>                                               |
|      | IX21-1-C1D9  | 80                             | 70   | 2.50E-05                     | 9          | 9       | 0.77         | 0.01509           | 0.249   | <b>0.0123</b>                                              | 0.0909   | <b>0.0128</b>                                               | 1.0046   | <b>0.0132</b>                                               | 0.1490  | <b>0.0141</b>                                              | 0.1072   | <b>0.0034</b>                                               |
|      | IX21-1-C1D10 | 80                             | 70   | 2.50E-05                     | 10         | 9       | 0.77         | 0.01509           | 0.279   | <b>0.0163</b>                                              | 0.0956   | <b>0.0151</b>                                               | 1.0585   | <b>0.0158</b>                                               | 0.1556  | <b>0.0152</b>                                              | 0.1401   | <b>0.0072</b>                                               |
| 4    | IX21-1-D1D1  | 140                            | 70   | 2.50E-05                     | 1          | 10      | 0.50         | 0.00972           | 0.186   | 0.0302                                                     | 0.1421   | 0.0661                                                      | 1.5719   | <b>0.0655</b>                                               | 0.1338  | 0.0341                                                     | 0.1127   | 0.0086                                                      |
|      | IX21-1-D1D2  | 140                            | 70   | 2.50E-05                     | 2          | 10      | 0.50         | 0.00972           | 0.141   | 0.0077                                                     | 0.1041   | 0.0154                                                      | 1.1983   | 0.0139                                                      | 0.1028  | 0.0074                                                     | 0.1001   | 0.0023                                                      |
|      | IX21-1-D1D3  | 140                            | 70   | 2.50E-05                     | 3          | 10      | 0.50         | 0.00971           | 0.106   | 0.0056                                                     | 0.0775   | 0.0118                                                      | 0.9444   | 0.0106                                                      | 0.0803  | 0.0053                                                     | 0.0868   | 0.0012                                                      |
|      | IX21-1-D1D4  | 140                            | 70   | 2.50E-05                     | 4          | 10      | 0.50         | 0.00971           | 0.082   | 0.0044                                                     | 0.0611   | 0.0103                                                      | 0.7960   | 0.0095                                                      | 0.0699  | 0.0055                                                     | 0.0742   | <b>0.0002</b>                                               |
|      | IX21-1-D1D5  | 140                            | 70   | 2.50E-05                     | 5          | 10      | 0.50         | 0.00971           | 0.068   | 0.0043                                                     | 0.0492   | 0.0086                                                      | 0.6868   | 0.0077                                                      | 0.0598  | 0.0040                                                     | 0.0716   | <b>0.0008</b>                                               |
|      | IX21-1-D1D6  | 140                            | 70   | 2.50E-05                     | 6          | 10      | 0.50         | 0.00971           | 0.059   | 0.0038                                                     | 0.0411   | 0.0076                                                      | 0.6246   | 0.0073                                                      | 0.0575  | 0.0049                                                     | 0.0662   | <b>0.0002</b>                                               |
|      | IX21-1-D1D7  | 140                            | 70   | 2.50E-05                     | 7          | 10      | 0.50         | 0.00971           | 0.068   | 0.0061                                                     | 0.0414   | 0.0096                                                      | 0.6222   | 0.0088                                                      | 0.0588  | <b>0.0056</b>                                              | 0.0726   | <i>0.0016</i>                                               |
|      | IX21-1-D1D8  | 140                            | 70   | 2.50E-05                     | 8          | 10      | 0.50         | 0.00971           | 0.052   | <b>0.0027</b>                                              | 0.0342   | <b>0.0062</b>                                               | 0.5610   | <b>0.0058</b>                                               | 0.0528  | <b>0.0036</b>                                              | 0.0666   | <b>0.0001</b>                                               |
|      | IX21-1-D1D9  | 140                            | 70   | 2.50E-05                     | 9          | 10      | 0.50         | 0.00971           | 0.048   | <b>0.0034</b>                                              | 0.0302   | <b>0.0060</b>                                               | 0.5341   | <b>0.0059</b>                                               | 0.0517  | <b>0.0042</b>                                              | 0.0618   | <i>-0.0001</i>                                              |
|      | IX21-1-D1D10 | 140                            | 70   | 2.50E-05                     | 10         | 10      | 0.50         | 0.00971           | 0.055   | <b>0.0049</b>                                              | 0.0305   | <b>0.0071</b>                                               | 0.5544   | <b>0.0076</b>                                               | 0.0905  | <i>0.0164</i>                                              | 0.0611   | <b>0.0001</b>                                               |
| 5    | IX21-1-E1D1  | 360                            | 70   | 2.50E-05                     | 1          | 11      | 0.50         | 0.00972           | 0.090   | 0.0143                                                     | 0.1033   | 0.0399                                                      | 1.839    | 0.0468                                                      | 0.1097  | 0.0067                                                     | 0.1208   | 0.0006                                                      |
|      | IX21-1-E1D2  | 360                            | 70   | 2.50E-05                     | 2          | 11      | 0.50         | 0.00972           | 0.060   | 0.0022                                                     | 0.0903   | 0.0180                                                      | 1.560    | 0.0093                                                      | 0.0910  | 0.0014                                                     | 0.1173   | -0.0002                                                     |
|      | IX21-1-E1D3  | 360                            | 70   | 2.50E-05                     | 3          | 11      | 0.50         | 0.00972           | 0.040   | 0.0014                                                     | 0.0773   | 0.0149                                                      | 1.361    | 0.0064                                                      | 0.0723  | 0.0004                                                     | 0.1115   | -0.0009                                                     |
|      | IX21-1-E1D4  | 360                            | 70   | 2.50E-05                     | 4          | 11      | 0.50         | 0.00972           | 0.030   | 0.0014                                                     | 0.0710   | 0.0150                                                      | 1.305    | 0.0086                                                      | 0.0681  | 0.0010                                                     | 0.1037   | -0.0017                                                     |
|      | IX21-1-E1D5  | 360                            | 70   | 2.50E-05                     | 5          | 11      | 0.50         | 0.00972           | 0.016   | -0.0001                                                    | 0.0589   | 0.0108                                                      | 1.150    | 0.0022                                                      | 0.0527  | -0.0004                                                    | 0.0949   | -0.0024                                                     |
|      | IX21-1-E1D6  | 360                            | 70   | 2.50E-05                     | 6          | 11      | 0.50         | 0.00972           | 0.011   | 0.0003                                                     | 0.0579   | 0.0132                                                      | 1.161    | 0.0066                                                      | 0.0540  | 0.0005                                                     | 0.0981   | -0.0012                                                     |
|      | IX21-1-E1D7  | 360                            | 70   | 2.50E-05                     | 7          | 11      | 0.50         | 0.00972           | 0.014   | 0.0011                                                     | 0.0588   | 0.0139                                                      | 1.209    | 0.0088                                                      | 0.0586  | 0.0009                                                     | 0.1084   | 0.0001                                                      |
|      | IX21-1-E1D8  | 360                            | 70   | 2.50E-05                     | 8          | 11      | 0.50         | 0.00972           | 0.008   | -0.0002                                                    | 0.0516   | <b>0.0102</b>                                               | 1.100    | <b>0.0021</b>                                               | 0.0476  | -0.0005                                                    | 0.0995   | -0.0021                                                     |
|      | IX21-1-E1D9  | 360                            | 70   | 2.50E-05                     | 9          | 11      | 0.50         | 0.00972           | 0.008   | <b>0.0004</b>                                              | 0.0488   | <b>0.0107</b>                                               | 1.097    | <b>0.0047</b>                                               | 0.0440  | -0.0003                                                    | 0.1021   | -0.0010                                                     |
|      | IX21-1-E1D10 | 360                            | 70   | 2.50E-05                     | 10         | 11      | 0.50         | 0.00972           | 0.007   | <b>0.0001</b>                                              | 0.0504   | <b>0.0120</b>                                               | 1.086    | <b>0.0042</b>                                               | 0.0526  | 0.0008                                                     | 0.1063   | -0.0005                                                     |

Table A2. DCP-AES Analysis Results from Dissolution of Glass IDFIX21-1at 40°C.

| Exp. | Sample ID    | Target [Si] <sub>inf</sub> ppm | T °C | Flow Rate, m <sup>3</sup> /d | Time, days | pH 23°C | Glass Mass g | SA m <sup>2</sup> | [B] ppm | B Rate g-glass m <sup>-2</sup> d <sup>-1</sup> | [Li] ppm | Li Rate g-glass m <sup>-2</sup> d <sup>-1</sup> | [Na] ppm | Na Rate g-glass m <sup>-2</sup> d <sup>-1</sup> | [K] ppm | K Rate g-glass m <sup>-2</sup> d <sup>-1</sup> | [Al] ppm | Al Rate g-glass m <sup>-2</sup> d <sup>-1</sup> |
|------|--------------|--------------------------------|------|------------------------------|------------|---------|--------------|-------------------|---------|------------------------------------------------|----------|-------------------------------------------------|----------|-------------------------------------------------|---------|------------------------------------------------|----------|-------------------------------------------------|
| 1    | IX21-1-A2D1  | 40                             | 40   | 8.33E-06                     | 3          | 7       | 1.65         | 0.03239           | 1.110   | 0.0183                                         | 0.5530   | 0.0258                                          | 5.5340   | 0.0274                                          | 0.6220  | 0.0190                                         | 0.0660   | 0.0007                                          |
|      | IX21-1-A2D2  | 40                             | 40   | 8.33E-06                     | 6          | 7       | 1.65         | 0.03238           | 1.031   | 0.0079                                         | 0.4810   | 0.0095                                          | 4.5070   | 0.0085                                          | 0.5410  | 0.0070                                         | 0.0450   | 0.0000                                          |
|      | IX21-1-A2D3  | 40                             | 40   | 8.33E-06                     | 9          | 7       | 1.65         | 0.03237           | 0.822   | 0.0051                                         | 0.3570   | 0.0054                                          | 3.3270   | 0.0052                                          | 0.4280  | 0.0047                                         | 0.0410   | 0.0001                                          |
|      | IX21-1-A2D4  | 40                             | 40   | 8.33E-06                     | 12         | 7       | 1.65         | 0.03236           | 0.841   | 0.0071                                         | 0.3250   | 0.0068                                          | 3.0120   | 0.0066                                          | 0.4290  | 0.0065                                         | 0.2160   | 0.0029                                          |
|      | IX21-1-A2D5  | 40                             | 40   | 8.33E-06                     | 15         | 7       | 1.65         | 0.03235           | 0.768   | 0.0057                                         | 0.3160   | 0.0071                                          | 2.9180   | 0.0069                                          | 0.3890  | 0.0053                                         | 0.0420   | -0.0012                                         |
|      | IX21-1-A2D6  | 40                             | 40   | 8.33E-06                     | 18         | 7       | 1.65         | 0.03234           | 0.733   | 0.0058                                         | 0.2910   | 0.0062                                          | 2.6800   | 0.0059                                          | 0.3700  | 0.0053                                         | 0.0500   | 0.0003                                          |
|      | IX21-1-A2D7  | 40                             | 40   | 8.33E-06                     | 21         | 7       | 1.65         | 0.03234           | 0.695   | <b>0.0054</b>                                  | 0.2650   | <b>0.0055</b>                                   | 2.4440   | <b>0.0054</b>                                   | 0.3530  | <b>0.0051</b>                                  | 0.0550   | 0.0003                                          |
|      | IX21-1-A2D8  | 40                             | 40   | 8.33E-06                     | 24         | 7       | 1.65         | 0.03233           | 0.673   | <b>0.0054</b>                                  | 0.2530   | <b>0.0056</b>                                   | 2.3290   | <b>0.0054</b>                                   | 0.3300  | <b>0.0046</b>                                  | 0.0690   | <b>0.0005</b>                                   |
|      | IX21-1-A2D9  | 40                             | 40   | 8.33E-06                     | 27         | 7       | 1.65         | 0.03232           | 0.690   | <b>0.0058</b>                                  | 0.2570   | <b>0.0061</b>                                   | 2.3740   | <b>0.0059</b>                                   | 0.4180  | <b>0.0077</b>                                  | 0.1040   | <b>0.0009</b>                                   |
|      | IX21-1-A2D10 | 40                             | 40   | 8.33E-06                     | 30         | 7       | 1.65         | 0.03231           | 0.669   | <b>0.0054</b>                                  | 0.2510   | <b>0.0057</b>                                   | 2.3210   | <b>0.0055</b>                                   | 0.3490  | <b>0.0042</b>                                  | 0.0670   | <b>0.0001</b>                                   |
| 2    | IX21-1-B2D1  | 45                             | 40   | 8.33E-06                     | 3          | 8       | 1.65         | 0.03239           | 0.507   | 0.0083                                         | 0.3370   | 0.0156                                          | 3.4300   | 0.0168                                          | 0.3490  | 0.0106                                         | 0.0820   | 0.0010                                          |
|      | IX21-1-B2D2  | 45                             | 40   | 8.33E-06                     | 6          | 8       | 1.65         | 0.03239           | 0.394   | 0.0023                                         | 0.2520   | 0.0038                                          | 2.4260   | 0.0034                                          | 0.2670  | 0.0028                                         | 0.0660   | 0.0002                                          |
|      | IX21-1-B2D3  | 45                             | 40   | 8.33E-06                     | 9          | 8       | 1.65         | 0.03238           | 0.327   | 0.0021                                         | 0.1930   | 0.0031                                          | 1.8440   | 0.0030                                          | 0.2080  | 0.0022                                         | 0.0710   | 0.0005                                          |
|      | IX21-1-B2D4  | 45                             | 40   | 8.33E-06                     | 12         | 8       | 1.65         | 0.03238           | 0.252   | 0.0014                                         | 0.1460   | 0.0022                                          | 1.3890   | 0.0021                                          | 0.1640  | 0.0017                                         | 0.0085   | -0.0006                                         |
|      | IX21-1-B2D5  | 45                             | 40   | 8.33E-06                     | 15         | 8       | 1.65         | 0.03238           | 0.250   | 0.0020                                         | 0.1240   | 0.0023                                          | 1.1790   | 0.0022                                          | 0.1530  | 0.0021                                         | 0.1120   | 0.0016                                          |
|      | IX21-1-B2D6  | 45                             | 40   | 8.33E-06                     | 18         | 8       | 1.65         | 0.03238           | 0.213   | 0.0014                                         | 0.1180   | 0.0025                                          | 1.1240   | 0.0025                                          | 0.1350  | 0.0017                                         | 0.0510   | -0.0002                                         |
|      | IX21-1-B2D7  | 45                             | 40   | 8.33E-06                     | 21         | 8       | 1.65         | 0.03237           | 0.201   | 0.0015                                         | 0.0980   | 0.0017                                          | 0.9540   | 0.0018                                          | 0.1190  | 0.0015                                         | 0.0210   | -0.0002                                         |
|      | IX21-1-B2D8  | 45                             | 40   | 8.33E-06                     | 24         | 8       | 1.65         | 0.03237           | 0.198   | <b>0.0016</b>                                  | 0.0940   | <b>0.0020</b>                                   | 0.9220   | <b>0.0020</b>                                   | 0.1220  | <b>0.0018</b>                                  | 0.0800   | <b>0.0010</b>                                   |
|      | IX21-1-B2D9  | 45                             | 40   | 8.33E-06                     | 27         | 8       | 1.65         | 0.03237           | 0.181   | <b>0.0013</b>                                  | 0.0850   | <b>0.0017</b>                                   | 0.8430   | <b>0.0017</b>                                   | 0.1090  | <b>0.0014</b>                                  | 0.0520   | <b>0.0000</b>                                   |
|      | IX21-1-B2D10 | 45                             | 40   | 8.33E-06                     | 30         | 8       | 1.65         | 0.03237           | 0.189   | <b>0.0016</b>                                  | 0.0860   | <b>0.0020</b>                                   | 0.8500   | <b>0.0020</b>                                   | 0.1160  | <b>0.0018</b>                                  | 0.0780   | <b>0.0007</b>                                   |
| 3    | IX21-1-C2D1  | 60                             | 40   | 8.33E-06                     | 3          | 9       | 1.65         | 0.03239           | 0.338   | 0.0055                                         | 0.2450   | 0.0113                                          | 2.6240   | 0.0127                                          | 0.2370  | 0.0072                                         | 0.0610   | 0.0006                                          |
|      | IX21-1-C2D2  | 60                             | 40   | 8.33E-06                     | 6          | 9       | 1.65         | 0.03239           | 0.266   | 0.0016                                         | 0.1850   | 0.0029                                          | 1.8930   | 0.0027                                          | 0.1740  | 0.0016                                         | 0.0480   | 0.0001                                          |
|      | IX21-1-C2D3  | 60                             | 40   | 8.33E-06                     | 9          | 9       | 1.65         | 0.03239           | 0.209   | 0.0012                                         | 0.1380   | 0.0021                                          | 1.4070   | 0.0021                                          | 0.1320  | 0.0013                                         | 0.0540   | 0.0003                                          |
|      | IX21-1-C2D4  | 60                             | 40   | 8.33E-06                     | 12         | 9       | 1.65         | 0.03239           | 0.172   | 0.0011                                         | 0.1100   | 0.0018                                          | 1.1180   | 0.0018                                          | 0.1080  | 0.0012                                         | 0.0480   | 0.0001                                          |
|      | IX21-1-C2D5  | 60                             | 40   | 8.33E-06                     | 15         | 9       | 1.65         | 0.03238           | 0.120   | 0.0005                                         | 0.0820   | 0.0012                                          | 0.8500   | 0.0012                                          | 0.0840  | 0.0008                                         | 0.0590   | 0.0004                                          |
|      | IX21-1-C2D6  | 60                             | 40   | 8.33E-06                     | 18         | 9       | 1.65         | 0.03238           | 0.105   | 0.0007                                         | 0.0700   | 0.0013                                          | 0.7390   | 0.0013                                          | 0.0740  | 0.0009                                         | 0.0570   | 0.0002                                          |
|      | IX21-1-C2D7  | 60                             | 40   | 8.33E-06                     | 21         | 9       | 1.65         | 0.03238           | 0.099   | 0.0007                                         | 0.0620   | 0.0012                                          | 0.6710   | 0.0013                                          | 0.0660  | 0.0008                                         | 0.0420   | 0.0000                                          |
|      | IX21-1-C2D8  | 60                             | 40   | 8.33E-06                     | 24         | 9       | 1.65         | 0.03238           | 0.085   | <b>0.0006</b>                                  | 0.0550   | <b>0.0010</b>                                   | 0.6060   | <b>0.0011</b>                                   | 0.0610  | <b>0.0008</b>                                  | 0.0320   | <b>0.0000</b>                                   |
|      | IX21-1-C2D9  | 60                             | 40   | 8.33E-06                     | 27         | 9       | 1.65         | 0.03238           | 0.077   | <b>0.0005</b>                                  | 0.0480   | <b>0.0009</b>                                   | 0.5430   | <b>0.0009</b>                                   | 0.0570  | <b>0.0007</b>                                  | 0.0370   | <b>0.0001</b>                                   |
|      | IX21-1-C2D10 | 60                             | 40   | 8.33E-06                     | 30         | 9       | 1.65         | 0.03238           | 0.070   | <b>0.0005</b>                                  | 0.0440   | <b>0.0009</b>                                   | 0.5090   | <b>0.0009</b>                                   | 0.0550  | <b>0.0007</b>                                  | 0.0430   | <b>0.0002</b>                                   |
| 4    | IX21-1-D2D1  | 105                            | 40   | 8.33E-06                     | 3          | 10      | 0.83         | 0.01622           | 0.135   | 0.0044                                         | 0.1060   | 0.0096                                          | 1.3010   | <b>0.0112</b>                                   | 0.1060  | 0.0061                                         | 0.0850   | 0.0012                                          |
|      | IX21-1-D2D2  | 105                            | 40   | 8.33E-06                     | 6          | 10      | 0.83         | 0.01622           | 0.112   | 0.0014                                         | 0.0840   | 0.0027                                          | 1.0220   | 0.0028                                          | 0.0820  | 0.0016                                         | 0.0870   | 0.0007                                          |
|      | IX21-1-D2D3  | 105                            | 40   | 8.33E-06                     | 9          | 10      | 0.83         | 0.01621           | 0.080   | 0.0007                                         | 0.0610   | 0.0016                                          | 0.7680   | 0.0016                                          | 0.0610  | 0.0010                                         | 0.0660   | 0.0000                                          |
|      | IX21-1-D2D4  | 105                            | 40   | 8.33E-06                     | 12         | 10      | 0.83         | 0.01621           | 0.054   | 0.0004                                         | 0.0470   | 0.0014                                          | 0.6220   | 0.0015                                          | 0.0490  | 0.0009                                         | 0.0430   | -0.0004                                         |
|      | IX21-1-D2D5  | 105                            | 40   | 8.33E-06                     | 15         | 10      | 0.83         | 0.01621           | 0.040   | 0.0004                                         | 0.0360   | 0.0010                                          | 0.5240   | 0.0012                                          | 0.0400  | 0.0007                                         | 0.0640   | 0.0006                                          |
|      | IX21-1-D2D6  | 105                            | 40   | 8.33E-06                     | 18         | 10      | 0.83         | 0.01621           | 0.030   | 0.0003                                         | 0.0310   | 0.0011                                          | 0.4610   | 0.0011                                          | 0.0350  | 0.0007                                         | 0.0510   | -0.0001                                         |
|      | IX21-1-D2D7  | 105                            | 40   | 8.33E-06                     | 21         | 10      | 0.83         | 0.01621           | 0.027   | <b>0.0003</b>                                  | 0.0270   | 0.0009                                          | 0.4260   | 0.0010                                          | 0.0330  | 0.0007                                         | 0.0640   | 0.0005                                          |
|      | IX21-1-D2D8  | 105                            | 40   | 8.33E-06                     | 24         | 10      | 0.83         | 0.01621           | 0.023   | <b>0.0003</b>                                  | 0.0240   | <b>0.0008</b>                                   | 0.4020   | <b>0.0010</b>                                   | 0.0340  | <b>0.0008</b>                                  | 0.0560   | <i>0.0000</i>                                   |
|      | IX21-1-D2D9  | 105                            | 40   | 8.33E-06                     | 27         | 10      | 0.83         | 0.01621           | 0.012   | <i>0.0000</i>                                  | 0.0200   | <b>0.0006</b>                                   | 0.3570   | <b>0.0006</b>                                   | 0.0280  | <b>0.0004</b>                                  | 0.0380   | <i>-0.0004</i>                                  |
|      | IX21-1-D2D10 | 105                            | 40   | 8.33E-06                     | 30         | 10      | 0.83         | 0.01621           | 0.024   | <b>0.0005</b>                                  | 0.0220   | <b>0.0010</b>                                   | 0.3870   | <b>0.0012</b>                                   | 0.0390  | <b>0.0013</b>                                  | 0.0640   | 0.0007                                          |
| 5    | IX21-1-E2D1  | 270                            | 40   | 8.33E-06                     | 3          | 11      | 0.83         | 0.01622           | 0.193   | 0.0063                                         | 0.1166   | 0.0106                                          | 1.899    | <b>0.0126</b>                                   | 0.1460  | 0.0077                                         | 0.3045   | 0.0068                                          |
|      | IX21-1-E2D2  | 270                            | 40   | 8.33E-06                     | 6          | 11      | 0.83         | 0.01621           | 0.213   | 0.0038                                         | 0.1176   | 0.0054                                          | 1.854    | 0.0058                                          | 0.1397  | 0.0035                                         | 0.2300   | 0.0010                                          |
|      | IX21-1-E2D3  | 270                            | 40   | 8.33E-06                     | 9          | 11      | 0.83         | 0.01621           | 0.179   | 0.0023                                         | 0.0935   | 0.0031                                          | 1.550    | 0.0030                                          | 0.1134  | 0.0020                                         | 0.2058   | 0.0015                                          |
|      | IX21-1-E2D4  | 270                            | 40   | 8.33E-06                     | 12         | 11      | 0.83         | 0.01621           | 0.162   | 0.0023                                         | 0.0861   | 0.0035                                          | 1.512    | 0.0042                                          | 0.1050  | 0.0023                                         | 0.1575   | 0.0003                                          |
|      | IX21-1-E2D5  | 270                            | 40   | 8.33E-06                     | 15         | 11      | 0.83         | 0.01621           | 0.120   | 0.0012                                         | 0.0651   | 0.0019                                          | 1.285    | 0.0021                                          | 0.0851  | 0.0014                                         | 0.1649   | 0.0013                                          |
|      | IX21-1-E2D6  | 270                            | 40   | 8.33E-06                     | 18         | 11      | 0.83         | 0.01621           | 0.100   | 0.0013                                         | 0.0546   | 0.0019                                          | 1.182    | 0.0022                                          | 0.0735  | 0.0013                                         | 0.1449   | 0.0006                                          |
|      | IX21-1-E2D7  | 270                            | 40   | 8.33E-06                     | 21         | 11      | 0.83         | 0.01621           | 0.086   | <b>0.0011</b>                                  | 0.0473   | 0.0017                                          | 1.113    | 0.0020                                          | 0.0683  | 0.0013                                         | 0.1334   | 0.0005                                          |
|      | IX21-1-E2D8  | 270                            | 40   | 8.33E-06                     | 24         | 11      | 0.83         | 0.01621           | 0.074   | <b>0.0010</b>                                  | 0.0410   | <b>0.0015</b>                                   | 1.068    | <b>0.0019</b>                                   | 0.0588  | <b>0.0009</b>                                  | 0.1187   | 0.0002                                          |
|      | IX21-1-E2D9  | 270                            | 40   | 8.33E-06                     | 27         | 11      | 0.83         | 0.01621           | 0.059   | <b>0.0007</b>                                  | 0.0357   | <b>0.0013</b>                                   | 1.028    | <b>0.0017</b>                                   | 0.0525  | <b>0.0008</b>                                  | 0.0987   | -0.0002                                         |
|      | IX21-1-E2D10 | 270                            | 40   | 8.33E-06                     | 30         | 11      | 0.83         | 0.01621           | 0.056   | <b>0.0008</b>                                  | 0.0336   | <b>0.0013</b>                                   | 1.014    | <b>0.0018</b>                                   | 0.0546  | <b>0.0011</b>                                  | 0.0987   | 0.0001                                          |

Table A3. DCP-AES Analysis Results from Dissolution of Glass IDFIX21-1at 23 °C.

| Exp. | Sample ID    | Target<br>[Si] <sub>inf</sub><br>ppm | T<br>°C | Flow Rate,<br>m <sup>3</sup> /d | Time,<br>days | pH<br>23°C | Glass<br>Mass g | SA<br>m <sup>2</sup> | [B]<br>ppm | B Rate<br>g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [Li]<br>ppm | Li Rate<br>g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [Na]<br>ppm | Na Rate<br>g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [K]<br>ppm | K Rate<br>g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [Al]<br>ppm | Al Rate<br>g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> |
|------|--------------|--------------------------------------|---------|---------------------------------|---------------|------------|-----------------|----------------------|------------|--------------------------------------------------------------|-------------|---------------------------------------------------------------|-------------|---------------------------------------------------------------|------------|--------------------------------------------------------------|-------------|---------------------------------------------------------------|
| 1    | IX21-1-A3D1  | 35                                   | 23      | 8.33E-06                        | 3             | 7          | 3.28            | 0.064355             | 0.846      | 0.0070                                                       | 0.5320      | 0.0125                                                        | 5.3840      | 0.0134                                                        | 0.5120     | 0.0077                                                       | 0.0430      | 0.0002                                                        |
|      | IX21-1-A3D2  | 35                                   | 23      | 8.33E-06                        | 6             | 7          | 3.28            | 0.064347             | 0.675      | 0.0021                                                       | 0.4100      | 0.0034                                                        | 3.8130      | 0.0027                                                        | 0.3800     | 0.0018                                                       | 0.0470      | 0.0001                                                        |
|      | IX21-1-A3D3  | 35                                   | 23      | 8.33E-06                        | 9             | 7          | 3.28            | 0.064341             | 0.536      | 0.0016                                                       | 0.3140      | 0.0025                                                        | 2.7280      | 0.0020                                                        | 0.2870     | 0.0014                                                       | 0.0390      | 0.0000                                                        |
|      | IX21-1-A3D4  | 35                                   | 23      | 8.33E-06                        | 12            | 7          | 3.28            | 0.064336             | 0.448      | 0.0015                                                       | 0.2450      | 0.0020                                                        | 2.0760      | 0.0017                                                        | 0.2370     | 0.0013                                                       | 0.0530      | 0.0002                                                        |
|      | IX21-1-A3D5  | 35                                   | 23      | 8.33E-06                        | 15            | 7          | 3.28            | 0.064332             | 0.354      | 0.0011                                                       | 0.1910      | 0.0016                                                        | 1.5780      | 0.0013                                                        | 0.1900     | 0.0010                                                       | 0.0420      | 0.0000                                                        |
|      | IX21-1-A3D6  | 35                                   | 23      | 8.33E-06                        | 18            | 7          | 3.28            | 0.064328             | 0.278      | 0.0008                                                       | 0.1470      | 0.0012                                                        | 1.2180      | 0.0010                                                        | 0.1600     | 0.0009                                                       | 0.0610      | 0.0002                                                        |
|      | IX21-1-A3D7  | 35                                   | 23      | 8.33E-06                        | 21            | 7          | 3.28            | 0.064326             | 0.239      | <b>0.0008</b>                                                | 0.1230      | <b>0.0011</b>                                                 | 1.0180      | <b>0.0009</b>                                                 | 0.1370     | <b>0.0007</b>                                                | 0.0380      | 0.0000                                                        |
|      | IX21-1-A3D8  | 35                                   | 23      | 8.33E-06                        | 24            | 7          | 3.28            | 0.064323             | 0.204      | <b>0.0007</b>                                                | 0.1030      | <b>0.0009</b>                                                 | 0.8590      | <b>0.0008</b>                                                 | 0.1180     | <b>0.0006</b>                                                | 0.0370      | <b>0.0001</b>                                                 |
|      | IX21-1-A3D9  | 35                                   | 23      | 8.33E-06                        | 27            | 7          | 3.28            | 0.064321             | 0.217      | <b>0.0009</b>                                                | 0.1040      | <b>0.0012</b>                                                 | 0.8740      | <b>0.0010</b>                                                 | 0.1260     | <b>0.0009</b>                                                | 0.0970      | <b>0.0005</b>                                                 |
|      | IX21-1-A3D10 | 35                                   | 23      | 8.33E-06                        | 30            | 7          | 3.28            | 0.064319             | 0.187      | <b>0.0006</b>                                                | 0.0900      | <b>0.0009</b>                                                 | 0.7630      | <b>0.0007</b>                                                 | 0.1160     | <b>0.0007</b>                                                | 0.0620      | <b>0.0000</b>                                                 |
| 2    | IX21-1-B3D1  | 40                                   | 23      | 8.33E-06                        | 3             | 8          | 3.28            | 0.064357             | 0.447      | 0.0037                                                       | 0.3470      | 0.0081                                                        | 3.7040      | 0.0092                                                        | 0.3050     | 0.0045                                                       | 0.0550      | 0.0003                                                        |
|      | IX21-1-B3D2  | 40                                   | 23      | 8.33E-06                        | 6             | 8          | 3.28            | 0.064353             | 0.365      | 0.0012                                                       | 0.2650      | 0.0021                                                        | 2.6140      | 0.0018                                                        | 0.2230     | 0.0010                                                       | 0.0370      | 0.0000                                                        |
|      | IX21-1-B3D3  | 40                                   | 23      | 8.33E-06                        | 9             | 8          | 3.28            | 0.064350             | 0.262      | 0.0006                                                       | 0.1860      | 0.0012                                                        | 1.7230      | 0.0009                                                        | 0.1530     | 0.0005                                                       | 0.0640      | 0.0003                                                        |
|      | IX21-1-B3D4  | 40                                   | 23      | 8.33E-06                        | 12            | 8          | 3.28            | 0.064347             | 0.229      | 0.0008                                                       | 0.1530      | 0.0014                                                        | 1.3610      | 0.0012                                                        | 0.1270     | 0.0006                                                       | 0.0280      | -0.0001                                                       |
|      | IX21-1-B3D5  | 40                                   | 23      | 8.33E-06                        | 15            | 8          | 3.28            | 0.064345             | 0.172      | 0.0005                                                       | 0.1150      | 0.0009                                                        | 1.0070      | 0.0007                                                        | 0.1000     | 0.0004                                                       | 0.0540      | 0.0002                                                        |
|      | IX21-1-B3D6  | 40                                   | 23      | 8.33E-06                        | 18            | 8          | 3.28            | 0.064344             | 0.123      | 0.0003                                                       | 0.0840      | 0.0006                                                        | 0.7370      | 0.0005                                                        | 0.0760     | 0.0003                                                       | 0.0200      | -0.0001                                                       |
|      | IX21-1-B3D7  | 40                                   | 23      | 8.33E-06                        | 21            | 8          | 3.28            | 0.064342             | 0.133      | 0.0006                                                       | 0.0840      | 0.0010                                                        | 0.7300      | 0.0008                                                        | 0.0870     | 0.0006                                                       | 0.0830      | 0.0005                                                        |
|      | IX21-1-B3D8  | 40                                   | 23      | 8.33E-06                        | 24            | 8          | 3.28            | 0.064341             | 0.085      | <b>0.0001</b>                                                | 0.0590      | <b>0.0004</b>                                                 | 0.5260      | <b>0.0003</b>                                                 | 0.0630     | <b>0.0002</b>                                                | 0.0430      | -0.0001                                                       |
|      | IX21-1-B3D9  | 40                                   | 23      | 8.33E-06                        | 27            | 8          | 3.28            | 0.064340             | 0.077      | <b>0.0003</b>                                                | 0.0500      | <b>0.0004</b>                                                 | 0.4690      | <b>0.0004</b>                                                 | 0.0670     | <b>0.0004</b>                                                | 0.0490      | <b>0.0001</b>                                                 |
|      | IX21-1-B3D10 | 40                                   | 23      | 8.33E-06                        | 30            | 8          | 3.28            | 0.064340             | 0.084      | <b>0.0004</b>                                                | 0.0520      | <b>0.0006</b>                                                 | 0.4750      | <b>0.0005</b>                                                 | 0.0710     | <b>0.0004</b>                                                | 0.0600      | <b>0.0002</b>                                                 |
| 3    | IX21-1-C3D1  | 52                                   | 23      | 8.33E-06                        | 3             | 9          | 3.28            | 0.064358             | 0.381      | 0.0031                                                       | 0.3040      | 0.0071                                                        | 3.3000      | 0.0080                                                        | 0.2600     | 0.0015                                                       | 0.1250      | 0.0008                                                        |
|      | IX21-1-C3D2  | 52                                   | 23      | 8.33E-06                        | 6             | 9          | 3.28            | 0.064354             | 0.244      | 0.0004                                                       | 0.2010      | 0.0011                                                        | 2.0610      | 0.0008                                                        | 0.1560     | -0.0009                                                      | 0.0630      | -0.0001                                                       |
|      | IX21-1-C3D3  | 52                                   | 23      | 8.33E-06                        | 9             | 9          | 3.28            | 0.064352             | 0.195      | 0.0006                                                       | 0.1460      | 0.0010                                                        | 1.4330      | 0.0008                                                        | 0.1150     | -0.0007                                                      | 0.0530      | 0.0001                                                        |
|      | IX21-1-C3D4  | 52                                   | 23      | 8.33E-06                        | 12            | 9          | 3.28            | 0.064350             | 0.162      | 0.0005                                                       | 0.1180      | 0.0010                                                        | 1.1250      | 0.0008                                                        | 0.0960     | -0.0007                                                      | 0.0670      | 0.0002                                                        |
|      | IX21-1-C3D5  | 52                                   | 23      | 8.33E-06                        | 15            | 9          | 3.28            | 0.064349             | 0.132      | 0.0004                                                       | 0.0910      | 0.0007                                                        | 0.8620      | 0.0006                                                        | 0.0770     | -0.0009                                                      | 0.0470      | 0.0000                                                        |
|      | IX21-1-C3D6  | 52                                   | 23      | 8.33E-06                        | 18            | 9          | 3.28            | 0.064348             | 0.095      | 0.0002                                                       | 0.0690      | 0.0005                                                        | 0.6600      | 0.0004                                                        | 0.0610     | -0.0010                                                      | 0.0420      | 0.0000                                                        |
|      | IX21-1-C3D7  | 52                                   | 23      | 8.33E-06                        | 21            | 9          | 3.28            | 0.064347             | 0.087      | 0.0003                                                       | 0.0620      | 0.0006                                                        | 0.5940      | 0.0005                                                        | 0.0590     | -0.0009                                                      | 0.0560      | 0.0002                                                        |
|      | IX21-1-C3D8  | 52                                   | 23      | 8.33E-06                        | 24            | 9          | 3.28            | 0.064346             | 0.069      | <b>0.0002</b>                                                | 0.0500      | <b>0.0004</b>                                                 | 0.4850      | <b>0.0003</b>                                                 | 0.0450     | -0.0011                                                      | 0.0340      | -0.0001                                                       |
|      | IX21-1-C3D9  | 52                                   | 23      | 8.33E-06                        | 27            | 9          | 3.28            | 0.064345             | 0.061      | <b>0.0002</b>                                                | 0.0430      | <b>0.0004</b>                                                 | 0.4300      | <b>0.0003</b>                                                 | 0.0420     | -0.0010                                                      | 0.0400      | 0.0001                                                        |
|      | IX21-1-C3D10 | 52                                   | 23      | 8.33E-06                        | 30            | 9          | 3.28            | 0.064345             | 0.056      | <b>0.0002</b>                                                | 0.0400      | <b>0.0004</b>                                                 | 0.4050      | <b>0.0003</b>                                                 | 0.0410     | -0.0010                                                      | 0.0360      | 0.00002                                                       |
| 4    | IX21-1-D3D1  | 90                                   | 23      | 8.33E-06                        | 3             | 10         | 1.64            | 0.032179             | 0.163      | 0.0027                                                       | 0.1220      | 0.0056                                                        | 1.5160      | 0.0067                                                        | 0.1200     | 0.0034                                                       | 0.1260      | 0.0013                                                        |
|      | IX21-1-D3D2  | 90                                   | 23      | 8.33E-06                        | 6             | 10         | 1.64            | 0.032177             | 0.153      | 0.0012                                                       | 0.0990      | 0.0017                                                        | 1.1670      | 0.0016                                                        | 0.0970     | 0.0010                                                       | 0.1080      | 0.0004                                                        |
|      | IX21-1-D3D3  | 90                                   | 23      | 8.33E-06                        | 9             | 10         | 1.64            | 0.032176             | 0.130      | 0.0009                                                       | 0.0790      | 0.0013                                                        | 0.9160      | 0.0012                                                        | 0.0790     | 0.0008                                                       | 0.0860      | 0.0001                                                        |
|      | IX21-1-D3D4  | 90                                   | 23      | 8.33E-06                        | 12            | 10         | 1.64            | 0.032175             | 0.102      | 0.0006                                                       | 0.0620      | 0.0010                                                        | 0.7280      | 0.0009                                                        | 0.0650     | 0.0006                                                       | 0.0680      | 0.0000                                                        |
|      | IX21-1-D3D5  | 90                                   | 23      | 8.33E-06                        | 15            | 10         | 1.64            | 0.032174             | 0.076      | 0.0004                                                       | 0.0480      | 0.0007                                                        | 0.5950      | 0.0007                                                        | 0.0530     | 0.0005                                                       | 0.0680      | 0.0002                                                        |
|      | IX21-1-D3D6  | 90                                   | 23      | 8.33E-06                        | 18            | 10         | 1.64            | 0.032173             | 0.060      | 0.0003                                                       | 0.0360      | 0.0005                                                        | 0.4880      | 0.0005                                                        | 0.0450     | 0.0004                                                       | 0.0650      | 0.0001                                                        |
|      | IX21-1-D3D7  | 90                                   | 23      | 8.33E-06                        | 21            | 10         | 1.64            | 0.032173             | 0.048      | <b>0.0003</b>                                                | 0.0320      | 0.0006                                                        | 0.4410      | 0.0005                                                        | 0.0410     | 0.0004                                                       | 0.0530      | 0.0000                                                        |
|      | IX21-1-D3D8  | 90                                   | 23      | 8.33E-06                        | 24            | 10         | 1.64            | 0.032172             | 0.045      | <b>0.0003</b>                                                | 0.0280      | <b>0.0005</b>                                                 | 0.4040      | <b>0.0004</b>                                                 | 0.0390     | <b>0.0004</b>                                                | 0.0570      | <b>0.0001</b>                                                 |
|      | IX21-1-D3D9  | 90                                   | 23      | 8.33E-06                        | 27            | 10         | 1.64            | 0.032172             | 0.030      | <b>0.0001</b>                                                | 0.0210      | <b>0.0002</b>                                                 | 0.3510      | <b>0.0003</b>                                                 | 0.0320     | <b>0.0002</b>                                                | 0.0590      | <b>0.0001</b>                                                 |
|      | IX21-1-D3D10 | 90                                   | 23      | 8.33E-06                        | 30            | 10         | 1.64            | 0.032172             | 0.032      | <b>0.0003</b>                                                | 0.0210      | <b>0.0004</b>                                                 | 0.3570      | <b>0.0004</b>                                                 | 0.0370     | <b>0.0005</b>                                                | 0.0540      | <b>0.0000</b>                                                 |
| 5    | IX21-1-E3D1  | 230                                  | 23      | 8.33E-06                        | 3             | 11         | 1.64            | 0.032179             | 0.116      | 0.0019                                                       | 0.0914      | 0.0041                                                        | 1.693       | <b>0.0055</b>                                                 | 0.1113     | 0.0029                                                       | 0.2121      | 0.0016                                                        |
|      | IX21-1-E3D2  | 230                                  | 23      | 8.33E-06                        | 6             | 11         | 1.64            | 0.032178             | 0.146      | 0.0014                                                       | 0.0903      | 0.0020                                                        | 1.603       | 0.0023                                                        | 0.1134     | 0.0015                                                       | 0.2174      | 0.0009                                                        |
|      | IX21-1-E3D3  | 230                                  | 23      | 8.33E-06                        | 9             | 11         | 1.64            | 0.032176             | 0.139      | 0.0011                                                       | 0.0767      | 0.0014                                                        | 1.347       | 0.0012                                                        | 0.0966     | 0.0010                                                       | 0.1827      | 0.0003                                                        |
|      | IX21-1-E3D4  | 230                                  | 23      | 8.33E-06                        | 12            | 11         | 1.64            | 0.032175             | 0.147      | 0.0013                                                       | 0.0746      | 0.0016                                                        | 1.304       | 0.0017                                                        | 0.0966     | 0.0012                                                       | 0.1754      | 0.0004                                                        |
|      | IX21-1-E3D5  | 230                                  | 23      | 8.33E-06                        | 15            | 11         | 1.64            | 0.032174             | 0.124      | 0.0008                                                       | 0.0630      | 0.0011                                                        | 1.157       | 0.0010                                                        | 0.0851     | 0.0009                                                       | 0.1670      | 0.0004                                                        |
|      | IX21-1-E3D6  | 230                                  | 23      | 8.33E-06                        | 18            | 11         | 1.64            | 0.032172             | 0.117      | 0.0009                                                       | 0.0588      | 0.0012                                                        | 1.126       | 0.0013                                                        | 0.0819     | 0.0009                                                       | 0.1932      | 0.0008                                                        |
|      | IX21-1-E3D7  | 230                                  | 23      | 8.33E-06                        | 21            | 11         | 1.64            | 0.032171             | 0.117      | <b>0.0009</b>                                                | 0.0588      | 0.0013                                                        | 1.120       | 0.0013                                                        | 0.0830     | 0.0010                                                       | 0.1785      | 0.0004                                                        |
|      | IX21-1-E3D8  | 230                                  | 23      | 8.33E-06                        | 24            | 11         | 1.64            | 0.032170             | 0.092      | <b>0.0005</b>                                                | 0.0473      | <b>0.0008</b>                                                 | 1.008       | <b>0.0008</b>                                                 | 0.0746     | <b>0.0008</b>                                                | 0.1575      | <b>0.0002</b>                                                 |
|      | IX21-1-E3D9  | 230                                  | 23      | 8.33E-06                        | 27            | 11         | 1.64            | 0.032169             | 0.081      | <b>0.0005</b>                                                | 0.0431      | <b>0.0008</b>                                                 | 0.965       | <b>0.0008</b>                                                 | 0.0672     | <b>0.0007</b>                                                | 0.1554      | <b>0.0003</b>                                                 |
|      | IX21-1-E3D10 | 230                                  | 23      | 8.33E-06                        | 30            | 11         | 1.64            | 0.032168             | 0.066      | <b>0.0004</b>                                                | 0.0368      | <b>0.0006</b>                                                 | 0.900       | <b>0.0006</b>                                                 | 0.0725     | <b>0.0009</b>                                                | 0.1428      | <b>0.0001</b>                                                 |

Table A4. DCP-AES Analysis Results from Dissolution of Glass IDFIX21-2at 70°C.

| Exp. | Sample ID    | Target [Si] <sub>inf</sub> ppm | T °C | Flow Rate, m <sup>3</sup> /d | Time, days | pH 23°C | Glass Mass g | SA m <sup>2</sup> | [B] ppm | B Rate g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [Li] ppm | Li Rate g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [Na] ppm | Na Rate g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [K] ppm | K Rate g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [Al] ppm | Al Rate g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> |
|------|--------------|--------------------------------|------|------------------------------|------------|---------|--------------|-------------------|---------|-----------------------------------------------------------|----------|------------------------------------------------------------|----------|------------------------------------------------------------|---------|-----------------------------------------------------------|----------|------------------------------------------------------------|
| 1    | IX21-2-A1D1  | 55                             | 70   | 2.50E-05                     | 1          | 7       | 0.77         | 0.01508           | 1.111   | 0.1182                                                    | 0.8064   | 0.1498                                                     | 3.1869   | <b>0.1400</b>                                              | 0.3277  | 0.0402                                                    | 0.1467   | 0.0127                                                     |
|      | IX21-2-A1D2  | 55                             | 70   | 2.50E-05                     | 2          | 7       | 0.77         | 0.01507           | 0.972   | 0.0443                                                    | 0.6607   | 0.0479                                                     | 2.6098   | 0.0437                                                     | 0.2622  | 0.0114                                                    | 0.0747   | -0.0010                                                    |
|      | IX21-2-A1D3  | 55                             | 70   | 2.50E-05                     | 3          | 7       | 0.77         | 0.01506           | 0.924   | 0.0466                                                    | 0.5855   | 0.0475                                                     | 2.3652   | 0.0457                                                     | 0.2444  | 0.0134                                                    | 0.0828   | 0.0035                                                     |
|      | IX21-2-A1D4  | 55                             | 70   | 2.50E-05                     | 4          | 7       | 0.77         | 0.01505           | 0.887   | 0.0453                                                    | 0.5417   | 0.0463                                                     | 2.2344   | 0.0454                                                     | 0.3707  | 0.0314                                                    | 0.0962   | 0.0045                                                     |
|      | IX21-2-A1D5  | 55                             | 70   | 2.50E-05                     | 5          | 7       | 0.77         | 0.01504           | 0.816   | 0.0396                                                    | 0.4877   | 0.0404                                                     | 2.0058   | 0.0379                                                     | 0.2205  | 0.0030                                                    | 0.0850   | 0.0026                                                     |
|      | IX21-2-A1D6  | 55                             | 70   | 2.50E-05                     | 6          | 7       | 0.77         | 0.01503           | 0.802   | 0.0420                                                    | 0.4781   | 0.0436                                                     | 1.9621   | 0.0412                                                     | 0.2911  | 0.0224                                                    | 0.1049   | 0.0052                                                     |
|      | IX21-2-A1D7  | 55                             | 70   | 2.50E-05                     | 7          | 7       | 0.77         | 0.01503           | 0.762   | 0.0385                                                    | 0.4515   | 0.0396                                                     | 1.8347   | 0.0363                                                     | 0.1993  | 0.0055                                                    | 0.0875   | 0.0024                                                     |
|      | IX21-2-A1D8  | 55                             | 70   | 2.50E-05                     | 8          | 7       | 0.77         | 0.01502           | 0.702   | <b>0.0342</b>                                             | 0.4116   | <b>0.0346</b>                                              | 1.7026   | <b>0.0332</b>                                              | 0.1841  | <b>0.0096</b>                                             | 0.0757   | <b>0.0021</b>                                              |
|      | IX21-2-A1D9  | 55                             | 70   | 2.50E-05                     | 9          | 7       | 0.77         | 0.01501           | 0.670   | <b>0.0341</b>                                             | 0.3868   | <b>0.0338</b>                                              | 1.6122   | <b>0.0321</b>                                              | 0.1776  | <b>0.0097</b>                                             | 0.0774   | <b>0.0029</b>                                              |
|      | IX21-2-A1D10 | 55                             | 70   | 2.50E-05                     | 10         | 7       | 0.77         | 0.01500           | 0.655   | <b>0.0341</b>                                             | 0.3788   | <b>0.0346</b>                                              | 1.6030   | <b>0.0338</b>                                              | 0.1791  | <b>0.0104</b>                                             | 0.0772   | <b>0.0028</b>                                              |
| 2    | IX21-2-B1D1  | 60                             | 70   | 2.50E-05                     | 1          | 8       | 0.77         | 0.01509           | 0.481   | 0.0510                                                    | 0.4667   | 0.0867                                                     | 1.8503   | 0.0789                                                     | 0.1585  | 0.0567                                                    | 0.0883   | 0.0064                                                     |
|      | IX21-2-B1D2  | 60                             | 70   | 2.50E-05                     | 2          | 8       | 0.77         | 0.01508           | 0.397   | 0.0166                                                    | 0.3531   | 0.0222                                                     | 1.4418   | 0.0208                                                     | 0.1304  | 0.0171                                                    | 0.1185   | 0.0063                                                     |
|      | IX21-2-B1D3  | 60                             | 70   | 2.50E-05                     | 3          | 8       | 0.77         | 0.01508           | 0.360   | 0.0171                                                    | 0.2839   | 0.0199                                                     | 1.2379   | 0.0208                                                     | 0.1259  | 0.0210                                                    | 0.1244   | 0.0053                                                     |
|      | IX21-2-B1D4  | 60                             | 70   | 2.50E-05                     | 4          | 8       | 0.77         | 0.01507           | 0.325   | 0.0153                                                    | 0.2406   | 0.0183                                                     | 1.0581   | 0.0173                                                     | 0.1100  | 0.0155                                                    | 0.1195   | 0.0045                                                     |
|      | IX21-2-B1D5  | 60                             | 70   | 2.50E-05                     | 5          | 8       | 0.77         | 0.01507           | 0.278   | 0.0121                                                    | 0.1942   | 0.0137                                                     | 0.8831   | 0.0134                                                     | 0.0917  | <b>0.0114</b>                                             | 0.1142   | 0.0042                                                     |
|      | IX21-2-B1D6  | 60                             | 70   | 2.50E-05                     | 6          | 8       | 0.77         | 0.01507           | 0.279   | 0.0148                                                    | 0.1840   | 0.0161                                                     | 0.8400   | 0.0154                                                     | 0.0842  | <b>0.0120</b>                                             | 0.1213   | 0.0053                                                     |
|      | IX21-2-B1D7  | 60                             | 70   | 2.50E-05                     | 7          | 8       | 0.77         | 0.01506           | 0.294   | 0.0163                                                    | 0.1896   | 0.0181                                                     | 0.8739   | 0.0180                                                     | 0.1119  | <i>0.0246</i>                                             | 0.1539   | 0.0082                                                     |
|      | IX21-2-B1D8  | 60                             | 70   | 2.50E-05                     | 8          | 8       | 0.77         | 0.01506           | 0.262   | <b>0.0121</b>                                             | 0.1668   | <b>0.0134</b>                                              | 0.7773   | <b>0.0128</b>                                              | 0.0879  | <b>0.0095</b>                                             | 0.1176   | <b>0.0028</b>                                              |
|      | IX21-2-B1D9  | 60                             | 70   | 2.50E-05                     | 9          | 8       | 0.77         | 0.01506           | 0.231   | <b>0.0105</b>                                             | 0.1464   | <b>0.0117</b>                                              | 0.7082   | <b>0.0118</b>                                              | 0.0758  | <b>0.0094</b>                                             | 0.0995   | <b>0.0028</b>                                              |
|      | IX21-2-B1D10 | 60                             | 70   | 2.50E-05                     | 10         | 8       | 0.77         | 0.01506           | 0.245   | <b>0.0137</b>                                             | 0.1541   | <b>0.0150</b>                                              | 0.7353   | <b>0.0146</b>                                              | 0.0921  | <i>0.0184</i>                                             | 0.1184   | <b>0.0057</b>                                              |
| 3    | IX21-2-C1D1  | 80                             | 70   | 2.50E-05                     | 1          | 9       | 0.77         | 0.01509           | 0.390   | 0.0413                                                    | 0.3947   | 0.0733                                                     | 1.6130   | 0.0674                                                     | 0.1307  | 0.0484                                                    | 0.1373   | 0.0107                                                     |
|      | IX21-2-C1D2  | 80                             | 70   | 2.50E-05                     | 2          | 9       | 0.77         | 0.01508           | 0.334   | 0.0146                                                    | 0.3027   | 0.0196                                                     | 1.2817   | 0.0186                                                     | 0.1204  | 0.0201                                                    | 0.1419   | 0.0058                                                     |
|      | IX21-2-C1D3  | 80                             | 70   | 2.50E-05                     | 3          | 9       | 0.77         | 0.01508           | 0.304   | 0.0145                                                    | 0.2501   | 0.0183                                                     | 1.0853   | 0.0172                                                     | 0.1003  | 0.0141                                                    | 0.1452   | 0.0059                                                     |
|      | IX21-2-C1D4  | 80                             | 70   | 2.50E-05                     | 4          | 9       | 0.77         | 0.01508           | 0.297   | 0.0153                                                    | 0.2255   | 0.0186                                                     | 0.9975   | 0.0177                                                     | 0.1101  | 0.0221                                                    | 0.1578   | 0.0071                                                     |
|      | IX21-2-C1D5  | 80                             | 70   | 2.50E-05                     | 5          | 9       | 0.77         | 0.01507           | 0.271   | 0.0129                                                    | 0.1966   | 0.0156                                                     | 0.8963   | 0.0150                                                     | 0.0870  | 0.0109                                                    | 0.1543   | 0.0060                                                     |
|      | IX21-2-C1D6  | 80                             | 70   | 2.50E-05                     | 6          | 9       | 0.77         | 0.01507           | 0.275   | <b>0.0147</b>                                             | 0.1892   | 0.0169                                                     | 0.8698   | 0.0162                                                     | 0.0837  | 0.0142                                                    | 0.1596   | 0.0068                                                     |
|      | IX21-2-C1D7  | 80                             | 70   | 2.50E-05                     | 7          | 9       | 0.77         | 0.01507           | 0.278   | <b>0.0148</b>                                             | 0.1850   | <b>0.0168</b>                                              | 0.8496   | <b>0.0158</b>                                              | 0.0950  | <b>0.0194</b>                                             | 0.1604   | <b>0.0066</b>                                              |
|      | IX21-2-C1D8  | 80                             | 70   | 2.50E-05                     | 8          | 9       | 0.77         | 0.01506           | 0.280   | <b>0.0149</b>                                             | 0.1887   | <b>0.0179</b>                                              | 0.8959   | <b>0.0184</b>                                              | 0.1203  | <i>0.0272</i>                                             | 0.1759   | <b>0.0081</b>                                              |
|      | IX21-2-C1D9  | 80                             | 70   | 2.50E-05                     | 9          | 9       | 0.77         | 0.01506           | 0.242   | <b>0.0107</b>                                             | 0.1641   | <b>0.0129</b>                                              | 0.7938   | <b>0.0127</b>                                              | 0.0897  | <b>0.0099</b>                                             | 0.1466   | <b>0.0043</b>                                              |
|      | IX21-2-C1D10 | 80                             | 70   | 2.50E-05                     | 10         | 9       | 0.77         | 0.01506           | 0.311   | <i>0.0201</i>                                             | 0.1920   | <i>0.0204</i>                                              | 0.9056   | <i>0.0201</i>                                              | 0.1007  | <b>0.0204</b>                                             | 0.2012   | <i>0.0115</i>                                              |
| 4    | IX21-2-D1D1  | 140                            | 70   | 2.50E-05                     | 1          | 10      | 0.50         | 0.00970           | 0.136   | 0.0221                                                    | 0.1637   | 0.0470                                                     | 0.8396   | 0.0404                                                     | 0.0624  | 0.0240                                                    | 0.0951   | 0.0058                                                     |
|      | IX21-2-D1D2  | 140                            | 70   | 2.50E-05                     | 2          | 10      | 0.50         | 0.00970           | 0.102   | 0.0053                                                    | 0.1223   | 0.0115                                                     | 0.6853   | 0.0092                                                     | 0.0440  | 0.0006                                                    | 0.0974   | 0.0033                                                     |
|      | IX21-2-D1D3  | 140                            | 70   | 2.50E-05                     | 3          | 10      | 0.50         | 0.00970           | 0.078   | 0.0043                                                    | 0.0965   | 0.0101                                                     | 0.5976   | 0.0085                                                     | 0.0371  | 0.0020                                                    | 0.0845   | 0.0010                                                     |
|      | IX21-2-D1D4  | 140                            | 70   | 2.50E-05                     | 4          | 10      | 0.50         | 0.00970           | 0.054   | 0.0022                                                    | 0.0703   | 0.0062                                                     | 0.4928   | 0.0042                                                     | 0.0306  | 0.0001                                                    | 0.0759   | 0.0007                                                     |
|      | IX21-2-D1D5  | 140                            | 70   | 2.50E-05                     | 5          | 10      | 0.50         | 0.00970           | 0.043   | 0.0024                                                    | 0.0583   | 0.0065                                                     | 0.4555   | 0.0052                                                     | 0.0299  | 0.0017                                                    | 0.0743   | 0.0011                                                     |
|      | IX21-2-D1D6  | 140                            | 70   | 2.50E-05                     | 6          | 10      | 0.50         | 0.00970           | 0.026   | 0.0005                                                    | 0.0460   | 0.0047                                                     | 0.4100   | 0.0033                                                     | 0.0230  | <i>-0.0024</i>                                            | 0.0650   | -0.0002                                                    |
|      | IX21-2-D1D7  | 140                            | 70   | 2.50E-05                     | 7          | 10      | 0.50         | 0.00970           | 0.019   | 0.0008                                                    | 0.0366   | 0.0038                                                     | 0.3667   | 0.0019                                                     | 0.0214  | <i>-0.0012</i>                                            | 0.0649   | <b>0.0005</b>                                              |
|      | IX21-2-D1D8  | 140                            | 70   | 2.50E-05                     | 8          | 10      | 0.50         | 0.00970           | 0.020   | <b>0.0014</b>                                             | 0.0352   | <b>0.0047</b>                                              | 0.3765   | <i>0.0041</i>                                              | 0.0242  | 0.0010                                                    | 0.0664   | <b>0.0007</b>                                              |
|      | IX21-2-D1D9  | 140                            | 70   | 2.50E-05                     | 9          | 10      | 0.50         | 0.00970           | 0.013   | <b>0.0003</b>                                             | 0.0298   | <b>0.0034</b>                                              | 0.3549   | <b>0.0022</b>                                              | 0.0199  | <i>-0.0025</i>                                            | 0.0595   | -0.0005                                                    |
|      | IX21-2-D1D10 | 140                            | 70   | 2.50E-05                     | 10         | 10      | 0.50         | 0.00969           | 0.012   | <b>0.0006</b>                                             | 0.0274   | <b>0.0034</b>                                              | 0.3461   | <b>0.0024</b>                                              | 0.0439  | 0.0137                                                    | 0.0622   | <b>0.0005</b>                                              |
| 5    | IX21-2-E1D1  | 360                            | 70   | 2.50E-05                     | 1          | 11      | 0.50         | 0.00970           | 0.100   | 0.0161                                                    | 0.1399   | 0.0352                                                     | 1.534    | 0.0444                                                     | 0.0930  | 0.0099                                                    | 0.1260   | 0.0015                                                     |
|      | IX21-2-E1D2  | 360                            | 70   | 2.50E-05                     | 2          | 11      | 0.50         | 0.00970           | 0.064   | 0.0020                                                    | 0.1263   | 0.0137                                                     | 1.451    | 0.0163                                                     | 0.0760  | 0.0014                                                    | 0.1199   | -0.0002                                                    |
|      | IX21-2-E1D3  | 360                            | 70   | 2.50E-05                     | 3          | 11      | 0.50         | 0.00970           | 0.040   | 0.0010                                                    | 0.1033   | 0.0090                                                     | 1.316    | 0.0097                                                     | 0.0642  | 0.0007                                                    | 0.1117   | -0.0011                                                    |
|      | IX21-2-E1D4  | 360                            | 70   | 2.50E-05                     | 4          | 11      | 0.50         | 0.00970           | 0.027   | 0.0009                                                    | 0.0851   | 0.0070                                                     | 1.217    | 0.0074                                                     | 0.0579  | 0.0006                                                    | 0.1017   | -0.0020                                                    |
|      | IX21-2-E1D5  | 360                            | 70   | 2.50E-05                     | 5          | 11      | 0.50         | 0.00970           | 0.013   | -0.0003                                                   | 0.0732   | 0.0062                                                     | 1.143    | 0.0057                                                     | 0.0527  | 0.0002                                                    | 0.0992   | -0.0016                                                    |
|      | IX21-2-E1D6  | 360                            | 70   | 2.50E-05                     | 6          | 11      | 0.50         | 0.00970           | 0.010   | 0.0003                                                    | 0.0688   | 0.0067                                                     | 1.162    | 0.0097                                                     | 0.0470  | -0.0004                                                   | 0.0965   | -0.0018                                                    |
|      | IX21-2-E1D7  | 360                            | 70   | 2.50E-05                     | 7          | 11      | 0.50         | 0.00970           | 0.006   | -0.0001                                                   | 0.0636   | <b>0.0058</b>                                              | 1.126    | <b>0.0064</b>                                              | 0.0458  | -0.0001                                                   | 0.0956   | -0.0018                                                    |
|      | IX21-2-E1D8  | 360                            | 70   | 2.50E-05                     | 8          | 11      | 0.50         | 0.00970           | 0.001   | -0.0007                                                   | 0.0611   | <b>0.0058</b>                                              | 1.147    | <b>0.0092</b>                                              | 0.0531  | <b>0.0016</b>                                             | 0.0923   | -0.0022                                                    |
|      | IX21-2-E1D9  | 360                            | 70   | 2.50E-05                     | 9          | 11      | 0.50         | 0.00970           | 0.026   | 0.0040                                                    | 0.0570   | <b>0.0050</b>                                              | 1.113    | <b>0.0061</b>                                              | 0.0564  | <b>0.0015</b>                                             | 0.1183   | 0.0022                                                     |
|      | IX21-2-E1D10 | 360                            | 70   | 2.50E-05                     | 10         | 11      | 0.50         | 0.00970           | 0.008   | -0.0011                                                   | 0.0650   | <i>0.0079</i>                                              | 1.170    | <i>0.0113</i>                                              | 0.0620  | <b>0.0023</b>                                             | 0.1056   | -0.0019                                                    |

Table A5. DCP-AES Analysis Results from Dissolution of Glass IDFIX21-2 at 40°C.

| Exp. | Sample ID    | Target<br>[Si] <sub>inf</sub><br>ppm | T<br>°C | Flow Rate,<br>m <sup>3</sup> /d | Time,<br>days | pH<br>23°C | Glass<br>Mass g | SA<br>m <sup>2</sup> | [B]<br>ppm | B Rate<br>g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [Li]<br>ppm   | Li Rate<br>g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [Na]<br>ppm  | Na Rate<br>g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [K]<br>ppm    | K Rate<br>g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [Al]<br>ppm   | Al Rate<br>g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> |
|------|--------------|--------------------------------------|---------|---------------------------------|---------------|------------|-----------------|----------------------|------------|--------------------------------------------------------------|---------------|---------------------------------------------------------------|--------------|---------------------------------------------------------------|---------------|--------------------------------------------------------------|---------------|---------------------------------------------------------------|
| 1    | IX21-2-A2D1  | 40                                   | 40      | 8.33E-06                        | 3             | 7          | 1.65            | 0.0323               | 0.625      | 0.0103                                                       | 0.5910        | 0.0170                                                        | 2.3950       | <b>0.0164</b>                                                 | 0.1920        | 0.0113                                                       | 0.0480        | 0.0004                                                        |
|      | IX21-2-A2D2  | 40                                   | 40      | 8.33E-06                        | 6             | 7          | 1.65            | 0.0323               | 0.476      | 0.0027                                                       | 0.4240        | 0.0037                                                        | 1.6940       | 0.0032                                                        | 0.1380        | 0.0023                                                       | 0.0410        | 0.0001                                                        |
|      | IX21-2-A2D3  | 40                                   | 40      | 8.33E-06                        | 9             | 7          | 1.65            | 0.0323               | 0.371      | 0.0022                                                       | 0.3140        | 0.0029                                                        | 1.2470       | 0.0025                                                        | 0.1080        | 0.0021                                                       | 0.0460        | 0.0002                                                        |
|      | IX21-2-A2D4  | 40                                   | 40      | 8.33E-06                        | 12            | 7          | 1.65            | 0.0323               | 0.311      | 0.0021                                                       | 0.2430        | 0.0024                                                        | 0.9970       | 0.0024                                                        | 0.0930        | 0.0021                                                       | 0.0610        | 0.0004                                                        |
|      | IX21-2-A2D5  | 40                                   | 40      | 8.33E-06                        | 15            | 7          | 1.65            | 0.0323               | 0.265      | 0.0018                                                       | 0.1970        | 0.0021                                                        | 0.8150       | 0.0020                                                        | 0.0780        | 0.0016                                                       | 0.0430        | 0.0000                                                        |
|      | IX21-2-A2D6  | 40                                   | 40      | 8.33E-06                        | 18            | 7          | 1.65            | 0.0323               | 0.241      | 0.0018                                                       | 0.1710        | 0.0020                                                        | 0.7200       | 0.0019                                                        | 0.0710        | 0.0017                                                       | 0.0610        | 0.0005                                                        |
|      | IX21-2-A2D7  | 40                                   | 40      | 8.33E-06                        | 21            | 7          | 1.65            | 0.0323               | 0.250      | 0.0021                                                       | 0.1670        | 0.0023                                                        | 0.7100       | 0.0022                                                        | 0.0710        | 0.0019                                                       | 0.0900        | 0.0008                                                        |
|      | IX21-2-A2D8  | 40                                   | 40      | 8.33E-06                        | 24            | 7          | 1.65            | 0.0323               | 0.192      | <b>0.0011</b>                                                | 0.1270        | <b>0.0012</b>                                                 | 0.5590       | <b>0.0012</b>                                                 | 0.0580        | <b>0.0011</b>                                                | 0.0410        | -0.0002                                                       |
|      | IX21-2-A2D9  | 40                                   | 40      | 8.33E-06                        | 27            | 7          | 1.65            | 0.0323               | 0.188      | <b>0.0015</b>                                                | 0.1220        | <b>0.0016</b>                                                 | 0.5440       | <b>0.0016</b>                                                 | 0.0570        | <b>0.0014</b>                                                | 0.0530        | 0.0003                                                        |
|      | IX21-2-A2D10 | 40                                   | 40      | 8.33E-06                        | 30            | 7          | 1.65            | 0.0323               | 0.173      | <b>0.0013</b>                                                | 0.1120        | <b>0.0014</b>                                                 | 0.5040       | <b>0.0014</b>                                                 | 0.0560        | <b>0.0014</b>                                                | 0.0410        | 0.0001                                                        |
| 2    | IX21-2-B2D1  | 45                                   | 40      | 8.33E-06                        | 3             | 8          | 1.65            | 0.0323               | 0.394      | 0.0065                                                       | 0.4490        | 0.0129                                                        | 1.8620       | 0.0126                                                        | 0.1380        | 0.0081                                                       | 0.0800        | 0.0010                                                        |
|      | IX21-2-B2D2  | 45                                   | 40      | 8.33E-06                        | 6             | 8          | 1.65            | 0.0323               | 0.311      | 0.0019                                                       | 0.3450        | 0.0034                                                        | 1.3880       | 0.0030                                                        | 0.1050        | 0.0020                                                       | 0.0700        | 0.0003                                                        |
|      | IX21-2-B2D3  | 45                                   | 40      | 8.33E-06                        | 9             | 8          | 1.65            | 0.0323               | 0.235      | 0.0013                                                       | 0.2450        | 0.0020                                                        | 1.0000       | 0.0019                                                        | 0.0790        | 0.0014                                                       | 0.0700        | 0.0004                                                        |
|      | IX21-2-B2D4  | 45                                   | 40      | 8.33E-06                        | 12            | 8          | 1.65            | 0.0323               | 0.185      | 0.0011                                                       | 0.1830        | 0.0017                                                        | 0.7640       | 0.0016                                                        | 0.0640        | 0.0013                                                       | 0.0760        | 0.0005                                                        |
|      | IX21-2-B2D5  | 45                                   | 40      | 8.33E-06                        | 15            | 8          | 1.65            | 0.0323               | 0.140      | 0.0008                                                       | 0.1410        | 0.0014                                                        | 0.6100       | 0.0013                                                        | 0.0520        | 0.0010                                                       | 0.0540        | 0.0001                                                        |
|      | IX21-2-B2D6  | 45                                   | 40      | 8.33E-06                        | 18            | 8          | 1.65            | 0.0323               | 0.117      | 0.0008                                                       | 0.1140        | 0.0012                                                        | 0.5150       | 0.0012                                                        | 0.0500        | 0.0013                                                       | 0.0500        | 0.0002                                                        |
|      | IX21-2-B2D7  | 45                                   | 40      | 8.33E-06                        | 21            | 8          | 1.65            | 0.0323               | 0.105      | <b>0.0007</b>                                                | 0.1000        | <b>0.0012</b>                                                 | 0.4540       | <b>0.0011</b>                                                 | 0.0420        | <b>0.0008</b>                                                | 0.0560        | <b>0.0003</b>                                                 |
|      | IX21-2-B2D8  | 45                                   | 40      | 8.33E-06                        | 24            | 8          | 1.65            | 0.0323               | 0.089      | <b>0.0006</b>                                                | 0.0850        | <b>0.0010</b>                                                 | 0.4050       | <b>0.0010</b>                                                 | 0.0430        | <b>0.0011</b>                                                | 0.0510        | <b>0.0002</b>                                                 |
|      | IX21-2-B2D9  | 45                                   | 40      | 8.33E-06                        | 27            | 8          | 1.65            | 0.0323               | 0.091      | <b>0.0007</b>                                                | 0.0820        | <b>0.0011</b>                                                 | 0.4020       | <b>0.0011</b>                                                 | 0.0420        | <b>0.0010</b>                                                | 0.0550        | <b>0.0003</b>                                                 |
|      | IX21-2-B2D10 | 45                                   | 40      | 8.33E-06                        | 30            | 8          | 1.65            | 0.0323               | 0.126      | <i>0.0013</i>                                                | 0.1060        | <i>0.0018</i>                                                 | 0.5020       | <i>0.0018</i>                                                 | 0.0500        | <i>0.0016</i>                                                | 0.0700        | <i>0.0005</i>                                                 |
| 3    | IX21-2-C2D1  | 60                                   | 40      | 8.33E-06                        | 3             | 9          | 1.65            | 0.0323               | 0.310      | 0.0051                                                       | 0.3620        | 0.0104                                                        | 1.5420       | 0.0102                                                        | 0.1010        | 0.0059                                                       | 0.0820        | 0.0009                                                        |
|      | IX21-2-C2D2  | 60                                   | 40      | 8.33E-06                        | 6             | 9          | 1.65            | 0.0323               | 0.246      | 0.0015                                                       | 0.2680        | 0.0025                                                        | 1.1470       | 0.0023                                                        | 0.0770        | 0.0015                                                       | 0.0650        | 0.0002                                                        |
|      | IX21-2-C2D3  | 60                                   | 40      | 8.33E-06                        | 9             | 9          | 1.65            | 0.0323               | 0.180      | 0.0009                                                       | 0.1940        | 0.0017                                                        | 0.8560       | 0.0016                                                        | 0.0710        | 0.0018                                                       | 0.0390        | -0.0001                                                       |
|      | IX21-2-C2D4  | 60                                   | 40      | 8.33E-06                        | 12            | 9          | 1.65            | 0.0323               | 0.139      | 0.0008                                                       | 0.1470        | 0.0014                                                        | 0.6690       | 0.0013                                                        | 0.0540        | 0.0010                                                       | 0.0740        | 0.0004                                                        |
|      | IX21-2-C2D5  | 60                                   | 40      | 8.33E-06                        | 15            | 9          | 1.65            | 0.0323               | 0.115      | 0.0007                                                       | 0.1170        | 0.0012                                                        | 0.5810       | 0.0014                                                        | 0.0550        | 0.0016                                                       | 0.0540        | 0.0000                                                        |
|      | IX21-2-C2D6  | 60                                   | 40      | 8.33E-06                        | 18            | 9          | 1.65            | 0.0323               | 0.089      | 0.0005                                                       | 0.0910        | 0.0009                                                        | 0.4590       | 0.0008                                                        | 0.0390        | 0.0005                                                       | 0.0440        | 0.0000                                                        |
|      | IX21-2-C2D7  | 60                                   | 40      | 8.33E-06                        | 21            | 9          | 1.65            | 0.0323               | 0.071      | 0.0004                                                       | 0.0770        | 0.0009                                                        | 0.3990       | 0.0008                                                        | 0.0340        | 0.0007                                                       | 0.0440        | 0.0001                                                        |
|      | IX21-2-C2D8  | 60                                   | 40      | 8.33E-06                        | 24            | 9          | 1.65            | 0.0323               | 0.058      | <b>0.0003</b>                                                | 0.0660        | <b>0.0007</b>                                                 | 0.3530       | <b>0.0007</b>                                                 | 0.0250        | <b>0.0003</b>                                                | 0.0280        | -0.0001                                                       |
|      | IX21-2-C2D9  | 60                                   | 40      | 8.33E-06                        | 27            | 9          | 1.65            | 0.0323               | 0.051      | <b>0.0003</b>                                                | 0.0590        | <b>0.0007</b>                                                 | 0.3270       | <b>0.0007</b>                                                 | 0.0240        | <b>0.0005</b>                                                | 0.0350        | <b>0.0001</b>                                                 |
|      | IX21-2-C2D10 | 60                                   | 40      | 8.33E-06                        | 30            | 9          | 1.65            | 0.0323               | 0.047      | <b>0.0003</b>                                                | 0.0550        | <b>0.0007</b>                                                 | 0.3250       | <b>0.0008</b>                                                 | 0.0310        | <b>0.0010</b>                                                | 0.0430        | <b>0.0001</b>                                                 |
| 4    | IX21-2-D2D1  | 105                                  | 40      | 8.33E-06                        | 3             | 10         | 0.826           | 0.0162               | 0.116      | 0.0037                                                       | 0.1450        | 0.0082                                                        | 0.7610       | 0.0081                                                        | 0.0460        | 0.0047                                                       | 0.1020        | 0.0018                                                        |
|      | IX21-2-D2D2  | 105                                  | 40      | 8.33E-06                        | 6             | 10         | 0.826           | 0.0162               | 0.091      | 0.0010                                                       | 0.1130        | 0.0022                                                        | 0.6160       | 0.0020                                                        | 0.0380        | 0.0014                                                       | 0.0810        | 0.0002                                                        |
|      | IX21-2-D2D3  | 105                                  | 40      | 8.33E-06                        | 9             | 10         | 0.826           | 0.0162               | 0.065      | 0.0006                                                       | 0.0810        | 0.0013                                                        | 0.4950       | 0.0013                                                        | 0.0320        | 0.0011                                                       | 0.0690        | 0.0002                                                        |
|      | IX21-2-D2D4  | 105                                  | 40      | 8.33E-06                        | 12            | 10         | 0.826           | 0.0162               | 0.042      | 0.0003                                                       | 0.0600        | 0.0010                                                        | 0.4000       | 0.0008                                                        | 0.0250        | 0.0006                                                       | 0.0620        | 0.0001                                                        |
|      | IX21-2-D2D5  | 105                                  | 40      | 8.33E-06                        | 15            | 10         | 0.826           | 0.0162               | 0.032      | 0.0003                                                       | 0.0470        | 0.0009                                                        | 0.3470       | 0.0008                                                        | 0.0200        | 0.0004                                                       | 0.0660        | 0.0004                                                        |
|      | IX21-2-D2D6  | 105                                  | 40      | 8.33E-06                        | 18            | 10         | 0.826           | 0.0162               | 0.026      | 0.0003                                                       | 0.0410        | 0.0009                                                        | 0.3290       | 0.0009                                                        | 0.0190        | 0.0006                                                       | 0.0630        | 0.0002                                                        |
|      | IX21-2-D2D7  | 105                                  | 40      | 8.33E-06                        | 21            | 10         | 0.826           | 0.0162               | 0.014      | <b>0.0000</b>                                                | 0.0310        | <b>0.0005</b>                                                 | 0.2880       | <b>0.0004</b>                                                 | 0.0160        | <b>0.0003</b>                                                | 0.0560        | 0.0000                                                        |
|      | IX21-2-D2D8  | 105                                  | 40      | 8.33E-06                        | 24            | 10         | 0.826           | 0.0162               | 0.009      | <b>0.0000</b>                                                | 0.0270        | <b>0.0006</b>                                                 | 0.2770       | <b>0.0006</b>                                                 | 0.0160        | <b>0.0005</b>                                                | 0.0490        | -0.0001                                                       |
|      | IX21-2-D2D9  | 105                                  | 40      | 8.33E-06                        | 27            | 10         | 0.826           | 0.0162               | 0.008      | <b>0.0001</b>                                                | 0.0260        | <b>0.0006</b>                                                 | 0.2730       | <b>0.0006</b>                                                 | 0.0160        | <b>0.0005</b>                                                | 0.0550        | 0.0002                                                        |
|      | IX21-2-D2D10 | 105                                  | 40      | 8.33E-06                        | 30            | 10         | 0.826           | 0.0162               | 0.003      | -0.0001                                                      | 0.0220        | <i>0.0004</i>                                                 | 0.2580       | <i>0.0004</i>                                                 | 0.0370        | <i>0.0031</i>                                                | 0.0440        | -0.0002                                                       |
| 5    | IX21-2-E2D1  | 270                                  | 40      | 8.33E-06                        | 3             | 11         | 0.826           | 0.01619              | 0.161      | 0.0052                                                       | 0.1649        | 0.0093                                                        | 1.395        | 0.0106                                                        | 0.0693        | 0.0060                                                       | 0.2762        | 0.0060                                                        |
|      | IX21-2-E2D2  | 270                                  | 40      | 8.33E-06                        | 6             | 11         | 0.826           | 0.01618              | 0.173      | 0.0030                                                       | 0.1596        | 0.0044                                                        | 1.386        | 0.0052                                                        | 0.0767        | 0.0039                                                       | 0.1953        | 0.0004                                                        |
|      | IX21-2-E2D3  | 270                                  | 40      | 8.33E-06                        | 9             | 11         | 0.826           | 0.01618              | 0.156      | 0.0023                                                       | 0.1376        | 0.0032                                                        | 1.314        | 0.0042                                                        | 0.0693        | 0.0025                                                       | 0.1691        | 0.0005                                                        |
|      | IX21-2-E2D4  | 270                                  | 40      | 8.33E-06                        | 12            | 11         | 0.826           | 0.01618              | 0.155      | 0.0025                                                       | 0.1271        | 0.0033                                                        | 1.264        | 0.0040                                                        | 0.0788        | 0.0042                                                       | 0.1764        | 0.0009                                                        |
|      | IX21-2-E2D5  | 270                                  | 40      | 8.33E-06                        | 15            | 11         | 0.826           | 0.01618              | 0.139      | 0.0020                                                       | 0.1124        | 0.0027                                                        | 1.290        | 0.0047                                                        | 0.0683        | 0.0023                                                       | 0.1565        | 0.0005                                                        |
|      | IX21-2-E2D6  | 270                                  | 40      | 8.33E-06                        | 18            | 11         | 0.826           | 0.01618              | 0.114      | <b>0.0014</b>                                                | 0.0914        | <b>0.0019</b>                                                 | 1.149        | <b>0.0025</b>                                                 | 0.0567        | <b>0.0015</b>                                                | 0.1407        | <b>0.0003</b>                                                 |
|      | IX21-2-E2D7  | 270                                  | 40      | 8.33E-06                        | 21            | 11         | 0.826           | 0.01618              | 0.100      | <b>0.0014</b>                                                | 0.0798        | <b>0.0019</b>                                                 | 1.079        | <b>0.0026</b>                                                 | 0.0473        | <b>0.0010</b>                                                | 0.1323        | <b>0.0003</b>                                                 |
|      | IX21-2-E2D8  | 270                                  | 40      | 8.33E-06                        | 24            | 11         | 0.826           | 0.01618              | 0.084      | <b>0.0011</b>                                                | 0.0704        | <b>0.0017</b>                                                 | 1.052        | <b>0.0027</b>                                                 | 0.0431        | <b>0.0011</b>                                                | 0.1208        | <b>0.0002</b>                                                 |
|      | IX21-2-E2D9  | 270                                  | 40      | 8.33E-06                        | 27            | 11         | 0.826           | 0.01617              | 0.065      | <i>0.0007</i>                                                | <i>0.0546</i> | <i>0.0010</i>                                                 | <i>0.925</i> | <i>0.0011</i>                                                 | <i>0.0368</i> | <i>0.0006</i>                                                | <i>0.1040</i> | <i>0.0000</i>                                                 |
|      | IX21-2-E2D10 | 270                                  | 40      | 8.33E-06                        | 30            | 11         | 0.826           | 0.01617              | 0.063      | <i>0.0010</i>                                                | <i>0.0546</i> | <i>0.0015</i>                                                 | <i>0.998</i> | <i>0.0030</i>                                                 | <i>0.0420</i> | <i>0.0016</i>                                                | <i>0.1061</i> | <i>0.0002</i>                                                 |

Table A6. DCP-AES Analysis Results from Dissolution of Glass IDFIX21-2 at 23 °C.

| Exp. | Sample ID    | Target<br>[Si] <sub>inf</sub><br>ppm | T<br>°C | Flow Rate,<br>m <sup>3</sup> /d | Time,<br>days | pH<br>23°C | Glass<br>Mass g | SA<br>m <sup>2</sup> | [B]<br>ppm | B Rate<br>g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [Li]<br>ppm | Li Rate<br>g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [Na]<br>ppm | Na Rate<br>g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [K]<br>ppm | K Rate<br>g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [Al]<br>ppm | Al Rate<br>g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> |
|------|--------------|--------------------------------------|---------|---------------------------------|---------------|------------|-----------------|----------------------|------------|--------------------------------------------------------------|-------------|---------------------------------------------------------------|-------------|---------------------------------------------------------------|------------|--------------------------------------------------------------|-------------|---------------------------------------------------------------|
| 1    | IX21-2-A3D1  | 35                                   | 23      | 8.33E-06                        | 3             | 7          | 3.28            | 0.064231             | 0.609      | 0.0051                                                       | 0.7000      | 0.0101                                                        | 2.7870      | <b>0.0097</b>                                                 | 0.1910     | 0.0054                                                       | 0.0470      | 0.0002                                                        |
|      | IX21-2-A3D2  | 35                                   | 23      | 8.33E-06                        | 6             | 7          | 3.28            | 0.064226             | 0.452      | 0.0012                                                       | 0.4940      | 0.0021                                                        | 1.8600      | 0.0015                                                        | 0.1360     | 0.0010                                                       | 0.0440      | 0.0001                                                        |
|      | IX21-2-A3D3  | 35                                   | 23      | 8.33E-06                        | 9             | 7          | 3.28            | 0.064222             | 0.337      | 0.0009                                                       | 0.3540      | 0.0015                                                        | 1.3060      | 0.0012                                                        | 0.1010     | 0.0008                                                       | 0.0420      | 0.0001                                                        |
|      | IX21-2-A3D4  | 35                                   | 23      | 8.33E-06                        | 12            | 7          | 3.28            | 0.064218             | 0.287      | 0.0010                                                       | 0.2860      | 0.0016                                                        | 1.0390      | 0.0012                                                        | 0.0910     | 0.0010                                                       | 0.0770      | 0.0004                                                        |
|      | IX21-2-A3D5  | 35                                   | 23      | 8.33E-06                        | 15            | 7          | 3.28            | 0.064216             | 0.188      | 0.0004                                                       | 0.1920      | 0.0007                                                        | 0.7140      | 0.0006                                                        | 0.0710     | 0.0005                                                       | 0.0440      | 0.0000                                                        |
|      | IX21-2-A3D6  | 35                                   | 23      | 8.33E-06                        | 18            | 7          | 3.28            | 0.064214             | 0.141      | 0.0004                                                       | 0.1420      | 0.0006                                                        | 0.5350      | 0.0005                                                        | 0.0540     | 0.0003                                                       | 0.0430      | 0.0001                                                        |
|      | IX21-2-A3D7  | 35                                   | 23      | 8.33E-06                        | 21            | 7          | 3.28            | 0.064213             | 0.122      | 0.0004                                                       | 0.1190      | 0.0007                                                        | 0.4590      | 0.0005                                                        | 0.0520     | 0.0005                                                       | 0.0840      | 0.0004                                                        |
|      | IX21-2-A3D8  | 35                                   | 23      | 8.33E-06                        | 24            | 7          | 3.28            | 0.064212             | 0.090      | <b>0.0002</b>                                                | 0.0910      | <b>0.0004</b>                                                 | 0.3750      | <b>0.0004</b>                                                 | 0.0420     | <b>0.0002</b>                                                | 0.0540      | 0.00001                                                       |
|      | IX21-2-A3D9  | 35                                   | 23      | 8.33E-06                        | 27            | 7          | 3.28            | 0.064211             | 0.084      | <b>0.0003</b>                                                | 0.0830      | <b>0.0005</b>                                                 | 0.3370      | <b>0.0004</b>                                                 | 0.0420     | <b>0.0004</b>                                                | 0.0650      | 0.0002                                                        |
|      | IX21-2-A3D10 | 35                                   | 23      | 8.33E-06                        | 30            | 7          | 3.28            | 0.064210             | 0.075      | <b>0.0003</b>                                                | 0.0750      | <b>0.0005</b>                                                 | 0.3140      | <b>0.0004</b>                                                 | 0.0400     | <b>0.0003</b>                                                | 0.0500      | 0.0001                                                        |
| 2    | IX21-2-B3D1  | 40                                   | 23      | 8.33E-06                        | 3             | 8          | 3.28            | 0.064233             | 0.357      | 0.0030                                                       | 0.4920      | 0.0071                                                        | 2.0030      | 0.0069                                                        | 0.1220     | 0.0032                                                       | 0.0840      | 0.0005                                                        |
|      | IX21-2-B3D2  | 40                                   | 23      | 8.33E-06                        | 6             | 8          | 3.28            | 0.064229             | 0.262      | 0.0007                                                       | 0.3380      | 0.0013                                                        | 1.3050      | 0.0009                                                        | 0.0850     | 0.0005                                                       | 0.0640      | 0.0001                                                        |
|      | IX21-2-B3D3  | 40                                   | 23      | 8.33E-06                        | 9             | 8          | 3.28            | 0.064227             | 0.212      | 0.0007                                                       | 0.2560      | 0.0012                                                        | 0.9740      | 0.0010                                                        | 0.0650     | 0.0004                                                       | 0.0550      | 0.0001                                                        |
|      | IX21-2-B3D4  | 40                                   | 23      | 8.33E-06                        | 12            | 8          | 3.28            | 0.064225             | 0.152      | 0.0004                                                       | 0.1830      | 0.0008                                                        | 0.6940      | 0.0006                                                        | 0.0500     | 0.0003                                                       | 0.0510      | 0.0001                                                        |
|      | IX21-2-B3D5  | 40                                   | 23      | 8.33E-06                        | 15            | 8          | 3.28            | 0.064224             | 0.123      | 0.0004                                                       | 0.1440      | 0.0007                                                        | 0.5520      | 0.0006                                                        | 0.0430     | 0.0003                                                       | 0.0550      | 0.0002                                                        |
|      | IX21-2-B3D6  | 40                                   | 23      | 8.33E-06                        | 18            | 8          | 3.28            | 0.064222             | 0.088      | 0.0002                                                       | 0.1060      | 0.0005                                                        | 0.4210      | 0.0004                                                        | 0.0350     | 0.0001                                                       | 0.0450      | 0.0001                                                        |
|      | IX21-2-B3D7  | 40                                   | 23      | 8.33E-06                        | 21            | 8          | 3.28            | 0.064222             | 0.078      | <b>0.0003</b>                                                | 0.0900      | <b>0.0005</b>                                                 | 0.3660      | <b>0.0004</b>                                                 | 0.0330     | <b>0.0002</b>                                                | 0.0480      | <b>0.0001</b>                                                 |
|      | IX21-2-B3D8  | 40                                   | 23      | 8.33E-06                        | 24            | 8          | 3.28            | 0.064221             | 0.062      | <b>0.0002</b>                                                | 0.0740      | <b>0.0004</b>                                                 | 0.3100      | <b>0.0003</b>                                                 | 0.0280     | <b>0.0001</b>                                                | 0.0460      | <b>0.0001</b>                                                 |
|      | IX21-2-B3D9  | 40                                   | 23      | 8.33E-06                        | 27            | 8          | 3.28            | 0.064220             | 0.050      | <b>0.0001</b>                                                | 0.0610      | <b>0.0003</b>                                                 | 0.2650      | <b>0.0002</b>                                                 | 0.0250     | <b>0.0001</b>                                                | 0.0410      | <b>0.0001</b>                                                 |
|      | IX21-2-B3D10 | 40                                   | 23      | 8.33E-06                        | 30            | 8          | 3.28            | 0.064220             | 0.068      | <i>0.0003</i>                                                | 0.0700      | <i>0.0005</i>                                                 | 0.3020      | <i>0.0005</i>                                                 | 0.0350     | <i>0.0004</i>                                                | 0.0670      | <i>0.0003</i>                                                 |
| 3    | IX21-2-C2D1  | 52                                   | 23      | 8.33E-06                        | 3             | 9          | 3.28            | 0.064233             | 0.310      | 0.0026                                                       | 0.3620      | 0.0052                                                        | 1.5420      | 0.0050                                                        | 0.1010     | -0.0021                                                      | 0.0820      | 0.0004                                                        |
|      | IX21-2-C3D2  | 52                                   | 23      | 8.33E-06                        | 6             | 9          | 3.28            | 0.064230             | 0.202      | 0.0004                                                       | 0.2880      | 0.0015                                                        | 1.1430      | 0.0011                                                        | 0.0640     | -0.0022                                                      | 0.0490      | 0.0000                                                        |
|      | IX21-2-C3D3  | 52                                   | 23      | 8.33E-06                        | 9             | 9          | 3.28            | 0.064228             | 0.162      | 0.0005                                                       | 0.2150      | 0.0010                                                        | 0.8340      | 0.0007                                                        | 0.0470     | -0.0021                                                      | 0.0310      | 0.0000                                                        |
|      | IX21-2-C3D4  | 52                                   | 23      | 8.33E-06                        | 12            | 9          | 3.28            | 0.064227             | 0.134      | 0.0004                                                       | 0.1630      | 0.0008                                                        | 0.6420      | 0.0005                                                        | 0.0420     | -0.0020                                                      | 0.0360      | 0.0000                                                        |
|      | IX21-2-C3D5  | 52                                   | 23      | 8.33E-06                        | 15            | 9          | 3.28            | 0.064225             | 0.108      | 0.0003                                                       | 0.1270      | 0.0006                                                        | 0.5210      | 0.0004                                                        | 0.0340     | -0.0022                                                      | 0.0310      | 0.0000                                                        |
|      | IX21-2-C3D6  | 52                                   | 23      | 8.33E-06                        | 18            | 9          | 3.28            | 0.064225             | 0.077      | 0.0002                                                       | 0.0940      | 0.0004                                                        | 0.4010      | 0.0002                                                        | 0.0290     | -0.0022                                                      | 0.0350      | 0.0000                                                        |
|      | IX21-2-C3D7  | 52                                   | 23      | 8.33E-06                        | 21            | 9          | 3.28            | 0.064224             | 0.073      | 0.0003                                                       | 0.0860      | 0.0005                                                        | 0.3750      | 0.0004                                                        | 0.0290     | -0.0022                                                      | 0.0570      | 0.0001                                                        |
|      | IX21-2-C3D8  | 52                                   | 23      | 8.33E-06                        | 24            | 9          | 3.28            | 0.064223             | 0.058      | <b>0.0002</b>                                                | 0.0700      | <b>0.0004</b>                                                 | 0.3170      | <b>0.0002</b>                                                 | 0.0240     | -0.0023                                                      | 0.0250      | <i>-0.0001</i>                                                |
|      | IX21-2-C3D9  | 52                                   | 23      | 8.33E-06                        | 27            | 9          | 3.28            | 0.064223             | 0.049      | <b>0.0002</b>                                                | 0.0570      | <b>0.0003</b>                                                 | 0.2760      | <b>0.0001</b>                                                 | 0.0230     | -0.0023                                                      | 0.0370      | <b>0.0001</b>                                                 |
|      | IX21-2-C3D10 | 52                                   | 23      | 8.33E-06                        | 30            | 9          | 3.28            | 0.064222             | 0.045      | <b>0.0002</b>                                                | 0.0530      | <b>0.0003</b>                                                 | 0.2660      | <b>0.0002</b>                                                 | 0.0210     | -0.0023                                                      | 0.0340      | <b>0.0000</b>                                                 |
| 4    | IX21-2-D3D1  | 90                                   | 23      | 8.33E-06                        | 3             | 10         | 1.64            | 0.032117             | 0.126      | 0.0020                                                       | 0.1770      | 0.0051                                                        | 0.8860      | 0.0050                                                        | 0.0550     | 0.0027                                                       | 0.1150      | 0.0011                                                        |
|      | IX21-2-D3D2  | 90                                   | 23      | 8.33E-06                        | 6             | 10         | 1.64            | 0.032115             | 0.127      | 0.0010                                                       | 0.1460      | 0.0016                                                        | 0.7390      | 0.0014                                                        | 0.0480     | 0.0009                                                       | 0.1050      | 0.0004                                                        |
|      | IX21-2-D3D3  | 90                                   | 23      | 8.33E-06                        | 9             | 10         | 1.64            | 0.032114             | 0.106      | 0.0007                                                       | 0.1110      | 0.0011                                                        | 0.5970      | 0.0009                                                        | 0.0400     | 0.0006                                                       | 0.0870      | 0.0002                                                        |
|      | IX21-2-D3D4  | 90                                   | 23      | 8.33E-06                        | 12            | 10         | 1.64            | 0.032113             | 0.085      | 0.0005                                                       | 0.0870      | 0.0009                                                        | 0.4820      | 0.0006                                                        | 0.0340     | 0.0005                                                       | 0.0690      | 0.0000                                                        |
|      | IX21-2-D3D5  | 90                                   | 23      | 8.33E-06                        | 15            | 10         | 1.64            | 0.032112             | 0.067      | 0.0004                                                       | 0.0690      | 0.0007                                                        | 0.4190      | 0.0006                                                        | 0.0280     | 0.0003                                                       | 0.0620      | 0.0001                                                        |
|      | IX21-2-D3D6  | 90                                   | 23      | 8.33E-06                        | 18            | 10         | 1.64            | 0.032112             | 0.049      | 0.0002                                                       | 0.0530      | 0.0005                                                        | 0.3590      | 0.0004                                                        | 0.0250     | 0.0003                                                       | 0.0640      | 0.0002                                                        |
|      | IX21-2-D3D7  | 90                                   | 23      | 8.33E-06                        | 21            | 10         | 1.64            | 0.032111             | 0.039      | 0.0002                                                       | 0.0430      | 0.0004                                                        | 0.3240      | 0.0003                                                        | 0.0240     | 0.0004                                                       | 0.0580      | 0.0001                                                        |
|      | IX21-2-D3D8  | 90                                   | 23      | 8.33E-06                        | 24            | 10         | 1.64            | 0.032111             | 0.032      | <b>0.0002</b>                                                | 0.0360      | <b>0.0004</b>                                                 | 0.2980      | <b>0.0003</b>                                                 | 0.0210     | <b>0.0002</b>                                                | 0.0510      | 0.0000                                                        |
|      | IX21-2-D3D9  | 90                                   | 23      | 8.33E-06                        | 27            | 10         | 1.64            | 0.032111             | 0.023      | <b>0.0001</b>                                                | 0.0290      | <b>0.0003</b>                                                 | 0.2710      | <b>0.0002</b>                                                 | 0.0210     | <b>0.0003</b>                                                | 0.0520      | 0.0001                                                        |
|      | IX21-2-D3D10 | 90                                   | 23      | 8.33E-06                        | 30            | 10         | 1.64            | 0.032111             | 0.020      | <b>0.0001</b>                                                | 0.0260      | <b>0.0003</b>                                                 | 0.2620      | <b>0.0002</b>                                                 | 0.0220     | <b>0.0004</b>                                                | 0.0490      | 0.0000                                                        |
| 5    | IX21-2-E3D1  | 230                                  | 23      | 8.33E-06                        | 3             | 11         | 1.64            | 0.032117             | 0.093      | 0.0015                                                       | 0.1334      | 0.0038                                                        | 1.166       | 0.0041                                                        | 0.0504     | 0.0020                                                       | 0.1754      | 0.0010                                                        |
|      | IX21-2-E3D2  | 230                                  | 23      | 8.33E-06                        | 6             | 11         | 1.64            | 0.032116             | 0.134      | 0.0014                                                       | 0.1355      | 0.0020                                                        | 1.190       | 0.0022                                                        | 0.0567     | 0.0014                                                       | 0.1838      | 0.0006                                                        |
|      | IX21-2-E3D3  | 230                                  | 23      | 8.33E-06                        | 9             | 11         | 1.64            | 0.032114             | 0.113      | 0.0007                                                       | 0.1040      | 0.0010                                                        | 0.990       | 0.0007                                                        | 0.0483     | 0.0007                                                       | 0.1649      | 0.0002                                                        |
|      | IX21-2-E3D4  | 230                                  | 23      | 8.33E-06                        | 12            | 11         | 1.64            | 0.032113             | 0.124      | 0.0011                                                       | 0.1061      | 0.0015                                                        | 1.024       | 0.0016                                                        | 0.0494     | 0.0010                                                       | 0.1806      | 0.0004                                                        |
|      | IX21-2-E3D5  | 230                                  | 23      | 8.33E-06                        | 15            | 11         | 1.64            | 0.032112             | 0.108      | 0.0007                                                       | 0.0914      | 0.0011                                                        | 0.978       | 0.0012                                                        | 0.0494     | 0.0010                                                       | 0.1659      | 0.0002                                                        |
|      | IX21-2-E3D6  | 230                                  | 23      | 8.33E-06                        | 18            | 11         | 1.64            | 0.032111             | 0.099      | 0.0007                                                       | 0.0819      | 0.0010                                                        | 0.912       | 0.0009                                                        | 0.0462     | 0.0008                                                       | 0.1680      | <b>0.0003</b>                                                 |
|      | IX21-2-E3D7  | 230                                  | 23      | 8.33E-06                        | 21            | 11         | 1.64            | 0.032110             | 0.111      | <b>0.0010</b>                                                | 0.0914      | 0.0014                                                        | 0.992       | 0.0017                                                        | 0.0515     | 0.0012                                                       | 0.1890      | <b>0.0005</b>                                                 |
|      | IX21-2-E3D8  | 230                                  | 23      | 8.33E-06                        | 24            | 11         | 1.64            | 0.032109             | 0.082      | <b>0.0004</b>                                                | 0.0693      | <b>0.0006</b>                                                 | 0.932       | <b>0.0010</b>                                                 | 0.0441     | <b>0.0006</b>                                                | 0.1995      | <b>0.0005</b>                                                 |
|      | IX21-2-E3D9  | 230                                  | 23      | 8.33E-06                        | 27            | 11         | 1.64            | 0.032108             | 0.075      | <b>0.0005</b>                                                | 0.0641      | <b>0.0008</b>                                                 | 0.916       | <b>0.0011</b>                                                 | 0.0420     | <b>0.0007</b>                                                | 0.1575      | <i>0.0000</i>                                                 |
|      | IX21-2-E3D10 | 230                                  | 23      | 8.33E-06                        | 30            | 11         | 1.64            | contaminated         |            |                                                              |             |                                                               |             |                                                               |            |                                                              |             |                                                               |

Table A7. DCP-AES Analysis Results from Dissolution of Glass IDFIX21-3 at 70°C.

| Exp. | Sample ID    | Target<br>[Si] <sub>inf</sub><br>ppm | T<br>°C | Flow Rate,<br>m <sup>3</sup> /d | Time,<br>days | pH<br>23°C | Glass<br>Mass g | SA<br>m <sup>2</sup> | [B]<br>ppm | B Rate<br>g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [Na]<br>ppm | Na Rate<br>g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [K]<br>ppm | K Rate<br>g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [Al]<br>ppm | Al Rate<br>g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> |
|------|--------------|--------------------------------------|---------|---------------------------------|---------------|------------|-----------------|----------------------|------------|--------------------------------------------------------------|-------------|---------------------------------------------------------------|------------|--------------------------------------------------------------|-------------|---------------------------------------------------------------|
| 1    | IX21-3-A1D1  | 55                                   | 70      | 2.50E-05                        | 1             | 7          | 0.77            | 0.01525              | 5.258      | 0.5547                                                       | 27.4210     | 0.5744                                                        | 0.9509     | 0.4872                                                       | 0.0631      | 0.0041                                                        |
|      | IX21-3-A1D2  | 55                                   | 70      | 2.50E-05                        | 2             | 7          | 0.77            | 0.01519              | 5.757      | 0.3313                                                       | 29.2190     | 0.3263                                                        | 1.0046     | 0.2730                                                       | 0.0698      | 0.0027                                                        |
|      | IX21-3-A1D3  | 55                                   | 70      | 2.50E-05                        | 3             | 7          | 0.77            | 0.01513              | 6.222      | 0.3557                                                       | 30.9680     | 0.3457                                                        | 1.1257     | 0.3242                                                       | 0.1005      | 0.0055                                                        |
|      | IX21-3-A1D4  | 55                                   | 70      | 2.50E-05                        | 4             | 7          | 0.77            | 0.01506              | 6.229      | 0.3331                                                       | 30.3320     | 0.3150                                                        | 1.1320     | 0.2967                                                       | 0.0937      | 0.0033                                                        |
|      | IX21-3-A1D5  | 55                                   | 70      | 2.50E-05                        | 5             | 7          | 0.77            | 0.01500              | 5.620      | 0.2688                                                       | 27.5070     | 0.2627                                                        | 1.0195     | 0.2360                                                       | 0.0946      | 0.0037                                                        |
|      | IX21-3-A1D6  | 55                                   | 70      | 2.50E-05                        | 6             | 7          | 0.77            | 0.01494              | 5.106      | 0.2472                                                       | 24.9200     | 0.2385                                                        | 0.9197     | 0.2135                                                       | 0.0816      | 0.0024                                                        |
|      | IX21-3-A1D7  | 55                                   | 70      | 2.50E-05                        | 7             | 7          | 0.77            | 0.01489              | 4.868      | 0.2502                                                       | 23.8910     | 0.2451                                                        | 0.8995     | 0.2303                                                       | 0.0898      | 0.0039                                                        |
|      | IX21-3-A1D8  | 55                                   | 70      | 2.50E-05                        | 8             | 7          | 0.77            | 0.01484              | 4.742      | <b>0.2502</b>                                                | 23.2940     | <b>0.2442</b>                                                 | 0.9194     | <b>0.2473</b>                                                | 0.0877      | <b>0.0033</b>                                                 |
|      | IX21-3-A1D9  | 55                                   | 70      | 2.50E-05                        | 9             | 7          | 0.77            | 0.01479              | 4.616      | <b>0.2443</b>                                                | 23.0910     | <b>0.2471</b>                                                 | 0.9186     | <b>0.2423</b>                                                | 0.0907      | <b>0.0037</b>                                                 |
|      | IX21-3-A1D10 | 55                                   | 70      | 2.50E-05                        | 10            | 7          | 0.77            | 0.01474              | 4.276      | <b>0.2148</b>                                                | 21.2750     | <b>0.2105</b>                                                 | 0.8499     | <b>0.2059</b>                                                | 0.0793      | <b>0.0024</b>                                                 |
| 2    | IX21-3-B1D1  | 60                                   | 70      | 2.50E-05                        | 1             | 8          | 0.77            | 0.01527              | 2.207      | 0.2324                                                       | 13.2810     | 0.2766                                                        | 0.4169     | 0.2107                                                       | 0.0941      | 0.00689                                                       |
|      | IX21-3-B1D2  | 60                                   | 70      | 2.50E-05                        | 2             | 8          | 0.77            | 0.01524              | 2.255      | 0.1214                                                       | 12.2990     | 0.1178                                                        | 0.4193     | 0.1068                                                       | 0.0953      | 0.00357                                                       |
|      | IX21-3-B1D3  | 60                                   | 70      | 2.50E-05                        | 3             | 8          | 0.77            | 0.01522              | 2.449      | 0.1396                                                       | 12.2030     | 0.1263                                                        | 0.4560     | 0.1257                                                       | 0.1151      | 0.00553                                                       |
|      | IX21-3-B1D4  | 60                                   | 70      | 2.50E-05                        | 4             | 8          | 0.77            | 0.01519              | 2.375      | 0.1217                                                       | 11.9480     | 0.1222                                                        | 0.4531     | 0.1147                                                       | 0.1151      | 0.00453                                                       |
|      | IX21-3-B1D5  | 60                                   | 70      | 2.50E-05                        | 5             | 8          | 0.77            | 0.01517              | 2.208      | 0.1082                                                       | 11.1900     | 0.1090                                                        | 0.4166     | 0.0963                                                       | 0.1083      | 0.00384                                                       |
|      | IX21-3-B1D6  | 60                                   | 70      | 2.50E-05                        | 6             | 8          | 0.77            | 0.01515              | 2.124      | 0.1083                                                       | 10.4630     | 0.1018                                                        | 0.3902     | 0.0921                                                       | 0.1093      | 0.00430                                                       |
|      | IX21-3-B1D7  | 60                                   | 70      | 2.50E-05                        | 7             | 8          | 0.77            | 0.01512              | 2.052      | 0.1052                                                       | 9.9675      | 0.0992                                                        | 0.3936     | 0.1011                                                       | 0.1314      | 0.00652                                                       |
|      | IX21-3-B1D8  | 60                                   | 70      | 2.50E-05                        | 8             | 8          | 0.77            | 0.01510              | 1.975      | <b>0.1009</b>                                                | 9.6505      | <b>0.0979</b>                                                 | 0.3643     | <b>0.0847</b>                                                | 0.1031      | <b>0.00249</b>                                                |
|      | IX21-3-B1D9  | 60                                   | 70      | 2.50E-05                        | 9             | 8          | 0.77            | 0.01508              | 1.848      | <b>0.0917</b>                                                | 8.8074      | <b>0.0834</b>                                                 | 0.3502     | <b>0.0851</b>                                                | 0.0944      | <b>0.00306</b>                                                |
|      | IX21-3-B1D10 | 60                                   | 70      | 2.50E-05                        | 10            | 8          | 0.77            | 0.01506              | 1.736      | <b>0.0866</b>                                                | 8.5161      | <b>0.0863</b>                                                 | 0.3477     | <b>0.0876</b>                                                | 0.0910      | <b>0.00316</b>                                                |
| 3    | IX21-3-C1D1  | 80                                   | 70      | 2.50E-05                        | 1             | 9          | 0.77            | 0.01528              | 0.772      | 0.0810                                                       | 7.5153      | 0.1561                                                        | 0.1605     | 0.0794                                                       | 0.1434      | 0.0112                                                        |
|      | IX21-3-C1D2  | 80                                   | 70      | 2.50E-05                        | 2             | 9          | 0.77            | 0.01527              | 0.770      | 0.0403                                                       | 6.3926      | 0.0539                                                        | 0.1534     | 0.0360                                                       | 0.1462      | 0.0059                                                        |
|      | IX21-3-C1D3  | 80                                   | 70      | 2.50E-05                        | 3             | 9          | 0.77            | 0.01526              | 0.809      | 0.0446                                                       | 5.7207      | 0.0517                                                        | 0.1521     | 0.0372                                                       | 0.1577      | 0.0069                                                        |
|      | IX21-3-C1D4  | 80                                   | 70      | 2.50E-05                        | 4             | 9          | 0.77            | 0.01525              | 0.793      | 0.0409                                                       | 5.1312      | 0.0463                                                        | 0.1486     | 0.0357                                                       | 0.1474      | 0.0053                                                        |
|      | IX21-3-C1D5  | 80                                   | 70      | 2.50E-05                        | 5             | 9          | 0.77            | 0.01524              | 0.708      | 0.0327                                                       | 4.6897      | 0.0433                                                        | 0.1384     | 0.0313                                                       | 0.1438      | 0.0054                                                        |
|      | IX21-3-C1D6  | 80                                   | 70      | 2.50E-05                        | 6             | 9          | 0.77            | 0.01524              | 0.696      | 0.0360                                                       | 4.3057      | 0.0399                                                        | 0.1283     | 0.0287                                                       | 0.1330      | 0.0045                                                        |
|      | IX21-3-C1D7  | 80                                   | 70      | 2.50E-05                        | 7             | 9          | 0.77            | 0.01523              | 0.692      | 0.0361                                                       | 3.9601      | 0.0366                                                        | 0.1259     | 0.0301                                                       | 0.1427      | 0.0061                                                        |
|      | IX21-3-C1D8  | 80                                   | 70      | 2.50E-05                        | 8             | 9          | 0.77            | 0.01522              | 0.664      | <b>0.0334</b>                                                | 3.7880      | <b>0.0367</b>                                                 | 0.1390     | <b>0.0376</b>                                                | 0.1411      | <b>0.0054</b>                                                 |
|      | IX21-3-C1D9  | 80                                   | 70      | 2.50E-05                        | 9             | 9          | 0.77            | 0.01521              | 0.587      | <b>0.0269</b>                                                | 3.3807      | <b>0.0299</b>                                                 | 0.1183     | <b>0.0233</b>                                                | 0.1110      | <b>0.0024</b>                                                 |
|      | IX21-3-C1D10 | 80                                   | 70      | 2.50E-05                        | 10            | 9          | 0.77            | 0.01521              | 0.579      | <b>0.0301</b>                                                | 3.2468      | <b>0.0314</b>                                                 | 0.1176     | <b>0.0284</b>                                                | 0.1170      | <b>0.0046</b>                                                 |
| 4    | IX21-3-D1D1  | 140                                  | 70      | 2.50E-05                        | 1             | 10         | 0.50            | 0.00982              | 0.296      | 0.0480                                                       | 3.8229      | 0.1193                                                        | 0.0708     | 0.0385                                                       | 0.1265      | 0.0107                                                        |
|      | IX21-3-D1D2  | 140                                  | 70      | 2.50E-05                        | 2             | 10         | 0.50            | 0.00982              | 0.251      | 0.0165                                                       | 3.2046      | 0.0378                                                        | 0.0610     | 0.0112                                                       | 0.0987      | 0.0010                                                        |
|      | IX21-3-D1D3  | 140                                  | 70      | 2.50E-05                        | 3             | 10         | 0.50            | 0.00982              | 0.241      | 0.0187                                                       | 2.8584      | 0.0366                                                        | 0.0525     | 0.0083                                                       | 0.0843      | 0.0009                                                        |
|      | IX21-3-D1D4  | 140                                  | 70      | 2.50E-05                        | 4             | 10         | 0.50            | 0.00981              | 0.221      | 0.0162                                                       | 2.3495      | 0.0257                                                        | 0.0489     | 0.0088                                                       | 0.0826      | 0.0017                                                        |
|      | IX21-3-D1D5  | 140                                  | 70      | 2.50E-05                        | 5             | 10         | 0.50            | 0.00981              | 0.209      | 0.0159                                                       | 2.0942      | 0.0256                                                        | 0.0478     | 0.0094                                                       | 0.0719      | 0.0002                                                        |
|      | IX21-3-D1D6  | 140                                  | 70      | 2.50E-05                        | 6             | 10         | 0.50            | 0.00981              | 0.215      | 0.0178                                                       | 1.9385      | 0.0247                                                        | 0.0436     | <b>0.0064</b>                                                | 0.0740      | <b>0.0014</b>                                                 |
|      | IX21-3-D1D7  | 140                                  | 70      | 2.50E-05                        | 7             | 10         | 0.50            | 0.00981              | 0.210      | 0.0165                                                       | 1.7401      | 0.0208                                                        | 0.0448     | <b>0.0091</b>                                                | 0.0633      | -0.0005                                                       |
|      | IX21-3-D1D8  | 140                                  | 70      | 2.50E-05                        | 8             | 10         | 0.50            | 0.00980              | 0.229      | <b>0.0201</b>                                                | 1.7562      | <b>0.0246</b>                                                 | 0.0428     | <b>0.0070</b>                                                | 0.0631      | <b>0.0003</b>                                                 |
|      | IX21-3-D1D9  | 140                                  | 70      | 2.50E-05                        | 9             | 10         | 0.50            | 0.00980              | 0.228      | <b>0.0183</b>                                                | 1.7132      | <b>0.0229</b>                                                 | 0.0458     | <i>0.0103</i>                                                | 0.0571      | -0.0006                                                       |
|      | IX21-3-D1D10 | 140                                  | 70      | 2.50E-05                        | 10            | 10         | 0.50            | 0.00980              | 0.242      | <b>0.0208</b>                                                | 1.7207      | <b>0.0239</b>                                                 | 0.0723     | <i>0.0308</i>                                                | 0.0667      | <b>0.0014</b>                                                 |
| 5    | IX21-3-E1D1  | 360                                  | 70      | 2.50E-05                        | 1             | 11         | 0.50            | 0.00982              | 0.161      | 0.0258                                                       | 3.822       | 0.0952                                                        | 0.0917     | 0.0379                                                       | 0.1306      | 0.0022                                                        |
|      | IX21-3-E1D2  | 360                                  | 70      | 2.50E-05                        | 2             | 11         | 0.50            | 0.00982              | 0.107      | 0.0041                                                       | 3.044       | 0.0222                                                        | 0.0576     | -0.0089                                                      | 0.1173      | -0.0010                                                       |
|      | IX21-3-E1D3  | 360                                  | 70      | 2.50E-05                        | 3             | 11         | 0.50            | 0.00982              | 0.082      | 0.0044                                                       | 2.799       | 0.0269                                                        | 0.0510     | -0.0004                                                      | 0.1055      | -0.0018                                                       |
|      | IX21-3-E1D4  | 360                                  | 70      | 2.50E-05                        | 4             | 11         | 0.50            | 0.00982              | 0.060      | 0.0028                                                       | 2.331       | 0.0156                                                        | 0.0512     | 0.0025                                                       | 0.1037      | -0.0012                                                       |
|      | IX21-3-E1D5  | 360                                  | 70      | 2.50E-05                        | 5             | 11         | 0.50            | 0.00982              | 0.041      | 0.0015                                                       | 2.036       | 0.0136                                                        | 0.0456     | -0.0022                                                      | 0.1030      | -0.0011                                                       |
|      | IX21-3-E1D6  | 360                                  | 70      | 2.50E-05                        | 6             | 11         | 0.50            | 0.00982              | 0.033      | 0.0018                                                       | 1.974       | 0.0164                                                        | 0.0543     | 0.0072                                                       | 0.1008      | -0.0014                                                       |
|      | IX21-3-E1D7  | 360                                  | 70      | 2.50E-05                        | 7             | 11         | 0.50            | 0.00982              | 0.025      | <b>0.0011</b>                                                | 1.799       | <b>0.0117</b>                                                 | 0.0423     | -0.0061                                                      | 0.1063      | -0.0004                                                       |
|      | IX21-3-E1D8  | 360                                  | 70      | 2.50E-05                        | 8             | 11         | 0.50            | 0.00982              | 0.022      | <b>0.0012</b>                                                | 1.922       | <i>0.0186</i>                                                 | 0.0458     | 0.0016                                                       | 0.0953      | -0.0026                                                       |
|      | IX21-3-E1D9  | 360                                  | 70      | 2.50E-05                        | 9             | 11         | 0.50            | 0.00982              | 0.016      | <b>0.0006</b>                                                | 1.792       | <b>0.0123</b>                                                 | 0.0463     | 0.0006                                                       | 0.0970      | -0.0014                                                       |
|      | IX21-3-E1D10 | 360                                  | 70      | 2.50E-05                        | 10            | 11         | 0.50            | 0.00982              | 0.022      | <i>0.0019</i>                                                | 1.719       | <b>0.0121</b>                                                 | 0.0479     | 0.0017                                                       | 0.0967      | -0.0016                                                       |

Table A8. DCP-AES Analysis Results from Dissolution of Glass IDFIX21-3 at 40°C.

| Exp. | Sample ID    | Target [Si] <sub>inf</sub> ppm | T °C | Flow Rate, m <sup>3</sup> /d | Time, days | pH 23°C | Glass Mass g | SA m <sup>2</sup> | [B] ppm | B Rate g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [Na] ppm | Na Rate g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [K] ppm | K Rate g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [Al] ppm | Al Rate g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> |
|------|--------------|--------------------------------|------|------------------------------|------------|---------|--------------|-------------------|---------|-----------------------------------------------------------|----------|------------------------------------------------------------|---------|-----------------------------------------------------------|----------|------------------------------------------------------------|
| 1    | IX21-3-A2D1  | 40                             | 40   | 8.33E-06                     | 3          | 7       | 1.65         | 0.0327            | 1.688   | 0.0276                                                    | 12.9860  | 0.0422                                                     | 0.3350  | 0.0266                                                    | 0.0450   | 0.0004                                                     |
|      | IX21-3-A2D2  | 40                             | 40   | 8.33E-06                     | 6          | 7       | 1.65         | 0.0327            | 1.796   | 0.0156                                                    | 11.6830  | 0.0168                                                     | 0.3300  | 0.0129                                                    | 0.0410   | 0.0001                                                     |
|      | IX21-3-A2D3  | 40                             | 40   | 8.33E-06                     | 9          | 7       | 1.65         | 0.0327            | 1.775   | 0.0144                                                    | 10.8580  | 0.0163                                                     | 0.3200  | 0.0123                                                    | 0.0450   | 0.0002                                                     |
|      | IX21-3-A2D4  | 40                             | 40   | 8.33E-06                     | 12         | 7       | 1.65         | 0.0327            | 1.705   | 0.0134                                                    | 9.7180   | 0.0139                                                     | 0.3070  | 0.0116                                                    | 0.0430   | 0.0002                                                     |
|      | IX21-3-A2D5  | 40                             | 40   | 8.33E-06                     | 15         | 7       | 1.65         | 0.0327            | 1.632   | 0.0128                                                    | 9.0470   | 0.0136                                                     | 0.2940  | 0.0111                                                    | 0.0400   | 0.0001                                                     |
|      | IX21-3-A2D6  | 40                             | 40   | 8.33E-06                     | 18         | 7       | 1.65         | 0.0326            | 1.584   | 0.0126                                                    | 8.5130   | 0.0129                                                     | 0.2890  | 0.0112                                                    | 0.0390   | 0.0001                                                     |
|      | IX21-3-A2D7  | 40                             | 40   | 8.33E-06                     | 21         | 7       | 1.65         | 0.0326            | 1.565   | 0.0127                                                    | 8.0730   | 0.0124                                                     | 0.2840  | 0.0110                                                    | 0.0400   | 0.0002                                                     |
|      | IX21-3-A2D8  | 40                             | 40   | 8.33E-06                     | 24         | 7       | 1.65         | 0.0326            | 1.527   | <b>0.0122</b>                                             | 7.9560   | <b>0.0127</b>                                              | 0.2800  | <b>0.0109</b>                                             | 0.0570   | <b>0.0004</b>                                              |
|      | IX21-3-A2D9  | 40                             | 40   | 8.33E-06                     | 27         | 7       | 1.65         | 0.0326            | 1.488   | <b>0.0119</b>                                             | 7.5490   | <b>0.0116</b>                                              | 0.2740  | <b>0.0106</b>                                             | 0.0640   | <b>0.0004</b>                                              |
|      | IX21-3-A2D10 | 40                             | 40   | 8.33E-06                     | 30         | 7       | 1.65         | 0.0326            | 1.423   | <b>0.0112</b>                                             | 7.2700   | <b>0.0113</b>                                              | 0.2650  | <b>0.0101</b>                                             | 0.0560   | <b>0.0002</b>                                              |
| 2    | IX21-3-B2D1  | 45                             | 40   | 8.33E-06                     | 3          | 8       | 1.65         | 0.0327            | 0.680   | 0.0111                                                    | 8.0180   | 0.0259                                                     | 0.1610  | 0.0126                                                    | 0.0820   | 0.00100                                                    |
|      | IX21-3-B2D2  | 45                             | 40   | 8.33E-06                     | 6          | 8       | 1.65         | 0.0327            | 0.630   | 0.0047                                                    | 6.4100   | 0.0077                                                     | 0.1320  | 0.0039                                                    | 0.0820   | 0.00050                                                    |
|      | IX21-3-B2D3  | 45                             | 40   | 8.33E-06                     | 9          | 8       | 1.65         | 0.0327            | 0.583   | 0.0044                                                    | 5.1060   | 0.0061                                                     | 0.1170  | 0.0039                                                    | 0.0940   | 0.00069                                                    |
|      | IX21-3-B2D4  | 45                             | 40   | 8.33E-06                     | 12         | 8       | 1.65         | 0.0327            | 0.518   | 0.0037                                                    | 4.1820   | 0.0052                                                     | 0.1010  | 0.0032                                                    | 0.0110   | -0.00072                                                   |
|      | IX21-3-B2D5  | 45                             | 40   | 8.33E-06                     | 15         | 8       | 1.65         | 0.0327            | 0.507   | 0.0035                                                    | 3.6400   | 0.0049                                                     | 0.0950  | 0.0033                                                    | 0.0660   | 0.00081                                                    |
|      | IX21-3-B2D6  | 45                             | 40   | 8.33E-06                     | 18         | 8       | 1.65         | 0.0327            | 0.515   | 0.0043                                                    | 3.4670   | 0.0053                                                     | 0.0980  | 0.0038                                                    | 0.0380   | -0.00007                                                   |
|      | IX21-3-B2D7  | 45                             | 40   | 8.33E-06                     | 21         | 8       | 1.65         | 0.0327            | 0.458   | <b>0.0033</b>                                             | 3.0190   | <b>0.0041</b>                                              | 0.0870  | 0.0028                                                    | 0.0630   | 0.00055                                                    |
|      | IX21-3-B2D8  | 45                             | 40   | 8.33E-06                     | 24         | 8       | 1.65         | 0.0327            | 0.432   | <b>0.0033</b>                                             | 2.7670   | <b>0.0040</b>                                              | 0.0840  | <b>0.0030</b>                                             | 0.0480   | <b>0.00011</b>                                             |
|      | IX21-3-B2D9  | 45                             | 40   | 8.33E-06                     | 27         | 8       | 1.65         | 0.0327            | 0.413   | <b>0.0032</b>                                             | 2.5940   | <b>0.0038</b>                                              | 0.0800  | <b>0.0028</b>                                             | 0.0480   | <b>0.00023</b>                                             |
|      | IX21-3-B2D10 | 45                             | 40   | 8.33E-06                     | 30         | 8       | 1.65         | 0.0327            | 0.423   | <b>0.0035</b>                                             | 2.5670   | <b>0.0040</b>                                              | 0.0800  | <b>0.0030</b>                                             | 0.0580   | <b>0.00039</b>                                             |
| 3    | IX21-3-C2D1  | 60                             | 40   | 8.33E-06                     | 3          | 9       | 1.65         | 0.0327            | 0.391   | 0.0064                                                    | 6.4420   | 0.0207                                                     | 0.0970  | 0.0074                                                    | 0.0760   | 0.0008                                                     |
|      | IX21-3-C2D2  | 60                             | 40   | 8.33E-06                     | 6          | 9       | 1.65         | 0.0327            | 0.341   | 0.0024                                                    | 4.7960   | 0.0050                                                     | 0.0790  | 0.0022                                                    | 0.0610   | 0.0002                                                     |
|      | IX21-3-C2D3  | 60                             | 40   | 8.33E-06                     | 9          | 9       | 1.65         | 0.0327            | 0.281   | 0.0018                                                    | 3.7260   | 0.0042                                                     | 0.0620  | 0.0016                                                    | 0.0530   | 0.0001                                                     |
|      | IX21-3-C2D4  | 60                             | 40   | 8.33E-06                     | 12         | 9       | 1.65         | 0.0327            | 0.239   | 0.0016                                                    | 3.0380   | 0.0037                                                     | 0.0560  | 0.0018                                                    | 0.0490   | 0.0001                                                     |
|      | IX21-3-C2D5  | 60                             | 40   | 8.33E-06                     | 15         | 9       | 1.65         | 0.0327            | 0.203   | 0.0013                                                    | 2.5100   | 0.0031                                                     | 0.0460  | 0.0012                                                    | 0.0570   | 0.0003                                                     |
|      | IX21-3-C2D6  | 60                             | 40   | 8.33E-06                     | 18         | 9       | 1.65         | 0.0327            | 0.187   | 0.0014                                                    | 2.2720   | 0.0032                                                     | 0.0440  | 0.0015                                                    | 0.0420   | 0.0000                                                     |
|      | IX21-3-C2D7  | 60                             | 40   | 8.33E-06                     | 21         | 9       | 1.65         | 0.0327            | 0.177   | 0.0013                                                    | 2.0550   | 0.0028                                                     | 0.0390  | 0.0011                                                    | 0.0470   | 0.0002                                                     |
|      | IX21-3-C2D8  | 60                             | 40   | 8.33E-06                     | 24         | 9       | 1.65         | 0.0327            | 0.173   | <b>0.0014</b>                                             | 1.9080   | <b>0.0027</b>                                              | 0.0420  | <b>0.0016</b>                                             | 0.0520   | <b>0.0002</b>                                              |
|      | IX21-3-C2D9  | 60                             | 40   | 8.33E-06                     | 27         | 9       | 1.65         | 0.0327            | 0.165   | <b>0.0013</b>                                             | 1.7610   | <b>0.0025</b>                                              | 0.0370  | <b>0.0011</b>                                             | 0.0400   | <b>0.0000</b>                                              |
|      | IX21-3-C2D10 | 60                             | 40   | 8.33E-06                     | 30         | 9       | 1.65         | 0.0327            | 0.160   | <b>0.0012</b>                                             | 1.6460   | <b>0.0023</b>                                              | 0.0360  | <b>0.0012</b>                                             | 0.0560   | <b>0.0004</b>                                              |
| 4    | IX21-3-D2D1  | 105                            | 40   | 8.33E-06                     | 3          | 10      | 0.83         | 0.0164            | 0.160   | 0.0051                                                    | 2.9650   | 0.0186                                                     | 0.0480  | 0.0066                                                    | 0.0710   | 0.0008                                                     |
|      | IX21-3-D2D2  | 105                            | 40   | 8.33E-06                     | 6          | 10      | 0.83         | 0.0164            | 0.135   | 0.0017                                                    | 2.2850   | 0.0046                                                     | 0.0380  | 0.0017                                                    | 0.0850   | 0.0008                                                     |
|      | IX21-3-D2D3  | 105                            | 40   | 8.33E-06                     | 9          | 10      | 0.83         | 0.0164            | 0.099   | 0.0010                                                    | 1.7710   | 0.0035                                                     | 0.0310  | 0.0013                                                    | 0.0730   | 0.0002                                                     |
|      | IX21-3-D2D4  | 105                            | 40   | 8.33E-06                     | 12         | 10      | 0.83         | 0.0164            | 0.076   | 0.0008                                                    | 1.4440   | 0.0030                                                     | 0.0260  | 0.0011                                                    | 0.0640   | 0.0001                                                     |
|      | IX21-3-D2D5  | 105                            | 40   | 8.33E-06                     | 15         | 10      | 0.83         | 0.0164            | 0.051   | 0.0004                                                    | 1.2010   | 0.0025                                                     | 0.0240  | 0.0012                                                    | 0.0680   | 0.0004                                                     |
|      | IX21-3-D2D6  | 105                            | 40   | 8.33E-06                     | 18         | 10      | 0.83         | 0.0164            | 0.044   | <b>0.0006</b>                                             | 1.0790   | 0.0025                                                     | 0.0250  | 0.0015                                                    | 0.0610   | 0.0001                                                     |
|      | IX21-3-D2D7  | 105                            | 40   | 8.33E-06                     | 21         | 10      | 0.83         | 0.0164            | 0.035   | <b>0.0004</b>                                             | 0.9800   | 0.0023                                                     | 0.0190  | 0.0004                                                    | 0.0580   | 0.0001                                                     |
|      | IX21-3-D2D8  | 105                            | 40   | 8.33E-06                     | 24         | 10      | 0.83         | 0.0164            | 0.031   | <b>0.0004</b>                                             | 0.8910   | <b>0.0020</b>                                              | 0.0190  | <b>0.0009</b>                                             | 0.0650   | <b>0.0004</b>                                              |
|      | IX21-3-D2D9  | 105                            | 40   | 8.33E-06                     | 27         | 10      | 0.83         | 0.0164            | 0.021   | <b>0.0001</b>                                             | 0.8090   | <b>0.0018</b>                                              | 0.0180  | <b>0.0008</b>                                             | 0.0580   | <b>0.0001</b>                                              |
|      | IX21-3-D2D10 | 105                            | 40   | 8.33E-06                     | 30         | 10      | 0.83         | 0.0164            | 0.018   | <b>0.0002</b>                                             | 0.7890   | <b>0.0019</b>                                              | 0.0170  | <b>0.0007</b>                                             | 0.0530   | <b>0.0000</b>                                              |
| 5    | IX21-3-E2D1  | 270                            | 40   | 8.33E-06                     | 3          | 11      | 0.83         | 0.0164            | 0.154   | 0.0049                                                    | 2.879    | 0.0146                                                     | 0.0536  | 0.0053                                                    | 0.2856   | 0.0062                                                     |
|      | IX21-3-E2D2  | 270                            | 40   | 8.33E-06                     | 6          | 11      | 0.83         | 0.0164            | 0.165   | 0.0028                                                    | 2.619    | 0.0056                                                     | 0.0525  | 0.0025                                                    | 0.1817   | -0.0002                                                    |
|      | IX21-3-E2D3  | 270                            | 40   | 8.33E-06                     | 9          | 11      | 0.83         | 0.0164            | 0.159   | 0.0024                                                    | 2.334    | 0.0046                                                     | 0.0494  | 0.0020                                                    | 0.1785   | 0.0014                                                     |
|      | IX21-3-E2D4  | 270                            | 40   | 8.33E-06                     | 12         | 11      | 0.83         | 0.0164            | 0.141   | 0.0020                                                    | 2.101    | 0.0040                                                     | 0.0462  | 0.0018                                                    | 0.1691   | 0.0011                                                     |
|      | IX21-3-E2D5  | 270                            | 40   | 8.33E-06                     | 15         | 11      | 0.83         | 0.0164            | 0.129   | 0.0019                                                    | 1.926    | 0.0036                                                     | 0.0441  | 0.0017                                                    | 0.1607   | 0.0010                                                     |
|      | IX21-3-E2D6  | 270                            | 40   | 8.33E-06                     | 18         | 11      | 0.83         | 0.0164            | 0.118   | 0.0017                                                    | 1.886    | 0.0039                                                     | 0.0483  | 0.0026                                                    | 0.1439   | 0.0006                                                     |
|      | IX21-3-E2D7  | 270                            | 40   | 8.33E-06                     | 21         | 11      | 0.83         | 0.0164            | 0.095   | <b>0.0011</b>                                             | 1.638    | <b>0.0024</b>                                              | 0.0389  | <b>0.0007</b>                                             | 0.1323   | 0.0005                                                     |
|      | IX21-3-E2D8  | 270                            | 40   | 8.33E-06                     | 24         | 11      | 0.83         | 0.0164            | 0.091   | <b>0.0014</b>                                             | 1.649    | <b>0.0033</b>                                              | 0.0378  | <b>0.0013</b>                                             | 0.1659   | <b>0.0017</b>                                              |
|      | IX21-3-E2D9  | 270                            | 40   | 8.33E-06                     | 27         | 11      | 0.83         | 0.0164            | 0.072   | <b>0.0008</b>                                             | 1.493    | <b>0.0023</b>                                              | 0.0378  | <b>0.0014</b>                                             | 0.1302   | <b>0.0001</b>                                              |
|      | IX21-3-E2D10 | 270                            | 40   | 8.33E-06                     | 30         | 11      | 0.83         | 0.01638           | 0.077   | <b>0.0013</b>                                             | 1.512    | <b>0.0029</b>                                              | 0.0609  | <i>0.0051</i>                                             | 0.1292   | <b>0.0006</b>                                              |

Table A9. DCP-AES Analysis Results from Dissolution of Glass IDFIX21-3 at 23 °C.

| Exp. | Sample ID    | Target [Si] <sub>inf</sub> ppm | T °C | Flow Rate, m <sup>3</sup> /d | Time, days | pH 23°C | Glass Mass g | SA m <sup>2</sup> | [B] ppm | B Rate g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [Na] ppm | Na Rate g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [K] ppm | K Rate g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [Al] ppm | Al Rate g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> |
|------|--------------|--------------------------------|------|------------------------------|------------|---------|--------------|-------------------|---------|-----------------------------------------------------------|----------|------------------------------------------------------------|---------|-----------------------------------------------------------|----------|------------------------------------------------------------|
| 1    | IX21-3-A3D1  | 35                             | 23   | 8.33E-06                     | 3          | 7       | 3.28         | 0.065044          | 1.090   | 0.0090                                                    | 14.6280  | 0.0239                                                     | 0.2830  | 0.0109                                                    | 0.0720   | 0.0004                                                     |
|      | IX21-3-A3D2  | 35                             | 23   | 8.33E-06                     | 6          | 7       | 3.28         | 0.065033          | 0.952   | 0.0033                                                    | 10.4860  | 0.0052                                                     | 0.2110  | 0.0025                                                    | 0.0620   | 0.0001                                                     |
|      | IX21-3-A3D3  | 35                             | 23   | 8.33E-06                     | 9          | 7       | 3.28         | 0.065023          | 0.820   | 0.0028                                                    | 7.4630   | 0.0036                                                     | 0.1650  | 0.0021                                                    | 0.0480   | 0.0000                                                     |
|      | IX21-3-A3D4  | 35                             | 23   | 8.33E-06                     | 12         | 7       | 3.28         | 0.065015          | 0.736   | 0.0027                                                    | 5.7090   | 0.0032                                                     | 0.1460  | 0.0022                                                    | 0.0480   | 0.0001                                                     |
|      | IX21-3-A3D5  | 35                             | 23   | 8.33E-06                     | 15         | 7       | 3.28         | 0.065008          | 0.610   | 0.0020                                                    | 4.5700   | 0.0028                                                     | 0.1180  | 0.0015                                                    | 0.0440   | 0.0001                                                     |
|      | IX21-3-A3D6  | 35                             | 23   | 8.33E-06                     | 18         | 7       | 3.28         | 0.065002          | 0.527   | 0.0018                                                    | 3.6460   | 0.0022                                                     | 0.1040  | 0.0015                                                    | 0.0620   | 0.0002                                                     |
|      | IX21-3-A3D7  | 35                             | 23   | 8.33E-06                     | 21         | 7       | 3.28         | 0.064997          | 0.499   | 0.0019                                                    | 3.2600   | 0.0023                                                     | 0.1020  | 0.0017                                                    | 0.0410   | 0.0000                                                     |
|      | IX21-3-A3D8  | 35                             | 23   | 8.33E-06                     | 24         | 7       | 3.28         | 0.064991          | 0.464   | <b>0.0018</b>                                             | 2.8700   | <b>0.0020</b>                                              | 0.0910  | <b>0.0013</b>                                             | 0.0680   | <b>0.0003</b>                                              |
|      | IX21-3-A3D9  | 35                             | 23   | 8.33E-06                     | 27         | 7       | 3.28         | 0.064987          | 0.402   | <b>0.0014</b>                                             | 2.4340   | <b>0.0016</b>                                              | 0.0810  | <b>0.0011</b>                                             | 0.0470   | <b>0.0000</b>                                              |
|      | IX21-3-A3D10 | 35                             | 23   | 8.33E-06                     | 30         | 7       | 3.28         | 0.064982          | 0.423   | <b>0.0018</b>                                             | 2.4290   | <b>0.0019</b>                                              | 0.0860  | <b>0.0015</b>                                             | 0.0700   | <b>0.0003</b>                                              |
| 2    | IX21-3-B3D1  | 40                             | 23   | 8.33E-06                     | 3          | 8       | 3.28         | 0.065047          | 0.427   | 0.0035                                                    | 8.4380   | 0.0137                                                     | 0.1170  | 0.0041                                                    | 0.0560   | 0.00028                                                    |
|      | IX21-3-B3D2  | 40                             | 23   | 8.33E-06                     | 6          | 8       | 3.28         | 0.065043          | 0.342   | 0.0010                                                    | 5.7550   | 0.0025                                                     | 0.0830  | 0.0006                                                    | 0.0660   | 0.00022                                                    |
|      | IX21-3-B3D3  | 40                             | 23   | 8.33E-06                     | 9          | 8       | 3.28         | 0.065040          | 0.300   | 0.0011                                                    | 4.2850   | 0.0022                                                     | 0.0680  | 0.0007                                                    | 0.0590   | 0.00012                                                    |
|      | IX21-3-B3D4  | 40                             | 23   | 8.33E-06                     | 12         | 8       | 3.28         | 0.065038          | 0.251   | 0.0008                                                    | 3.2990   | 0.0018                                                     | 0.0520  | 0.0004                                                    | < 0.008  | Not available                                              |
|      | IX21-3-B3D5  | 40                             | 23   | 8.33E-06                     | 15         | 8       | 3.28         | 0.065034          | 0.198   | 0.0006                                                    | 2.5260   | 0.0014                                                     | 0.0480  | 0.0005                                                    | 0.0530   | Not available                                              |
|      | IX21-3-B3D6  | 40                             | 23   | 8.33E-06                     | 18         | 8       | 3.28         | 0.065033          | 0.159   | 0.0005                                                    | 1.9960   | 0.0011                                                     | 0.0370  | 0.0002                                                    | 0.0490   | 0.00010                                                    |
|      | IX21-3-B3D7  | 40                             | 23   | 8.33E-06                     | 21         | 8       | 3.28         | 0.065031          | 0.143   | <b>0.0005</b>                                             | 1.7500   | <b>0.0012</b>                                              | 0.0350  | <b>0.0003</b>                                             | 0.0480   | <b>0.00010</b>                                             |
|      | IX21-3-B3D8  | 40                             | 23   | 8.33E-06                     | 24         | 8       | 3.28         | 0.065030          | 0.116   | <b>0.0004</b>                                             | 1.4370   | <b>0.0009</b>                                              | 0.0290  | <b>0.0001</b>                                             | 0.0440   | <b>0.00008</b>                                             |
|      | IX21-3-B3D9  | 40                             | 23   | 8.33E-06                     | 27         | 8       | 3.28         | 0.065028          | 0.112   | <b>0.0004</b>                                             | 1.3400   | <b>0.0010</b>                                              | 0.0300  | <b>0.0003</b>                                             | 0.0420   | <b>0.00008</b>                                             |
|      | IX21-3-B3D10 | 40                             | 23   | 8.33E-06                     | 30         | 8       | 3.28         | 0.065027          | 0.130   | 0.0006                                                    | 1.3480   | <b>0.0010</b>                                              | 0.0390  | <b>0.0006</b>                                             | 0.0750   | <b>0.00035</b>                                             |
| 3    | IX21-3-C3D1  | 52                             | 23   | 8.33E-06                     | 3          | 9       | 3.28         | 0.065048          | 0.259   | 0.0021                                                    | 6.8150   | 0.0110                                                     | 0.0790  | -0.0036                                                   | 0.0920   | 0.0005                                                     |
|      | IX21-3-C3D2  | 52                             | 23   | 8.33E-06                     | 6          | 9       | 3.28         | 0.065045          | 0.242   | 0.0009                                                    | 4.6800   | 0.0020                                                     | 0.0610  | -0.0026                                                   | 0.1170   | 0.0005                                                     |
|      | IX21-3-C3D3  | 52                             | 23   | 8.33E-06                     | 9          | 9       | 3.28         | 0.065043          | 0.196   | 0.0006                                                    | 3.4380   | 0.0017                                                     | 0.0440  | -0.0029                                                   | 0.0500   | -0.0002                                                    |
|      | IX21-3-C3D4  | 52                             | 23   | 8.33E-06                     | 12         | 9       | 3.28         | 0.065041          | 0.171   | 0.0006                                                    | 2.6860   | 0.0015                                                     | 0.0390  | -0.0027                                                   | 0.0500   | 0.0001                                                     |
|      | IX21-3-C3D5  | 52                             | 23   | 8.33E-06                     | 15         | 9       | 3.28         | 0.065040          | 0.135   | 0.0004                                                    | 2.0730   | 0.0011                                                     | 0.0310  | -0.0030                                                   | 0.0500   | 0.0001                                                     |
|      | IX21-3-C3D6  | 52                             | 23   | 8.33E-06                     | 18         | 9       | 3.28         | 0.065038          | 0.104   | 0.0003                                                    | 1.6620   | 0.0009                                                     | 0.0270  | -0.0030                                                   | 0.0440   | 0.0000                                                     |
|      | IX21-3-C3D7  | 52                             | 23   | 8.33E-06                     | 21         | 9       | 3.28         | 0.065037          | 0.095   | 0.0003                                                    | 1.5030   | 0.0010                                                     | 0.0250  | -0.0030                                                   | 0.0450   | 0.0001                                                     |
|      | IX21-3-C3D8  | 52                             | 23   | 8.33E-06                     | 24         | 9       | 3.28         | 0.065036          | 0.073   | <b>0.0002</b>                                             | 1.2360   | <b>0.0007</b>                                              | 0.0220  | -0.0030                                                   | 0.0300   | -0.0001                                                    |
|      | IX21-3-C3D9  | 52                             | 23   | 8.33E-06                     | 27         | 9       | 3.28         | 0.065036          | 0.062   | <b>0.0002</b>                                             | 1.0780   | <b>0.0006</b>                                              | 0.0210  | -0.0030                                                   | 0.0400   | 0.0001                                                     |
|      | IX21-3-C3D10 | 52                             | 23   | 8.33E-06                     | 30         | 9       | 3.28         | 0.065035          | 0.062   | <b>0.0002</b>                                             | 1.0250   | <b>0.0007</b>                                              | 0.0200  | -0.0030                                                   | 0.0370   | 0.0000                                                     |
| 4    | IX21-3-D3D1  | 90                             | 23   | 8.33E-06                     | 3          | 10      | 1.64         | 0.032524          | 0.175   | 0.0028                                                    | 3.4750   | 0.0110                                                     | 0.0480  | 0.0030                                                    | 0.1350   | 0.0014                                                     |
|      | IX21-3-D3D2  | 90                             | 23   | 8.33E-06                     | 6          | 10      | 1.64         | 0.032522          | 0.159   | 0.0012                                                    | 2.5740   | 0.0024                                                     | 0.0400  | 0.0009                                                    | 0.1100   | 0.0003                                                     |
|      | IX21-3-D3D3  | 90                             | 23   | 8.33E-06                     | 9          | 10      | 1.64         | 0.032520          | 0.150   | 0.0011                                                    | 2.0780   | 0.0023                                                     | 0.0410  | 0.0013                                                    | 0.0950   | 0.0003                                                     |
|      | IX21-3-D3D4  | 90                             | 23   | 8.33E-06                     | 12         | 10      | 1.64         | 0.032519          | 0.123   | 0.0008                                                    | 1.6420   | 0.0017                                                     | 0.0530  | 0.0022                                                    | 0.0880   | 0.0003                                                     |
|      | IX21-3-D3D5  | 90                             | 23   | 8.33E-06                     | 15         | 10      | 1.64         | 0.032518          | 0.096   | 0.0005                                                    | 1.2740   | 0.0012                                                     | 0.0380  | 0.0005                                                    | 0.0660   | 0.0000                                                     |
|      | IX21-3-D3D6  | 90                             | 23   | 8.33E-06                     | 18         | 10      | 1.64         | 0.032517          | 0.078   | 0.0005                                                    | 1.0610   | 0.0011                                                     | 0.0310  | 0.0005                                                    | 0.0740   | 0.0003                                                     |
|      | IX21-3-D3D7  | 90                             | 23   | 8.33E-06                     | 21         | 10      | 1.64         | 0.032516          | 0.068   | 0.0005                                                    | 0.9530   | 0.0011                                                     | 0.0320  | 0.0009                                                    | 0.0680   | 0.0001                                                     |
|      | IX21-3-D3D8  | 90                             | 23   | 8.33E-06                     | 24         | 10      | 1.64         | 0.032516          | 0.051   | <b>0.0003</b>                                             | 0.7930   | <b>0.0007</b>                                              | 0.0260  | <b>0.0004</b>                                             | 0.0550   | -0.00003                                                   |
|      | IX21-3-D3D9  | 90                             | 23   | 8.33E-06                     | 27         | 10      | 1.64         | 0.032515          | 0.042   | <b>0.0002</b>                                             | 0.7060   | <b>0.0007</b>                                              | 0.0250  | <b>0.0005</b>                                             | 0.0600   | <b>0.0002</b>                                              |
|      | IX21-3-D3D10 | 90                             | 23   | 8.33E-06                     | 30         | 10      | 1.64         | 0.032515          | 0.039   | <b>0.0003</b>                                             | 0.6800   | <b>0.0008</b>                                              | 0.0290  | <b>0.0009</b>                                             | 0.0600   | <b>0.0001</b>                                              |
| 5    | IX21-3-E3D1  | 230                            | 23   | 8.33E-06                     | 3          | 11      | 1.64         | 0.032524          | 0.096   | 0.0015                                                    | 2.875    | 0.0075                                                     | 0.0410  | 0.0019                                                    | 0.2520   | 0.0022                                                     |
|      | IX21-3-E3D2  | 230                            | 23   | 8.33E-06                     | 6          | 11      | 1.64         | 0.032523          | 0.109   | 0.0010                                                    | 2.388    | 0.0021                                                     | 0.0368  | 0.0006                                                    | 0.1743   | -0.0001                                                    |
|      | IX21-3-E3D3  | 230                            | 23   | 8.33E-06                     | 9          | 11      | 1.64         | 0.032522          | 0.118   | 0.0010                                                    | 2.007    | 0.0017                                                     | 0.0357  | 0.0007                                                    | 0.1712   | 0.0004                                                     |
|      | IX21-3-E3D4  | 230                            | 23   | 8.33E-06                     | 12         | 11      | 1.64         | 0.032521          | 0.123   | 0.0010                                                    | 1.818    | 0.0017                                                     | 0.0368  | 0.0008                                                    | 0.1796   | 0.0006                                                     |
|      | IX21-3-E3D5  | 230                            | 23   | 8.33E-06                     | 15         | 11      | 1.64         | 0.032519          | 0.128   | 0.0011                                                    | 1.783    | 0.0019                                                     | 0.0410  | 0.0011                                                    | 0.1964   | 0.0008                                                     |
|      | IX21-3-E3D6  | 230                            | 23   | 8.33E-06                     | 18         | 11      | 1.64         | 0.032518          | 0.105   | 0.0006                                                    | 1.498    | 0.0010                                                     | 0.0347  | 0.0004                                                    | 0.1775   | 0.0003                                                     |
|      | IX21-3-E3D7  | 230                            | 23   | 8.33E-06                     | 21         | 11      | 1.64         | 0.032517          | 0.103   | 0.0008                                                    | 1.484    | 0.0014                                                     | 0.0368  | 0.0009                                                    | 0.1764   | 0.0005                                                     |
|      | IX21-3-E3D8  | 230                            | 23   | 8.33E-06                     | 24         | 11      | 1.64         | 0.032516          | 0.079   | <b>0.0004</b>                                             | 1.261    | <b>0.0007</b>                                              | 0.0294  | <b>0.0002</b>                                             | 0.1586   | <b>0.0002</b>                                              |
|      | IX21-3-E3D9  | 230                            | 23   | 8.33E-06                     | 27         | 11      | 1.64         | 0.032515          | 0.064   | <b>0.0004</b>                                             | 1.167    | <b>0.0008</b>                                              | 0.0284  | <b>0.0004</b>                                             | 0.1481   | <b>0.0002</b>                                              |
|      | IX21-3-E3D10 | 230                            | 23   | 8.33E-06                     | 30         | 11      | 1.64         | 0.032515          | 0.078   | <b>0.0007</b>                                             | 1.244    | <b>0.0012</b>                                              | 0.0357  | <b>0.0010</b>                                             | 0.1701   | 0.0006                                                     |

**Table A10. DCP-AES Analysis Results from Dissolution of Glass IDFIX21-4at 70°C.**

| Exp. | Sample ID    | Target<br>[Si] <sub>inf</sub><br>ppm | T<br>°C | Flow Rate,<br>m <sup>3</sup> /d | Time,<br>days | pH<br>23°C | Glass<br>Mass g | SA<br>m <sup>2</sup> | [B]<br>ppm | B Rate<br>g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [Na]<br>ppm | Na Rate<br>g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [K]<br>ppm | K Rate<br>g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [Al]<br>ppm | Al Rate<br>g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> |
|------|--------------|--------------------------------------|---------|---------------------------------|---------------|------------|-----------------|----------------------|------------|--------------------------------------------------------------|-------------|---------------------------------------------------------------|------------|--------------------------------------------------------------|-------------|---------------------------------------------------------------|
| 1    | IX21-4-A1D1  | 55                                   | 70      | 2.50E-05                        | 1             | 7          | 0.77            | 0.01510              | 25.204     | 2.4433                                                       | 115.3100    | 2.4485                                                        | 18.8600    | 1.5034                                                       | 0.1198      | 0.0018                                                        |
|      | IX21-4-A1D2  | 55                                   | 70      | 2.50E-05                        | 2             | 7          | 0.77            | 0.01484              | 28.277     | 1.5462                                                       | 129.2300    | 1.5468                                                        | 21.7180    | 0.9970                                                       | 0.1174      | 0.0048                                                        |
|      | IX21-4-A1D3  | 55                                   | 70      | 2.50E-05                        | 3             | 7          | 0.77            | 0.01456              | 29.011     | 1.4954                                                       | 136.1200    | 1.5751                                                        | 22.9550    | 1.0004                                                       | 0.1144      | 0.0047                                                        |
|      | IX21-4-A1D4  | 55                                   | 70      | 2.50E-05                        | 4             | 7          | 0.77            | 0.01428              | 27.527     | 1.3349                                                       | 126.4300    | 1.3107                                                        | 22.3260    | 0.9147                                                       | 0.1190      | 0.0055                                                        |
|      | IX21-4-A1D5  | 55                                   | 70      | 2.50E-05                        | 5             | 7          | 0.77            | 0.01401              | 25.108     | 1.1848                                                       | 114.8200    | 1.1804                                                        | 21.2310    | 0.8648                                                       | 0.1087      | 0.0042                                                        |
|      | IX21-4-A1D6  | 55                                   | 70      | 2.50E-05                        | 6             | 7          | 0.77            | 0.01377              | 23.761     | 1.1914                                                       | 109.9900    | 1.2243                                                        | 20.8560    | 0.8953                                                       | 0.1190      | 0.0060                                                        |
|      | IX21-4-A1D7  | 55                                   | 70      | 2.50E-05                        | 7             | 7          | 0.77            | 0.01353              | 21.829     | 1.0757                                                       | 102.9200    | 1.1349                                                        | 19.5250    | 0.8089                                                       | 0.1858      | 0.0131                                                        |
|      | IX21-4-A1D8  | 55                                   | 70      | 2.50E-05                        | 8             | 7          | 0.77            | 0.01332              | 20.461     | <b>1.0491</b>                                                | 102.2700    | <b>1.2229</b>                                                 | 18.8760    | <b>0.8236</b>                                                | 0.1226      | <b>0.0021</b>                                                 |
|      | IX21-4-A1D9  | 55                                   | 70      | 2.50E-05                        | 9             | 7          | 0.77            | 0.01311              | 18.906     | <b>0.9682</b>                                                | 90.8530     | <b>0.9705</b>                                                 | 17.7330    | <b>0.7611</b>                                                | 0.1146      | <b>0.0049</b>                                                 |
|      | IX21-4-A1D10 | 55                                   | 70      | 2.50E-05                        | 10            | 7          | 0.77            | 0.01293              | 16.931     | <b>0.8466</b>                                                | 78.8160     | <b>0.8274</b>                                                 | 15.8270    | <b>0.6477</b>                                                | 0.1067      | <b>0.0045</b>                                                 |
| 2    | IX21-4-B1D1  | 60                                   | 70      | 2.50E-05                        | 1             | 8          | 0.77            | 0.01512              | 19.857     | 1.8570                                                       | 85.3390     | 1.8083                                                        | 14.2850    | 1.1370                                                       | 0.1457      | 0.00699                                                       |
|      | IX21-4-B1D2  | 60                                   | 70      | 2.50E-05                        | 2             | 8          | 0.77            | 0.01493              | 19.977     | 0.9850                                                       | 85.4000     | 0.9172                                                        | 14.7380    | 0.6124                                                       | 0.1216      | 0.00370                                                       |
|      | IX21-4-B1D3  | 60                                   | 70      | 2.50E-05                        | 3             | 8          | 0.77            | 0.01473              | 20.535     | 1.0477                                                       | 90.5160     | 1.0403                                                        | 15.7290    | 0.6832                                                       | 0.1272      | 0.00560                                                       |
|      | IX21-4-B1D4  | 60                                   | 70      | 2.50E-05                        | 4             | 8          | 0.77            | 0.01453              | 21.099     | 1.0912                                                       | 93.0710     | 1.0549                                                        | 16.4020    | 0.7076                                                       | 0.1298      | 0.00566                                                       |
|      | IX21-4-B1D5  | 60                                   | 70      | 2.50E-05                        | 5             | 8          | 0.77            | 0.01433              | 18.969     | 0.8599                                                       | 84.9070     | 0.8580                                                        | 15.2610    | 0.5931                                                       | 0.1305      | 0.00567                                                       |
|      | IX21-4-B1D6  | 60                                   | 70      | 2.50E-05                        | 6             | 8          | 0.77            | 0.01415              | 16.575     | 0.7332                                                       | 78.3370     | 0.8123                                                        | 13.2880    | 0.4811                                                       | 0.1234      | 0.00493                                                       |
|      | IX21-4-B1D7  | 60                                   | 70      | 2.50E-05                        | 7             | 8          | 0.77            | 0.01399              | 14.779     | 0.6788                                                       | 70.1150     | 0.7082                                                        | 12.2870    | 0.4852                                                       | 0.1563      | 0.00902                                                       |
|      | IX21-4-B1D8  | 60                                   | 70      | 2.50E-05                        | 8             | 8          | 0.77            | 0.01385              | 13.714     | <b>0.6682</b>                                                | 66.9450     | <b>0.7374</b>                                                 | 11.7110    | <b>0.4837</b>                                                | 0.1216      | <b>0.00339</b>                                                |
|      | IX21-4-B1D9  | 60                                   | 70      | 2.50E-05                        | 9             | 8          | 0.77            | 0.01372              | 12.250     | <b>0.5752</b>                                                | 59.5270     | <b>0.6080</b>                                                 | 10.5880    | <b>0.4150</b>                                                | 0.1117      | <b>0.00427</b>                                                |
|      | IX21-4-B1D10 | 60                                   | 70      | 2.50E-05                        | 10            | 8          | 0.77            | 0.01360              | 11.335     | <b>0.5606</b>                                                | 54.3820     | <b>0.5795</b>                                                 | 10.0970    | <b>0.4249</b>                                                | 0.1081      | <b>0.00446</b>                                                |
| 3    | IX21-4-C1D1R | 80                                   | 70      | 2.50E-05                        | 1             | 9          | 0.77            | 0.01517              | 10.629     | 1.0252                                                       | 48.8175     | 1.0252                                                        | 7.9894     | 0.6340                                                       | 0.1570      | 0.0046                                                        |
|      | IX21-4-C1D2R | 80                                   | 70      | 2.50E-05                        | 2             | 9          | 0.77            | 0.01506              | 12.096     | 0.6590                                                       | 54.1467     | 0.6323                                                        | 8.5876     | 0.3672                                                       | 0.1310      | 0.0037                                                        |
|      | IX21-4-C1D3R | 80                                   | 70      | 2.50E-05                        | 3             | 9          | 0.77            | 0.01494              | 12.364     | 0.6187                                                       | 55.0249     | 0.5990                                                        | 8.8348     | 0.3659                                                       | 0.1320      | 0.0052                                                        |
|      | IX21-4-C1D4R | 80                                   | 70      | 2.50E-05                        | 4             | 9          | 0.77            | 0.01482              | 11.466     | 0.5216                                                       | 50.9205     | 0.5053                                                        | 7.9452     | 0.2864                                                       | 0.1830      | 0.0105                                                        |
|      | IX21-4-C1D5R | 80                                   | 70      | 2.50E-05                        | 5             | 9          | 0.77            | 0.01472              | 10.431     | 0.4671                                                       | 46.5688     | 0.4588                                                        | 7.2319     | 0.2665                                                       | 0.2280      | 0.0126                                                        |
|      | IX21-4-C1D6  | 80                                   | 70      | 2.50E-05                        | 6             | 9          | 0.77            | 0.01462              | 9.512      | 0.4301                                                       | 44.4399     | 0.4629                                                        | 6.6304     | 0.2481                                                       | 0.2110      | 0.0085                                                        |
|      | IX21-4-C1D7  | 80                                   | 70      | 2.50E-05                        | 7             | 9          | 0.77            | 0.01453              | 8.643      | 0.3915                                                       | 37.6501     | 0.3393                                                        | 6.1978     | 0.2387                                                       | 0.0980      | -0.0026                                                       |
|      | IX21-4-C1D8  | 80                                   | 70      | 2.50E-05                        | 8             | 9          | 0.77            | 0.01445              | 8.138      | <b>0.3865</b>                                                | 35.5104     | <b>0.3692</b>                                                 | 5.6120     | <b>0.2093</b>                                                | 0.1150      | <b>0.0053</b>                                                 |
|      | IX21-4-C1D9  | 80                                   | 70      | 2.50E-05                        | 9             | 9          | 0.77            | 0.01437              | 7.818      | <b>0.3818</b>                                                | 34.7753     | <b>0.3787</b>                                                 | 5.4362     | <b>0.2202</b>                                                | 0.0970      | <b>0.0025</b>                                                 |
|      | IX21-4-C1D10 | 80                                   | 70      | 2.50E-05                        | 10            | 9          | 0.77            | 0.01429              | 7.184      | <b>0.3352</b>                                                | 33.3652     | <b>0.3572</b>                                                 | 5.2332     | <b>0.2117</b>                                                | 0.1000      | <b>0.0038</b>                                                 |
| 4    | IX21-4-D1D1  | 140                                  | 70      | 2.50E-05                        | 1             | 10         | 0.50            | 0.00976              | 4.725      | 0.7081                                                       | 19.0360     | 0.6169                                                        | 2.6220     | 0.3208                                                       | 0.1286      | -0.0044                                                       |
|      | IX21-4-D1D2  | 140                                  | 70      | 2.50E-05                        | 2             | 10         | 0.50            | 0.00971              | 5.824      | 0.5215                                                       | 23.4580     | 0.4562                                                        | 3.3034     | 0.2458                                                       | 0.0952      | 0.0002                                                        |
|      | IX21-4-D1D3  | 140                                  | 70      | 2.50E-05                        | 3             | 10         | 0.50            | 0.00965              | 5.669      | 0.4178                                                       | 22.9980     | 0.3701                                                        | 3.1460     | 0.1850                                                       | 0.0796      | 0.0004                                                        |
|      | IX21-4-D1D4  | 140                                  | 70      | 2.50E-05                        | 4             | 10         | 0.50            | 0.00960              | 5.223      | 0.3639                                                       | 21.7760     | 0.3390                                                        | 3.0387     | 0.1825                                                       | 0.0689      | 0.0000                                                        |
|      | IX21-4-D1D5  | 140                                  | 70      | 2.50E-05                        | 5             | 10         | 0.50            | 0.00955              | 5.088      | 0.3792                                                       | 20.2110     | 0.3087                                                        | 2.7697     | 0.1563                                                       | 0.0657      | 0.0003                                                        |
|      | IX21-4-D1D6  | 140                                  | 70      | 2.50E-05                        | 6             | 10         | 0.50            | 0.00950              | 4.560      | 0.3102                                                       | 19.1380     | 0.3004                                                        | 2.6675     | 0.1611                                                       | 0.0638      | 0.0003                                                        |
|      | IX21-4-D1D7  | 140                                  | 70      | 2.50E-05                        | 7             | 10         | 0.50            | 0.00946              | 4.547      | 0.3506                                                       | 18.5590     | 0.3004                                                        | 2.6709     | 0.1688                                                       | 0.0605      | -0.0001                                                       |
|      | IX21-4-D1D8  | 140                                  | 70      | 2.50E-05                        | 8             | 10         | 0.50            | 0.00942              | 4.393      | <b>0.3292</b>                                                | 18.0710     | <b>0.2950</b>                                                 | 2.6834     | <b>0.1710</b>                                                | 0.0650      | 0.0009                                                        |
|      | IX21-4-D1D9  | 140                                  | 70      | 2.50E-05                        | 9             | 10         | 0.50            | 0.00937              | 4.031      | <b>0.2862</b>                                                | 17.3010     | <b>0.2783</b>                                                 | 2.4816     | <b>0.1450</b>                                                | 0.0505      | -0.0019                                                       |
|      | IX21-4-D1D10 | 140                                  | 70      | 2.50E-05                        | 10            | 10         | 0.50            | 0.00933              | 4.058      | <b>0.3201</b>                                                | 18.1560     | <b>0.3221</b>                                                 | 2.8293     | <b>0.2036</b>                                                | 0.1389      | 0.0140                                                        |
| 5    | IX21-4-E1D1  | 360                                  | 70      | 2.50E-05                        | 1             | 11         | 0.50            | 0.00978              | 1.618      | 0.2417                                                       | 8.812       | 0.2594                                                        | 1.1808     | 0.1400                                                       | 0.1419      | 0.0040                                                        |
|      | IX21-4-E1D2  | 360                                  | 70      | 2.50E-05                        | 2             | 11         | 0.50            | 0.00976              | 1.871      | 0.1591                                                       | 9.057       | 0.1380                                                        | 1.2795     | 0.0823                                                       | 0.1233      | -0.0010                                                       |
|      | IX21-4-E1D3  | 360                                  | 70      | 2.50E-05                        | 3             | 11         | 0.50            | 0.00974              | 1.724      | 0.1182                                                       | 8.661       | 0.1212                                                        | 1.1711     | 0.0629                                                       | 0.1029      | -0.0027                                                       |
|      | IX21-4-E1D4  | 360                                  | 70      | 2.50E-05                        | 4             | 11         | 0.50            | 0.00973              | 1.627      | 0.1149                                                       | 7.960       | 0.1048                                                        | 1.1071     | 0.0618                                                       | 0.1008      | -0.0014                                                       |
|      | IX21-4-E1D5  | 360                                  | 70      | 2.50E-05                        | 5             | 11         | 0.50            | 0.00971              | 1.308      | 0.0743                                                       | 7.735       | 0.1091                                                        | 0.9258     | 0.0434                                                       | 0.0978      | -0.0018                                                       |
|      | IX21-4-E1D6  | 360                                  | 70      | 2.50E-05                        | 6             | 11         | 0.50            | 0.00970              | 1.180      | 0.0791                                                       | 6.979       | 0.0879                                                        | 0.8465     | 0.0448                                                       | 0.1009      | -0.0010                                                       |
|      | IX21-4-E1D7  | 360                                  | 70      | 2.50E-05                        | 7             | 11         | 0.50            | 0.00969              | 1.083      | 0.0743                                                       | 6.070       | 0.0704                                                        | 0.7946     | 0.0434                                                       | 0.1026      | -0.0010                                                       |
|      | IX21-4-E1D8  | 360                                  | 70      | 2.50E-05                        | 8             | 11         | 0.50            | 0.00968              | 0.970      | <b>0.0646</b>                                                | 5.646       | <b>0.0715</b>                                                 | 0.7460     | <b>0.0406</b>                                                | 0.0908      | -0.0030                                                       |
|      | IX21-4-E1D9  | 360                                  | 70      | 2.50E-05                        | 9             | 11         | 0.50            | 0.00967              | 0.851      | <b>0.0551</b>                                                | 5.176       | <b>0.0630</b>                                                 | 0.6831     | <b>0.0358</b>                                                | 0.0975      | -0.0010                                                       |
|      | IX21-4-E1D10 | 360                                  | 70      | 2.50E-05                        | 10            | 11         | 0.50            | 0.00966              | 0.785      | <b>0.0543</b>                                                | 4.855       | <b>0.0602</b>                                                 | 0.6657     | <b>0.0376</b>                                                | 0.0988      | -0.0013                                                       |

Table A11. DCP-AES Analysis Results from Dissolution of Glass IDFIX21-4 at 40°C.

| Exp. | Sample ID    | Target<br>[Si] <sub>inf</sub><br>ppm | T<br>°C | Flow Rate,<br>m <sup>3</sup> /d | Time,<br>days | pH<br>23°C | Glass<br>Mass g | SA<br>m <sup>2</sup> | [B]<br>ppm | B Rate<br>g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [Na]<br>ppm | Na Rate<br>g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [K]<br>ppm | K Rate<br>g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [Al]<br>ppm | Al Rate<br>g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> |
|------|--------------|--------------------------------------|---------|---------------------------------|---------------|------------|-----------------|----------------------|------------|--------------------------------------------------------------|-------------|---------------------------------------------------------------|------------|--------------------------------------------------------------|-------------|---------------------------------------------------------------|
| 1    | IX21-4-A2D1  | 40                                   | 40      | 8.33E-06                        | 3             | 7          | 1.65            | 0.0326               | 12.370     | 0.1854                                                       | 56.9840     | 0.1870                                                        | 9.7410     | 0.1201                                                       | 0.0830      | 0.0010                                                        |
|      | IX21-4-A2D2  | 40                                   | 40      | 8.33E-06                        | 6             | 7          | 1.65            | 0.0324               | 14.251     | 0.1213                                                       | 63.9310     | 0.1168                                                        | 10.8910    | 0.0745                                                       | 0.0790      | 0.0004                                                        |
|      | IX21-4-A2D3  | 40                                   | 40      | 8.33E-06                        | 9             | 7          | 1.65            | 0.0323               | 14.487     | 0.1112                                                       | 64.6910     | 0.1083                                                        | 10.9930    | 0.0690                                                       | 0.0810      | 0.0005                                                        |
|      | IX21-4-A2D4  | 40                                   | 40      | 8.33E-06                        | 12            | 7          | 1.65            | 0.0321               | 13.801     | 0.0995                                                       | 62.0980     | 0.0989                                                        | 10.6060    | 0.0638                                                       | 0.0580      | 0.0001                                                        |
|      | IX21-4-A2D5  | 40                                   | 40      | 8.33E-06                        | 15            | 7          | 1.65            | 0.0320               | 13.363     | 0.0985                                                       | 58.8830     | 0.0929                                                        | 10.3730    | 0.0636                                                       | 0.0530      | 0.0002                                                        |
|      | IX21-4-A2D6  | 40                                   | 40      | 8.33E-06                        | 18            | 7          | 1.65            | 0.0319               | 12.975     | 0.0963                                                       | 55.7530     | 0.0881                                                        | 10.2330    | 0.0635                                                       | 0.0520      | 0.0002                                                        |
|      | IX21-4-A2D7  | 40                                   | 40      | 8.33E-06                        | 21            | 7          | 1.65            | 0.0318               | 12.857     | 0.0978                                                       | 55.3390     | 0.0924                                                        | 10.1900    | 0.0641                                                       | 0.0560      | 0.0003                                                        |
|      | IX21-4-A2D8  | 40                                   | 40      | 8.33E-06                        | 24            | 7          | 1.65            | 0.0316               | 11.933     | <b>0.0849</b>                                                | 52.2380     | <b>0.0829</b>                                                 | 9.5660     | <b>0.0567</b>                                                | 0.0580      | <b>0.0003</b>                                                 |
|      | IX21-4-A2D9  | 40                                   | 40      | 8.33E-06                        | 27            | 7          | 1.65            | 0.0315               | 11.585     | <b>0.0869</b>                                                | 51.0120     | <b>0.0843</b>                                                 | 9.3300     | <b>0.0579</b>                                                | 0.0670      | <b>0.0004</b>                                                 |
|      | IX21-4-A2D10 | 40                                   | 40      | 8.33E-06                        | 30            | 7          | 1.65            | 0.0314               | 11.222     | <b>0.0843</b>                                                | 48.4120     | <b>0.0779</b>                                                 | 8.9960     | <b>0.0553</b>                                                | 0.0690      | <b>0.0004</b>                                                 |
| 2    | IX21-4-B2D1  | 45                                   | 40      | 8.33E-06                        | 3             | 8          | 1.65            | 0.0326               | 6.057      | 0.0906                                                       | 29.2320     | 0.0957                                                        | 4.8490     | 0.0597                                                       | 0.1450      | 0.00200                                                       |
|      | IX21-4-B2D2  | 45                                   | 40      | 8.33E-06                        | 6             | 8          | 1.65            | 0.0325               | 7.165      | 0.0620                                                       | 32.7480     | 0.0595                                                        | 5.3210     | 0.0357                                                       | 0.1010      | 0.00030                                                       |
|      | IX21-4-B2D3  | 45                                   | 40      | 8.33E-06                        | 9             | 8          | 1.65            | 0.0324               | 7.635      | 0.0609                                                       | 34.8060     | 0.0606                                                        | 5.5810     | 0.0361                                                       | 0.0830      | 0.00037                                                       |
|      | IX21-4-B2D4  | 45                                   | 40      | 8.33E-06                        | 12            | 8          | 1.65            | 0.0324               | 7.261      | 0.0519                                                       | 33.4690     | 0.0529                                                        | 5.3200     | 0.0313                                                       | 0.0690      | 0.00029                                                       |
|      | IX21-4-B2D5  | 45                                   | 40      | 8.33E-06                        | 15            | 8          | 1.65            | 0.0323               | 7.139      | 0.0530                                                       | 31.8350     | 0.0499                                                        | 5.1070     | 0.0304                                                       | 0.0610      | 0.00027                                                       |
|      | IX21-4-B2D6  | 45                                   | 40      | 8.33E-06                        | 18            | 8          | 1.65            | 0.0322               | 7.064      | 0.0529                                                       | 31.8650     | 0.0528                                                        | 5.1900     | 0.0328                                                       | 0.0590      | 0.00031                                                       |
|      | IX21-4-B2D7  | 45                                   | 40      | 8.33E-06                        | 21            | 8          | 1.65            | 0.0322               | 6.892      | 0.0509                                                       | 31.4850     | 0.0516                                                        | 5.0360     | 0.0304                                                       | 0.0590      | 0.00032                                                       |
|      | IX21-4-B2D8  | 45                                   | 40      | 8.33E-06                        | 24            | 8          | 1.65            | 0.0321               | 6.522      | <b>0.0467</b>                                                | 30.2040     | <b>0.0480</b>                                                 | 4.7770     | <b>0.0282</b>                                                | 0.0530      | <b>0.00023</b>                                                |
|      | IX21-4-B2D9  | 45                                   | 40      | 8.33E-06                        | 27            | 8          | 1.65            | 0.0320               | 6.342      | <b>0.0469</b>                                                | 29.2280     | <b>0.0470</b>                                                 | 4.6770     | <b>0.0286</b>                                                | 0.0720      | <b>0.00058</b>                                                |
|      | IX21-4-B2D10 | 45                                   | 40      | 8.33E-06                        | 30            | 8          | 1.65            | 0.0320               | 6.318      | <b>0.0480</b>                                                | 29.0120     | <b>0.0480</b>                                                 | 4.5930     | <b>0.0283</b>                                                | 0.0590      | <b>0.00022</b>                                                |
| 3    | IX21-4-C2D1  | 60                                   | 40      | 8.33E-06                        | 3             | 9          | 1.65            | 0.0326               | 2.930      | 0.0438                                                       | 16.1600     | 0.0527                                                        | 2.2640     | 0.0278                                                       | 0.1510      | 0.0020                                                        |
|      | IX21-4-C2D2  | 60                                   | 40      | 8.33E-06                        | 6             | 9          | 1.65            | 0.0326               | 3.909      | 0.0366                                                       | 18.6620     | 0.0346                                                        | 2.6340     | 0.0185                                                       | 0.1150      | 0.0004                                                        |
|      | IX21-4-C2D3  | 60                                   | 40      | 8.33E-06                        | 9             | 9          | 1.65            | 0.0325               | 4.121      | 0.0325                                                       | 18.8100     | 0.0310                                                        | 2.6790     | 0.0168                                                       | 0.0690      | 0.0000                                                        |
|      | IX21-4-C2D4  | 60                                   | 40      | 8.33E-06                        | 12            | 9          | 1.65            | 0.0325               | 4.052      | 0.0299                                                       | 18.5070     | 0.0298                                                        | 2.6180     | 0.0158                                                       | 0.0500      | 0.0000                                                        |
|      | IX21-4-C2D5  | 60                                   | 40      | 8.33E-06                        | 15            | 9          | 1.65            | 0.0324               | 4.045      | 0.0303                                                       | 18.3270     | 0.0297                                                        | 2.5800     | 0.0157                                                       | 0.0620      | 0.0004                                                        |
|      | IX21-4-C2D6  | 60                                   | 40      | 8.33E-06                        | 18            | 9          | 1.65            | 0.0324               | 4.043      | 0.0304                                                       | 17.9250     | 0.0287                                                        | 2.5870     | 0.0160                                                       | 0.0500      | 0.0001                                                        |
|      | IX21-4-C2D7  | 60                                   | 40      | 8.33E-06                        | 21            | 9          | 1.65            | 0.0324               | 4.021      | 0.0301                                                       | 17.5180     | 0.0281                                                        | 2.5320     | 0.0153                                                       | 0.0540      | 0.0003                                                        |
|      | IX21-4-C2D8  | 60                                   | 40      | 8.33E-06                        | 24            | 9          | 1.65            | 0.0323               | 3.884      | <b>0.0282</b>                                                | 17.5420     | <b>0.0289</b>                                                 | 2.5470     | <b>0.0159</b>                                                | 0.0430      | <b>0.0000</b>                                                 |
|      | IX21-4-C2D9  | 60                                   | 40      | 8.33E-06                        | 27            | 9          | 1.65            | 0.0323               | 3.898      | <b>0.0295</b>                                                | 17.2380     | <b>0.0279</b>                                                 | 2.4990     | <b>0.0152</b>                                                | 0.0470      | <b>0.0002</b>                                                 |
|      | IX21-4-C2D10 | 60                                   | 40      | 8.33E-06                        | 30            | 9          | 1.65            | 0.0323               | 3.831      | <b>0.0284</b>                                                | 17.4800     | <b>0.0292</b>                                                 | 2.4880     | <b>0.0154</b>                                                | 0.0420      | <b>0.0001</b>                                                 |
| 4    | IX21-4-D2D1  | 105                                  | 40      | 8.33E-06                        | 3             | 10         | 0.83            | 0.0163               | 0.807      | 0.0240                                                       | 5.1810      | 0.0327                                                        | 0.6620     | 0.0161                                                       | 0.0990      | 0.0017                                                        |
|      | IX21-4-D2D2  | 105                                  | 40      | 8.33E-06                        | 6             | 10         | 0.83            | 0.0163               | 1.081      | 0.0202                                                       | 5.3810      | 0.0177                                                        | 0.7150     | 0.0094                                                       | 0.0950      | 0.0007                                                        |
|      | IX21-4-D2D3  | 105                                  | 40      | 8.33E-06                        | 9             | 10         | 0.83            | 0.0163               | 1.287      | 0.0223                                                       | 5.6800      | 0.0190                                                        | 0.7600     | 0.0098                                                       | 0.0730      | 0.0001                                                        |
|      | IX21-4-D2D4  | 105                                  | 40      | 8.33E-06                        | 12            | 10         | 0.83            | 0.0163               | 1.288      | 0.0193                                                       | 5.5840      | 0.0174                                                        | 0.7450     | 0.0089                                                       | 0.0620      | 0.0001                                                        |
|      | IX21-4-D2D5  | 105                                  | 40      | 8.33E-06                        | 15            | 10         | 0.83            | 0.0163               | 1.296      | 0.0195                                                       | 5.3880      | 0.0164                                                        | 0.7270     | 0.0087                                                       | 0.0640      | 0.0003                                                        |
|      | IX21-4-D2D6  | 105                                  | 40      | 8.33E-06                        | 18            | 10         | 0.83            | 0.0163               | 1.280      | 0.0189                                                       | 5.3650      | 0.0170                                                        | 0.7380     | 0.0092                                                       | 0.0760      | 0.0007                                                        |
|      | IX21-4-D2D7  | 105                                  | 40      | 8.33E-06                        | 21            | 10         | 0.83            | 0.0163               | 1.338      | 0.0209                                                       | 5.4320      | 0.0175                                                        | 0.7400     | 0.0091                                                       | 0.0570      | -0.0001                                                       |
|      | IX21-4-D2D8  | 105                                  | 40      | 8.33E-06                        | 24            | 10         | 0.83            | 0.0162               | 1.298      | <b>0.0188</b>                                                | 5.4170      | <b>0.0172</b>                                                 | 0.7270     | <b>0.0087</b>                                                | 0.0530      | <b>0.0000</b>                                                 |
|      | IX21-4-D2D9  | 105                                  | 40      | 8.33E-06                        | 27            | 10         | 0.83            | 0.0162               | 1.265      | <b>0.0185</b>                                                | 5.4360      | <b>0.0174</b>                                                 | 0.7290     | <b>0.0090</b>                                                | 0.0530      | <b>0.0001</b>                                                 |
|      | IX21-4-D2D10 | 105                                  | 40      | 8.33E-06                        | 30            | 10         | 0.83            | 0.0162               | 1.255      | <b>0.0187</b>                                                | 5.4520      | <b>0.0174</b>                                                 | 0.7200     | <b>0.0087</b>                                                | 0.0610      | <b>0.0004</b>                                                 |
| 5    | IX21-4-E2D1  | 270                                  | 40      | 8.33E-06                        | 3             | 11         | 0.83            | 0.0163               | 0.291      | 0.0258                                                       | 3.749       | 0.0203                                                        | 0.4295     | 0.0100                                                       | 0.2877      | 0.0063                                                        |
|      | IX21-4-E2D2  | 270                                  | 40      | 8.33E-06                        | 6             | 11         | 0.83            | 0.0163               | 0.270      | 0.0110                                                       | 3.299       | 0.0072                                                        | 0.3507     | 0.0031                                                       | 0.1775      | -0.0004                                                       |
|      | IX21-4-E2D3  | 270                                  | 40      | 8.33E-06                        | 9             | 11         | 0.83            | 0.0163               | 0.219      | 0.0074                                                       | 2.692       | 0.0047                                                        | 0.2688     | 0.0020                                                       | 0.1334      | 0.0000                                                        |
|      | IX21-4-E2D4  | 270                                  | 40      | 8.33E-06                        | 12            | 11         | 0.83            | 0.0163               | 0.182      | 0.0063                                                       | 2.238       | 0.0037                                                        | 0.2195     | 0.0018                                                       | 0.1176      | 0.0002                                                        |
|      | IX21-4-E2D5  | 270                                  | 40      | 8.33E-06                        | 15            | 11         | 0.83            | 0.0163               | 0.170      | 0.0070                                                       | 2.118       | 0.0044                                                        | 0.2058     | 0.0021                                                       | 0.1229      | 0.0006                                                        |
|      | IX21-4-E2D6  | 270                                  | 40      | 8.33E-06                        | 18            | 11         | 0.83            | 0.0163               | 0.152      | 0.0059                                                       | 1.974       | 0.0039                                                        | 0.1911     | 0.0019                                                       | 0.1061      | 0.0000                                                        |
|      | IX21-4-E2D7  | 270                                  | 40      | 8.33E-06                        | 21            | 11         | 0.83            | 0.0163               | 0.146      | 0.0061                                                       | 1.866       | 0.0036                                                        | 0.1764     | 0.0017                                                       | 0.1050      | 0.0002                                                        |
|      | IX21-4-E2D8  | 270                                  | 40      | 8.33E-06                        | 24            | 11         | 0.83            | 0.0163               | 0.144      | <b>0.0062</b>                                                | 1.818       | <b>0.0037</b>                                                 | 0.1743     | <b>0.0019</b>                                                | 0.1061      | 0.0003                                                        |
|      | IX21-4-E2D9  | 270                                  | 40      | 8.33E-06                        | 27            | 11         | 0.83            | 0.0163               | 0.152      | <b>0.0071</b>                                                | 1.805       | <b>0.0038</b>                                                 | 0.1827     | <b>0.0021</b>                                                | 0.1344      | 0.0012                                                        |
|      | IX21-4-E2D10 | 270                                  | 40      | 8.33E-06                        | 30            | 11         | 0.83            | 0.0163               | 0.145      | <b>0.0060</b>                                                | 1.744       | <b>0.0034</b>                                                 | 0.1932     | <b>0.0022</b>                                                | 0.1187      | 0.0002                                                        |

Table A12. DCP-AES Analysis Results from Dissolution of Glass IDFIX21-4 at 23 °C.

| Exp. | Sample ID    | Target [Si] <sub>inf</sub> ppm | T °C | Flow Rate, m <sup>3</sup> /d | Time, days | pH 23°C | Glass Mass g | SA m <sup>2</sup> | [B] ppm | B Rate g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [Na] ppm | Na Rate g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [K] ppm | K Rate g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> | [Al] ppm | Al Rate g <sub>glass</sub> m <sup>-2</sup> d <sup>-1</sup> |
|------|--------------|--------------------------------|------|------------------------------|------------|---------|--------------|-------------------|---------|-----------------------------------------------------------|----------|------------------------------------------------------------|---------|-----------------------------------------------------------|----------|------------------------------------------------------------|
| 1    | IX21-4-A3D1  | 35                             | 23   | 8.33E-06                     | 3          | 7       | 3.28         | 0.064764          | 5.204   | 0.0392                                                    | 30.0790  | 0.0496                                                     | 4.6730  | 0.0289                                                    | 0.0930   | 0.0006                                                     |
|      | IX21-4-A3D2  | 35                             | 23   | 8.33E-06                     | 6          | 7       | 3.28         | 0.064709          | 6.173   | 0.0269                                                    | 31.5170  | 0.0272                                                     | 5.0070  | 0.0165                                                    | 0.0830   | 0.0002                                                     |
|      | IX21-4-A3D3  | 35                             | 23   | 8.33E-06                     | 9          | 7       | 3.28         | 0.064649          | 6.288   | 0.0241                                                    | 32.0620  | 0.0269                                                     | 4.9370  | 0.0151                                                    | 0.0780   | 0.0002                                                     |
|      | IX21-4-A3D4  | 35                             | 23   | 8.33E-06                     | 12         | 7       | 3.28         | 0.064588          | 6.397   | 0.0246                                                    | 31.9280  | 0.0263                                                     | 4.9720  | 0.0155                                                    | 0.0770   | 0.0002                                                     |
|      | IX21-4-A3D5  | 35                             | 23   | 8.33E-06                     | 15         | 7       | 3.28         | 0.064530          | 5.556   | 0.0178                                                    | 28.4090  | 0.0206                                                     | 4.3840  | 0.0118                                                    | 0.0650   | 0.0001                                                     |
|      | IX21-4-A3D6  | 35                             | 23   | 8.33E-06                     | 18         | 7       | 3.28         | 0.064480          | 4.745   | 0.0149                                                    | 23.3220  | 0.0151                                                     | 4.0320  | 0.0114                                                    | 0.0610   | 0.0001                                                     |
|      | IX21-4-A3D7  | 35                             | 23   | 8.33E-06                     | 21         | 7       | 3.28         | 0.064434          | 4.797   | 0.0183                                                    | 22.3890  | 0.0177                                                     | 4.0800  | 0.0128                                                    | 0.0600   | 0.0001                                                     |
|      | IX21-4-A3D8  | 35                             | 23   | 8.33E-06                     | 24         | 7       | 3.28         | 0.064390          | 4.268   | <b>0.0142</b>                                             | 19.6680  | <b>0.0140</b>                                              | 3.5230  | <b>0.0092</b>                                             | 0.0620   | <b>0.0002</b>                                              |
|      | IX21-4-A3D9  | 35                             | 23   | 8.33E-06                     | 27         | 7       | 3.28         | 0.064352          | 3.743   | <b>0.0122</b>                                             | 17.3940  | <b>0.0125</b>                                              | 3.1220  | <b>0.0084</b>                                             | 0.0540   | <b>0.0001</b>                                              |
|      | IX21-4-A3D10 | 35                             | 23   | 8.33E-06                     | 30         | 7       | 3.28         | 0.064315          | 3.826   | <b>0.0148</b>                                             | 17.0830  | <b>0.0139</b>                                              | 3.2900  | <b>0.0107</b>                                             | 0.0560   | <b>0.0001</b>                                              |
| 2    | IX21-4-B3D1  | 40                             | 23   | 8.33E-06                     | 3          | 8       | 3.28         | 0.064781          | 1.584   | 0.0119                                                    | 14.3980  | 0.0236                                                     | 1.8570  | 0.0114                                                    | 0.1830   | 0.00129                                                    |
|      | IX21-4-B3D2  | 40                             | 23   | 8.33E-06                     | 6          | 8       | 3.28         | 0.064765          | 1.761   | 0.0073                                                    | 11.7380  | 0.0074                                                     | 1.6520  | 0.0044                                                    | 0.1320   | 0.00024                                                    |
|      | IX21-4-B3D3  | 40                             | 23   | 8.33E-06                     | 9          | 8       | 3.28         | 0.064748          | 1.924   | 0.0079                                                    | 10.8660  | 0.0082                                                     | 1.5830  | 0.0046                                                    | 0.0990   | 0.00018                                                    |
|      | IX21-4-B3D4  | 40                             | 23   | 8.33E-06                     | 12         | 8       | 3.28         | 0.064728          | 2.041   | 0.0081                                                    | 10.2630  | 0.0079                                                     | 1.5420  | 0.0046                                                    | 0.0520   | -0.00006                                                   |
|      | IX21-4-B3D5  | 40                             | 23   | 8.33E-06                     | 15         | 8       | 3.28         | 0.064710          | 1.788   | 0.0058                                                    | 9.2300   | 0.0067                                                     | 1.3510  | 0.0035                                                    | 0.0750   | 0.00031                                                    |
|      | IX21-4-B3D6  | 40                             | 23   | 8.33E-06                     | 18         | 8       | 3.28         | 0.064694          | 1.576   | 0.0051                                                    | 7.9190   | 0.0054                                                     | 1.1890  | 0.0031                                                    | 0.0620   | 0.00011                                                    |
|      | IX21-4-B3D7  | 40                             | 23   | 8.33E-06                     | 21         | 8       | 3.28         | 0.064679          | 1.586   | 0.0060                                                    | 7.9200   | 0.0065                                                     | 1.2020  | 0.0037                                                    | 0.0670   | 0.00020                                                    |
|      | IX21-4-B3D8  | 40                             | 23   | 8.33E-06                     | 24         | 8       | 3.28         | 0.064664          | 1.404   | <b>0.0046</b>                                             | 6.5630   | <b>0.0042</b>                                              | 1.0560  | <b>0.0028</b>                                             | 0.0900   | <b>0.00037</b>                                             |
|      | IX21-4-B3D9  | 40                             | 23   | 8.33E-06                     | 27         | 8       | 3.28         | 0.064652          | 1.199   | <b>0.0037</b>                                             | 5.7780   | <b>0.0041</b>                                              | 0.9080  | <b>0.0023</b>                                             | 0.0550   | 0.00000                                                    |
|      | IX21-4-B3D10 | 40                             | 23   | 8.33E-06                     | 30         | 8       | 3.28         | 0.064640          | 1.200   | <b>0.0045</b>                                             | 5.7000   | <b>0.0046</b>                                              | 0.9410  | <b>0.0030</b>                                             | 0.0490   | <b>0.00009</b>                                             |
| 3    | IX21-4-C3D1  | 52                             | 23   | 8.33E-06                     | 3          | 9       | 3.28         | 0.064785          | 0.900   | 0.0068                                                    | 10.3480  | 0.0168                                                     | 1.1300  | 0.0060                                                    | 0.1570   | 0.0010                                                     |
|      | IX21-4-C3D2  | 52                             | 23   | 8.33E-06                     | 6          | 9       | 3.28         | 0.064776          | 0.896   | 0.0033                                                    | 8.5720   | 0.0055                                                     | 0.8720  | 0.0014                                                    | 0.1000   | 0.0001                                                     |
|      | IX21-4-C3D3  | 52                             | 23   | 8.33E-06                     | 9          | 9       | 3.28         | 0.064767          | 0.895   | 0.0034                                                    | 6.9630   | 0.0043                                                     | 0.7330  | 0.0013                                                    | 0.0810   | 0.0001                                                     |
|      | IX21-4-C3D4  | 52                             | 23   | 8.33E-06                     | 12         | 9       | 3.28         | 0.064759          | 0.830   | 0.0029                                                    | 5.7500   | 0.0036                                                     | 0.6320  | 0.0011                                                    | 0.0850   | 0.0002                                                     |
|      | IX21-4-C3D5  | 52                             | 23   | 8.33E-06                     | 15         | 9       | 3.28         | 0.064751          | 0.835   | 0.0032                                                    | 4.8910   | 0.0032                                                     | 0.5840  | 0.0011                                                    | 0.0590   | 0.0000                                                     |
|      | IX21-4-C3D6  | 52                             | 23   | 8.33E-06                     | 18         | 9       | 3.28         | 0.064744          | 0.742   | 0.0024                                                    | 4.1010   | 0.0026                                                     | 0.5110  | 0.0008                                                    | 0.0540   | 0.0001                                                     |
|      | IX21-4-C3D7  | 52                             | 23   | 8.33E-06                     | 21         | 9       | 3.28         | 0.064736          | 0.766   | 0.0030                                                    | 4.0400   | 0.0032                                                     | 0.5360  | 0.0012                                                    | 0.0510   | 0.0001                                                     |
|      | IX21-4-C3D8  | 52                             | 23   | 8.33E-06                     | 24         | 9       | 3.28         | 0.064730          | 0.660   | <b>0.0021</b>                                             | 3.4810   | <b>0.0023</b>                                              | 0.4980  | <b>0.0009</b>                                             | 0.0360   | 0.0000                                                     |
|      | IX21-4-C3D9  | 52                             | 23   | 8.33E-06                     | 27         | 9       | 3.28         | 0.064723          | 0.620   | <b>0.0022</b>                                             | 3.1920   | <b>0.0023</b>                                              | 0.4360  | <b>0.0006</b>                                             | 0.0440   | <b>0.00010</b>                                             |
|      | IX21-4-C3D10 | 52                             | 23   | 8.33E-06                     | 30         | 9       | 3.28         | 0.064717          | 0.669   | <b>0.0027</b>                                             | 3.3400   | <b>0.0028</b>                                              | 0.4710  | <b>0.0011</b>                                             | 0.0420   | <b>0.00005</b>                                             |
| 4    | IX21-4-D3D1  | 90                             | 23   | 8.33E-06                     | 3          | 10      | 1.64         | 0.032393          | 0.414   | 0.0062                                                    | 4.8910   | 0.0155                                                     | 0.5480  | 0.0067                                                    | 0.1510   | 0.0017                                                     |
|      | IX21-4-D3D2  | 90                             | 23   | 8.33E-06                     | 6          | 10      | 1.64         | 0.032389          | 0.409   | 0.0030                                                    | 3.6530   | 0.0037                                                     | 0.4100  | 0.0016                                                    | 0.1050   | 0.0001                                                     |
|      | IX21-4-D3D3  | 90                             | 23   | 8.33E-06                     | 9          | 10      | 1.64         | 0.032385          | 0.417   | 0.0032                                                    | 3.0900   | 0.0039                                                     | 0.3570  | 0.0018                                                    | 0.0910   | 0.0002                                                     |
|      | IX21-4-D3D4  | 90                             | 23   | 8.33E-06                     | 12         | 10      | 1.64         | 0.032381          | 0.401   | 0.0029                                                    | 2.6540   | 0.0033                                                     | 0.3180  | 0.0017                                                    | 0.0830   | 0.0002                                                     |
|      | IX21-4-D3D5  | 90                             | 23   | 8.33E-06                     | 15         | 10      | 1.64         | 0.032377          | 0.358   | 0.0023                                                    | 2.2410   | 0.0027                                                     | 0.2720  | 0.0013                                                    | 0.0680   | 0.0001                                                     |
|      | IX21-4-D3D6  | 90                             | 23   | 8.33E-06                     | 18         | 10      | 1.64         | 0.032374          | 0.324   | 0.0022                                                    | 1.9760   | 0.0025                                                     | 0.2510  | 0.0014                                                    | 0.0620   | 0.0001                                                     |
|      | IX21-4-D3D7  | 90                             | 23   | 8.33E-06                     | 21         | 10      | 1.64         | 0.032371          | 0.323   | 0.0024                                                    | 1.8750   | 0.0026                                                     | 0.2470  | 0.0014                                                    | 0.0640   | 0.0002                                                     |
|      | IX21-4-D3D8  | 90                             | 23   | 8.33E-06                     | 24         | 10      | 1.64         | 0.032368          | 0.283   | <b>0.0018</b>                                             | 1.6320   | <b>0.0020</b>                                              | 0.2180  | <b>0.0011</b>                                             | 0.0560   | <b>0.0000</b>                                              |
|      | IX21-4-D3D9  | 90                             | 23   | 8.33E-06                     | 27         | 10      | 1.64         | 0.032365          | 0.255   | <b>0.0017</b>                                             | 1.4980   | <b>0.0019</b>                                              | 0.2100  | <b>0.0012</b>                                             | 0.0590   | <b>0.0001</b>                                              |
|      | IX21-4-D3D10 | 90                             | 23   | 8.33E-06                     | 30         | 10      | 1.64         | 0.032363          | 0.284   | <b>0.0023</b>                                             | 1.5620   | <b>0.0024</b>                                              | 0.2220  | <b>0.0014</b>                                             | 0.0590   | <b>0.0001</b>                                              |
| 5    | IX21-4-E3D1  | 230                            | 23   | 8.33E-06                     | 3          | 11      | 1.64         | 0.032394          | 0.156   | 0.0069                                                    | 3.596    | 0.0099                                                     | 0.3770  | 0.0045                                                    | 0.1617   | 0.0008                                                     |
|      | IX21-4-E3D2  | 230                            | 23   | 8.33E-06                     | 6          | 11      | 1.64         | 0.032392          | 0.156   | 0.0035                                                    | 3.016    | 0.0030                                                     | 0.2909  | 0.0012                                                    | 0.1460   | 0.0001                                                     |
|      | IX21-4-E3D3  | 230                            | 23   | 8.33E-06                     | 9          | 11      | 1.64         | 0.032391          | 0.123   | 0.0019                                                    | 2.227    | 0.0014                                                     | 0.2069  | 0.0007                                                    | 0.1313   | 0.0000                                                     |
|      | IX21-4-E3D4  | 230                            | 23   | 8.33E-06                     | 12         | 11      | 1.64         | 0.032390          | 0.097   | 0.0015                                                    | 1.788    | 0.0012                                                     | 0.1607  | 0.0006                                                    | 0.1344   | 0.0002                                                     |
|      | IX21-4-E3D5  | 230                            | 23   | 8.33E-06                     | 15         | 11      | 1.64         | 0.032389          | 0.083   | 0.0015                                                    | 1.676    | 0.0016                                                     | 0.1481  | 0.0007                                                    | 0.1323   | 0.0001                                                     |
|      | IX21-4-E3D6  | 230                            | 23   | 8.33E-06                     | 18         | 11      | 1.64         | 0.032388          | 0.078   | 0.0016                                                    | 1.436    | 0.0010                                                     | 0.1397  | 0.0007                                                    | 0.1586   | 0.0006                                                     |
|      | IX21-4-E3D7  | 230                            | 23   | 8.33E-06                     | 21         | 11      | 1.64         | 0.032388          | 0.055   | 0.0006                                                    | 1.371    | 0.0012                                                     | 0.1197  | 0.0005                                                    | 0.1344   | 0.0000                                                     |
|      | IX21-4-E3D8  | 230                            | 23   | 8.33E-06                     | 24         | 11      | 1.64         | 0.032387          | 0.037   | <b>0.0004</b>                                             | 1.148    | <b>0.0005</b>                                              | 0.0945  | <b>0.0003</b>                                             | 0.1292   | <b>0.0001</b>                                              |
|      | IX21-4-E3D9  | 230                            | 23   | 8.33E-06                     | 27         | 11      | 1.64         | 0.032387          | 0.029   | <b>0.0004</b>                                             | 1.100    | <b>0.0008</b>                                              | 0.0872  | <b>0.0004</b>                                             | 0.1344   | <b>0.0002</b>                                              |
|      | IX21-4-E3D10 | 230                            | 23   | 8.33E-06                     | 30         | 11      | 1.64         | 0.032387          | 0.038   | <b>0.0010</b>                                             | 1.177    | <b>0.0011</b>                                              | 0.1071  | <b>0.0007</b>                                             | 0.1386   | <b>0.0002</b>                                              |

**Table A13. ICP-MS Analysis Results from Dissolution of Glass IDFIX21-1 at 70 °C.**

| Exp. | Sample ID    | Target [Si] <sub>inf</sub> ppm | T °C | Flow Rate, m <sup>3</sup> /d | Time, days | pH 23°C | Glass Mass g | SA m <sup>2</sup> | [Mo] ppm | Mo Rate g-glass m <sup>-2</sup> d <sup>-1</sup> | [Cs] ppm | Cs Rate g-glass m <sup>-2</sup> d <sup>-1</sup> | [Re] ppm | Re Rate g-glass m <sup>-2</sup> d <sup>-1</sup> |
|------|--------------|--------------------------------|------|------------------------------|------------|---------|--------------|-------------------|----------|-------------------------------------------------|----------|-------------------------------------------------|----------|-------------------------------------------------|
| 1    | IX21-1-A1D1  | 55                             | 70   | 2.50E-05                     | 1          | 7       | 0.77         | 0.01511           | 0.00630  | 0.0399                                          | 0.06374  | 0.1703                                          | 0.0391   | 0.1410                                          |
|      | IX21-1-A1D2  | 55                             | 70   | 2.50E-05                     | 2          | 7       | 0.77         | 0.01508           | 0.00370  | 0.0029                                          | 0.07170  | 0.1066                                          | 0.0361   | 0.0597                                          |
|      | IX21-1-A1D3  | 55                             | 70   | 2.50E-05                     | 3          | 7       | 0.77         | 0.01505           | 0.00370  | 0.0115                                          | 0.07322  | 0.1002                                          | 0.0310   | 0.0468                                          |
|      | IX21-1-A1D4  | 55                             | 70   | 2.50E-05                     | 4          | 7       | 0.77         | 0.01503           | 0.00240  | 0.0030                                          | 0.07569  | 0.1050                                          | 0.0285   | 0.0469                                          |
|      | IX21-1-A1D5  | 55                             | 70   | 2.50E-05                     | 5          | 7       | 0.77         | 0.01500           | 0.00240  | 0.0072                                          | 0.07204  | 0.0920                                          | 0.0229   | 0.0310                                          |
|      | IX21-1-A1D6  | 55                             | 70   | 2.50E-05                     | 6          | 7       | 0.77         | 0.01497           | 0.00210  | <b>0.0053</b>                                   | 0.06702  | 0.0836                                          | 0.0202   | 0.0318                                          |
|      | IX21-1-A1D7  | 55                             | 70   | 2.50E-05                     | 7          | 7       | 0.77         | 0.01495           | 0.00130  | <b>0.0010</b>                                   | 0.06893  | 0.0957                                          | 0.0179   | 0.0281                                          |
|      | IX21-1-A1D8  | 55                             | 70   | 2.50E-05                     | 8          | 7       | 0.77         | 0.01492           | 0.00283  | <b>0.0138</b>                                   | 0.06741  | <b>0.0891</b>                                   | 0.0162   | <b>0.0263</b>                                   |
|      | IX21-1-A1D9  | 55                             | 70   | 2.50E-05                     | 9          | 7       | 0.77         | 0.01490           | 0.00080  | -0.0047                                         | 0.06626  | <b>0.0882</b>                                   | 0.0153   | <b>0.0261</b>                                   |
|      | IX21-1-A1D10 | 55                             | 70   | 2.50E-05                     | 10         | 7       | 0.77         | 0.01487           | 0.00120  | <b>0.0046</b>                                   | 0.06742  | <b>0.0931</b>                                   | 0.0143   | <b>0.0242</b>                                   |
| 2    | IX21-1-B1D1  | 60                             | 70   | 2.50E-05                     | 1          | 8       | 0.77         | 0.01511           | 0.00740  | 0.0467                                          | 0.03174  | 0.0844                                          | 0.0196   | 0.0706                                          |
|      | IX21-1-B1D2  | 60                             | 70   | 2.50E-05                     | 2          | 8       | 0.77         | 0.01510           | 0.00610  | 0.0148                                          | 0.02149  | 0.0148                                          | 0.0186   | 0.0318                                          |
|      | IX21-1-B1D3  | 60                             | 70   | 2.50E-05                     | 3          | 8       | 0.77         | 0.01509           | 0.00470  | 0.0100                                          | 0.02920  | 0.0492                                          | 0.0165   | 0.0259                                          |
|      | IX21-1-B1D4  | 60                             | 70   | 2.50E-05                     | 4          | 8       | 0.77         | 0.01508           | 0.00380  | 0.0087                                          | 0.02833  | 0.0365                                          | 0.0128   | 0.0165                                          |
|      | IX21-1-B1D5  | 60                             | 70   | 2.50E-05                     | 5          | 8       | 0.77         | 0.01507           | 0.00300  | 0.0064                                          | 0.02789  | 0.0366                                          | 0.0104   | 0.0143                                          |
|      | IX21-1-B1D6  | 60                             | 70   | 2.50E-05                     | 6          | 8       | 0.77         | 0.01506           | 0.00210  | <b>0.0031</b>                                   | 0.02363  | 0.0257                                          | 0.0087   | 0.0124                                          |
|      | IX21-1-B1D7  | 60                             | 70   | 2.50E-05                     | 7          | 8       | 0.77         | 0.01505           | 0.00150  | <b>0.0021</b>                                   | 0.02375  | 0.0318                                          | 0.0076   | <b>0.0116</b>                                   |
|      | IX21-1-B1D8  | 60                             | 70   | 2.50E-05                     | 8          | 8       | 0.77         | 0.01504           | 0.00230  | <i>0.0093</i>                                   | 0.02440  | <b>0.0334</b>                                   | 0.0078   | <i>0.0145</i>                                   |
|      | IX21-1-B1D9  | 60                             | 70   | 2.50E-05                     | 9          | 8       | 0.77         | 0.01503           | 0.00200  | <b>0.0047</b>                                   | 0.02123  | <b>0.0240</b>                                   | 0.0066   | <b>0.0097</b>                                   |
|      | IX21-1-B1D10 | 60                             | 70   | 2.50E-05                     | 10         | 8       | 0.77         | 0.01502           | 0.00160  | <b>0.0031</b>                                   | 0.02289  | <b>0.0328</b>                                   | 0.0057   | <b>0.0086</b>                                   |
| 3    | IX21-1-C1D1  | 80                             | 70   | 2.50E-05                     | 1          | 9       | 0.77         | 0.01512           | 0.00620  | 0.0402                                          | 0.01953  | 0.0520                                          | 0.0126   | 0.0454                                          |
|      | IX21-1-C1D2  | 80                             | 70   | 2.50E-05                     | 2          | 9       | 0.77         | 0.01511           | 0.00290  | -0.0015                                         | 0.01755  | 0.0207                                          | 0.0103   | 0.0141                                          |
|      | IX21-1-C1D3  | 80                             | 70   | 2.50E-05                     | 3          | 9       | 0.77         | 0.01511           | 0.00290  | 0.0093                                          | 0.01778  | 0.0240                                          | 0.0096   | 0.0161                                          |
|      | IX21-1-C1D4  | 80                             | 70   | 2.50E-05                     | 4          | 9       | 0.77         | 0.01510           | 0.00270  | 0.0080                                          | 0.01721  | 0.0222                                          | 0.0091   | 0.0152                                          |
|      | IX21-1-C1D5  | 80                             | 70   | 2.50E-05                     | 5          | 9       | 0.77         | 0.01510           | 0.00150  | 0.0008                                          | 0.01456  | 0.0158                                          | 0.0069   | 0.0085                                          |
|      | IX21-1-C1D6  | 80                             | 70   | 2.50E-05                     | 6          | 9       | 0.77         | 0.01510           | 0.00250  | <b>0.0113</b>                                   | 0.01591  | 0.0230                                          | 0.0068   | 0.0118                                          |
|      | IX21-1-C1D7  | 80                             | 70   | 2.50E-05                     | 7          | 9       | 0.77         | 0.01509           | 0.00290  | <b>0.0106</b>                                   | 0.01450  | <b>0.0174</b>                                   | 0.0063   | <b>0.0104</b>                                   |
|      | IX21-1-C1D8  | 80                             | 70   | 2.50E-05                     | 8          | 9       | 0.77         | 0.01509           | 0.002    | <b>0.0048</b>                                   | 0.01413  | <b>0.0183</b>                                   | 0.0061   | <b>0.0105</b>                                   |
|      | IX21-1-C1D9  | 80                             | 70   | 2.50E-05                     | 9          | 9       | 0.77         | 0.01509           | 0.00150  | <b>0.0025</b>                                   | 0.01352  | <b>0.0172</b>                                   | 0.0056   | <b>0.0092</b>                                   |
|      | IX21-1-C1D10 | 80                             | 70   | 2.50E-05                     | 10         | 9       | 0.77         | 0.01509           | 0.00260  | <b>0.0120</b>                                   | 0.01448  | <b>0.0206</b>                                   | 0.0054   | <b>0.0093</b>                                   |
| 4    | IX21-1-D1D1  | 140                            | 70   | 2.50E-05                     | 1          | 10      | 0.50         | 0.00972           | 0.00269  | 0.0245                                          | 0.00710  | 0.0207                                          | 0.0044   | 0.0179                                          |
|      | IX21-1-D1D2  | 140                            | 70   | 2.50E-05                     | 2          | 10      | 0.50         | 0.00972           | 0.00168  | 0.0020                                          | 0.00559  | 0.0040                                          | 0.0036   | 0.0045                                          |
|      | IX21-1-D1D3  | 140                            | 70   | 2.50E-05                     | 3          | 10      | 0.50         | 0.00971           | 0.00121  | 0.0024                                          | 0.00428  | 0.0018                                          | 0.0020   | -0.0025                                         |
|      | IX21-1-D1D4  | 140                            | 70   | 2.50E-05                     | 4          | 10      | 0.50         | 0.00971           | 0.00095  | 0.0021                                          | 0.00298  | -0.0009                                         | 0.0013   | -0.0018                                         |
|      | IX21-1-D1D5  | 140                            | 70   | 2.50E-05                     | 5          | 10      | 0.50         | 0.00971           | 0.00087  | 0.0026                                          | 0.00257  | 0.0001                                          | 0.0016   | 0.0018                                          |
|      | IX21-1-D1D6  | 140                            | 70   | 2.50E-05                     | 6          | 10      | 0.50         | 0.00971           | 0.00095  | 0.0038                                          | 0.00352  | 0.0049                                          | 0.0016   | 0.0013                                          |
|      | IX21-1-D1D7  | 140                            | 70   | 2.50E-05                     | 7          | 10      | 0.50         | 0.00971           | 0.00094  | 0.0034                                          | 0.00305  | <b>0.0009</b>                                   | 0.0013   | -0.0005                                         |
|      | IX21-1-D1D8  | 140                            | 70   | 2.50E-05                     | 8          | 10      | 0.50         | 0.00971           | 0.00086  | <b>0.0026</b>                                   | 0.00277  | <b>0.0008</b>                                   | 0.0012   | -0.0004                                         |
|      | IX21-1-D1D9  | 140                            | 70   | 2.50E-05                     | 9          | 10      | 0.50         | 0.00971           | 0.00080  | <b>0.0024</b>                                   | 0.00199  | <i>-0.0019</i>                                  | 0.0007   | -0.0029                                         |
|      | IX21-1-D1D10 | 140                            | 70   | 2.50E-05                     | 10         | 10      | 0.50         | 0.00971           | 0.00083  | <b>0.0030</b>                                   | 0.00248  | <b>0.0018</b>                                   | 0.0006   | -0.0019                                         |
| 5    | IX21-1-E1D1  | 360                            | 70   | 2.50E-05                     | 1          | 11      | 0.50         | 0.00972           | 0.00240  | 0.0214                                          | 0.00459  | 0.0172                                          | 0.0044   | 0.0195                                          |
|      | IX21-1-E1D2  | 360                            | 70   | 2.50E-05                     | 2          | 11      | 0.50         | 0.00972           | 0.00266  | 0.0134                                          | 0.00351  | 0.0041                                          | 0.0036   | 0.0056                                          |
|      | IX21-1-E1D3  | 360                            | 70   | 2.50E-05                     | 3          | 11      | 0.50         | 0.00972           | 0.00170  | 0.0023                                          | 0.00249  | 0.0021                                          | 0.0035   | 0.0068                                          |
|      | IX21-1-E1D4  | 360                            | 70   | 2.50E-05                     | 4          | 11      | 0.50         | 0.00972           | 0.00203  | 0.0105                                          | 0.00131  | -0.0007                                         | 0.0031   | 0.0051                                          |
|      | IX21-1-E1D5  | 360                            | 70   | 2.50E-05                     | 5          | 11      | 0.50         | 0.00972           | 0.00117  | 0.0001                                          | 0.00101  | 0.0005                                          | 0.0025   | 0.0028                                          |
|      | IX21-1-E1D6  | 360                            | 70   | 2.50E-05                     | 6          | 11      | 0.50         | 0.00972           | 0.00303  | 0.0233                                          | 0.00180  | 0.0044                                          | 0.0028   | 0.0063                                          |
|      | IX21-1-E1D7  | 360                            | 70   | 2.50E-05                     | 7          | 11      | 0.50         | 0.00972           | 0.00124  | -0.0043                                         | 0.00095  | -0.0008                                         | 0.0026   | <b>0.0040</b>                                   |
|      | IX21-1-E1D8  | 360                            | 70   | 2.50E-05                     | 8          | 11      | 0.50         | 0.00972           | 0.00201  | <b>0.0127</b>                                   | 0.00066  | -0.0002                                         | 0.0026   | <b>0.0048</b>                                   |
|      | IX21-1-E1D9  | 360                            | 70   | 2.50E-05                     | 9          | 11      | 0.50         | 0.00972           | 0.00110  | <i>-0.0005</i>                                  | 0.00057  | <b>0.0000</b>                                   | 0.0032   | <b>0.0082</b>                                   |
|      | IX21-1-E1D10 | 360                            | 70   | 2.50E-05                     | 10         | 11      | 0.50         | 0.00972           | 0.00165  | <b>0.0097</b>                                   | 0.00075  | <b>0.0010</b>                                   | 0.0008   | <i>-0.0071</i>                                  |

**Table A14. ICP-MS Analysis Results from Dissolution of Glass IDFIX21-1 at 40 °C.**

| Exp. | Sample ID    | Target<br>[Si] <sub>inf</sub><br>ppm | T<br>°C | Flow Rate,<br>m <sup>3</sup> /d | Time,<br>days | pH<br>23°C | Glass<br>Mass g | SA<br>m <sup>2</sup> | [Mo]<br>ppm | Mo Rate<br>g-glass m <sup>-2</sup> d <sup>-1</sup> | [Cs]<br>ppm | Cs Rate<br>g-glass m <sup>-2</sup> d <sup>-1</sup> | [Re]<br>ppm | Re Rate<br>g-glass m <sup>-2</sup> d <sup>-1</sup> |
|------|--------------|--------------------------------------|---------|---------------------------------|---------------|------------|-----------------|----------------------|-------------|----------------------------------------------------|-------------|----------------------------------------------------|-------------|----------------------------------------------------|
| 1    | IX21-1-A2D1  | 40                                   | 40      | 8.33E-06                        | 3             | 7          | 1.65            | 0.03239              | 0.00875     | 0.0075                                             | 0.02836     | 0.0117                                             | 0.0272      | 0.0149                                             |
|      | IX21-1-A2D2  | 40                                   | 40      | 8.33E-06                        | 6             | 7          | 1.65            | 0.03238              | 0.00615     | 0.0011                                             | 0.02218     | 0.0033                                             | 0.0211      | 0.0040                                             |
|      | IX21-1-A2D3  | 40                                   | 40      | 8.33E-06                        | 9             | 7          | 1.65            | 0.03237              | 0.00386     | 0.0001                                             | 0.02016     | 0.0037                                             | 0.0156      | 0.0026                                             |
|      | IX21-1-A2D4  | 40                                   | 40      | 8.33E-06                        | 12            | 7          | 1.65            | 0.03236              | 0.00324     | 0.0007                                             | 0.01853     | 0.0035                                             | 0.0135      | 0.0030                                             |
|      | IX21-1-A2D5  | 40                                   | 40      | 8.33E-06                        | 15            | 7          | 1.65            | 0.03235              | 0.00210     | -0.0002                                            | 0.01788     | 0.0036                                             | 0.0121      | 0.0028                                             |
|      | IX21-1-A2D6  | 40                                   | 40      | 8.33E-06                        | 18            | 7          | 1.65            | 0.03234              | 0.00389     | 0.0022                                             | 0.02295     | 0.0058                                             | 0.0126      | 0.0035                                             |
|      | IX21-1-A2D7  | 40                                   | 40      | 8.33E-06                        | 21            | 7          | 1.65            | 0.03234              | 0.00174     | -0.0009                                            | 0.01731     | 0.0024                                             | 0.0100      | <b>0.0019</b>                                      |
|      | IX21-1-A2D8  | 40                                   | 40      | 8.33E-06                        | 24            | 7          | 1.65            | 0.03233              | 0.00258     | <b>0.0011</b>                                      | 0.01737     | <b>0.0036</b>                                      | 0.0083      | <b>0.0017</b>                                      |
|      | IX21-1-A2D9  | 40                                   | 40      | 8.33E-06                        | 27            | 7          | 1.65            | 0.03232              | 0.00263     | <b>0.0007</b>                                      | 0.01722     | <b>0.0035</b>                                      | 0.0089      | <b>0.0025</b>                                      |
|      | IX21-1-A2D10 | 40                                   | 40      | 8.33E-06                        | 30            | 7          | 1.65            | 0.03231              | 0.00254     | <b>0.0006</b>                                      | 0.01646     | <b>0.0032</b>                                      | 0.0085      | <b>0.0021</b>                                      |
| 2    | IX21-1-B2D1  | 45                                   | 40      | 8.33E-06                        | 3             | 8          | 1.65            | 0.03239              | 0.00866     | 0.0079                                             | 0.01728     | 0.0072                                             | 0.0139      | 0.0076                                             |
|      | IX21-1-B2D2  | 45                                   | 40      | 8.33E-06                        | 6             | 8          | 1.65            | 0.03239              | 0.00601     | 0.0013                                             | 0.01243     | 0.0016                                             | 0.0098      | 0.0015                                             |
|      | IX21-1-B2D3  | 45                                   | 40      | 8.33E-06                        | 9             | 8          | 1.65            | 0.03238              | 0.00436     | 0.0009                                             | 0.01011     | 0.0016                                             | 0.0076      | 0.0014                                             |
|      | IX21-1-B2D4  | 45                                   | 40      | 8.33E-06                        | 12            | 8          | 1.65            | 0.03238              | 0.00324     | 0.0006                                             | 0.00821     | 0.0013                                             | 0.0056      | 0.0009                                             |
|      | IX21-1-B2D5  | 45                                   | 40      | 8.33E-06                        | 15            | 8          | 1.65            | 0.03238              | 0.00332     | 0.0013                                             | 0.00778     | 0.0015                                             | 0.0046      | 0.0009                                             |
|      | IX21-1-B2D6  | 45                                   | 40      | 8.33E-06                        | 18            | 8          | 1.65            | 0.03238              | 0.00332     | 0.0013                                             | 0.00891     | 0.0021                                             | 0.0050      | 0.0014                                             |
|      | IX21-1-B2D7  | 45                                   | 40      | 8.33E-06                        | 21            | 8          | 1.65            | 0.03237              | 0.00214     | 0.0001                                             | 0.00612     | 0.0007                                             | 0.0029      | 0.0001                                             |
|      | IX21-1-B2D8  | 45                                   | 40      | 8.33E-06                        | 24            | 8          | 1.65            | 0.03237              | 0.00223     | <b>0.0007</b>                                      | 0.00681     | <b>0.0015</b>                                      | 0.0030      | <b>0.0008</b>                                      |
|      | IX21-1-B2D9  | 45                                   | 40      | 8.33E-06                        | 27            | 8          | 1.65            | 0.03237              | 0.00188     | <b>0.0003</b>                                      | 0.00567     | <b>0.0009</b>                                      | 0.0031      | <b>0.0007</b>                                      |
|      | IX21-1-B2D10 | 45                                   | 40      | 8.33E-06                        | 30            | 8          | 1.65            | 0.03237              | 0.00205     | <b>0.0007</b>                                      | 0.00631     | <b>0.0014</b>                                      | 0.0028      | <b>0.0006</b>                                      |
| 3    | IX21-1-C2D1  | 60                                   | 40      | 8.33E-06                        | 3             | 9          | 1.65            | 0.03239              | 0.00609     | 0.0060                                             | 0.01179     | 0.0049                                             | 0.0098      | 0.0055                                             |
|      | IX21-1-C2D2  | 60                                   | 40      | 8.33E-06                        | 6             | 9          | 1.65            | 0.03239              | 0.00384     | 0.0007                                             | 0.00914     | 0.0013                                             | 0.0082      | 0.0018                                             |
|      | IX21-1-C2D3  | 60                                   | 40      | 8.33E-06                        | 9             | 9          | 1.65            | 0.03239              | 0.00217     | 0.0001                                             | 0.00695     | 0.0010                                             | 0.0055      | 0.0008                                             |
|      | IX21-1-C2D4  | 60                                   | 40      | 8.33E-06                        | 12            | 9          | 1.65            | 0.03239              | 0.00207     | 0.0009                                             | 0.00595     | 0.0010                                             | 0.0038      | 0.0006                                             |
|      | IX21-1-C2D5  | 60                                   | 40      | 8.33E-06                        | 15            | 9          | 1.65            | 0.03238              | 0.00107     | -0.0001                                            | 0.00471     | 0.0007                                             | 0.0031      | 0.0007                                             |
|      | IX21-1-C2D6  | 60                                   | 40      | 8.33E-06                        | 18            | 9          | 1.65            | 0.03238              | 0.00106     | 0.0004                                             | 0.00498     | 0.0011                                             | 0.0028      | 0.0007                                             |
|      | IX21-1-C2D7  | 60                                   | 40      | 8.33E-06                        | 21            | 9          | 1.65            | 0.03238              | 0.00086     | 0.0002                                             | 0.00412     | 0.0007                                             | 0.0033      | <b>0.0011</b>                                      |
|      | IX21-1-C2D8  | 60                                   | 40      | 8.33E-06                        | 24            | 9          | 1.65            | 0.03238              | 0.00070     | <b>0.0002</b>                                      | 0.00379     | <b>0.0007</b>                                      | 0.0017      | <b>0.0000</b>                                      |
|      | IX21-1-C2D9  | 60                                   | 40      | 8.33E-06                        | 27            | 9          | 1.65            | 0.03238              | 0.00057     | <b>0.0001</b>                                      | 0.00347     | <b>0.0007</b>                                      | 0.0020      | <b>0.0007</b>                                      |
|      | IX21-1-C2D10 | 60                                   | 40      | 8.33E-06                        | 30            | 9          | 1.65            | 0.03238              | 0.00112     | <b>0.0007</b>                                      | 0.00347     | <b>0.0007</b>                                      | 0.0021      | <b>0.0006</b>                                      |
| 4    | IX21-1-D2D1  | 105                                  | 40      | 8.33E-06                        | 3             | 10         | 0.83            | 0.01622              | 0.00473     | 0.0088                                             | 0.00550     | 0.0046                                             | 0.0045      | 0.0051                                             |
|      | IX21-1-D2D2  | 105                                  | 40      | 8.33E-06                        | 6             | 10         | 0.83            | 0.01622              | 0.00390     | 0.0027                                             | 0.00421     | 0.0012                                             | 0.0035      | 0.0014                                             |
|      | IX21-1-D2D3  | 105                                  | 40      | 8.33E-06                        | 9             | 10         | 0.83            | 0.01621              | 0.00212     | -0.0001                                            | 0.00325     | 0.0009                                             | 0.0026      | 0.0010                                             |
|      | IX21-1-D2D4  | 105                                  | 40      | 8.33E-06                        | 12            | 10         | 0.83            | 0.01621              | 0.00145     | 0.0004                                             | 0.00270     | 0.0009                                             | 0.0020      | 0.0007                                             |
|      | IX21-1-D2D5  | 105                                  | 40      | 8.33E-06                        | 15            | 10         | 0.83            | 0.01621              | 0.00107     | 0.0003                                             | 0.00210     | 0.0006                                             | 0.0014      | 0.0005                                             |
|      | IX21-1-D2D6  | 105                                  | 40      | 8.33E-06                        | 18            | 10         | 0.83            | 0.01621              | 0.00084     | 0.0002                                             | 0.00186     | <b>0.0007</b>                                      | 0.0013      | 0.0006                                             |
|      | IX21-1-D2D7  | 105                                  | 40      | 8.33E-06                        | 21            | 10         | 0.83            | 0.01621              | 0.00065     | 0.0001                                             | 0.00178     | <b>0.0007</b>                                      | 0.0011      | <b>0.0005</b>                                      |
|      | IX21-1-D2D8  | 105                                  | 40      | 8.33E-06                        | 24            | 10         | 0.83            | 0.01621              | 0.00065     | 0.0003                                             | 0.00171     | <b>0.0007</b>                                      | 0.0011      | <b>0.0006</b>                                      |
|      | IX21-1-D2D9  | 105                                  | 40      | 8.33E-06                        | 27            | 10         | 0.83            | 0.01621              | 0.00047     | -0.0001                                            | 0.00131     | <b>0.0004</b>                                      | 0.0008      | <b>0.0003</b>                                      |
|      | IX21-1-D2D10 | 105                                  | 40      | 8.33E-06                        | 30            | 10         | 0.83            | 0.01621              | 0.00094     | 0.0010                                             | 0.00174     | <b>0.0009</b>                                      | 0.0011      | <b>0.0008</b>                                      |
| 5    | IX21-1-E2D1  | 270                                  | 40      | 8.33E-06                        | 3             | 11         | 0.83            | 0.01622              | 0.00742     | 0.0146                                             | 0.00838     | 0.0069                                             | 0.0061      | 0.0063                                             |
|      | IX21-1-E2D2  | 270                                  | 40      | 8.33E-06                        | 6             | 11         | 0.83            | 0.01621              | 0.00581     | 0.0040                                             | 0.00776     | 0.0029                                             | 0.0070      | 0.0042                                             |
|      | IX21-1-E2D3  | 270                                  | 40      | 8.33E-06                        | 9             | 11         | 0.83            | 0.01621              | 0.00392     | 0.0018                                             | 0.00584     | 0.0016                                             | 0.0057      | 0.0022                                             |
|      | IX21-1-E2D4  | 270                                  | 40      | 8.33E-06                        | 12            | 11         | 0.83            | 0.01621              | 0.00281     | 0.0015                                             | 0.00463     | 0.0014                                             | 0.0041      | 0.0011                                             |
|      | IX21-1-E2D5  | 270                                  | 40      | 8.33E-06                        | 15            | 11         | 0.83            | 0.01621              | 0.00272     | 0.0025                                             | 0.00428     | 0.0016                                             | 0.0034      | 0.0013                                             |
|      | IX21-1-E2D6  | 270                                  | 40      | 8.33E-06                        | 18            | 11         | 0.83            | 0.01621              | 0.00298     | 0.0030                                             | 0.00694     | 0.0040                                             | 0.0047      | 0.0031                                             |
|      | IX21-1-E2D7  | 270                                  | 40      | 8.33E-06                        | 21            | 11         | 0.83            | 0.01621              | 0.00151     | -0.0002                                            | 0.00392     | 0.0003                                             | 0.0032      | 0.0007                                             |
|      | IX21-1-E2D8  | 270                                  | 40      | 8.33E-06                        | 24            | 11         | 0.83            | 0.01621              | 0.00131     | 0.0009                                             | 0.00353     | <b>0.0013</b>                                      | 0.0030      | <b>0.0013</b>                                      |
|      | IX21-1-E2D9  | 270                                  | 40      | 8.33E-06                        | 27            | 11         | 0.83            | 0.01621              | 0.00076     | 0.0000                                             | 0.00268     | <b>0.0007</b>                                      | 0.0027      | <b>0.0011</b>                                      |
|      | IX21-1-E2D10 | 270                                  | 40      | 8.33E-06                        | 30            | 11         | 0.83            | 0.01621              | 0.00158     | 0.0022                                             | 0.00253     | <b>0.0010</b>                                      | 0.0026      | <b>0.0012</b>                                      |

**Table A15. ICP-MS Analysis Results from Dissolution of Glass IDFIX21-1 at 23 °C.**

| Exp. | Sample ID    | Target<br>[Si] <sub>inf</sub><br>ppm | T<br>°C | Flow Rate,<br>m <sup>3</sup> /d | Time,<br>days | pH<br>23°C | Glass<br>Mass g | SA<br>m <sup>2</sup> | [Mo]<br>ppm | Mo Rate<br>g-glass m <sup>-2</sup> d <sup>-1</sup> | [Cs]<br>ppm | Cs Rate<br>g-glass m <sup>-2</sup> d <sup>-1</sup> | [Re]<br>ppm | Re Rate<br>g-glass m <sup>-2</sup> d <sup>-1</sup> |
|------|--------------|--------------------------------------|---------|---------------------------------|---------------|------------|-----------------|----------------------|-------------|----------------------------------------------------|-------------|----------------------------------------------------|-------------|----------------------------------------------------|
| 1    | IX21-1-A3D1  | 35                                   | 23      | 8.33E-06                        | 3             | 7          | 3.28            | 0.064355             | 0.01065     | 0.0051                                             | 0.02287     | 0.0047                                             | 0.0251      | 0.0071                                             |
|      | IX21-1-A3D2  | 35                                   | 23      | 8.33E-06                        | 6             | 7          | 3.28            | 0.064347             | 0.00757     | 0.0010                                             | 0.01699     | 0.0011                                             | 0.0184      | 0.0016                                             |
|      | IX21-1-A3D3  | 35                                   | 23      | 8.33E-06                        | 9             | 7          | 3.28            | 0.064341             | 0.00604     | 0.0010                                             | 0.01331     | 0.0010                                             | 0.0149      | 0.0016                                             |
|      | IX21-1-A3D4  | 35                                   | 23      | 8.33E-06                        | 12            | 7          | 3.28            | 0.064336             | 0.00362     | 0.0001                                             | 0.01206     | 0.0011                                             | 0.0121      | 0.0013                                             |
|      | IX21-1-A3D5  | 35                                   | 23      | 8.33E-06                        | 15            | 7          | 3.28            | 0.064332             | 0.00249     | 0.0002                                             | 0.00974     | 0.0007                                             | 0.0087      | 0.0007                                             |
|      | IX21-1-A3D6  | 35                                   | 23      | 8.33E-06                        | 18            | 7          | 3.28            | 0.064328             | 0.00221     | 0.0003                                             | 0.00882     | 0.0008                                             | 0.0079      | 0.0010                                             |
|      | IX21-1-A3D7  | 35                                   | 23      | 8.33E-06                        | 21            | 7          | 3.28            | 0.064326             | 0.00264     | <b>0.0006</b>                                      | 0.00792     | 0.0007                                             | 0.0061      | <b>0.0006</b>                                      |
|      | IX21-1-A3D8  | 35                                   | 23      | 8.33E-06                        | 24            | 7          | 3.28            | 0.064323             | 0.00176     | <b>0.00003</b>                                     | 0.00656     | <b>0.0005</b>                                      | 0.0047      | <b>0.0004</b>                                      |
|      | IX21-1-A3D9  | 35                                   | 23      | 8.33E-06                        | 27            | 7          | 3.28            | 0.064321             | 0.00254     | <b>0.00065</b>                                     | 0.00788     | <b>0.0009</b>                                      | 0.0051      | <b>0.0007</b>                                      |
|      | IX21-1-A3D10 | 35                                   | 23      | 8.33E-06                        | 30            | 7          | 3.28            | 0.064319             | 0.00157     | -0.00004                                           | 0.00698     | <b>0.0006</b>                                      | 0.0036      | <b>0.0003</b>                                      |
| 2    | IX21-1-B3D1  | 40                                   | 23      | 8.33E-06                        | 3             | 8          | 3.28            | 0.064357             | 0.00877     | 0.0041                                             | 0.01470     | 0.0031                                             | 0.0141      | 0.0039                                             |
|      | IX21-1-B3D2  | 40                                   | 23      | 8.33E-06                        | 6             | 8          | 3.28            | 0.064353             | 0.00658     | 0.0009                                             | 0.01151     | 0.0009                                             | 0.0115      | 0.0012                                             |
|      | IX21-1-B3D3  | 40                                   | 23      | 8.33E-06                        | 9             | 8          | 3.28            | 0.064350             | 0.00474     | 0.0006                                             | 0.00838     | 0.0005                                             | 0.0084      | 0.0007                                             |
|      | IX21-1-B3D4  | 40                                   | 23      | 8.33E-06                        | 12            | 8          | 3.28            | 0.064347             | 0.00333     | 0.0003                                             | 0.00667     | 0.0005                                             | 0.0064      | 0.0005                                             |
|      | IX21-1-B3D5  | 40                                   | 23      | 8.33E-06                        | 15            | 8          | 3.28            | 0.064345             | 0.00271     | 0.0003                                             | 0.00593     | 0.0005                                             | 0.0050      | 0.0004                                             |
|      | IX21-1-B3D6  | 40                                   | 23      | 8.33E-06                        | 18            | 8          | 3.28            | 0.064344             | 0.00193     | 0.0001                                             | 0.00480     | 0.0004                                             | 0.0037      | 0.0003                                             |
|      | IX21-1-B3D7  | 40                                   | 23      | 8.33E-06                        | 21            | 8          | 3.28            | 0.064342             | 0.00262     | 0.0007                                             | 0.00615     | 0.0008                                             | 0.0043      | 0.0006                                             |
|      | IX21-1-B3D8  | 40                                   | 23      | 8.33E-06                        | 24            | 8          | 3.28            | 0.064341             | 0.00161     | -0.00003                                           | 0.00444     | <b>0.0003</b>                                      | 0.0027      | <b>0.0001</b>                                      |
|      | IX21-1-B3D9  | 40                                   | 23      | 8.33E-06                        | 27            | 8          | 3.28            | 0.064340             | 0.00160     | <b>0.0002</b>                                      | 0.00435     | <b>0.0004</b>                                      | 0.0025      | <b>0.0003</b>                                      |
|      | IX21-1-B3D10 | 40                                   | 23      | 8.33E-06                        | 30            | 8          | 3.28            | 0.064340             | 0.00192     | <b>0.0004</b>                                      | 0.00472     | <b>0.0005</b>                                      | 0.0028      | <b>0.0004</b>                                      |
| 3    | IX21-1-C3D1  | 52                                   | 23      | 8.33E-06                        | 3             | 9          | 3.28            | 0.064358             | 0.00878     | 0.00390                                            | 0.01388     | 0.0029                                             | 0.0112      | 0.0032                                             |
|      | IX21-1-C3D2  | 52                                   | 23      | 8.33E-06                        | 6             | 9          | 3.28            | 0.064354             | 0.00592     | 0.00049                                            | 0.00773     | 0.0002                                             | 0.0073      | 0.0005                                             |
|      | IX21-1-C3D3  | 52                                   | 23      | 8.33E-06                        | 9             | 9          | 3.28            | 0.064352             | 0.00440     | 0.00045                                            | 0.00630     | 0.0005                                             | 0.0051      | 0.0004                                             |
|      | IX21-1-C3D4  | 52                                   | 23      | 8.33E-06                        | 12            | 9          | 3.28            | 0.064350             | 0.00365     | 0.00045                                            | 0.00545     | 0.0005                                             | 0.0045      | 0.0006                                             |
|      | IX21-1-C3D5  | 52                                   | 23      | 8.33E-06                        | 15            | 9          | 3.28            | 0.064349             | 0.00274     | 0.00017                                            | 0.00359     | 0.0002                                             | 0.0024      | 0.0000                                             |
|      | IX21-1-C3D6  | 52                                   | 23      | 8.33E-06                        | 18            | 9          | 3.28            | 0.064348             | 0.00207     | 0.00006                                            | 0.00428     | 0.0005                                             | 0.0025      | 0.0004                                             |
|      | IX21-1-C3D7  | 52                                   | 23      | 8.33E-06                        | 21            | 9          | 3.28            | 0.064347             | 0.00188     | 0.00014                                            | 0.00386     | 0.0004                                             | 0.0019      | <b>0.0002</b>                                      |
|      | IX21-1-C3D8  | 52                                   | 23      | 8.33E-06                        | 24            | 9          | 3.28            | 0.064346             | 0.00164     | 0.00007                                            | 0.00301     | <b>0.0002</b>                                      | 0.0021      | <b>0.0003</b>                                      |
|      | IX21-1-C3D9  | 52                                   | 23      | 8.33E-06                        | 27            | 9          | 3.28            | 0.064345             | 0.00130     | -0.00005                                           | 0.00278     | <b>0.0003</b>                                      | 0.0014      | <b>0.0001</b>                                      |
|      | IX21-1-C3D10 | 52                                   | 23      | 8.33E-06                        | 30            | 9          | 3.28            | 0.064345             | 0.00129     | 0.00004                                            | 0.00250     | <b>0.0002</b>                                      | 0.0014      | <b>0.0002</b>                                      |
| 4    | IX21-1-D3D1  | 90                                   | 23      | 8.33E-06                        | 3             | 10         | 1.64            | 0.032179             | 0.00729     | 0.0070                                             | 0.00758     | 0.0032                                             | 0.0055      | 0.0030                                             |
|      | IX21-1-D3D2  | 90                                   | 23      | 8.33E-06                        | 6             | 10         | 1.64            | 0.032177             | 0.00565     | 0.0018                                             | 0.00621     | 0.0010                                             | 0.0051      | 0.0012                                             |
|      | IX21-1-D3D3  | 90                                   | 23      | 8.33E-06                        | 9             | 10         | 1.64            | 0.032176             | 0.00438     | 0.0014                                             | 0.00519     | 0.0009                                             | 0.0043      | 0.0009                                             |
|      | IX21-1-D3D4  | 90                                   | 23      | 8.33E-06                        | 12            | 10         | 1.64            | 0.032175             | 0.00402     | 0.0017                                             | 0.00421     | 0.0007                                             | 0.0038      | 0.0009                                             |
|      | IX21-1-D3D5  | 90                                   | 23      | 8.33E-06                        | 15            | 10         | 1.64            | 0.032174             | 0.00268     | 0.0005                                             | 0.00330     | 0.0005                                             | 0.0027      | 0.0004                                             |
|      | IX21-1-D3D6  | 90                                   | 23      | 8.33E-06                        | 18            | 10         | 1.64            | 0.032173             | 0.00200     | 0.0005                                             | 0.00288     | <b>0.0005</b>                                      | 0.0019      | 0.0003                                             |
|      | IX21-1-D3D7  | 90                                   | 23      | 8.33E-06                        | 21            | 10         | 1.64            | 0.032173             | 0.00174     | <b>0.0005</b>                                      | 0.00251     | <b>0.0004</b>                                      | 0.0017      | 0.0004                                             |
|      | IX21-1-D3D8  | 90                                   | 23      | 8.33E-06                        | 24            | 10         | 1.64            | 0.032172             | 0.00163     | <b>0.0006</b>                                      | 0.00244     | <b>0.0005</b>                                      | 0.0015      | <b>0.0003</b>                                      |
|      | IX21-1-D3D9  | 90                                   | 23      | 8.33E-06                        | 27            | 10         | 1.64            | 0.032172             | 0.00125     | <b>0.0002</b>                                      | 0.00198     | <b>0.0003</b>                                      | 0.0011      | <b>0.0001</b>                                      |
|      | IX21-1-D3D10 | 90                                   | 23      | 8.33E-06                        | 30            | 10         | 1.64            | 0.032172             | 0.00114     | <b>0.0003</b>                                      | 0.00216     | <b>0.0005</b>                                      | 0.0011      | <b>0.0002</b>                                      |
| 5    | IX21-1-E3D1  | 230                                  | 23      | 8.33E-06                        | 3             | 11         | 1.64            | 0.032179             | 0.00364     | 0.0023                                             | 0.00640     | 0.0027                                             | 0.0036      | 0.0018                                             |
|      | IX21-1-E3D2  | 230                                  | 23      | 8.33E-06                        | 6             | 11         | 1.64            | 0.032178             | 0.00376     | 0.0013                                             | 0.00644     | 0.0013                                             | 0.0054      | 0.0019                                             |
|      | IX21-1-E3D3  | 230                                  | 23      | 8.33E-06                        | 9             | 11         | 1.64            | 0.032176             | 0.00367     | 0.0011                                             | 0.00618     | 0.0012                                             | 0.0045      | 0.0009                                             |
|      | IX21-1-E3D4  | 230                                  | 23      | 8.33E-06                        | 12            | 11         | 1.64            | 0.032175             | 0.00276     | 0.0002                                             | 0.00551     | 0.0010                                             | 0.0046      | 0.0012                                             |
|      | IX21-1-E3D5  | 230                                  | 23      | 8.33E-06                        | 15            | 11         | 1.64            | 0.032174             | 0.00225     | 0.0002                                             | 0.00512     | 0.0010                                             | 0.0049      | 0.0014                                             |
|      | IX21-1-E3D6  | 230                                  | 23      | 8.33E-06                        | 18            | 11         | 1.64            | 0.032172             | 0.00432     | 0.0025                                             | 0.00632     | 0.0016                                             | 0.0045      | 0.0010                                             |
|      | IX21-1-E3D7  | 230                                  | 23      | 8.33E-06                        | 21            | 11         | 1.64            | 0.032171             | 0.00223     | -0.0007                                            | 0.00516     | 0.0008                                             | 0.0044      | 0.0011                                             |
|      | IX21-1-E3D8  | 230                                  | 23      | 8.33E-06                        | 24            | 11         | 1.64            | 0.032170             | 0.00186     | 0.0000                                             | 0.00427     | <b>0.0007</b>                                      | 0.0030      | <b>0.0003</b>                                      |
|      | IX21-1-E3D9  | 230                                  | 23      | 8.33E-06                        | 27            | 11         | 1.64            | 0.032169             | 0.00179     | 0.0002                                             | 0.00381     | <b>0.0007</b>                                      | 0.0028      | <b>0.0006</b>                                      |
|      | IX21-1-E3D10 | 230                                  | 23      | 8.33E-06                        | 30            | 11         | 1.64            | 0.032168             | 0.00281     | 0.0012                                             | 0.00345     | <b>0.0006</b>                                      | 0.0030      | <b>0.0008</b>                                      |

**Table A16. ICP-MS Analysis Results from Dissolution of Glass IDFIX21-2 at 70 °C.**

| Exp. | Sample ID    | Target<br>[Si] <sub>inf</sub><br>ppm | T<br>°C | Flow Rate,<br>m <sup>3</sup> /d | Time,<br>days | pH<br>23°C | Glass<br>Mass g | SA<br>m <sup>2</sup> | [Mo]<br>ppm | Mo Rate<br>g-glass m <sup>-2</sup> d <sup>-1</sup> | [Cs]<br>ppm | Cs Rate<br>g-glass m <sup>-2</sup> d <sup>-1</sup> | [Re]<br>ppm | Re Rate<br>g-glass m <sup>-2</sup> d <sup>-1</sup> |
|------|--------------|--------------------------------------|---------|---------------------------------|---------------|------------|-----------------|----------------------|-------------|----------------------------------------------------|-------------|----------------------------------------------------|-------------|----------------------------------------------------|
| 1    | IX21-2-A1D1  | 55                                   | 70      | 2.50E-05                        | 1             | 7          | 0.77            | 0.01508              | 0.00730     | 0.0504                                             | 0.03828     | 0.1039                                             | 0.0162      | 0.0651                                             |
|      | IX21-2-A1D2  | 55                                   | 70      | 2.50E-05                        | 2             | 7          | 0.77            | 0.01507              | 0.00420     | 0.0032                                             | 0.03189     | 0.0345                                             | 0.0112      | 0.0121                                             |
|      | IX21-2-A1D3  | 55                                   | 70      | 2.50E-05                        | 3             | 7          | 0.77            | 0.01506              | 0.00190     | -0.0021                                            | 0.02982     | 0.0376                                             | 0.0083      | 0.0108                                             |
|      | IX21-2-A1D4  | 55                                   | 70      | 2.50E-05                        | 4             | 7          | 0.77            | 0.01505              | 0.00200     | 0.0068                                             | 0.02998     | 0.0409                                             | 0.0079      | 0.0150                                             |
|      | IX21-2-A1D5  | 55                                   | 70      | 2.50E-05                        | 5             | 7          | 0.77            | 0.01504              | 0.00180     | <b>0.0050</b>                                      | 0.02837     | 0.0363                                             | 0.0076      | 0.0143                                             |
|      | IX21-2-A1D6  | 55                                   | 70      | 2.50E-05                        | 6             | 7          | 0.77            | 0.01503              | 0.00130     | <b>0.0021</b>                                      | 0.02363     | 0.0256                                             | 0.0065      | 0.0108                                             |
|      | IX21-2-A1D7  | 55                                   | 70      | 2.50E-05                        | 7             | 7          | 0.77            | 0.01503              | 0.00040     | -0.0025                                            | 0.02521     | 0.0364                                             | 0.0056      | 0.0094                                             |
|      | IX21-2-A1D8  | 55                                   | 70      | 2.50E-05                        | 8             | 7          | 0.77            | 0.01502              | 0.00070     | <b>0.0029</b>                                      | 0.02369     | <b>0.0301</b>                                      | 0.0052      | <b>0.0095</b>                                      |
|      | IX21-2-A1D9  | 55                                   | 70      | 2.50E-05                        | 9             | 7          | 0.77            | 0.01501              | 0.00050     | 0.0004                                             | 0.02338     | <b>0.0314</b>                                      | 0.0047      | <b>0.0081</b>                                      |
|      | IX21-2-A1D10 | 55                                   | 70      | 2.50E-05                        | 10            | 7          | 0.77            | 0.01500              | 0.00100     | <b>0.0046</b>                                      | 0.02357     | <b>0.0323</b>                                      | 0.0042      | <b>0.0073</b>                                      |
| 2    | IX21-2-B1D1  | 60                                   | 70      | 2.50E-05                        | 1             | 8          | 0.77            | 0.01509              | 0.00630     | 0.0429                                             | 0.01577     | 0.0423                                             | 0.0081      | 0.0326                                             |
|      | IX21-2-B1D2  | 60                                   | 70      | 2.50E-05                        | 2             | 8          | 0.77            | 0.01508              | 0.00520     | 0.0137                                             | 0.01497     | 0.0190                                             | 0.0071      | 0.0122                                             |
|      | IX21-2-B1D3  | 60                                   | 70      | 2.50E-05                        | 3             | 8          | 0.77            | 0.01508              | 0.00500     | 0.0161                                             | 0.01421     | 0.0180                                             | 0.0058      | 0.0091                                             |
|      | IX21-2-B1D4  | 60                                   | 70      | 2.50E-05                        | 4             | 8          | 0.77            | 0.01507              | 0.00480     | 0.0154                                             | 0.01239     | 0.0141                                             | 0.0049      | 0.0076                                             |
|      | IX21-2-B1D5  | 60                                   | 70      | 2.50E-05                        | 5             | 8          | 0.77            | 0.01507              | 0.00290     | 0.0026                                             | 0.01091     | 0.0126                                             | 0.0029      | 0.0019                                             |
|      | IX21-2-B1D6  | 60                                   | 70      | 2.50E-05                        | 6             | 8          | 0.77            | 0.01507              | 0.00190     | 0.0023                                             | 0.00936     | 0.0103                                             | 0.0025      | 0.0042                                             |
|      | IX21-2-B1D7  | 60                                   | 70      | 2.50E-05                        | 7             | 8          | 0.77            | 0.01506              | 0.00150     | 0.0030                                             | 0.01109     | 0.0172                                             | 0.0039      | 0.0106                                             |
|      | IX21-2-B1D8  | 60                                   | 70      | 2.50E-05                        | 8             | 8          | 0.77            | 0.01506              | 0.00190     | <b>0.0073</b>                                      | 0.00950     | <b>0.0105</b>                                      | 0.0025      | <b>0.0018</b>                                      |
|      | IX21-2-B1D9  | 60                                   | 70      | 2.50E-05                        | 9             | 8          | 0.77            | 0.01506              | 0.00190     | <b>0.0059</b>                                      | 0.00843     | <b>0.0097</b>                                      | 0.0024      | <b>0.0047</b>                                      |
|      | IX21-2-B1D10 | 60                                   | 70      | 2.50E-05                        | 10            | 8          | 0.77            | 0.01506              | 0.00190     | <b>0.0059</b>                                      | 0.00941     | <b>0.0139</b>                                      | 0.0025      | <b>0.0051</b>                                      |
| 3    | IX21-2-C1D1  | 80                                   | 70      | 2.50E-05                        | 1             | 9          | 0.77            | 0.01509              | 0.00530     | 0.0373                                             | 0.01410     | 0.0382                                             | 0.0080      | 0.0322                                             |
|      | IX21-2-C1D2  | 80                                   | 70      | 2.50E-05                        | 2             | 9          | 0.77            | 0.01508              | 0.00460     | 0.0137                                             | 0.01242     | 0.0145                                             | 0.0076      | 0.0146                                             |
|      | IX21-2-C1D3  | 80                                   | 70      | 2.50E-05                        | 3             | 9          | 0.77            | 0.01508              | 0.00440     | 0.0148                                             | 0.01125     | 0.0136                                             | 0.0073      | 0.0139                                             |
|      | IX21-2-C1D4  | 80                                   | 70      | 2.50E-05                        | 4             | 9          | 0.77            | 0.01508              | 0.00450     | 0.0162                                             | 0.01072     | 0.0138                                             | 0.0063      | <b>0.0105</b>                                      |
|      | IX21-2-C1D5  | 80                                   | 70      | 2.50E-05                        | 5             | 9          | 0.77            | 0.01507              | 0.00320     | <b>0.0066</b>                                      | 0.01029     | <b>0.0133</b>                                      | 0.0058      | <b>0.0107</b>                                      |
|      | IX21-2-C1D6  | 80                                   | 70      | 2.50E-05                        | 6             | 9          | 0.77            | 0.01507              | 0.00290     | <b>0.0091</b>                                      | 0.00963     | <b>0.0121</b>                                      | 0.0061      | 0.0128                                             |
|      | IX21-2-C1D7  | 80                                   | 70      | 2.50E-05                        | 7             | 9          | 0.77            | 0.01507              | 0.00370     | <b>0.0158</b>                                      | 0.00983     | <b>0.0135</b>                                      | 0.0054      | <b>0.0094</b>                                      |
|      | IX21-2-C1D8  | 80                                   | 70      | 2.50E-05                        | 8             | 9          | 0.77            | 0.01506              | 0.00678     | 0.0349                                             | 0.01075     | <b>0.0158</b>                                      | 0.0063      | 0.0144                                             |
|      | IX21-2-C1D9  | 80                                   | 70      | 2.50E-05                        | 9             | 9          | 0.77            | 0.01506              | 0.00320     | -0.0015                                            | 0.00915     | <b>0.0102</b>                                      | 0.0053      | <b>0.0087</b>                                      |
|      | IX21-2-C1D10 | 80                                   | 70      | 2.50E-05                        | 10            | 9          | 0.77            | 0.01506              | 0.00430     | <b>0.0190</b>                                      | 0.01172     | 0.0194                                             | 0.0071      | 0.0179                                             |
| 4    | IX21-2-D1D1  | 140                                  | 70      | 2.50E-05                        | 1             | 10         | 0.50            | 0.00970              | 0.00366     | 0.0374                                             | 0.00562     | 0.0148                                             | 0.0019      | 0.0041                                             |
|      | IX21-2-D1D2  | 140                                  | 70      | 2.50E-05                        | 2             | 10         | 0.50            | 0.00970              | 0.00163     | -0.0037                                            | 0.00454     | 0.0028                                             | 0.0013      | -0.0013                                            |
|      | IX21-2-D1D3  | 140                                  | 70      | 2.50E-05                        | 3             | 10         | 0.50            | 0.00970              | 0.00092     | -0.0004                                            | 0.00347     | 0.0006                                             | 0.0017      | 0.0030                                             |
|      | IX21-2-D1D4  | 140                                  | 70      | 2.50E-05                        | 4             | 10         | 0.50            | 0.00970              | 0.00082     | 0.0025                                             | 0.00284     | 0.0002                                             | 0.0015      | 0.0002                                             |
|      | IX21-2-D1D5  | 140                                  | 70      | 2.50E-05                        | 5             | 10         | 0.50            | 0.00970              | 0.00034     | -0.0023                                            | 0.00231     | -0.0007                                            | 0.0012      | -0.0008                                            |
|      | IX21-2-D1D6  | 140                                  | 70      | 2.50E-05                        | 6             | 10         | 0.50            | 0.00970              | 0.00039     | 0.0009                                             | 0.00174     | -0.0020                                            | 0.0005      | -0.0047                                            |
|      | IX21-2-D1D7  | 140                                  | 70      | 2.50E-05                        | 7             | 10         | 0.50            | 0.00970              | 0.00054     | 0.0023                                             | 0.00158     | -0.0015                                            | 0.0004      | -0.0026                                            |
|      | IX21-2-D1D8  | 140                                  | 70      | 2.50E-05                        | 8             | 10         | 0.50            | 0.00970              | 0.00034     | -0.0007                                            | 0.00154     | -0.0013                                            | 0.0007      | -0.0005                                            |
|      | IX21-2-D1D9  | 140                                  | 70      | 2.50E-05                        | 9             | 10         | 0.50            | 0.00970              | 0.00035     | 0.0005                                             | 0.00133     | -0.0021                                            | 0.0006      | -0.0022                                            |
|      | IX21-2-D1D10 | 140                                  | 70      | 2.50E-05                        | 10            | 10         | 0.50            | 0.00969              | 0.00041     | 0.0011                                             | 0.00137     | -0.0015                                            | 0.0006      | -0.0017                                            |
| 5    | IX21-2-E1D1  | 360                                  | 70      | 2.50E-05                        | 1             | 11         | 0.50            | 0.00970              | 0.00224     | 0.0216                                             | 0.00393     | 0.0147                                             | 0.0035      | 0.0165                                             |
|      | IX21-2-E1D2  | 360                                  | 70      | 2.50E-05                        | 2             | 11         | 0.50            | 0.00970              | 0.00125     | -0.0002                                            | 0.00279     | 0.0015                                             | 0.0035      | 0.0079                                             |
|      | IX21-2-E1D3  | 360                                  | 70      | 2.50E-05                        | 3             | 11         | 0.50            | 0.00970              | 0.00141     | 0.0071                                             | 0.00196     | 0.0004                                             | 0.0033      | 0.0072                                             |
|      | IX21-2-E1D4  | 360                                  | 70      | 2.50E-05                        | 4             | 11         | 0.50            | 0.00970              | 0.00099     | 0.0015                                             | 0.00129     | -0.0006                                            | 0.0016      | -0.0034                                            |
|      | IX21-2-E1D5  | 360                                  | 70      | 2.50E-05                        | 5             | 11         | 0.50            | 0.00970              | 0.00091     | 0.0030                                             | 0.00080     | -0.0013                                            | 0.0020      | 0.0048                                             |
|      | IX21-2-E1D6  | 360                                  | 70      | 2.50E-05                        | 6             | 11         | 0.50            | 0.00970              | 0.00102     | 0.0046                                             | 0.00142     | 0.0024                                             | 0.0015      | 0.0002                                             |
|      | IX21-2-E1D7  | 360                                  | 70      | 2.50E-05                        | 7             | 11         | 0.50            | 0.00970              | 0.00095     | 0.0033                                             | 0.00074     | -0.0019                                            | 0.0020      | 0.0050                                             |
|      | IX21-2-E1D8  | 360                                  | 70      | 2.50E-05                        | 8             | 11         | 0.50            | 0.00970              | 0.00100     | <b>0.0041</b>                                      | 0.00056     | -0.0012                                            | 0.0013      | -0.0011                                            |
|      | IX21-2-E1D9  | 360                                  | 70      | 2.50E-05                        | 9             | 11         | 0.50            | 0.00970              | 0.00096     | <b>0.0035</b>                                      | 0.00047     | -0.0012                                            | 0.0014      | <b>0.0018</b>                                      |
|      | IX21-2-E1D10 | 360                                  | 70      | 2.50E-05                        | 10            | 11         | 0.50            | 0.00970              | 0.00102     | <b>0.0044</b>                                      | 0.00064     | -0.0002                                            | 0.0017      | <b>0.0034</b>                                      |

**Table A17. ICP-MS Analysis Results from Dissolution of Glass IDFIX21-2 at 40 °C.**

| Exp.     | Sample ID    | Target [Si] <sub>inf</sub> ppm | T °C | Flow Rate, m <sup>3</sup> /d | Time, days | pH 23°C | Glass Mass g | SA m <sup>2</sup> | [Mo] ppm | Mo Rate g-glass m <sup>-2</sup> d <sup>-1</sup> | [Cs] ppm | Cs Rate g-glass m <sup>-2</sup> d <sup>-1</sup> | [Re] ppm | Re Rate g-glass m <sup>-2</sup> d <sup>-1</sup> |
|----------|--------------|--------------------------------|------|------------------------------|------------|---------|--------------|-------------------|----------|-------------------------------------------------|----------|-------------------------------------------------|----------|-------------------------------------------------|
| <b>1</b> | IX21-1-A2D1  | 40                             | 40   | 8.33E-06                     | 3          | 7       | 1.65         | 0.03239           | 0.00875  | 0.0075                                          | 0.02836  | 0.0117                                          | 0.0272   | 0.0149                                          |
|          | IX21-1-A2D2  | 40                             | 40   | 8.33E-06                     | 6          | 7       | 1.65         | 0.03238           | 0.00615  | 0.0011                                          | 0.02218  | 0.0033                                          | 0.0211   | 0.0040                                          |
|          | IX21-1-A2D3  | 40                             | 40   | 8.33E-06                     | 9          | 7       | 1.65         | 0.03237           | 0.00386  | 0.0001                                          | 0.02016  | 0.0037                                          | 0.0156   | 0.0026                                          |
|          | IX21-1-A2D4  | 40                             | 40   | 8.33E-06                     | 12         | 7       | 1.65         | 0.03236           | 0.00324  | 0.0007                                          | 0.01853  | 0.0035                                          | 0.0135   | 0.0030                                          |
|          | IX21-1-A2D5  | 40                             | 40   | 8.33E-06                     | 15         | 7       | 1.65         | 0.03235           | 0.00210  | -0.0002                                         | 0.01788  | 0.0036                                          | 0.0121   | 0.0028                                          |
|          | IX21-1-A2D6  | 40                             | 40   | 8.33E-06                     | 18         | 7       | 1.65         | 0.03234           | 0.00389  | 0.0022                                          | 0.02295  | 0.0058                                          | 0.0126   | 0.0035                                          |
|          | IX21-1-A2D7  | 40                             | 40   | 8.33E-06                     | 21         | 7       | 1.65         | 0.03234           | 0.00174  | -0.0009                                         | 0.01731  | 0.0024                                          | 0.0100   | <b>0.0019</b>                                   |
|          | IX21-1-A2D8  | 40                             | 40   | 8.33E-06                     | 24         | 7       | 1.65         | 0.03233           | 0.00258  | <b>0.0011</b>                                   | 0.01737  | <b>0.0036</b>                                   | 0.0083   | <b>0.0017</b>                                   |
|          | IX21-1-A2D9  | 40                             | 40   | 8.33E-06                     | 27         | 7       | 1.65         | 0.03232           | 0.00263  | <b>0.0007</b>                                   | 0.01722  | <b>0.0035</b>                                   | 0.0089   | <b>0.0025</b>                                   |
|          | IX21-1-A2D10 | 40                             | 40   | 8.33E-06                     | 30         | 7       | 1.65         | 0.03231           | 0.00254  | <b>0.0006</b>                                   | 0.01646  | <b>0.0032</b>                                   | 0.0085   | <b>0.0021</b>                                   |
| <b>2</b> | IX21-1-B2D1  | 45                             | 40   | 8.33E-06                     | 3          | 8       | 1.65         | 0.03239           | 0.00866  | 0.0079                                          | 0.01728  | 0.0072                                          | 0.0139   | 0.0076                                          |
|          | IX21-1-B2D2  | 45                             | 40   | 8.33E-06                     | 6          | 8       | 1.65         | 0.03239           | 0.00601  | 0.0013                                          | 0.01243  | 0.0016                                          | 0.0098   | 0.0015                                          |
|          | IX21-1-B2D3  | 45                             | 40   | 8.33E-06                     | 9          | 8       | 1.65         | 0.03238           | 0.00436  | 0.0009                                          | 0.01011  | 0.0016                                          | 0.0076   | 0.0014                                          |
|          | IX21-1-B2D4  | 45                             | 40   | 8.33E-06                     | 12         | 8       | 1.65         | 0.03238           | 0.00324  | 0.0006                                          | 0.00821  | 0.0013                                          | 0.0056   | 0.0009                                          |
|          | IX21-1-B2D5  | 45                             | 40   | 8.33E-06                     | 15         | 8       | 1.65         | 0.03238           | 0.00332  | 0.0013                                          | 0.00778  | 0.0015                                          | 0.0046   | 0.0009                                          |
|          | IX21-1-B2D6  | 45                             | 40   | 8.33E-06                     | 18         | 8       | 1.65         | 0.03238           | 0.00332  | 0.0013                                          | 0.00891  | 0.0021                                          | 0.0050   | 0.0014                                          |
|          | IX21-1-B2D7  | 45                             | 40   | 8.33E-06                     | 21         | 8       | 1.65         | 0.03237           | 0.00214  | 0.0001                                          | 0.00612  | 0.0007                                          | 0.0029   | 0.0001                                          |
|          | IX21-1-B2D8  | 45                             | 40   | 8.33E-06                     | 24         | 8       | 1.65         | 0.03237           | 0.00223  | <b>0.0007</b>                                   | 0.00681  | <b>0.0015</b>                                   | 0.0030   | <b>0.0008</b>                                   |
|          | IX21-1-B2D9  | 45                             | 40   | 8.33E-06                     | 27         | 8       | 1.65         | 0.03237           | 0.00188  | <b>0.0003</b>                                   | 0.00567  | <b>0.0009</b>                                   | 0.0031   | <b>0.0007</b>                                   |
|          | IX21-1-B2D10 | 45                             | 40   | 8.33E-06                     | 30         | 8       | 1.65         | 0.03237           | 0.00205  | <b>0.0007</b>                                   | 0.00631  | <b>0.0014</b>                                   | 0.0028   | <b>0.0006</b>                                   |
| <b>3</b> | IX21-1-C2D1  | 60                             | 40   | 8.33E-06                     | 3          | 9       | 1.65         | 0.03239           | 0.00609  | 0.0060                                          | 0.01179  | 0.0049                                          | 0.0098   | 0.0055                                          |
|          | IX21-1-C2D2  | 60                             | 40   | 8.33E-06                     | 6          | 9       | 1.65         | 0.03239           | 0.00384  | 0.0007                                          | 0.00914  | 0.0013                                          | 0.0082   | 0.0018                                          |
|          | IX21-1-C2D3  | 60                             | 40   | 8.33E-06                     | 9          | 9       | 1.65         | 0.03239           | 0.00217  | 0.0001                                          | 0.00695  | 0.0010                                          | 0.0055   | 0.0008                                          |
|          | IX21-1-C2D4  | 60                             | 40   | 8.33E-06                     | 12         | 9       | 1.65         | 0.03239           | 0.00207  | 0.0009                                          | 0.00595  | 0.0010                                          | 0.0038   | 0.0006                                          |
|          | IX21-1-C2D5  | 60                             | 40   | 8.33E-06                     | 15         | 9       | 1.65         | 0.03238           | 0.00107  | -0.0001                                         | 0.00471  | 0.0007                                          | 0.0031   | 0.0007                                          |
|          | IX21-1-C2D6  | 60                             | 40   | 8.33E-06                     | 18         | 9       | 1.65         | 0.03238           | 0.00106  | 0.0004                                          | 0.00498  | 0.0011                                          | 0.0028   | 0.0007                                          |
|          | IX21-1-C2D7  | 60                             | 40   | 8.33E-06                     | 21         | 9       | 1.65         | 0.03238           | 0.00086  | 0.0002                                          | 0.00412  | 0.0007                                          | 0.0033   | <b>0.0011</b>                                   |
|          | IX21-1-C2D8  | 60                             | 40   | 8.33E-06                     | 24         | 9       | 1.65         | 0.03238           | 0.00070  | <b>0.0002</b>                                   | 0.00379  | <b>0.0007</b>                                   | 0.0017   | <b>0.0000</b>                                   |
|          | IX21-1-C2D9  | 60                             | 40   | 8.33E-06                     | 27         | 9       | 1.65         | 0.03238           | 0.00057  | <b>0.0001</b>                                   | 0.00347  | <b>0.0007</b>                                   | 0.0020   | <b>0.0007</b>                                   |
|          | IX21-1-C2D10 | 60                             | 40   | 8.33E-06                     | 30         | 9       | 1.65         | 0.03238           | 0.00112  | <b>0.0007</b>                                   | 0.00347  | <b>0.0007</b>                                   | 0.0021   | <b>0.0006</b>                                   |
| <b>4</b> | IX21-1-D2D1  | 105                            | 40   | 8.33E-06                     | 3          | 10      | 0.83         | 0.01622           | 0.00473  | 0.0088                                          | 0.00550  | 0.0046                                          | 0.0045   | 0.0051                                          |
|          | IX21-1-D2D2  | 105                            | 40   | 8.33E-06                     | 6          | 10      | 0.83         | 0.01622           | 0.00390  | 0.0027                                          | 0.00421  | 0.0012                                          | 0.0035   | 0.0014                                          |
|          | IX21-1-D2D3  | 105                            | 40   | 8.33E-06                     | 9          | 10      | 0.83         | 0.01621           | 0.00212  | -0.0001                                         | 0.00325  | 0.0009                                          | 0.0026   | 0.0010                                          |
|          | IX21-1-D2D4  | 105                            | 40   | 8.33E-06                     | 12         | 10      | 0.83         | 0.01621           | 0.00145  | 0.0004                                          | 0.00270  | 0.0009                                          | 0.0020   | 0.0007                                          |
|          | IX21-1-D2D5  | 105                            | 40   | 8.33E-06                     | 15         | 10      | 0.83         | 0.01621           | 0.00107  | 0.0003                                          | 0.00210  | 0.0006                                          | 0.0014   | 0.0005                                          |
|          | IX21-1-D2D6  | 105                            | 40   | 8.33E-06                     | 18         | 10      | 0.83         | 0.01621           | 0.00084  | 0.0002                                          | 0.00186  | <b>0.0007</b>                                   | 0.0013   | 0.0006                                          |
|          | IX21-1-D2D7  | 105                            | 40   | 8.33E-06                     | 21         | 10      | 0.83         | 0.01621           | 0.00065  | 0.0001                                          | 0.00178  | <b>0.0007</b>                                   | 0.0011   | <b>0.0005</b>                                   |
|          | IX21-1-D2D8  | 105                            | 40   | 8.33E-06                     | 24         | 10      | 0.83         | 0.01621           | 0.00065  | 0.0003                                          | 0.00171  | <b>0.0007</b>                                   | 0.0011   | <b>0.0006</b>                                   |
|          | IX21-1-D2D9  | 105                            | 40   | 8.33E-06                     | 27         | 10      | 0.83         | 0.01621           | 0.00047  | -0.0001                                         | 0.00131  | <b>0.0004</b>                                   | 0.0008   | <b>0.0003</b>                                   |
|          | IX21-1-D2D10 | 105                            | 40   | 8.33E-06                     | 30         | 10      | 0.83         | 0.01621           | 0.00094  | 0.0010                                          | 0.00174  | <b>0.0009</b>                                   | 0.0011   | <b>0.0008</b>                                   |
| <b>5</b> | IX21-1-E2D1  | 270                            | 40   | 8.33E-06                     | 3          | 11      | 0.83         | 0.01622           | 0.00742  | 0.0146                                          | 0.00838  | 0.0069                                          | 0.0061   | 0.0063                                          |
|          | IX21-1-E2D2  | 270                            | 40   | 8.33E-06                     | 6          | 11      | 0.83         | 0.01621           | 0.00581  | 0.0040                                          | 0.00776  | 0.0029                                          | 0.0070   | 0.0042                                          |
|          | IX21-1-E2D3  | 270                            | 40   | 8.33E-06                     | 9          | 11      | 0.83         | 0.01621           | 0.00392  | 0.0018                                          | 0.00584  | 0.0016                                          | 0.0057   | 0.0022                                          |
|          | IX21-1-E2D4  | 270                            | 40   | 8.33E-06                     | 12         | 11      | 0.83         | 0.01621           | 0.00281  | 0.0015                                          | 0.00463  | 0.0014                                          | 0.0041   | 0.0011                                          |
|          | IX21-1-E2D5  | 270                            | 40   | 8.33E-06                     | 15         | 11      | 0.83         | 0.01621           | 0.00272  | 0.0025                                          | 0.00428  | 0.0016                                          | 0.0034   | 0.0013                                          |
|          | IX21-1-E2D6  | 270                            | 40   | 8.33E-06                     | 18         | 11      | 0.83         | 0.01621           | 0.00298  | 0.0030                                          | 0.00694  | 0.0040                                          | 0.0047   | 0.0031                                          |
|          | IX21-1-E2D7  | 270                            | 40   | 8.33E-06                     | 21         | 11      | 0.83         | 0.01621           | 0.00151  | -0.0002                                         | 0.00392  | 0.0003                                          | 0.0032   | 0.0007                                          |
|          | IX21-1-E2D8  | 270                            | 40   | 8.33E-06                     | 24         | 11      | 0.83         | 0.01621           | 0.00131  | 0.0009                                          | 0.00353  | <b>0.0013</b>                                   | 0.0030   | <b>0.0013</b>                                   |
|          | IX21-1-E2D9  | 270                            | 40   | 8.33E-06                     | 27         | 11      | 0.83         | 0.01621           | 0.00076  | 0.0000                                          | 0.00268  | <b>0.0007</b>                                   | 0.0027   | <b>0.0011</b>                                   |
|          | IX21-1-E2D10 | 270                            | 40   | 8.33E-06                     | 30         | 11      | 0.83         | 0.01621           | 0.00158  | 0.0022                                          | 0.00253  | <b>0.0010</b>                                   | 0.0026   | <b>0.0012</b>                                   |

**Table A18. ICP-MS Analysis Results from Dissolution of Glass IDFIX21-2at 23 °C.**

| Exp. | Sample ID    | Target<br>[Si] <sub>inf</sub><br>ppm | T<br>°C | Flow Rate,<br>m <sup>3</sup> /d | Time,<br>days | pH<br>23°C | Glass<br>Mass g | SA<br>m <sup>2</sup> | [Mo]<br>ppm | Mo Rate<br>g-glass m <sup>-2</sup> d <sup>-1</sup> | [Cs]<br>ppm | Cs Rate<br>g-glass m <sup>-2</sup> d <sup>-1</sup> | [Re]<br>ppm | Re Rate<br>g-glass m <sup>-2</sup> d <sup>-1</sup> |
|------|--------------|--------------------------------------|---------|---------------------------------|---------------|------------|-----------------|----------------------|-------------|----------------------------------------------------|-------------|----------------------------------------------------|-------------|----------------------------------------------------|
| 1    | IX21-2-A3D1  | 35                                   | 23      | 8.33E-06                        | 3             | 7          | 3.28            | 0.064231             | 0.00979     | 0.0050                                             | 0.01684     | 0.0035                                             | 0.0133      | 0.0042                                             |
|      | IX21-2-A3D2  | 35                                   | 23      | 8.33E-06                        | 6             | 7          | 3.28            | 0.064226             | 0.00663     | 0.0008                                             | 0.01207     | 0.0007                                             | 0.0096      | 0.0009                                             |
|      | IX21-2-A3D3  | 35                                   | 23      | 8.33E-06                        | 9             | 7          | 3.28            | 0.064222             | 0.00444     | 0.0004                                             | 0.00948     | 0.0007                                             | 0.0069      | 0.0006                                             |
|      | IX21-2-A3D4  | 35                                   | 23      | 8.33E-06                        | 12            | 7          | 3.28            | 0.064218             | 0.00391     | 0.0007                                             | 0.00940     | 0.0010                                             | 0.0060      | 0.0008                                             |
|      | IX21-2-A3D5  | 35                                   | 23      | 8.33E-06                        | 15            | 7          | 3.28            | 0.064216             | 0.00239     | 0.0000                                             | 0.00657     | 0.0004                                             | 0.0038      | 0.0002                                             |
|      | IX21-2-A3D6  | 35                                   | 23      | 8.33E-06                        | 18            | 7          | 3.28            | 0.064214             | 0.00175     | 0.0001                                             | 0.00582     | 0.0005                                             | 0.0028      | 0.0003                                             |
|      | IX21-2-A3D7  | 35                                   | 23      | 8.33E-06                        | 21            | 7          | 3.28            | 0.064213             | 0.00177     | 0.0003                                             | 0.00553     | 0.0005                                             | 0.0025      | 0.0003                                             |
|      | IX21-2-A3D8  | 35                                   | 23      | 8.33E-06                        | 24            | 7          | 3.28            | 0.064212             | 0.00125     | -0.00001                                           | 0.00431     | <b>0.0003</b>                                      | 0.0020      | <b>0.0002</b>                                      |
|      | IX21-2-A3D9  | 35                                   | 23      | 8.33E-06                        | 27            | 7          | 3.28            | 0.064211             | 0.00138     | <b>0.0002</b>                                      | 0.00426     | <b>0.0004</b>                                      | 0.0017      | <b>0.0002</b>                                      |
|      | IX21-2-A3D10 | 35                                   | 23      | 8.33E-06                        | 30            | 7          | 3.28            | 0.064210             | 0.00119     | <b>0.0001</b>                                      | 0.00391     | <b>0.0003</b>                                      | 0.0014      | <b>0.0002</b>                                      |
| 2    | IX21-2-B3D1  | 40                                   | 23      | 8.33E-06                        | 3             | 8          | 3.28            | 0.064233             | 0.01969     | 0.0105                                             | 0.0484      | 0.0103                                             | 0.0210      | 0.0065                                             |
|      | IX21-2-B3D2  | 40                                   | 23      | 8.33E-06                        | 6             | 8          | 3.28            | 0.064229             | 0.00614     | -0.0023                                            | 0.0091      | -0.0032                                            | 0.0073      | -0.0011                                            |
|      | IX21-2-B3D3  | 40                                   | 23      | 8.33E-06                        | 9             | 8          | 3.28            | 0.064227             | 0.00300     | -0.0002                                            | 0.0342      | 0.0063                                             | 0.0060      | 0.0007                                             |
|      | IX21-2-B3D4  | 40                                   | 23      | 8.33E-06                        | 12            | 8          | 3.28            | 0.064225             | 0.00370     | 0.0010                                             | 0.0061      | -0.0024                                            | 0.0050      | 0.0006                                             |
|      | IX21-2-B3D5  | 40                                   | 23      | 8.33E-06                        | 15            | 8          | 3.28            | 0.064224             | 0.00316     | 0.0005                                             | 0.0051      | 0.0004                                             | 0.0031      | 0.0001                                             |
|      | IX21-2-B3D6  | 40                                   | 23      | 8.33E-06                        | 18            | 8          | 3.28            | 0.064222             | 0.00225     | 0.0002                                             | 0.0043      | 0.0003                                             | 0.0027      | 0.0003                                             |
|      | IX21-2-B3D7  | 40                                   | 23      | 8.33E-06                        | 21            | 8          | 3.28            | 0.064222             | 0.00179     | <b>0.0002</b>                                      | 0.0039      | <b>0.0004</b>                                      | 0.0025      | <b>0.0003</b>                                      |
|      | IX21-2-B3D8  | 40                                   | 23      | 8.33E-06                        | 24            | 8          | 3.28            | 0.064221             | 0.00223     | <b>0.0005</b>                                      | 0.0039      | <b>0.0004</b>                                      | 0.0029      | <b>0.0004</b>                                      |
|      | IX21-2-B3D9  | 40                                   | 23      | 8.33E-06                        | 27            | 8          | 3.28            | 0.064220             | 0.00154     | 0.0000                                             | 0.0031      | <b>0.0002</b>                                      | 0.0017      | <b>0.0000</b>                                      |
|      | IX21-2-B3D10 | 40                                   | 23      | 8.33E-06                        | 30            | 8          | 3.28            | 0.064220             | 0.00197     | 0.0005                                             | 0.0040      | 0.0005                                             | 0.0024      | 0.0004                                             |
| 3    | IX21-2-C3D1  | 52                                   | 23      | 8.33E-06                        | 3             | 9          | 3.28            | 0.064233             | 0.00773     | 0.0037                                             | 0.00793     | 0.0017                                             | 0.0055      | 0.0018                                             |
|      | IX21-2-C3D2  | 52                                   | 23      | 8.33E-06                        | 6             | 9          | 3.28            | 0.064230             | 0.00623     | 0.0010                                             | 0.00634     | 0.0005                                             | 0.0047      | 0.0006                                             |
|      | IX21-2-C3D3  | 52                                   | 23      | 8.33E-06                        | 9             | 9          | 3.28            | 0.064228             | 0.00457     | 0.0005                                             | 0.00525     | 0.0004                                             | 0.0038      | 0.0005                                             |
|      | IX21-2-C3D4  | 52                                   | 23      | 8.33E-06                        | 12            | 9          | 3.28            | 0.064227             | 0.00385     | 0.0006                                             | 0.00462     | 0.0004                                             | 0.0030      | 0.0004                                             |
|      | IX21-2-C3D5  | 52                                   | 23      | 8.33E-06                        | 15            | 9          | 3.28            | 0.064225             | 0.00279     | 0.0002                                             | 0.00280     | 0.0001                                             | 0.0024      | 0.0003                                             |
|      | IX21-2-C3D6  | 52                                   | 23      | 8.33E-06                        | 18            | 9          | 3.28            | 0.064225             | 0.00235     | 0.0002                                             | 0.00319     | 0.0004                                             | 0.0019      | 0.0002                                             |
|      | IX21-2-C3D7  | 52                                   | 23      | 8.33E-06                        | 21            | 9          | 3.28            | 0.064224             | 0.00200     | <b>0.000141</b>                                    | 0.00349     | 0.0004                                             | 0.0018      | 0.0003                                             |
|      | IX21-2-C3D8  | 52                                   | 23      | 8.33E-06                        | 24            | 9          | 3.28            | 0.064223             | 0.00177     | <b>0.000112</b>                                    | 0.00263     | <b>0.0002</b>                                      | 0.0014      | <b>0.0002</b>                                      |
|      | IX21-2-C3D9  | 52                                   | 23      | 8.33E-06                        | 27            | 9          | 3.28            | 0.064223             | 0.00194     | <b>0.000266</b>                                    | 0.00315     | <b>0.0004</b>                                      | 0.0016      | <b>0.0003</b>                                      |
|      | IX21-2-C3D10 | 52                                   | 23      | 8.33E-06                        | 30            | 9          | 3.28            | 0.064222             | 0.00152     | -0.000010                                          | 0.00227     | <b>0.0001</b>                                      | 0.0011      | <b>0.0001</b>                                      |
| 4    | IX21-2-D3D1  | 90                                   | 23      | 8.33E-06                        | 3             | 10         | 1.64            | 0.032117             | 0.00529     | 0.0054                                             | 0.00644     | 0.0027                                             | 0.0033      | 0.0019                                             |
|      | IX21-2-D3D2  | 90                                   | 23      | 8.33E-06                        | 6             | 10         | 1.64            | 0.032115             | 0.00482     | 0.0022                                             | 0.00558     | 0.0010                                             | 0.0033      | 0.0009                                             |
|      | IX21-2-D3D3  | 90                                   | 23      | 8.33E-06                        | 9             | 10         | 1.64            | 0.032114             | 0.00386     | 0.0014                                             | 0.00466     | 0.0008                                             | 0.0028      | 0.0006                                             |
|      | IX21-2-D3D4  | 90                                   | 23      | 8.33E-06                        | 12            | 10         | 1.64            | 0.032113             | 0.00289     | 0.0008                                             | 0.00374     | 0.0006                                             | 0.0022      | 0.0004                                             |
|      | IX21-2-D3D5  | 90                                   | 23      | 8.33E-06                        | 15            | 10         | 1.64            | 0.032112             | 0.00258     | 0.0010                                             | 0.00305     | 0.0005                                             | 0.0018      | 0.0003                                             |
|      | IX21-2-D3D6  | 90                                   | 23      | 8.33E-06                        | 18            | 10         | 1.64            | 0.032112             | 0.00192     | 0.0005                                             | 0.00265     | 0.0005                                             | 0.0013      | 0.0002                                             |
|      | IX21-2-D3D7  | 90                                   | 23      | 8.33E-06                        | 21            | 10         | 1.64            | 0.032111             | 0.00159     | 0.0005                                             | 0.00230     | 0.0004                                             | 0.0011      | 0.0002                                             |
|      | IX21-2-D3D8  | 90                                   | 23      | 8.33E-06                        | 24            | 10         | 1.64            | 0.032111             | 0.00163     | <b>0.0007</b>                                      | 0.00198     | <b>0.0004</b>                                      | 0.0009      | <b>0.0001</b>                                      |
|      | IX21-2-D3D9  | 90                                   | 23      | 8.33E-06                        | 27            | 10         | 1.64            | 0.032111             | 0.00143     | <b>0.0005</b>                                      | 0.00167     | <b>0.0003</b>                                      | 0.0007      | <b>0.0001</b>                                      |
|      | IX21-2-D3D10 | 90                                   | 23      | 8.33E-06                        | 30            | 10         | 1.64            | 0.032111             | 0.00138     | <b>0.0005</b>                                      | 0.00146     | <b>0.0003</b>                                      | 0.0007      | <b>0.0001</b>                                      |
| 5    | IX21-2-E3D1  | 230                                  | 23      | 8.33E-06                        | 3             | 11         | 1.64            | 0.032117             | 0.00468     | 0.0036                                             | 0.00520     | 0.0022                                             | 0.0032      | 0.0018                                             |
|      | IX21-2-E3D2  | 230                                  | 23      | 8.33E-06                        | 6             | 11         | 1.64            | 0.032116             | 0.00451     | 0.0016                                             | 0.00612     | 0.0015                                             | 0.0041      | 0.0014                                             |
|      | IX21-2-E3D3  | 230                                  | 23      | 8.33E-06                        | 9             | 11         | 1.64            | 0.032114             | 0.00432     | 0.0015                                             | 0.00557     | 0.0011                                             | 0.0038      | 0.0010                                             |
|      | IX21-2-E3D4  | 230                                  | 23      | 8.33E-06                        | 12            | 11         | 1.64            | 0.032113             | 0.00361     | 0.0008                                             | 0.00538     | 0.0011                                             | 0.0038      | 0.0011                                             |
|      | IX21-2-E3D5  | 230                                  | 23      | 8.33E-06                        | 15            | 11         | 1.64            | 0.032112             | 0.00358     | 0.0012                                             | 0.00489     | <b>0.0009</b>                                      | 0.0035      | 0.0009                                             |
|      | IX21-2-E3D6  | 230                                  | 23      | 8.33E-06                        | 18            | 11         | 1.64            | 0.032111             | 0.00317     | <b>0.0007</b>                                      | 0.00463     | <b>0.0009</b>                                      | 0.0032      | <b>0.0008</b>                                      |
|      | IX21-2-E3D7  | 230                                  | 23      | 8.33E-06                        | 21            | 11         | 1.64            | 0.032110             | 0.00318     | <b>0.0010</b>                                      | 0.00490     | 0.0011                                             | 0.0034      | <b>0.0010</b>                                      |
|      | IX21-2-E3D8  | 230                                  | 23      | 8.33E-06                        | 24            | 11         | 1.64            | 0.032109             | 0.00222     | -0.0001                                            | 0.00314     | 0.0003                                             | 0.0023      | <b>0.0003</b>                                      |
|      | IX21-2-E3D9  | 230                                  | 23      | 8.33E-06                        | 27            | 11         | 1.64            | 0.032108             | 0.00290     | <b>0.0012</b>                                      | 0.00343     | <b>0.0008</b>                                      | 0.0023      | <b>0.0006</b>                                      |
|      | IX21-2-E3D10 | 230                                  | 23      | 8.33E-06                        | 30            | 11         | 1.64            | contaminated         |             |                                                    |             |                                                    |             |                                                    |

**Table A19. ICP-MS Analysis Results from Dissolution of Glass IDFIX21-3 at 70 °C.**

| Exp.     | Sample ID    | Target [Si] <sub>inf</sub> ppm | T °C | Flow Rate, m <sup>3</sup> /d | Time, days | pH 23°C | Glass Mass g | SA m <sup>2</sup> | [Mo] ppm | Mo Rate g-glass m <sup>-2</sup> d <sup>-1</sup> | [Cs] ppm | Cs Rate g-glass m <sup>-2</sup> d <sup>-1</sup> | [Re] ppm | Re Rate g-glass m <sup>-2</sup> d <sup>-1</sup> |
|----------|--------------|--------------------------------|------|------------------------------|------------|---------|--------------|-------------------|----------|-------------------------------------------------|----------|-------------------------------------------------|----------|-------------------------------------------------|
| <b>1</b> | IX21-3-A1D1  | 55                             | 70   | 2.50E-05                     | 1          | 7       | 0.77         | 0.01525           | 0.00870  | 0.0606                                          | 0.10670  | 0.3248                                          | 0.0624   | 0.2821                                          |
|          | IX21-3-A1D2  | 55                             | 70   | 2.50E-05                     | 2          | 7       | 0.77         | 0.01519           | 0.00700  | 0.0182                                          | 0.10390  | 0.1545                                          | 0.0548   | 0.1070                                          |
|          | IX21-3-A1D3  | 55                             | 70   | 2.50E-05                     | 3          | 7       | 0.77         | 0.01513           | 0.00550  | 0.0137                                          | 0.11740  | 0.2009                                          | 0.0450   | 0.0800                                          |
|          | IX21-3-A1D4  | 55                             | 70   | 2.50E-05                     | 4          | 7       | 0.77         | 0.01506           | 0.00590  | 0.0220                                          | 0.12450  | 0.2029                                          | 0.0383   | 0.0724                                          |
|          | IX21-3-A1D5  | 55                             | 70   | 2.50E-05                     | 5          | 7       | 0.77         | 0.01500           | 0.00530  | 0.0163                                          | 0.11172  | 0.1531                                          | 0.0303   | 0.0511                                          |
|          | IX21-3-A1D6  | 55                             | 70   | 2.50E-05                     | 6          | 7       | 0.77         | 0.01494           | 0.00390  | 0.0084                                          | 0.10310  | 0.1468                                          | 0.0257   | 0.0486                                          |
|          | IX21-3-A1D7  | 55                             | 70   | 2.50E-05                     | 7          | 7       | 0.77         | 0.01489           | 0.00450  | 0.0179                                          | 0.09791  | 0.1445                                          | 0.0220   | 0.0419                                          |
|          | IX21-3-A1D8  | 55                             | 70   | 2.50E-05                     | 8          | 7       | 0.77         | 0.01484           | 0.00330  | <b>0.0070</b>                                   | 0.10241  | <b>0.1673</b>                                   | 0.0189   | <b>0.0366</b>                                   |
|          | IX21-3-A1D9  | 55                             | 70   | 2.50E-05                     | 9          | 7       | 0.77         | 0.01479           | 0.00330  | <b>0.0114</b>                                   | 0.10659  | <b>0.1739</b>                                   | 0.0174   | <b>0.0366</b>                                   |
|          | IX21-3-A1D10 | 55                             | 70   | 2.50E-05                     | 10         | 7       | 0.77         | 0.01474           | 0.00310  | <b>0.0100</b>                                   | 0.09706  | <b>0.1379</b>                                   | 0.0148   | <b>0.0283</b>                                   |
| <b>2</b> | IX21-3-B1D1  | 60                             | 70   | 2.50E-05                     | 1          | 8       | 0.77         | 0.01527           | 0.00680  | 0.0466                                          | 0.04342  | 0.1316                                          | 0.0283   | 0.1280                                          |
|          | IX21-3-B1D2  | 60                             | 70   | 2.50E-05                     | 2          | 8       | 0.77         | 0.01524           | 0.00440  | 0.0062                                          | 0.04288  | 0.0642                                          | 0.0228   | 0.0391                                          |
|          | IX21-3-B1D3  | 60                             | 70   | 2.50E-05                     | 3          | 8       | 0.77         | 0.01522           | 0.00360  | 0.0091                                          | 0.04566  | 0.0736                                          | 0.0198   | 0.0377                                          |
|          | IX21-3-B1D4  | 60                             | 70   | 2.50E-05                     | 4          | 8       | 0.77         | 0.01519           | 0.00190  | -0.0002                                         | 0.04603  | 0.0707                                          | 0.0169   | 0.0317                                          |
|          | IX21-3-B1D5  | 60                             | 70   | 2.50E-05                     | 5          | 8       | 0.77         | 0.01517           | 0.00170  | 0.0045                                          | 0.04454  | 0.0656                                          | 0.0133   | 0.0218                                          |
|          | IX21-3-B1D6  | 60                             | 70   | 2.50E-05                     | 6          | 8       | 0.77         | 0.01515           | 0.00180  | 0.0059                                          | 0.03832  | 0.0489                                          | 0.0115   | 0.0221                                          |
|          | IX21-3-B1D7  | 60                             | 70   | 2.50E-05                     | 7          | 8       | 0.77         | 0.01512           | 0.00290  | 0.0135                                          | 0.04026  | 0.0645                                          | 0.0108   | 0.0227                                          |
|          | IX21-3-B1D8  | 60                             | 70   | 2.50E-05                     | 8          | 8       | 0.77         | 0.01510           | 0.00150  | -0.0006                                         | 0.03751  | <b>0.0532</b>                                   | 0.0086   | <b>0.0146</b>                                   |
|          | IX21-3-B1D9  | 60                             | 70   | 2.50E-05                     | 9          | 8       | 0.77         | 0.01508           | 0.00170  | <b>0.0059</b>                                   | 0.03831  | <b>0.0600</b>                                   | 0.0088   | <b>0.0202</b>                                   |
|          | IX21-3-B1D10 | 60                             | 70   | 2.50E-05                     | 10         | 8       | 0.77         | 0.01506           | 0.00130  | <b>0.0023</b>                                   | 0.03720  | <b>0.0554</b>                                   | 0.0080   | <b>0.0164</b>                                   |
| <b>3</b> | IX21-3-C1D1  | 80                             | 70   | 2.50E-05                     | 1          | 9       | 0.77         | 0.01528           | 0.00800  | 0.0566                                          | 0.01953  | 0.0591                                          | 0.0148   | 0.0666                                          |
|          | IX21-3-C1D2  | 80                             | 70   | 2.50E-05                     | 2          | 9       | 0.77         | 0.01527           | 0.00340  | -0.0044                                         | 0.01755  | 0.0236                                          | 0.0133   | 0.0264                                          |
|          | IX21-3-C1D3  | 80                             | 70   | 2.50E-05                     | 3          | 9       | 0.77         | 0.01526           | 0.00240  | 0.0048                                          | 0.01778  | 0.0273                                          | 0.0111   | 0.0200                                          |
|          | IX21-3-C1D4  | 80                             | 70   | 2.50E-05                     | 4          | 9       | 0.77         | 0.01525           | 0.00270  | 0.0105                                          | 0.01721  | 0.0252                                          | 0.0110   | 0.0244                                          |
|          | IX21-3-C1D5  | 80                             | 70   | 2.50E-05                     | 5          | 9       | 0.77         | 0.01524           | 0.00070  | -0.0048                                         | 0.01591  | 0.0221                                          | 0.0081   | 0.0117                                          |
|          | IX21-3-C1D6  | 80                             | 70   | 2.50E-05                     | 6          | 9       | 0.77         | 0.01524           | 0.00090  | <b>0.0038</b>                                   | 0.01456  | 0.0200                                          | 0.0078   | 0.0167                                          |
|          | IX21-3-C1D7  | 80                             | 70   | 2.50E-05                     | 7          | 9       | 0.77         | 0.01523           | 0.00070  | <b>0.0016</b>                                   | 0.01450  | 0.0219                                          | 0.0067   | 0.0126                                          |
|          | IX21-3-C1D8  | 80                             | 70   | 2.50E-05                     | 8          | 9       | 0.77         | 0.01522           | 0.00110  | <b>0.0052</b>                                   | 0.01413  | <b>0.0209</b>                                   | 0.0052   | <b>0.0082</b>                                   |
|          | IX21-3-C1D9  | 80                             | 70   | 2.50E-05                     | 9          | 9       | 0.77         | 0.01521           | 0.00040  | -0.0012                                         | 0.01352  | <b>0.0196</b>                                   | 0.0048   | <b>0.0097</b>                                   |
|          | IX21-3-C1D10 | 80                             | 70   | 2.50E-05                     | 10         | 9       | 0.77         | 0.01521           | 0.00035  | <b>0.0009</b>                                   | 0.01448  | <b>0.0234</b>                                   | 0.0047   | <b>0.0102</b>                                   |
| <b>4</b> | IX21-3-D1D1  | 140                            | 70   | 2.50E-05                     | 1          | 10      | 0.50         | 0.00982           | 0.00180  | 0.0169                                          | 0.00844  | 0.0299                                          | 0.0062   | 0.0351                                          |
|          | IX21-3-D1D2  | 140                            | 70   | 2.50E-05                     | 2          | 10      | 0.50         | 0.00982           | 0.00035  | -0.0076                                         | 0.00701  | 0.0082                                          | 0.0049   | 0.0083                                          |
|          | IX21-3-D1D3  | 140                            | 70   | 2.50E-05                     | 3          | 10      | 0.50         | 0.00982           | 0.00035  | 0.0004                                          | 0.00608  | 0.0072                                          | 0.0048   | 0.0121                                          |
|          | IX21-3-D1D4  | 140                            | 70   | 2.50E-05                     | 4          | 10      | 0.50         | 0.00981           | 0.00040  | 0.0010                                          | 0.00580  | 0.0080                                          | 0.0030   | 0.0002                                          |
|          | IX21-3-D1D5  | 140                            | 70   | 2.50E-05                     | 5          | 10      | 0.50         | 0.00981           | 0.00035  | 0.0001                                          | 0.00493  | 0.0046                                          | 0.0028   | 0.0047                                          |
|          | IX21-3-D1D6  | 140                            | 70   | 2.50E-05                     | 6          | 10      | 0.50         | 0.00981           | 0.00035  | 0.0004                                          | 0.00478  | 0.0059                                          | 0.0030   | 0.0068                                          |
|          | IX21-3-D1D7  | 140                            | 70   | 2.50E-05                     | 7          | 10      | 0.50         | 0.00981           | 0.00035  | 0.0004                                          | 0.00500  | 0.0073                                          | 0.0012   | -0.0060                                         |
|          | IX21-3-D1D8  | 140                            | 70   | 2.50E-05                     | 8          | 10      | 0.50         | 0.00980           | 0.00035  | 0.0004                                          | 0.00517  | <b>0.0076</b>                                   | 0.0014   | <b>0.0010</b>                                   |
|          | IX21-3-D1D9  | 140                            | 70   | 2.50E-05                     | 9          | 10      | 0.50         | 0.00980           | 0.00035  | 0.0004                                          | 0.00510  | <b>0.0069</b>                                   | 0.0013   | -0.0001                                         |
|          | IX21-3-D1D10 | 140                            | 70   | 2.50E-05                     | 10         | 10      | 0.50         | 0.00980           | 0.00035  | 0.0004                                          | 0.00608  | <b>0.0117</b>                                   | 0.0017   | <b>0.0030</b>                                   |
| <b>5</b> | IX21-3-E1D1  | 360                            | 70   | 2.50E-05                     | 1          | 11      | 0.50         | 0.00982           | 0.00452  | 0.0468                                          | 0.00510  | 0.0220                                          | 0.0041   | 0.0222                                          |
|          | IX21-3-E1D2  | 360                            | 70   | 2.50E-05                     | 2          | 11      | 0.50         | 0.00982           | 0.24486  | 2.6835                                          | 0.00399  | 0.0107                                          | 0.0042   | 0.0122                                          |
|          | IX21-3-E1D3  | 360                            | 70   | 2.50E-05                     | 3          | 11      | 0.50         | 0.00982           | 0.00037  | -1.3527                                         | 0.00326  | 0.0085                                          | 0.0027   | 0.0008                                          |
|          | IX21-3-E1D4  | 360                            | 70   | 2.50E-05                     | 4          | 11      | 0.50         | 0.00982           | 0.00116  | 0.0091                                          | 0.00217  | 0.0042                                          | 0.0018   | 0.0002                                          |
|          | IX21-3-E1D5  | 360                            | 70   | 2.50E-05                     | 5          | 11      | 0.50         | 0.00982           | 0.00037  | -0.0039                                         | 0.00190  | 0.0042                                          | 0.0026   | 0.0084                                          |
|          | IX21-3-E1D6  | 360                            | 70   | 2.50E-05                     | 6          | 11      | 0.50         | 0.00982           | 0.00037  | 0.0004                                          | 0.00273  | 0.0085                                          | 0.0019   | 0.0011                                          |
|          | IX21-3-E1D7  | 360                            | 70   | 2.50E-05                     | 7          | 11      | 0.50         | 0.00982           | 0.00021  | -0.0013                                         | 0.00174  | 0.0028                                          | 0.0017   | <b>0.0022</b>                                   |
|          | IX21-3-E1D8  | 360                            | 70   | 2.50E-05                     | 8          | 11      | 0.50         | 0.00982           | 0.00284  | 0.0286                                          | 0.00158  | <b>0.0032</b>                                   | 0.0016   | <b>0.0022</b>                                   |
|          | IX21-3-E1D9  | 360                            | 70   | 2.50E-05                     | 9          | 11      | 0.50         | 0.00982           | 0.00037  | -0.0132                                         | 0.00132  | <b>0.0022</b>                                   | 0.0017   | <b>0.0031</b>                                   |
|          | IX21-3-E1D10 | 360                            | 70   | 2.50E-05                     | 10         | 11      | 0.50         | 0.00982           | 0.00037  | 0.0004                                          | 0.00144  | <b>0.0031</b>                                   | 0.0010   | -0.0023                                         |

**Table A20. ICP-MS Analysis Results from Dissolution of Glass IDFIX21-3 at 40 °C.**

| Exp.     | Sample ID    | Target<br>[Si] <sub>inf</sub><br>ppm | T<br>°C | Flow Rate,<br>m <sup>3</sup> /d | Time,<br>days | pH<br>23°C | Glass<br>Mass g | SA<br>m <sup>2</sup> | [Mo]<br>ppm | Mo Rate<br>g-glass m <sup>-2</sup> d <sup>-1</sup> | [Cs]<br>ppm | Cs Rate<br>g-glass m <sup>-2</sup> d <sup>-1</sup> | [Re]<br>ppm | Re Rate<br>g-glass m <sup>-2</sup> d <sup>-1</sup> |
|----------|--------------|--------------------------------------|---------|---------------------------------|---------------|------------|-----------------|----------------------|-------------|----------------------------------------------------|-------------|----------------------------------------------------|-------------|----------------------------------------------------|
| <b>1</b> | IX21-3-A2D1  | 40                                   | 40      | 8.33E-06                        | 3             | 7          | 1.65            | 0.0327               | 0.00903     | 0.0085                                             | 0.03196     | 0.0151                                             | 0.0308      | 0.0212                                             |
|          | IX21-3-A2D2  | 40                                   | 40      | 8.33E-06                        | 6             | 7          | 1.65            | 0.0327               | 0.00519     | 0.000013                                           | 0.03012     | 0.0067                                             | 0.0275      | 0.0083                                             |
|          | IX21-3-A2D3  | 40                                   | 40      | 8.33E-06                        | 9             | 7          | 1.65            | 0.0327               | 0.00349     | 0.0002                                             | 0.02913     | 0.0066                                             | 0.0231      | 0.0063                                             |
|          | IX21-3-A2D4  | 40                                   | 40      | 8.33E-06                        | 12            | 7          | 1.65            | 0.0327               | 0.00253     | 0.0001                                             | 0.02852     | 0.0066                                             | 0.0191      | 0.0050                                             |
|          | IX21-3-A2D5  | 40                                   | 40      | 8.33E-06                        | 15            | 7          | 1.65            | 0.0327               | 0.00257     | 0.0007                                             | 0.02740     | 0.0062                                             | 0.0167      | 0.0048                                             |
|          | IX21-3-A2D6  | 40                                   | 40      | 8.33E-06                        | 18            | 7          | 1.65            | 0.0326               | 0.00173     | -0.0002                                            | 0.02774     | 0.0066                                             | 0.0154      | 0.0047                                             |
|          | IX21-3-A2D7  | 40                                   | 40      | 8.33E-06                        | 21            | 7          | 1.65            | 0.0326               | 0.00257     | 0.0012                                             | 0.02686     | <b>0.0061</b>                                      | 0.0135      | <b>0.0038</b>                                      |
|          | IX21-3-A2D8  | 40                                   | 40      | 8.33E-06                        | 24            | 7          | 1.65            | 0.0326               | 0.00267     | <b>0.0008</b>                                      | 0.02585     | <b>0.0059</b>                                      | 0.0125      | <b>0.0038</b>                                      |
|          | IX21-3-A2D9  | 40                                   | 40      | 8.33E-06                        | 27            | 7          | 1.65            | 0.0326               | 0.00221     | <b>0.0002</b>                                      | 0.02620     | <b>0.0063</b>                                      | 0.0129      | <b>0.0044</b>                                      |
|          | IX21-3-A2D10 | 40                                   | 40      | 8.33E-06                        | 30            | 7          | 1.65            | 0.0326               | 0.00230     | <b>0.0006</b>                                      | 0.02557     | <b>0.0059</b>                                      | 0.0115      | <b>0.0033</b>                                      |
| <b>2</b> | IX21-3-B2D1  | 45                                   | 40      | 8.33E-06                        | 3             | 8          | 1.65            | 0.0327               | 0.00822     | 0.0081                                             | 0.01692     | 0.0080                                             | 0.0139      | 0.0095                                             |
|          | IX21-3-B2D2  | 45                                   | 40      | 8.33E-06                        | 6             | 8          | 1.65            | 0.0327               | 0.00493     | 0.0004                                             | 0.01368     | 0.0024                                             | 0.0121      | 0.0034                                             |
|          | IX21-3-B2D3  | 45                                   | 40      | 8.33E-06                        | 9             | 8          | 1.65            | 0.0327               | 0.00375     | 0.0009                                             | 0.01238     | 0.0026                                             | 0.0100      | 0.0027                                             |
|          | IX21-3-B2D4  | 45                                   | 40      | 8.33E-06                        | 12            | 8          | 1.65            | 0.0327               | 0.00225     | -0.0001                                            | 0.01014     | 0.0018                                             | 0.0073      | 0.0014                                             |
|          | IX21-3-B2D5  | 45                                   | 40      | 8.33E-06                        | 15            | 8          | 1.65            | 0.0327               | 0.00211     | 0.0006                                             | 0.01039     | 0.0025                                             | 0.0062      | 0.0016                                             |
|          | IX21-3-B2D6  | 45                                   | 40      | 8.33E-06                        | 18            | 8          | 1.65            | 0.0327               | 0.00257     | 0.0012                                             | 0.01018     | 0.0023                                             | 0.0061      | 0.0020                                             |
|          | IX21-3-B2D7  | 45                                   | 40      | 8.33E-06                        | 21            | 8          | 1.65            | 0.0327               | 0.00141     | -0.0003                                            | 0.00924     | 0.0019                                             | 0.0046      | 0.0009                                             |
|          | IX21-3-B2D8  | 45                                   | 40      | 8.33E-06                        | 24            | 8          | 1.65            | 0.0327               | 0.00126     | <b>0.0001</b>                                      | 0.00871     | <b>0.0019</b>                                      | 0.0047      | <b>0.0015</b>                                      |
|          | IX21-3-B2D9  | 45                                   | 40      | 8.33E-06                        | 27            | 8          | 1.65            | 0.0327               | 0.00091     | -0.0002                                            | 0.00856     | <b>0.0020</b>                                      | 0.0051      | <b>0.0017</b>                                      |
|          | IX21-3-B2D10 | 45                                   | 40      | 8.33E-06                        | 30            | 8          | 1.65            | 0.0327               | 0.00137     | <b>0.0005</b>                                      | 0.00859     | <b>0.0020</b>                                      | 0.0036      | <b>0.0006</b>                                      |
| <b>3</b> | IX21-3-C2D1  | 60                                   | 40      | 8.33E-06                        | 3             | 9          | 1.65            | 0.0327               | 0.00896     | 0.0097                                             | 0.01008     | 0.0048                                             | 0.0094      | 0.0066                                             |
|          | IX21-3-C2D2  | 60                                   | 40      | 8.33E-06                        | 6             | 9          | 1.65            | 0.0327               | 0.00624     | 0.0018                                             | 0.00888     | 0.0018                                             | 0.0079      | 0.0023                                             |
|          | IX21-3-C2D3  | 60                                   | 40      | 8.33E-06                        | 9             | 9          | 1.65            | 0.0327               | 0.00469     | 0.0016                                             | 0.00726     | 0.0013                                             | 0.0061      | 0.0015                                             |
|          | IX21-3-C2D4  | 60                                   | 40      | 8.33E-06                        | 12            | 9          | 1.65            | 0.0327               | 0.00304     | 0.0006                                             | 0.00670     | 0.0014                                             | 0.0052      | 0.0015                                             |
|          | IX21-3-C2D5  | 60                                   | 40      | 8.33E-06                        | 15            | 9          | 1.65            | 0.0327               | 0.00236     | 0.0008                                             | 0.00583     | 0.0012                                             | 0.0041      | 0.0010                                             |
|          | IX21-3-C2D6  | 60                                   | 40      | 8.33E-06                        | 18            | 9          | 1.65            | 0.0327               | 0.00154     | 0.0003                                             | 0.00547     | 0.0012                                             | 0.0036      | 0.0011                                             |
|          | IX21-3-C2D7  | 60                                   | 40      | 8.33E-06                        | 21            | 9          | 1.65            | 0.0327               | 0.00239     | 0.0017                                             | 0.00510     | <b>0.0011</b>                                      | 0.0031      | <b>0.0010</b>                                      |
|          | IX21-3-C2D8  | 60                                   | 40      | 8.33E-06                        | 24            | 9          | 1.65            | 0.0327               | 0.00222     | 0.0010                                             | 0.00511     | <b>0.0012</b>                                      | 0.0030      | <b>0.0010</b>                                      |
|          | IX21-3-C2D9  | 60                                   | 40      | 8.33E-06                        | 27            | 9          | 1.65            | 0.0327               | 0.00150     | <b>0.0003</b>                                      | 0.00459     | <b>0.0010</b>                                      | 0.0027      | <b>0.0008</b>                                      |
|          | IX21-3-C2D10 | 60                                   | 40      | 8.33E-06                        | 30            | 9          | 1.65            | 0.0327               | 0.00122     | <b>0.0004</b>                                      | 0.00450     | <b>0.0010</b>                                      | 0.0027      | <b>0.0009</b>                                      |
| <b>4</b> | IX21-3-D2D1  | 105                                  | 40      | 8.33E-06                        | 3             | 10         | 0.83            | 0.0164               | 0.00603     | 0.0125                                             | 0.00480     | 0.0045                                             | 0.0040      | 0.0057                                             |
|          | IX21-3-D2D2  | 105                                  | 40      | 8.33E-06                        | 6             | 10         | 0.83            | 0.0164               | 0.00396     | 0.0017                                             | 0.00409     | 0.0016                                             | 0.0034      | 0.0020                                             |
|          | IX21-3-D2D3  | 105                                  | 40      | 8.33E-06                        | 9             | 10         | 0.83            | 0.0164               | 0.00260     | 0.0009                                             | 0.00321     | 0.0011                                             | 0.0025      | 0.0011                                             |
|          | IX21-3-D2D4  | 105                                  | 40      | 8.33E-06                        | 12            | 10         | 0.83            | 0.0164               | 0.00183     | 0.0007                                             | 0.00292     | 0.0012                                             | 0.0020      | 0.0011                                             |
|          | IX21-3-D2D5  | 105                                  | 40      | 8.33E-06                        | 15            | 10         | 0.83            | 0.0164               | 0.00192     | 0.0018                                             | 0.00231     | 0.0008                                             | 0.0015      | 0.0006                                             |
|          | IX21-3-D2D6  | 105                                  | 40      | 8.33E-06                        | 18            | 10         | 0.83            | 0.0164               | 0.00116     | 0.0000                                             | 0.00216     | 0.0010                                             | 0.0013      | 0.0008                                             |
|          | IX21-3-D2D7  | 105                                  | 40      | 8.33E-06                        | 21            | 10         | 0.83            | 0.0164               | 0.00068     | -0.0002                                            | 0.00198     | <b>0.0008</b>                                      | 0.0010      | <b>0.0005</b>                                      |
|          | IX21-3-D2D8  | 105                                  | 40      | 8.33E-06                        | 24            | 10         | 0.83            | 0.0164               | 0.00057     | 0.0001                                             | 0.00196     | <b>0.0009</b>                                      | 0.0010      | <b>0.0007</b>                                      |
|          | IX21-3-D2D9  | 105                                  | 40      | 8.33E-06                        | 27            | 10         | 0.83            | 0.0164               | 0.00041     | -0.0001                                            | 0.00152     | <b>0.0005</b>                                      | 0.0007      | <b>0.0003</b>                                      |
|          | IX21-3-D2D10 | 105                                  | 40      | 8.33E-06                        | 30            | 10         | 0.83            | 0.0164               | 0.00094     | 0.0012                                             | 0.00154     | <b>0.0007</b>                                      | 0.0006      | <b>0.0004</b>                                      |
| <b>5</b> | IX21-3-E2D1  | 270                                  | 40      | 8.33E-06                        | 3             | 11         | 0.83            | 0.0164               | 0.00683     | 0.0146                                             | 0.00621     | 0.0058                                             | 0.0051      | 0.0065                                             |
|          | IX21-3-E2D2  | 270                                  | 40      | 8.33E-06                        | 6             | 11         | 0.83            | 0.0164               | 0.00613     | 0.0058                                             | 0.00629     | 0.0030                                             | 0.0054      | 0.0037                                             |
|          | IX21-3-E2D3  | 270                                  | 40      | 8.33E-06                        | 9             | 11         | 0.83            | 0.0164               | 0.00408     | 0.0020                                             | 0.00543     | 0.0021                                             | 0.0046      | 0.0023                                             |
|          | IX21-3-E2D4  | 270                                  | 40      | 8.33E-06                        | 12            | 11         | 0.83            | 0.0164               | 0.00325     | 0.0024                                             | 0.00515     | 0.0023                                             | 0.0043      | 0.0024                                             |
|          | IX21-3-E2D5  | 270                                  | 40      | 8.33E-06                        | 15            | 11         | 0.83            | 0.0164               | 0.00280     | 0.0023                                             | 0.00477     | 0.0020                                             | 0.0038      | 0.0020                                             |
|          | IX21-3-E2D6  | 270                                  | 40      | 8.33E-06                        | 18            | 11         | 0.83            | 0.0164               | 0.00284     | 0.0029                                             | 0.00440     | 0.0019                                             | 0.0034      | 0.0018                                             |
|          | IX21-3-E2D7  | 270                                  | 40      | 8.33E-06                        | 21            | 11         | 0.83            | 0.0164               | 0.00240     | 0.0019                                             | 0.00392     | 0.0016                                             | 0.0030      | 0.0015                                             |
|          | IX21-3-E2D8  | 270                                  | 40      | 8.33E-06                        | 24            | 11         | 0.83            | 0.0164               | 0.00161     | <b>0.0007</b>                                      | 0.00351     | <b>0.0014</b>                                      | 0.0026      | <b>0.0013</b>                                      |
|          | IX21-3-E2D9  | 270                                  | 40      | 8.33E-06                        | 27            | 11         | 0.83            | 0.0164               | 0.00161     | <b>0.0015</b>                                      | 0.00307     | <b>0.0012</b>                                      | 0.0022      | <b>0.0010</b>                                      |
|          | IX21-3-E2D10 | 270                                  | 40      | 8.33E-06                        | 30            | 11         | 0.83            | 0.01638              | 0.00138     | <b>0.0010</b>                                      | 0.00341     | <b>0.0017</b>                                      | 0.0024      | <b>0.0015</b>                                      |

**Table A21. ICP-MS Analysis Results from Dissolution of Glass IDFIX21-3 at 23 °C.**

| Exp. | Sample ID    | Target [Si] <sub>inf</sub> ppm | T °C | Flow Rate, m <sup>3</sup> /d | Time, days | pH 23°C | Glass Mass g | SA m <sup>2</sup> | [Mo] ppm     | Mo Rate g-glass m <sup>-2</sup> d <sup>-1</sup> | [Cs] ppm | Cs Rate g-glass m <sup>-2</sup> d <sup>-1</sup> | [Re] ppm | Re Rate g-glass m <sup>-2</sup> d <sup>-1</sup> |
|------|--------------|--------------------------------|------|------------------------------|------------|---------|--------------|-------------------|--------------|-------------------------------------------------|----------|-------------------------------------------------|----------|-------------------------------------------------|
| 1    | IX21-3-A3D1  | 35                             | 23   | 8.33E-06                     | 3          | 7       | 3.28         | 0.065044          | 0.01201      | 0.0063                                          | 0.02658  | 0.0063                                          | 0.0247   | 0.0087                                          |
|      | IX21-3-A3D2  | 35                             | 23   | 8.33E-06                     | 6          | 7       | 3.28         | 0.065033          | 0.00722      | 0.000468                                        | 0.01921  | 0.0014                                          | 0.0197   | 0.0026                                          |
|      | IX21-3-A3D3  | 35                             | 23   | 8.33E-06                     | 9          | 7       | 3.28         | 0.065023          | 0.00476      | 0.0004                                          | 0.01496  | 0.0012                                          | 0.0147   | 0.0017                                          |
|      | IX21-3-A3D4  | 35                             | 23   | 8.33E-06                     | 12         | 7       | 3.28         | 0.065015          | 0.00361      | 0.0005                                          | 0.01388  | 0.0015                                          | 0.0128   | 0.0019                                          |
|      | IX21-3-A3D5  | 35                             | 23   | 8.33E-06                     | 15         | 7       | 3.28         | 0.065008          | 0.00223      | 0.0000                                          | 0.01148  | 0.0010                                          | 0.0096   | 0.0011                                          |
|      | IX21-3-A3D6  | 35                             | 23   | 8.33E-06                     | 18         | 7       | 3.28         | 0.065002          | 0.00215      | 0.0004                                          | 0.01065  | 0.0011                                          | 0.0080   | 0.0011                                          |
|      | IX21-3-A3D7  | 35                             | 23   | 8.33E-06                     | 21         | 7       | 3.28         | 0.064997          | 0.00148      | 0.0000                                          | 0.00993  | <b>0.0011</b>                                   | 0.0065   | <b>0.0009</b>                                   |
|      | IX21-3-A3D8  | 35                             | 23   | 8.33E-06                     | 24         | 7       | 3.28         | 0.064991          | 0.00181      | <b>0.0004</b>                                   | 0.00933  | <b>0.0010</b>                                   | 0.0057   | <b>0.0009</b>                                   |
|      | IX21-3-A3D9  | 35                             | 23   | 8.33E-06                     | 27         | 7       | 3.28         | 0.064987          | 0.00153      | <b>0.0001</b>                                   | 0.00803  | <b>0.0008</b>                                   | 0.0047   | <b>0.0006</b>                                   |
|      | IX21-3-A3D10 | 35                             | 23   | 8.33E-06                     | 30         | 7       | 3.28         | 0.064982          | 0.00146      | <b>0.0002</b>                                   | 0.00903  | <b>0.0012</b>                                   | 0.0048   | <b>0.0009</b>                                   |
| 2    | IX21-3-B3D1  | 40                             | 23   | 8.33E-06                     | 3          | 8       | 3.28         | 0.065047          | 0.00725      | 0.0036                                          | 0.01261  | 0.0030                                          | 0.0112   | 0.0038                                          |
|      | IX21-3-B3D2  | 40                             | 23   | 8.33E-06                     | 6          | 8       | 3.28         | 0.065043          | 0.00645      | 0.0014                                          | 0.00965  | 0.0008                                          | 0.0090   | 0.0011                                          |
|      | IX21-3-B3D3  | 40                             | 23   | 8.33E-06                     | 9          | 8       | 3.28         | 0.065040          | 0.00376      | 0.0001                                          | 0.00819  | 0.0008                                          | 0.0078   | 0.0011                                          |
|      | IX21-3-B3D4  | 40                             | 23   | 8.33E-06                     | 12         | 8       | 3.28         | 0.065038          | 0.00317      | 0.0005                                          | 0.00685  | 0.0006                                          | 0.0064   | 0.0008                                          |
|      | IX21-3-B3D5  | 40                             | 23   | 8.33E-06                     | 15         | 8       | 3.28         | 0.065034          | 0.00246      | 0.0003                                          | 0.00571  | 0.0005                                          | 0.0074   | 0.0014                                          |
|      | IX21-3-B3D6  | 40                             | 23   | 8.33E-06                     | 18         | 8       | 3.28         | 0.065033          | 0.00195      | <b>0.0002</b>                                   | 0.00478  | <b>0.0004</b>                                   | 0.0037   | -0.0001                                         |
|      | IX21-3-B3D7  | 40                             | 23   | 8.33E-06                     | 21         | 8       | 3.28         | 0.065031          | 0.00153      | <b>0.0001</b>                                   | 0.00471  | <b>0.0005</b>                                   | 0.0032   | <b>0.0004</b>                                   |
|      | IX21-3-B3D8  | 40                             | 23   | 8.33E-06                     | 24         | 8       | 3.28         | 0.065030          | 0.00125      | <b>0.0001</b>                                   | 0.00398  | <b>0.0004</b>                                   | 0.0026   | <b>0.0003</b>                                   |
|      | IX21-3-B3D9  | 40                             | 23   | 8.33E-06                     | 27         | 8       | 3.28         | 0.065028          | 0.00132      | <b>0.0002</b>                                   | 0.00364  | <b>0.0004</b>                                   | 0.0022   | <b>0.0002</b>                                   |
|      | IX21-3-B3D10 | 40                             | 23   | 8.33E-06                     | 30         | 8       | 3.28         | 0.065027          | 0.00216      | <i>0.0006</i>                                   | 0.00526  | <i>0.0008</i>                                   | 0.0031   | <i>0.0006</i>                                   |
| 3    | IX21-3-C3D1  | 52                             | 23   | 8.33E-06                     | 3          | 9       | 3.28         | 0.065048          | 0.00776      | 0.0037                                          | 0.00772  | 0.0018                                          | 0.0070   | 0.0025                                          |
|      | IX21-3-C3D2  | 52                             | 23   | 8.33E-06                     | 6          | 9       | 3.28         | 0.065045          | 0.00550      | 0.0006                                          | 0.00758  | 0.0009                                          | 0.0071   | 0.0013                                          |
|      | IX21-3-C3D3  | 52                             | 23   | 8.33E-06                     | 9          | 9       | 3.28         | 0.065043          | 0.00365      | 0.0002                                          | 0.00504  | 0.0003                                          | 0.0051   | 0.0006                                          |
|      | IX21-3-C3D4  | 52                             | 23   | 8.33E-06                     | 12         | 9       | 3.28         | 0.065041          | 0.00307      | 0.0004                                          | 0.00479  | 0.0005                                          | 0.0045   | 0.0007                                          |
|      | IX21-3-C3D5  | 52                             | 23   | 8.33E-06                     | 15         | 9       | 3.28         | 0.065040          | 0.00239      | 0.0002                                          | 0.00396  | 0.0004                                          | 0.0035   | 0.0005                                          |
|      | IX21-3-C3D6  | 52                             | 23   | 8.33E-06                     | 18         | 9       | 3.28         | 0.065038          | 0.00182      | 0.0000                                          | 0.00282  | 0.0002                                          | 0.0027   | 0.0003                                          |
|      | IX21-3-C3D7  | 52                             | 23   | 8.33E-06                     | 21         | 9       | 3.28         | 0.065037          | 0.00220      | 0.0004                                          | 0.00403  | 0.0006                                          | 0.0029   | 0.0006                                          |
|      | IX21-3-C3D8  | 52                             | 23   | 8.33E-06                     | 24         | 9       | 3.28         | 0.065036          | 0.00141      | -0.0001                                         | 0.00300  | <b>0.0002</b>                                   | 0.0020   | <b>0.0002</b>                                   |
|      | IX21-3-C3D9  | 52                             | 23   | 8.33E-06                     | 27         | 9       | 3.28         | 0.065036          | 0.00116      | -0.0001                                         | 0.00263  | <b>0.0003</b>                                   | 0.0016   | <b>0.0002</b>                                   |
|      | IX21-3-C3D10 | 52                             | 23   | 8.33E-06                     | 30         | 9       | 3.28         | 0.065035          | 0.00124      | 0.0000                                          | 0.00264  | <b>0.0003</b>                                   | 0.0016   | <b>0.0003</b>                                   |
| 4    | IX21-3-D3D1  | 90                             | 23   | 8.33E-06                     | 3          | 10      | 1.64         | 0.032524          | 0.00450      | 0.0046                                          | 0.00522  | 0.0025                                          | 0.0040   | 0.0027                                          |
|      | IX21-3-D3D2  | 90                             | 23   | 8.33E-06                     | 6          | 10      | 1.64         | 0.032522          | 0.00353      | 0.0012                                          | 0.00398  | 0.0007                                          | 0.0035   | 0.0010                                          |
|      | IX21-3-D3D3  | 90                             | 23   | 8.33E-06                     | 9          | 10      | 1.64         | 0.032520          | 0.00290      | 0.0010                                          | 0.00421  | 0.0011                                          | 0.0033   | 0.0010                                          |
|      | IX21-3-D3D4  | 90                             | 23   | 8.33E-06                     | 12         | 10      | 1.64         | 0.032519          | 0.00275      | 0.0012                                          | 0.00497  | 0.0014                                          | 0.0029   | 0.0008                                          |
|      | IX21-3-D3D5  | 90                             | 23   | 8.33E-06                     | 15         | 10      | 1.64         | 0.032518          | 0.00225      | 0.0008                                          | 0.00379  | 0.0006                                          | 0.0021   | 0.0004                                          |
|      | IX21-3-D3D6  | 90                             | 23   | 8.33E-06                     | 18         | 10      | 1.64         | 0.032517          | 0.00124      | -0.0001                                         | 0.00321  | 0.0006                                          | 0.0017   | 0.0003                                          |
|      | IX21-3-D3D7  | 90                             | 23   | 8.33E-06                     | 21         | 10      | 1.64         | 0.032516          | 0.00114      | 0.0003                                          | 0.00285  | <b>0.0006</b>                                   | 0.0014   | <b>0.0003</b>                                   |
|      | IX21-3-D3D8  | 90                             | 23   | 8.33E-06                     | 24         | 10      | 1.64         | 0.032516          | 0.00100      | 0.0002                                          | 0.00229  | <b>0.0004</b>                                   | 0.0011   | <b>0.0002</b>                                   |
|      | IX21-3-D3D9  | 90                             | 23   | 8.33E-06                     | 27         | 10      | 1.64         | 0.032515          | 0.00069      | 0.0000                                          | 0.00213  | <b>0.0005</b>                                   | 0.0009   | <b>0.0002</b>                                   |
|      | IX21-3-D3D10 | 90                             | 23   | 8.33E-06                     | 30         | 10      | 1.64         | 0.032515          | contaminated |                                                 |          |                                                 |          |                                                 |
| 5    | IX21-3-E3D1  | 230                            | 23   | 8.33E-06                     | 3          | 11      | 1.64         | 0.032524          | 0.00466      | 0.0036                                          | 0.00439  | 0.0021                                          | 0.0038   | 0.0024                                          |
|      | IX21-3-E3D2  | 230                            | 23   | 8.33E-06                     | 6          | 11      | 1.64         | 0.032523          | 0.00524      | 0.0024                                          | 0.00649  | 0.0020                                          | 0.0052   | 0.0022                                          |
|      | IX21-3-E3D3  | 230                            | 23   | 8.33E-06                     | 9          | 11      | 1.64         | 0.032522          | 0.00386      | 0.0006                                          | 0.00477  | 0.0007                                          | 0.0045   | 0.0012                                          |
|      | IX21-3-E3D4  | 230                            | 23   | 8.33E-06                     | 12         | 11      | 1.64         | 0.032521          | 0.00375      | 0.0012                                          | 0.00487  | 0.0012                                          | 0.0046   | 0.0015                                          |
|      | IX21-3-E3D5  | 230                            | 23   | 8.33E-06                     | 15         | 11      | 1.64         | 0.032519          | 0.00411      | 0.0017                                          | 0.00501  | 0.0012                                          | 0.0043   | 0.0013                                          |
|      | IX21-3-E3D6  | 230                            | 23   | 8.33E-06                     | 18         | 11      | 1.64         | 0.032518          | 0.00380      | 0.0011                                          | 0.00473  | 0.0010                                          | 0.0040   | 0.0012                                          |
|      | IX21-3-E3D7  | 230                            | 23   | 8.33E-06                     | 21         | 11      | 1.64         | 0.032517          | 0.00349      | 0.0010                                          | 0.00454  | 0.0010                                          | 0.0037   | 0.0010                                          |
|      | IX21-3-E3D8  | 230                            | 23   | 8.33E-06                     | 24         | 11      | 1.64         | 0.032516          | 0.00221      | -0.0003                                         | 0.00393  | <b>0.0008</b>                                   | 0.0031   | <b>0.0007</b>                                   |
|      | IX21-3-E3D9  | 230                            | 23   | 8.33E-06                     | 27         | 11      | 1.64         | 0.032515          | 0.00207      | <b>0.0003</b>                                   | 0.00350  | <b>0.0007</b>                                   | 0.0027   | <b>0.0006</b>                                   |
|      | IX21-3-E3D10 | 230                            | 23   | 8.33E-06                     | 30         | 11      | 1.64         | 0.032515          | 0.00252      | <b>0.0009</b>                                   | 0.00430  | <i>0.0012</i>                                   | 0.0030   | <i>0.0011</i>                                   |

**Table A22. ICP-MS Analysis Results from Dissolution of Glass IDFIX21-4 at 70 °C.**

| Exp.     | Sample ID    | Target<br>[Si] <sub>inf</sub><br>ppm | T<br>°C | Flow Rate,<br>m <sup>3</sup> /d | Time,<br>days | pH<br>23°C | Glass<br>Mass g | SA<br>m <sup>2</sup> | [Mo]<br>ppm | Mo Rate<br>g-glass m <sup>-2</sup> d <sup>-1</sup> | [Cs]<br>ppm | Cs Rate<br>g-glass m <sup>-2</sup> d <sup>-1</sup> | [Re]<br>ppm | Re Rate<br>g-glass m <sup>-2</sup> d <sup>-1</sup> |
|----------|--------------|--------------------------------------|---------|---------------------------------|---------------|------------|-----------------|----------------------|-------------|----------------------------------------------------|-------------|----------------------------------------------------|-------------|----------------------------------------------------|
| <b>1</b> | IX21-4-A1D1  | 55                                   | 70      | 2.50E-05                        | 1             | 7          | 0.77            | 0.01510              | 0.02020     | 0.0994                                             | 0.31789     | 0.7802                                             | 0.1913      | 0.8759                                             |
|          | IX21-4-A1D2  | 55                                   | 70      | 2.50E-05                        | 2             | 7          | 0.77            | 0.01484              | 0.01260     | 0.0121                                             | 0.32769     | 0.4214                                             | 0.1333      | 0.1754                                             |
|          | IX21-4-A1D3  | 55                                   | 70      | 2.50E-05                        | 3             | 7          | 0.77            | 0.01456              | 0.00910     | 0.0139                                             | 0.33463     | 0.4347                                             | 0.0944      | 0.1312                                             |
|          | IX21-4-A1D4  | 55                                   | 70      | 2.50E-05                        | 4             | 7          | 0.77            | 0.01428              | 0.00580     | 0.0060                                             | 0.32794     | 0.4169                                             | 0.0665      | 0.0933                                             |
|          | IX21-4-A1D5  | 55                                   | 70      | 2.50E-05                        | 5             | 7          | 0.77            | 0.01401              | 0.00460     | 0.0086                                             | 0.31117     | 0.3892                                             | 0.0465      | 0.0650                                             |
|          | IX21-4-A1D6  | 55                                   | 70      | 2.50E-05                        | 6             | 7          | 0.77            | 0.01377              | 0.00450     | 0.0114                                             | 0.30151     | 0.3927                                             | 0.0355      | 0.0611                                             |
|          | IX21-4-A1D7  | 55                                   | 70      | 2.50E-05                        | 7             | 7          | 0.77            | 0.01353              | 0.00520     | 0.0158                                             | 0.28369     | 0.3639                                             | 0.0293      | 0.0585                                             |
|          | IX21-4-A1D8  | 55                                   | 70      | 2.50E-05                        | 8             | 7          | 0.77            | 0.01332              | 0.00450     | <b>0.0101</b>                                      | 0.28301     | <b>0.3927</b>                                      | 0.0232      | 0.0440                                             |
|          | IX21-4-A1D9  | 55                                   | 70      | 2.50E-05                        | 9             | 7          | 0.77            | 0.01311              | 0.00410     | <b>0.0100</b>                                      | 0.28177     | <b>0.3963</b>                                      | 0.0198      | <b>0.0430</b>                                      |
|          | IX21-4-A1D10 | 55                                   | 70      | 2.50E-05                        | 10            | 7          | 0.77            | 0.01293              | 0.00410     | <b>0.0113</b>                                      | 0.22900     | <b>0.2524</b>                                      | 0.0170      | <b>0.0373</b>                                      |
| <b>2</b> | IX21-4-B1D1  | 60                                   | 70      | 2.50E-05                        | 1             | 8          | 0.77            | 0.01512              | 0.01600     | 0.0781                                             | 0.24477     | 0.5994                                             | 0.1569      | 0.7173                                             |
|          | IX21-4-B1D2  | 60                                   | 70      | 2.50E-05                        | 2             | 8          | 0.77            | 0.01493              | 0.01030     | 0.0109                                             | 0.17846     | 0.1390                                             | 0.0974      | 0.0876                                             |
|          | IX21-4-B1D3  | 60                                   | 70      | 2.50E-05                        | 3             | 8          | 0.77            | 0.01473              | 0.00610     | 0.0042                                             | 0.19535     | 0.2667                                             | 0.0683      | 0.0920                                             |
|          | IX21-4-B1D4  | 60                                   | 70      | 2.50E-05                        | 4             | 8          | 0.77            | 0.01453              | 0.00540     | 0.0115                                             | 0.21826     | 0.3074                                             | 0.0493      | 0.0717                                             |
|          | IX21-4-B1D5  | 60                                   | 70      | 2.50E-05                        | 5             | 8          | 0.77            | 0.01433              | 0.00320     | 0.0019                                             | 0.18781     | 0.2033                                             | 0.0356      | 0.0528                                             |
|          | IX21-4-B1D6  | 60                                   | 70      | 2.50E-05                        | 6             | 8          | 0.77            | 0.01415              | 0.00320     | 0.0078                                             | 0.15443     | 0.1583                                             | 0.0252      | 0.0356                                             |
|          | IX21-4-B1D7  | 60                                   | 70      | 2.50E-05                        | 7             | 8          | 0.77            | 0.01399              | 0.00390     | 0.0116                                             | 0.14413     | 0.1770                                             | 0.0190      | 0.0317                                             |
|          | IX21-4-B1D8  | 60                                   | 70      | 2.50E-05                        | 8             | 8          | 0.77            | 0.01385              | 0.00300     | <b>0.0050</b>                                      | 0.13823     | <b>0.1768</b>                                      | 0.0149      | <b>0.0267</b>                                      |
|          | IX21-4-B1D9  | 60                                   | 70      | 2.50E-05                        | 9             | 8          | 0.77            | 0.01372              | 0.00240     | <b>0.0042</b>                                      | 0.13224     | <b>0.1703</b>                                      | 0.0134      | <b>0.0295</b>                                      |
|          | IX21-4-B1D10 | 60                                   | 70      | 2.50E-05                        | 10            | 8          | 0.77            | 0.01360              | 0.00260     | <b>0.0070</b>                                      | 0.12651     | <b>0.1643</b>                                      | 0.0114      | <b>0.0239</b>                                      |
| <b>3</b> | IX21-4-C1D1R | 80                                   | 70      | 2.50E-05                        | 1             | 9          | 0.77            | 0.01517              | 0.028000    | 0.1382                                             | 0.11230     | 0.2742                                             | 0.0896      | 0.4082                                             |
|          | IX21-4-C1D2R | 80                                   | 70      | 2.50E-05                        | 2             | 9          | 0.77            | 0.01506              | 0.014000    | -0.0001                                            | 0.11426     | 0.1429                                             | 0.0617      | 0.0775                                             |
|          | IX21-4-C1D3R | 80                                   | 70      | 2.50E-05                        | 3             | 9          | 0.77            | 0.01494              | 0.009000    | 0.0099                                             | 0.11150     | 0.1348                                             | 0.0403      | 0.0438                                             |
|          | IX21-4-C1D4R | 80                                   | 70      | 2.50E-05                        | 4             | 9          | 0.77            | 0.01482              | 0.008000    | 0.0176                                             | 0.10075     | 0.1124                                             | 0.0272      | 0.0326                                             |
|          | IX21-4-C1D5R | 80                                   | 70      | 2.50E-05                        | 5             | 9          | 0.77            | 0.01472              | 0.005000    | 0.0050                                             | 0.08936     | 0.0981                                             | 0.0186      | 0.0232                                             |
|          | IX21-4-C1D6  | 80                                   | 70      | 2.50E-05                        | 6             | 9          | 0.77            | 0.01462              | 0.007000    | 0.0230                                             | 0.08226     | 0.0952                                             | 0.0143      | 0.0237                                             |
|          | IX21-4-C1D7  | 80                                   | 70      | 2.50E-05                        | 7             | 9          | 0.77            | 0.01453              | 0.002000    | -0.0079                                            | 0.07667     | 0.0906                                             | 0.0086      | 0.0066                                             |
|          | IX21-4-C1D8  | 80                                   | 70      | 2.50E-05                        | 8             | 9          | 0.77            | 0.01445              | 0.003000    | <b>0.0103</b>                                      | 0.06996     | <b>0.0810</b>                                      | 0.0077      | <b>0.0163</b>                                      |
|          | IX21-4-C1D9  | 80                                   | 70      | 2.50E-05                        | 9             | 9          | 0.77            | 0.01437              | 0.001000    | -0.0027                                            | 0.06812     | <b>0.0854</b>                                      | 0.0065      | <b>0.0124</b>                                      |
|          | IX21-4-C1D10 | 80                                   | 70      | 2.50E-05                        | 10            | 9          | 0.77            | 0.01429              | 0.001000    | <b>0.0025</b>                                      | 0.06418     | <b>0.0780</b>                                      | 0.0046      | <b>0.0064</b>                                      |
| <b>4</b> | IX21-4-D1D1  | 140                                  | 70      | 2.50E-05                        | 1             | 10         | 0.50            | 0.00976              | 0.02578     | 0.1960                                             | 0.03340     | 0.1188                                             | 0.0369      | 0.2532                                             |
|          | IX21-4-D1D2  | 140                                  | 70      | 2.50E-05                        | 2             | 10         | 0.50            | 0.00971              | 0.02568     | 0.0977                                             | 0.03635     | 0.0710                                             | 0.0236      | 0.0322                                             |
|          | IX21-4-D1D3  | 140                                  | 70      | 2.50E-05                        | 3             | 10         | 0.50            | 0.00965              | 0.04316     | 0.2344                                             | 0.03554     | 0.0626                                             | 0.0158      | 0.0242                                             |
|          | IX21-4-D1D4  | 140                                  | 70      | 2.50E-05                        | 4             | 10         | 0.50            | 0.00960              | 0.02881     | 0.0554                                             | 0.03508     | 0.0627                                             | 0.0103      | 0.0133                                             |
|          | IX21-4-D1D5  | 140                                  | 70      | 2.50E-05                        | 5             | 10         | 0.50            | 0.00955              | 0.06621     | 0.4057                                             | 0.03152     | 0.0502                                             | 0.0074      | 0.0118                                             |
|          | IX21-4-D1D6  | 140                                  | 70      | 2.50E-05                        | 6             | 10         | 0.50            | 0.00950              | 0.04667     | 0.1060                                             | 0.02790     | 0.0432                                             | 0.0047      | 0.0032                                             |
|          | IX21-4-D1D7  | 140                                  | 70      | 2.50E-05                        | 7             | 10         | 0.50            | 0.00946              | 0.07664     | 0.4215                                             | 0.02824     | 0.0518                                             | 0.0037      | 0.0052                                             |
|          | IX21-4-D1D8  | 140                                  | 70      | 2.50E-05                        | 8             | 10         | 0.50            | 0.00942              | 0.04760     | 0.0729                                             | 0.02800     | <b>0.0505</b>                                      | 0.0041      | <b>0.0122</b>                                      |
|          | IX21-4-D1D9  | 140                                  | 70      | 2.50E-05                        | 9             | 10         | 0.50            | 0.00937              | 0.00000     | -0.1915                                            | 0.02722     | <b>0.0481</b>                                      | 0.0039      | <b>0.0092</b>                                      |
|          | IX21-4-D1D10 | 140                                  | 70      | 2.50E-05                        | 10            | 10         | 0.50            | 0.00933              | 0.00048     | 0.0028                                             | 0.03180     | <b>0.0680</b>                                      | 0.0057      | <b>0.0231</b>                                      |
| <b>5</b> | IX21-4-E1D1  | 360                                  | 70      | 2.50E-05                        | 1             | 11         | 0.50            | 0.00978              | 0.00390     | 0.0277                                             | 0.01688     | 0.0622                                             | 0.0109      | 0.0709                                             |
|          | IX21-4-E1D2  | 360                                  | 70      | 2.50E-05                        | 2             | 11         | 0.50            | 0.00976              | 0.00170     | -0.0030                                            | 0.01622     | 0.0278                                             | 0.0067      | 0.0056                                             |
|          | IX21-4-E1D3  | 360                                  | 70      | 2.50E-05                        | 3             | 11         | 0.50            | 0.00974              | 0.00035     | -0.0050                                            | 0.01454     | 0.0227                                             | 0.0035      | -0.0020                                            |
|          | IX21-4-E1D4  | 360                                  | 70      | 2.50E-05                        | 4             | 11         | 0.50            | 0.00973              | 0.00180     | 0.0114                                             | 0.01120     | 0.0132                                             | 0.0030      | 0.0056                                             |
|          | IX21-4-E1D5  | 360                                  | 70      | 2.50E-05                        | 5             | 11         | 0.50            | 0.00971              | 0.00035     | -0.0054                                            | 0.03133     | 0.0964                                             | 0.0033      | 0.0098                                             |
|          | IX21-4-E1D6  | 360                                  | 70      | 2.50E-05                        | 6             | 11         | 0.50            | 0.00970              | 0.00120     | 0.0068                                             | 0.01316     | -0.0114                                            | 0.0036      | 0.0107                                             |
|          | IX21-4-E1D7  | 360                                  | 70      | 2.50E-05                        | 7             | 11         | 0.50            | 0.00969              | 0.00080     | 0.0004                                             | 0.00955     | 0.0096                                             | 0.0022      | -0.0008                                            |
|          | IX21-4-E1D8  | 360                                  | 70      | 2.50E-05                        | 8             | 11         | 0.50            | 0.00968              | -0.00022    | -0.0059                                            | 0.00909     | <b>0.0148</b>                                      | 0.0020      | 0.0031                                             |
|          | IX21-4-E1D9  | 360                                  | 70      | 2.50E-05                        | 9             | 11         | 0.50            | 0.00967              | 0.00030     | 0.0020                                             | 0.00785     | <b>0.0109</b>                                      | 0.0007      | -0.0052                                            |
|          | IX21-4-E1D10 | 360                                  | 70      | 2.50E-05                        | 10            | 11         | 0.50            | 0.00966              | 0.00035     | 0.0004                                             | 0.00814     | <b>0.0144</b>                                      | 0.0006      | -0.0015                                            |

**Table A23. ICP-MS Analysis Results from Dissolution of Glass IDFIX21-4 at 40 °C.**

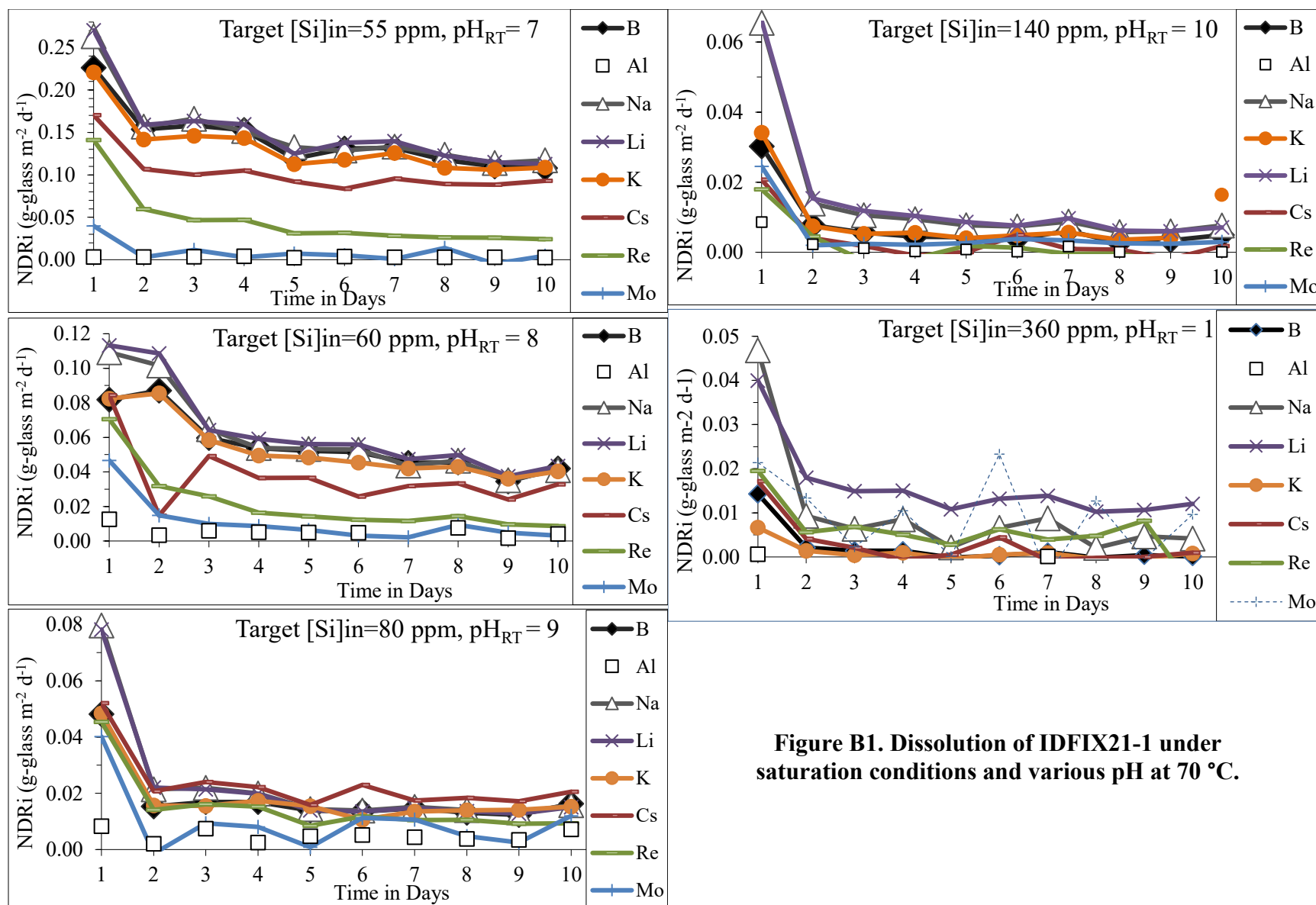
| Exp. | Sample ID    | Target [Si] <sub>inf</sub> ppm | T °C | Flow Rate, m <sup>3</sup> /d | Time, days | pH 23°C | Glass Mass g | SA m <sup>2</sup> | [Mo] ppm | Mo Rate g-glass m <sup>-2</sup> d <sup>-1</sup> | [Cs] ppm | Cs Rate g-glass m <sup>-2</sup> d <sup>-1</sup> | [Re] ppm | Re Rate g-glass m <sup>-2</sup> d <sup>-1</sup> |
|------|--------------|--------------------------------|------|------------------------------|------------|---------|--------------|-------------------|----------|-------------------------------------------------|----------|-------------------------------------------------|----------|-------------------------------------------------|
| 1    | IX21-4-A2D1  | 40                             | 40   | 8.33E-06                     | 3          | 7       | 1.65         | 0.0326            | 0.01751  | 0.0124                                          | 0.11898  | 0.0451                                          | 0.1316   | 0.0927                                          |
|      | IX21-4-A2D2  | 40                             | 40   | 8.33E-06                     | 6          | 7       | 1.65         | 0.0324            | 0.01131  | 0.0015                                          | 0.12585  | 0.0379                                          | 0.1169   | 0.0361                                          |
|      | IX21-4-A2D3  | 40                             | 40   | 8.33E-06                     | 9          | 7       | 1.65         | 0.0323            | 0.00829  | 0.0015                                          | 0.12300  | 0.0344                                          | 0.0984   | 0.0283                                          |
|      | IX21-4-A2D4  | 40                             | 40   | 8.33E-06                     | 12         | 7       | 1.65         | 0.0321            | 0.00493  | 0.0001                                          | 0.11456  | 0.0305                                          | 0.0797   | 0.0216                                          |
|      | IX21-4-A2D5  | 40                             | 40   | 8.33E-06                     | 15         | 7       | 1.65         | 0.0320            | 0.00375  | 0.0005                                          | 0.11165  | 0.0314                                          | 0.0681   | 0.0201                                          |
|      | IX21-4-A2D6  | 40                             | 40   | 8.33E-06                     | 18         | 7       | 1.65         | 0.0319            | 0.00292  | 0.0003                                          | 0.11031  | 0.0316                                          | 0.0590   | 0.0178                                          |
|      | IX21-4-A2D7  | 40                             | 40   | 8.33E-06                     | 21         | 7       | 1.65         | 0.0318            | 0.00263  | <b>0.0004</b>                                   | 0.10876  | 0.0312                                          | 0.0553   | 0.0184                                          |
|      | IX21-4-A2D8  | 40                             | 40   | 8.33E-06                     | 24         | 7       | 1.65         | 0.0316            | 0.00221  | <b>0.0002</b>                                   | 0.10551  | <b>0.0299</b>                                   | 0.0483   | <b>0.0148</b>                                   |
|      | IX21-4-A2D9  | 40                             | 40   | 8.33E-06                     | 27         | 7       | 1.65         | 0.0315            | 0.00242  | <b>0.0005</b>                                   | 0.10222  | <b>0.0290</b>                                   | 0.0442   | <b>0.0144</b>                                   |
|      | IX21-4-A2D10 | 40                             | 40   | 8.33E-06                     | 30         | 7       | 1.65         | 0.0314            | 0.00184  | <b>0.0000</b>                                   | 0.09509  | <b>0.0259</b>                                   | 0.0405   | <b>0.0132</b>                                   |
| 2    | IX21-4-B2D1  | 45                             | 40   | 8.33E-06                     | 3          | 8       | 1.65         | 0.0326            | 0.01242  | 0.0089                                          | 0.05754  | 0.0218                                          | 0.0667   | 0.0469                                          |
|      | IX21-4-B2D2  | 45                             | 40   | 8.33E-06                     | 6          | 8       | 1.65         | 0.0325            | 0.00835  | 0.0013                                          | 0.06056  | 0.0121                                          | 0.0608   | 0.0193                                          |
|      | IX21-4-B2D3  | 45                             | 40   | 8.33E-06                     | 9          | 8       | 1.65         | 0.0324            | 0.00536  | 0.0006                                          | 0.05962  | 0.0112                                          | 0.0502   | 0.0139                                          |
|      | IX21-4-B2D4  | 45                             | 40   | 8.33E-06                     | 12         | 8       | 1.65         | 0.0324            | 0.00319  | 0.0001                                          | 0.05495  | 0.0096                                          | 0.0403   | 0.0106                                          |
|      | IX21-4-B2D5  | 45                             | 40   | 8.33E-06                     | 15         | 8       | 1.65         | 0.0323            | 0.00252  | 0.0004                                          | 0.05250  | 0.0096                                          | 0.0343   | 0.0099                                          |
|      | IX21-4-B2D6  | 45                             | 40   | 8.33E-06                     | 18         | 8       | 1.65         | 0.0322            | 0.00175  | 0.00005                                         | 0.05370  | 0.0105                                          | 0.0284   | 0.0079                                          |
|      | IX21-4-B2D7  | 45                             | 40   | 8.33E-06                     | 21         | 8       | 1.65         | 0.0322            | 0.00162  | <b>0.0002</b>                                   | 0.05169  | 0.0095                                          | 0.0249   | 0.0075                                          |
|      | IX21-4-B2D8  | 45                             | 40   | 8.33E-06                     | 24         | 8       | 1.65         | 0.0321            | 0.00134  | <b>0.0001</b>                                   | 0.04917  | <b>0.0090</b>                                   | 0.0217   | <b>0.0065</b>                                   |
|      | IX21-4-B2D9  | 45                             | 40   | 8.33E-06                     | 27         | 8       | 1.65         | 0.0320            | 0.00146  | <b>0.0003</b>                                   | 0.04689  | <b>0.0086</b>                                   | 0.0193   | <b>0.0059</b>                                   |
|      | IX21-4-B2D10 | 45                             | 40   | 8.33E-06                     | 30         | 8       | 1.65         | 0.0320            | 0.00095  | <b>-0.0002</b>                                  | 0.04431  | <b>0.0080</b>                                   | 0.0178   | <b>0.0057</b>                                   |
| 3    | IX21-4-C2D1  | 60                             | 40   | 8.33E-06                     | 3          | 9       | 1.65         | 0.0326            | 0.009941 | 0.0075                                          | 0.02859  | 0.0108                                          | 0.0425   | 0.0301                                          |
|      | IX21-4-C2D2  | 60                             | 40   | 8.33E-06                     | 6          | 9       | 1.65         | 0.0326            | 0.006449 | 0.0010                                          | 0.03046  | 0.0061                                          | 0.0422   | 0.0148                                          |
|      | IX21-4-C2D3  | 60                             | 40   | 8.33E-06                     | 9          | 9       | 1.65         | 0.0325            | 0.003643 | 0.0002                                          | 0.02905  | 0.0052                                          | 0.0344   | 0.0094                                          |
|      | IX21-4-C2D4  | 60                             | 40   | 8.33E-06                     | 12         | 9       | 1.65         | 0.0325            | 0.002321 | 0.0003                                          | 0.02776  | 0.0050                                          | 0.0291   | 0.0084                                          |
|      | IX21-4-C2D5  | 60                             | 40   | 8.33E-06                     | 15         | 9       | 1.65         | 0.0324            | 0.001430 | 0.0001                                          | 0.02615  | 0.0047                                          | 0.0225   | 0.0056                                          |
|      | IX21-4-C2D6  | 60                             | 40   | 8.33E-06                     | 18         | 9       | 1.65         | 0.0324            | 0.001761 | 0.0007                                          | 0.02702  | 0.0053                                          | 0.0209   | 0.0069                                          |
|      | IX21-4-C2D7  | 60                             | 40   | 8.33E-06                     | 21         | 9       | 1.65         | 0.0324            | 0.000824 | <b>-0.0001</b>                                  | 0.02503  | 0.0044                                          | 0.0177   | 0.0051                                          |
|      | IX21-4-C2D8  | 60                             | 40   | 8.33E-06                     | 24         | 9       | 1.65         | 0.0323            | 0.000729 | <b>0.0002</b>                                   | 0.02501  | <b>0.0048</b>                                   | 0.0150   | <b>0.0044</b>                                   |
|      | IX21-4-C2D9  | 60                             | 40   | 8.33E-06                     | 27         | 9       | 1.65         | 0.0323            | 0.000709 | <b>0.0002</b>                                   | 0.02368  | <b>0.0043</b>                                   | 0.0132   | <b>0.0040</b>                                   |
|      | IX21-4-C2D10 | 60                             | 40   | 8.33E-06                     | 30         | 9       | 1.65         | 0.0323            | 0.000490 | <b>0.0000</b>                                   | 0.02412  | <b>0.0047</b>                                   | 0.0123   | <b>0.0041</b>                                   |
| 4    | IX21-4-D2D1  | 105                            | 40   | 8.33E-06                     | 3          | 10      | 0.83         | 0.0163            | 0.006760 | 0.0098                                          | 0.00960  | 0.0073                                          | 0.0137   | 0.0193                                          |
|      | IX21-4-D2D2  | 105                            | 40   | 8.33E-06                     | 6          | 10      | 0.83         | 0.0163            | 0.004315 | 0.0011                                          | 0.00905  | 0.0032                                          | 0.0139   | 0.0100                                          |
|      | IX21-4-D2D3  | 105                            | 40   | 8.33E-06                     | 9          | 10      | 0.83         | 0.0163            | 0.004268 | 0.0029                                          | 0.00890  | 0.0033                                          | 0.0120   | 0.0071                                          |
|      | IX21-4-D2D4  | 105                            | 40   | 8.33E-06                     | 12         | 10      | 0.83         | 0.0163            | 0.003521 | 0.0018                                          | 0.00840  | 0.0030                                          | 0.0100   | 0.0057                                          |
|      | IX21-4-D2D5  | 105                            | 40   | 8.33E-06                     | 15         | 10      | 0.83         | 0.0163            | 0.001168 | <b>-0.0012</b>                                  | 0.00758  | 0.0026                                          | 0.0081   | 0.0045                                          |
|      | IX21-4-D2D6  | 105                            | 40   | 8.33E-06                     | 18         | 10      | 0.83         | 0.0163            | 0.001151 | 0.0006                                          | 0.00812  | 0.0033                                          | 0.0073   | 0.0045                                          |
|      | IX21-4-D2D7  | 105                            | 40   | 8.33E-06                     | 21         | 10      | 0.83         | 0.0163            | 0.001474 | 0.0011                                          | 0.00723  | 0.0024                                          | 0.0061   | 0.0034                                          |
|      | IX21-4-D2D8  | 105                            | 40   | 8.33E-06                     | 24         | 10      | 0.83         | 0.0162            | 0.000458 | <b>-0.0007</b>                                  | 0.00698  | <b>0.0026</b>                                   | 0.0052   | <b>0.0031</b>                                   |
|      | IX21-4-D2D9  | 105                            | 40   | 8.33E-06                     | 27         | 10      | 0.83         | 0.0162            | 0.000342 | <b>-0.0001</b>                                  | 0.00721  | <b>0.0028</b>                                   | 0.0038   | <b>0.0017</b>                                   |
|      | IX21-4-D2D10 | 105                            | 40   | 8.33E-06                     | 30         | 10      | 0.83         | 0.0162            | 0.000607 | 0.0004                                          | 0.00696  | <b>0.0026</b>                                   | 0.0036   | <b>0.0024</b>                                   |
| 5    | IX21-4-E2D1  | 270                            | 40   | 8.33E-06                     | 3          | 11      | 0.83         | 0.0163            | 0.01300  | 0.0196                                          | 0.00768  | 0.0174                                          | 0.0085   | 0.0113                                          |
|      | IX21-4-E2D2  | 270                            | 40   | 8.33E-06                     | 6          | 11      | 0.83         | 0.0163            | 0.00500  | <b>-0.0025</b>                                  | 0.00575  | 0.0043                                          | 0.0065   | 0.0028                                          |
|      | IX21-4-E2D3  | 270                            | 40   | 8.33E-06                     | 9          | 11      | 0.83         | 0.0163            | 0.00200  | <b>-0.0009</b>                                  | 0.00468  | 0.0040                                          | 0.0038   | 0.0004                                          |
|      | IX21-4-E2D4  | 270                            | 40   | 8.33E-06                     | 12         | 11      | 0.83         | 0.0163            | 0.00100  | <b>-0.0002</b>                                  | 0.00372  | 0.0030                                          | 0.0029   | 0.0011                                          |
|      | IX21-4-E2D5  | 270                            | 40   | 8.33E-06                     | 15         | 11      | 0.83         | 0.0163            | 0.00035  | <b>-0.0004</b>                                  | 0.00316  | 0.0029                                          | 0.0020   | 0.0005                                          |
|      | IX21-4-E2D6  | 270                            | 40   | 8.33E-06                     | 18         | 11      | 0.83         | 0.0163            | 0.00100  | 0.0011                                          | 0.00365  | 0.0046                                          | 0.0025   | 0.0018                                          |
|      | IX21-4-E2D7  | 270                            | 40   | 8.33E-06                     | 21         | 11      | 0.83         | 0.0163            | 0.00035  | <b>-0.0004</b>                                  | 0.00297  | 0.0025                                          | 0.0019   | 0.0006                                          |
|      | IX21-4-E2D8  | 270                            | 40   | 8.33E-06                     | 24         | 11      | 0.83         | 0.0163            | 0.00083  | 0.0008                                          | 0.00287  | <b>0.0031</b>                                   | 0.0013   | <b>0.0002</b>                                   |
|      | IX21-4-E2D9  | 270                            | 40   | 8.33E-06                     | 27         | 11      | 0.83         | 0.0163            | 0.00035  | <b>-0.0003</b>                                  | 0.00311  | <b>0.0037</b>                                   | 0.0013   | <b>0.0006</b>                                   |
|      | IX21-4-E2D10 | 270                            | 40   | 8.33E-06                     | 30         | 11      | 0.83         | 0.0163            | 0.00100  | 0.0011                                          | 0.00288  | <b>0.0029</b>                                   | 0.0013   | <b>0.0005</b>                                   |

**Table A24. ICP-MS Analysis Results from Dissolution of Glass IDFIX21-4 at 23 °C.**

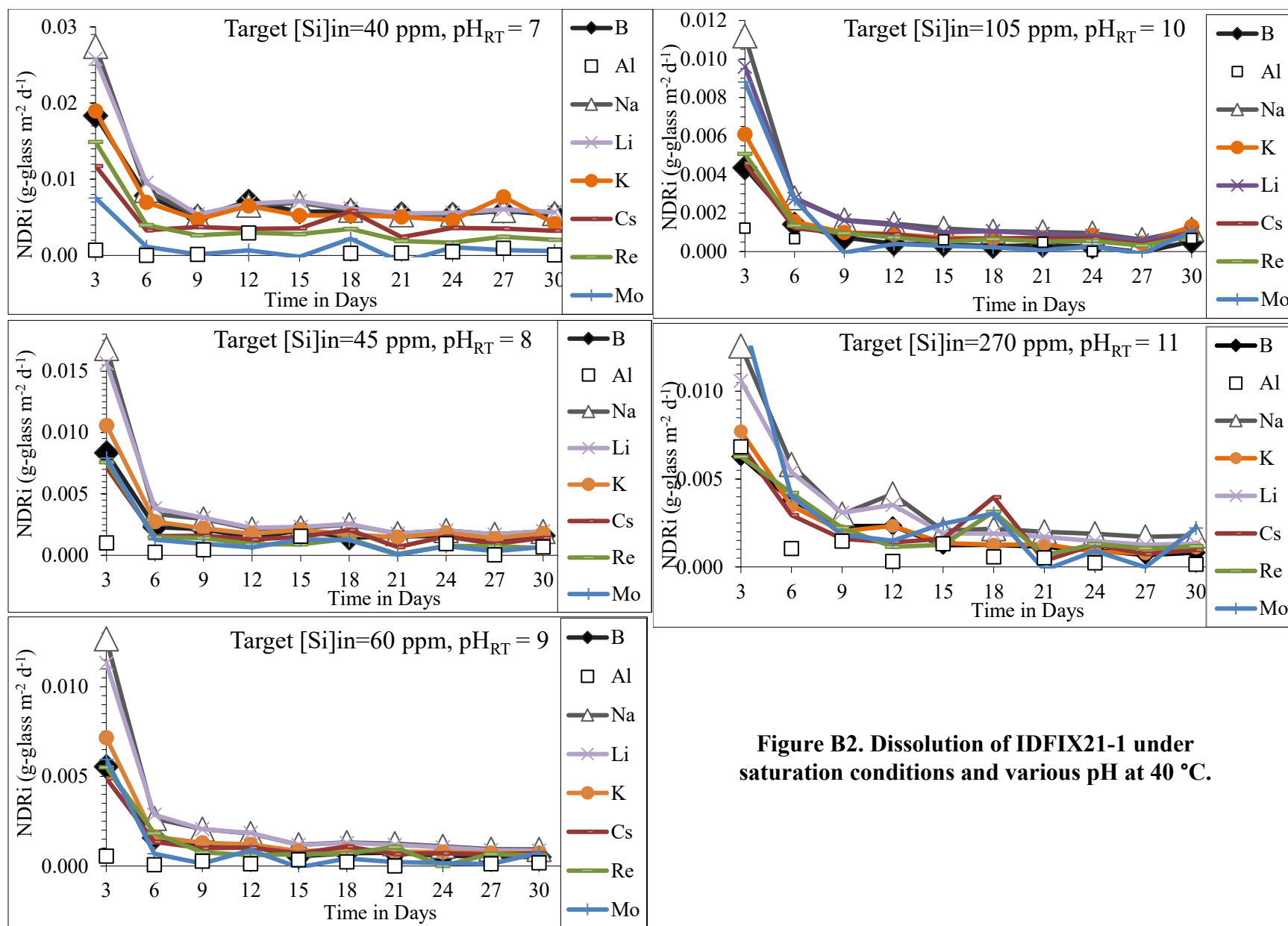
| Exp.     | Sample ID    | Target [Si] <sub>inf</sub> ppm | T °C | Flow Rate, m <sup>3</sup> /d | Time, days | pH 23°C | Glass Mass g | SA m <sup>2</sup> | [Mo] ppm | Mo Rate g-glass m <sup>-2</sup> d <sup>-1</sup> | [Cs] ppm | Cs Rate g-glass m <sup>-2</sup> d <sup>-1</sup> | [Re] ppm | Re Rate g-glass m <sup>-2</sup> d <sup>-1</sup> |
|----------|--------------|--------------------------------|------|------------------------------|------------|---------|--------------|-------------------|----------|-------------------------------------------------|----------|-------------------------------------------------|----------|-------------------------------------------------|
| <b>1</b> | IX21-4-A3D1  | 35                             | 23   | 8.33E-06                     | 3          | 7       | 3.28         | 0.064764          | 0.01826  | 0.0068                                          | 0.06262  | 0.0119                                          | 0.0832   | 0.0296                                          |
|          | IX21-4-A3D2  | 35                             | 23   | 8.33E-06                     | 6          | 7       | 3.28         | 0.064709          | 0.01193  | 0.0009                                          | 0.05954  | 0.0080                                          | 0.0744   | 0.0117                                          |
|          | IX21-4-A3D3  | 35                             | 23   | 8.33E-06                     | 9          | 7       | 3.28         | 0.064649          | 0.00840  | 0.0008                                          | 0.05824  | 0.0081                                          | 0.0654   | 0.0100                                          |
|          | IX21-4-A3D4  | 35                             | 23   | 8.33E-06                     | 12         | 7       | 3.28         | 0.064588          | 0.00640  | 0.0007                                          | 0.05672  | 0.0079                                          | 0.0583   | 0.0091                                          |
|          | IX21-4-A3D5  | 35                             | 23   | 8.33E-06                     | 15         | 7       | 3.28         | 0.064530          | 0.00451  | 0.0004                                          | 0.05208  | 0.0068                                          | 0.0465   | 0.0062                                          |
|          | IX21-4-A3D6  | 35                             | 23   | 8.33E-06                     | 18         | 7       | 3.28         | 0.064480          | 0.00320  | 0.0002                                          | 0.04387  | 0.0051                                          | 0.0368   | 0.0048                                          |
|          | IX21-4-A3D7  | 35                             | 23   | 8.33E-06                     | 21         | 7       | 3.28         | 0.064434          | 0.00255  | <b>0.0002</b>                                   | 0.04380  | 0.0062                                          | 0.0316   | 0.0047                                          |
|          | IX21-4-A3D8  | 35                             | 23   | 8.33E-06                     | 24         | 7       | 3.28         | 0.064390          | 0.00214  | <b>0.0002</b>                                   | 0.03736  | <b>0.0044</b>                                   | 0.0261   | <b>0.0037</b>                                   |
|          | IX21-4-A3D9  | 35                             | 23   | 8.33E-06                     | 27         | 7       | 3.28         | 0.064352          | 0.00186  | <b>0.0002</b>                                   | 0.03428  | <b>0.0044</b>                                   | 0.0212   | <b>0.0029</b>                                   |
|          | IX21-4-A3D10 | 35                             | 23   | 8.33E-06                     | 30         | 7       | 3.28         | 0.064315          | 0.00162  | <b>0.0001</b>                                   | 0.03613  | <b>0.0054</b>                                   | 0.0197   | <b>0.0033</b>                                   |
| <b>2</b> | IX21-4-B3D1  | 40                             | 23   | 8.33E-06                     | 3          | 8       | 3.28         | 0.064781          | 0.01331  | 0.0048                                          | 0.02889  | 0.0055                                          | 0.0339   | 0.0119                                          |
|          | IX21-4-B3D2  | 40                             | 23   | 8.33E-06                     | 6          | 8       | 3.28         | 0.064765          | 0.01018  | 0.0012                                          | 0.02453  | 0.0019                                          | 0.0293   | 0.0043                                          |
|          | IX21-4-B3D3  | 40                             | 23   | 8.33E-06                     | 9          | 8       | 3.28         | 0.064748          | 0.00641  | 0.0004                                          | 0.02180  | 0.0018                                          | 0.0262   | 0.0040                                          |
|          | IX21-4-B3D4  | 40                             | 23   | 8.33E-06                     | 12         | 8       | 3.28         | 0.064728          | 0.00434  | 0.0003                                          | 0.01955  | 0.0016                                          | 0.0215   | 0.0029                                          |
|          | IX21-4-B3D5  | 40                             | 23   | 8.33E-06                     | 15         | 8       | 3.28         | 0.064710          | 0.00343  | 0.0003                                          | 0.01758  | 0.0015                                          | 0.0167   | 0.0021                                          |
|          | IX21-4-B3D6  | 40                             | 23   | 8.33E-06                     | 18         | 8       | 3.28         | 0.064694          | 0.00232  | 0.0001                                          | 0.01524  | 0.0012                                          | 0.0127   | 0.0015                                          |
|          | IX21-4-B3D7  | 40                             | 23   | 8.33E-06                     | 21         | 8       | 3.28         | 0.064679          | 0.00191  | <b>0.0001</b>                                   | 0.01534  | 0.0015                                          | 0.0108   | 0.0015                                          |
|          | IX21-4-B3D8  | 40                             | 23   | 8.33E-06                     | 24         | 8       | 3.28         | 0.064664          | 0.00200  | <b>0.0003</b>                                   | 0.01360  | <b>0.0011</b>                                   | 0.0093   | <b>0.0013</b>                                   |
|          | IX21-4-B3D9  | 40                             | 23   | 8.33E-06                     | 27         | 8       | 3.28         | 0.064652          | 0.00155  | <b>0.0001</b>                                   | 0.01124  | <b>0.0008</b>                                   | 0.0072   | <b>0.0008</b>                                   |
|          | IX21-4-B3D10 | 40                             | 23   | 8.33E-06                     | 30         | 8       | 3.28         | 0.064640          | 0.00145  | <b>0.0001</b>                                   | 0.01169  | <b>0.0012</b>                                   | 0.0063   | <b>0.0009</b>                                   |
| <b>3</b> | IX21-4-C3D1  | 52                             | 23   | 8.33E-06                     | 3          | 9       | 3.28         | 0.064785          | 0.011896 | 0.0041                                          | 0.01657  | 0.0032                                          | 0.0208   | 0.0074                                          |
|          | IX21-4-C3D2  | 52                             | 23   | 8.33E-06                     | 6          | 9       | 3.28         | 0.064776          | 0.008684 | 0.0008                                          | 0.01317  | 0.0009                                          | 0.0182   | 0.0028                                          |
|          | IX21-4-C3D3  | 52                             | 23   | 8.33E-06                     | 9          | 9       | 3.28         | 0.064767          | 0.005520 | 0.0002                                          | 0.01067  | 0.0008                                          | 0.0148   | 0.0020                                          |
|          | IX21-4-C3D4  | 52                             | 23   | 8.33E-06                     | 12         | 9       | 3.28         | 0.064759          | 0.003834 | 0.0002                                          | 0.00936  | 0.0008                                          | 0.0127   | 0.0019                                          |
|          | IX21-4-C3D5  | 52                             | 23   | 8.33E-06                     | 15         | 9       | 3.28         | 0.064751          | 0.002940 | 0.0002                                          | 0.00798  | 0.0006                                          | 0.0106   | 0.0015                                          |
|          | IX21-4-C3D6  | 52                             | 23   | 8.33E-06                     | 18         | 9       | 3.28         | 0.064744          | 0.002143 | 0.0000                                          | 0.00714  | 0.0006                                          | 0.0084   | 0.0011                                          |
|          | IX21-4-C3D7  | 52                             | 23   | 8.33E-06                     | 21         | 9       | 3.28         | 0.064736          | 0.001710 | 0.0000                                          | 0.00746  | 0.0007                                          | 0.0065   | 0.0008                                          |
|          | IX21-4-C3D8  | 52                             | 23   | 8.33E-06                     | 24         | 9       | 3.28         | 0.064730          | 0.001383 | 0.0000                                          | 0.00619  | <b>0.0005</b>                                   | 0.0055   | <b>0.0008</b>                                   |
|          | IX21-4-C3D9  | 52                             | 23   | 8.33E-06                     | 27         | 9       | 3.28         | 0.064723          | 0.001239 | 0.0000                                          | 0.00574  | <b>0.0005</b>                                   | 0.0050   | <b>0.0008</b>                                   |
|          | IX21-4-C3D10 | 52                             | 23   | 8.33E-06                     | 30         | 9       | 3.28         | 0.064717          | 0.001061 | -0.0001                                         | 0.00614  | <b>0.0006</b>                                   | 0.0043   | <b>0.0006</b>                                   |
| <b>4</b> | IX21-4-D3D1  | 90                             | 23   | 8.33E-06                     | 3          | 10      | 1.64         | 0.032393          | 0.006681 | 0.0048                                          | 0.00937  | 0.0036                                          | 0.0105   | 0.0073                                          |
|          | IX21-4-D3D2  | 90                             | 23   | 8.33E-06                     | 6          | 10      | 1.64         | 0.032389          | 0.004511 | 0.0007                                          | 0.00699  | 0.0009                                          | 0.0091   | 0.0027                                          |
|          | IX21-4-D3D3  | 90                             | 23   | 8.33E-06                     | 9          | 10      | 1.64         | 0.032385          | 0.003142 | 0.0005                                          | 0.00594  | 0.0009                                          | 0.0060   | 0.0010                                          |
|          | IX21-4-D3D4  | 90                             | 23   | 8.33E-06                     | 12         | 10      | 1.64         | 0.032381          | 0.002194 | 0.0003                                          | 0.00510  | 0.0008                                          | 0.0065   | 0.0024                                          |
|          | IX21-4-D3D5  | 90                             | 23   | 8.33E-06                     | 15         | 10      | 1.64         | 0.032377          | 0.001378 | 0.0001                                          | 0.00413  | 0.0006                                          | 0.0048   | 0.0010                                          |
|          | IX21-4-D3D6  | 90                             | 23   | 8.33E-06                     | 18         | 10      | 1.64         | 0.032374          | 0.001317 | 0.0003                                          | 0.00392  | 0.0007                                          | 0.0038   | 0.0009                                          |
|          | IX21-4-D3D7  | 90                             | 23   | 8.33E-06                     | 21         | 10      | 1.64         | 0.032371          | 0.000706 | -0.0001                                         | 0.00367  | 0.0007                                          | 0.0031   | 0.0008                                          |
|          | IX21-4-D3D8  | 90                             | 23   | 8.33E-06                     | 24         | 10      | 1.64         | 0.032368          | 0.000628 | 0.0001                                          | 0.00329  | <b>0.0006</b>                                   | 0.0033   | <b>0.0012</b>                                   |
|          | IX21-4-D3D9  | 90                             | 23   | 8.33E-06                     | 27         | 10      | 1.64         | 0.032365          | 0.000457 | 0.0000                                          | 0.00301  | <b>0.0005</b>                                   | 0.0021   | <b>0.0002</b>                                   |
|          | IX21-4-D3D10 | 90                             | 23   | 8.33E-06                     | 30         | 10      | 1.64         | 0.032363          | 0.000397 | 0.0000                                          | 0.00332  | <b>0.0007</b>                                   | 0.0016   | <b>0.0003</b>                                   |
| <b>5</b> | IX21-4-E3D1  | 230                            | 23   | 8.33E-06                     | 3          | 11      | 1.64         | 0.032394          | 0.00553  | 0.0032                                          | 0.00691  | 0.0079                                          | 0.0069   | 0.0046                                          |
|          | IX21-4-E3D2  | 230                            | 23   | 8.33E-06                     | 6          | 11      | 1.64         | 0.032392          | 0.00373  | 0.0002                                          | 0.00499  | 0.0017                                          | 0.0053   | 0.0012                                          |
|          | IX21-4-E3D3  | 230                            | 23   | 8.33E-06                     | 9          | 11      | 1.64         | 0.032391          | 0.00297  | 0.0003                                          | 0.00392  | 0.0016                                          | 0.0037   | 0.0005                                          |
|          | IX21-4-E3D4  | 230                            | 23   | 8.33E-06                     | 12         | 11      | 1.64         | 0.032390          | 0.00151  | -0.0005                                         | 0.00277  | 0.0009                                          | 0.0027   | 0.0005                                          |
|          | IX21-4-E3D5  | 230                            | 23   | 8.33E-06                     | 15         | 11      | 1.64         | 0.032389          | 0.00164  | 0.0001                                          | 0.00326  | 0.0021                                          | 0.0017   | 0.0001                                          |
|          | IX21-4-E3D6  | 230                            | 23   | 8.33E-06                     | 18         | 11      | 1.64         | 0.032388          | 0.00269  | 0.0009                                          | 0.00327  | 0.0018                                          | 0.0027   | 0.0011                                          |
|          | IX21-4-E3D7  | 230                            | 23   | 8.33E-06                     | 21         | 11      | 1.64         | 0.032388          | 0.00113  | -0.0007                                         | 0.00241  | 0.0008                                          | 0.0018   | 0.0002                                          |
|          | IX21-4-E3D8  | 230                            | 23   | 8.33E-06                     | 24         | 11      | 1.64         | 0.032387          | 0.00077  | -0.0004                                         | 0.00196  | <b>0.0008</b>                                   | 0.0014   | <b>0.0002</b>                                   |
|          | IX21-4-E3D9  | 230                            | 23   | 8.33E-06                     | 27         | 11      | 1.64         | 0.032387          | 0.00097  | -0.0001                                         | 0.00173  | <b>0.0008</b>                                   | 0.0012   | <b>0.0002</b>                                   |
|          | IX21-4-E3D10 | 230                            | 23   | 8.33E-06                     | 30         | 11      | 1.64         | 0.032387          | 0.00088  | -0.0003                                         | 0.00213  | <b>0.0014</b>                                   | 0.0013   | <b>0.0003</b>                                   |

## **APPENDIX B**

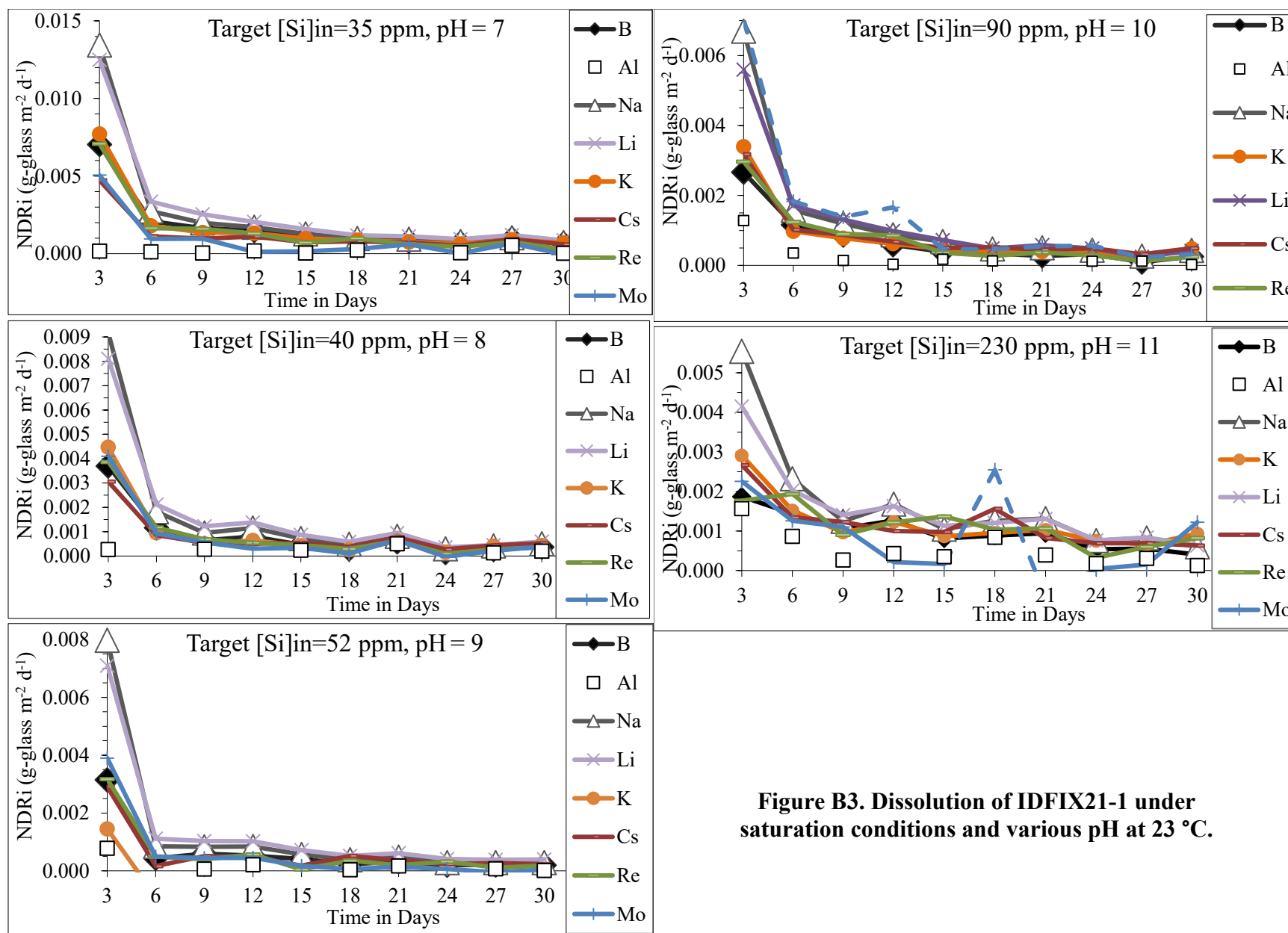
# **PLOTS OF PULSED-FLOW TEST DATA**



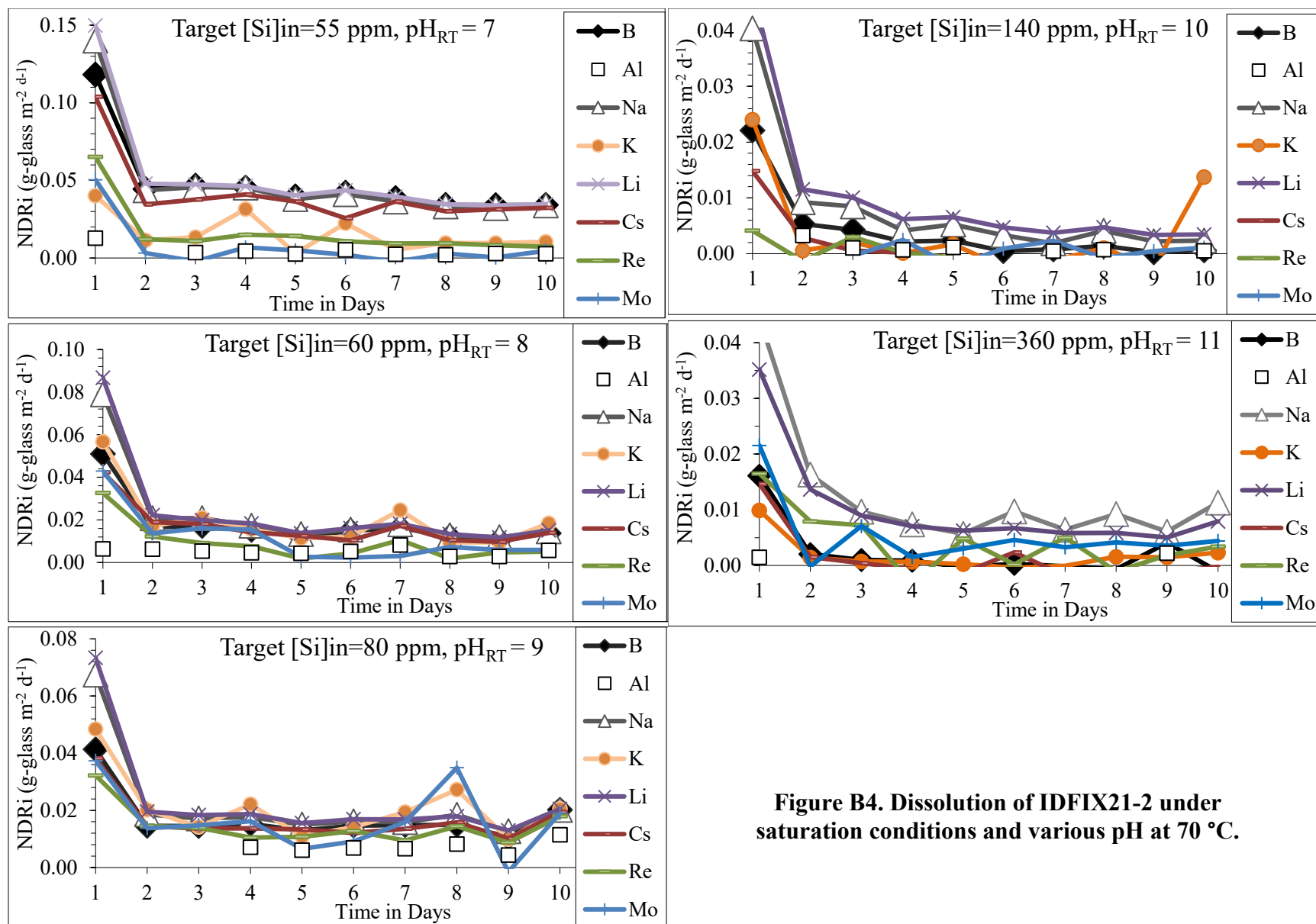
**Figure B1. Dissolution of IDFIX21-1 under saturation conditions and various pH at 70 °C.**



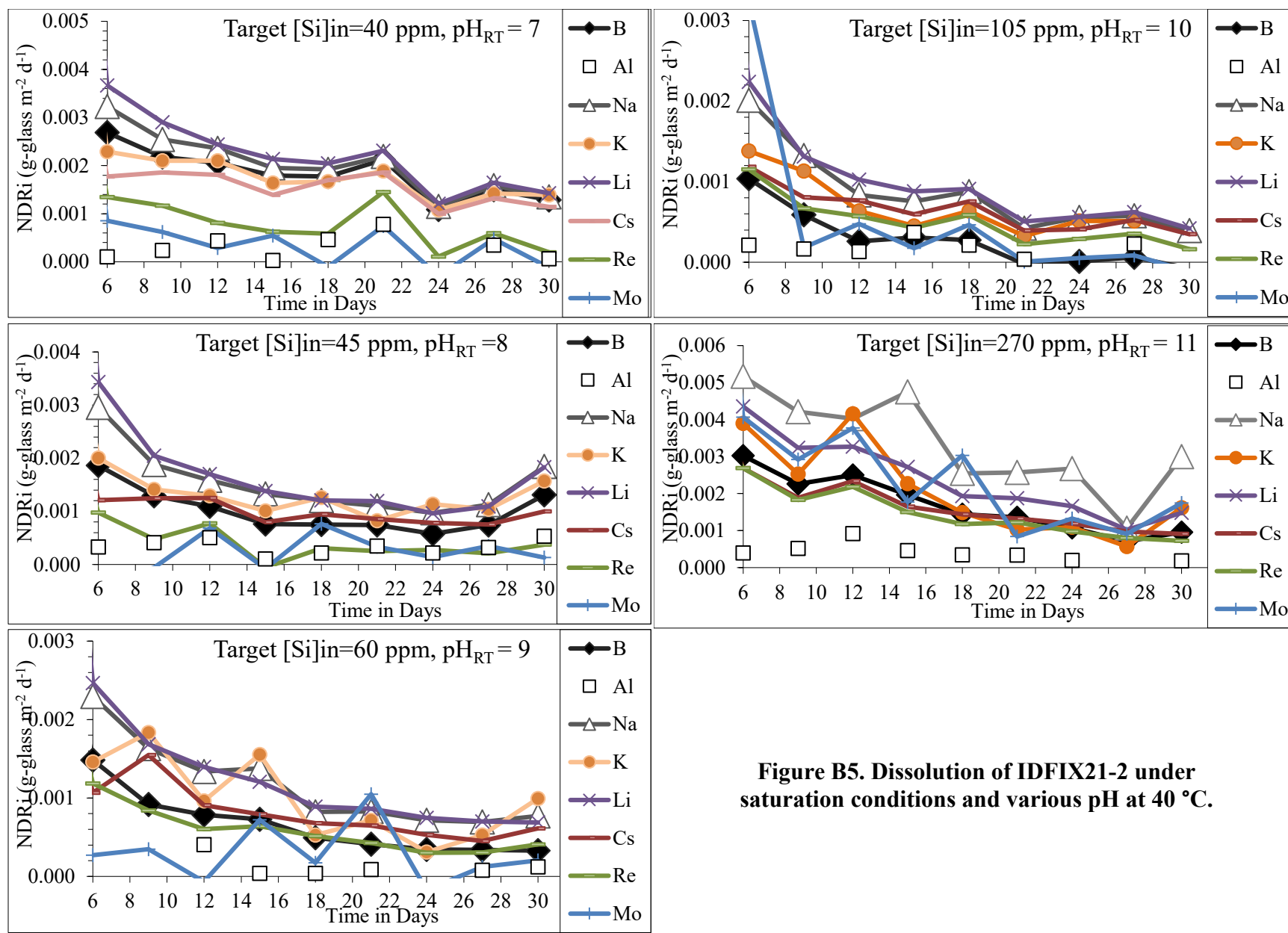
**Figure B2. Dissolution of IDFIX21-1 under saturation conditions and various pH at 40 °C.**



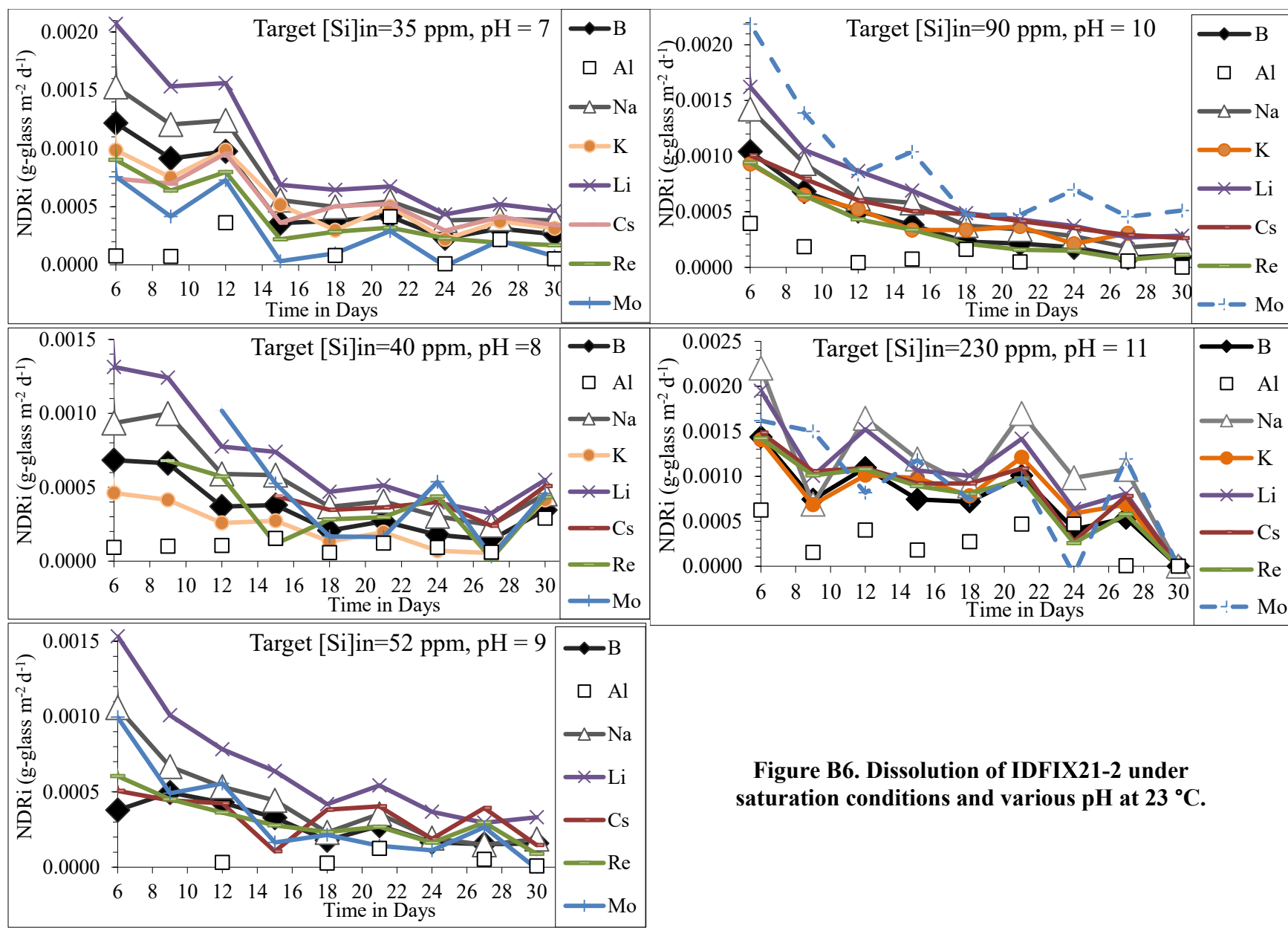
**Figure B3. Dissolution of IDFIX21-1 under saturation conditions and various pH at 23 °C.**



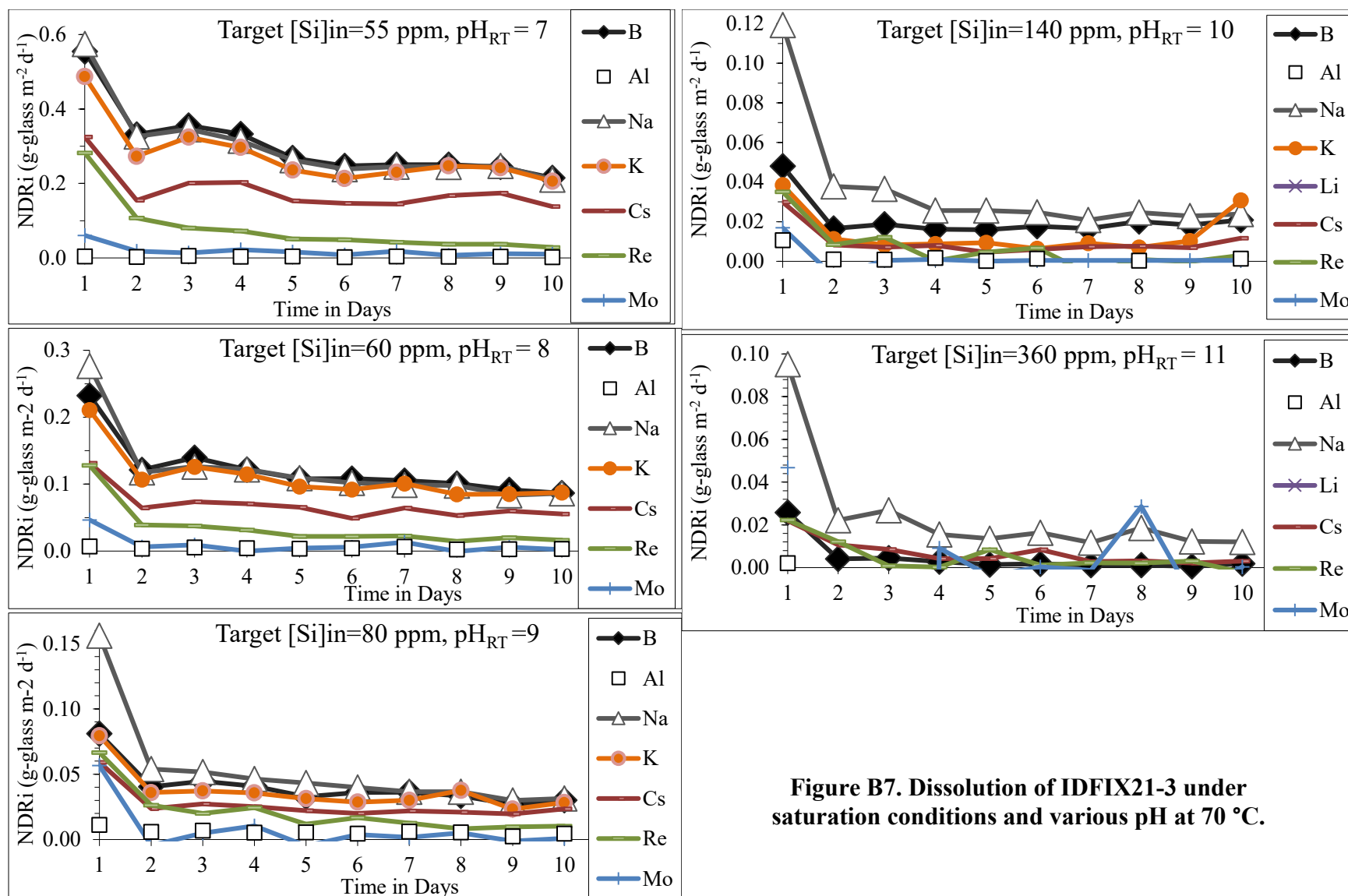
**Figure B4. Dissolution of IDFIX21-2 under saturation conditions and various pH at 70 °C.**



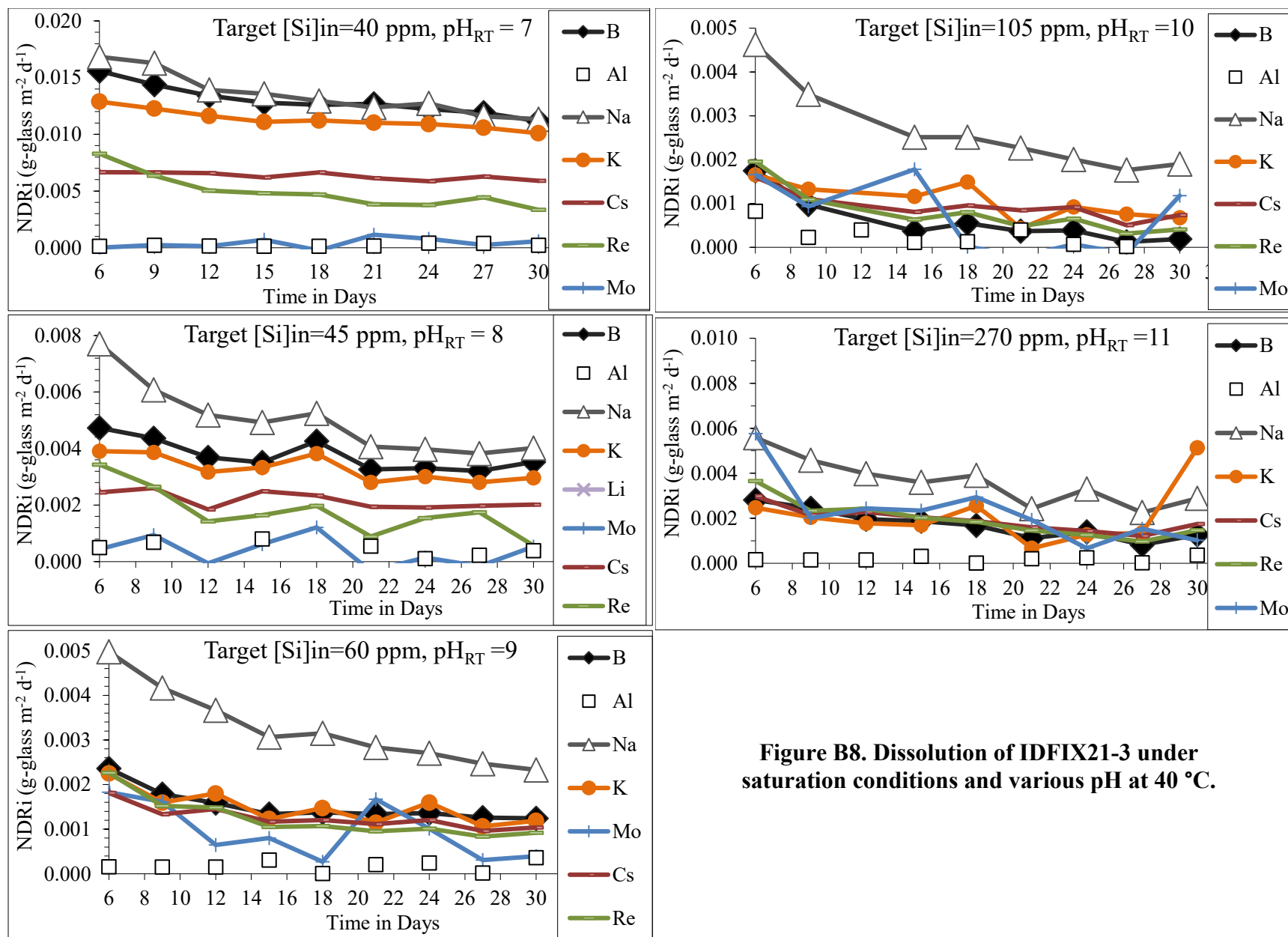
**Figure B5. Dissolution of IDFIX21-2 under saturation conditions and various pH at 40 °C.**



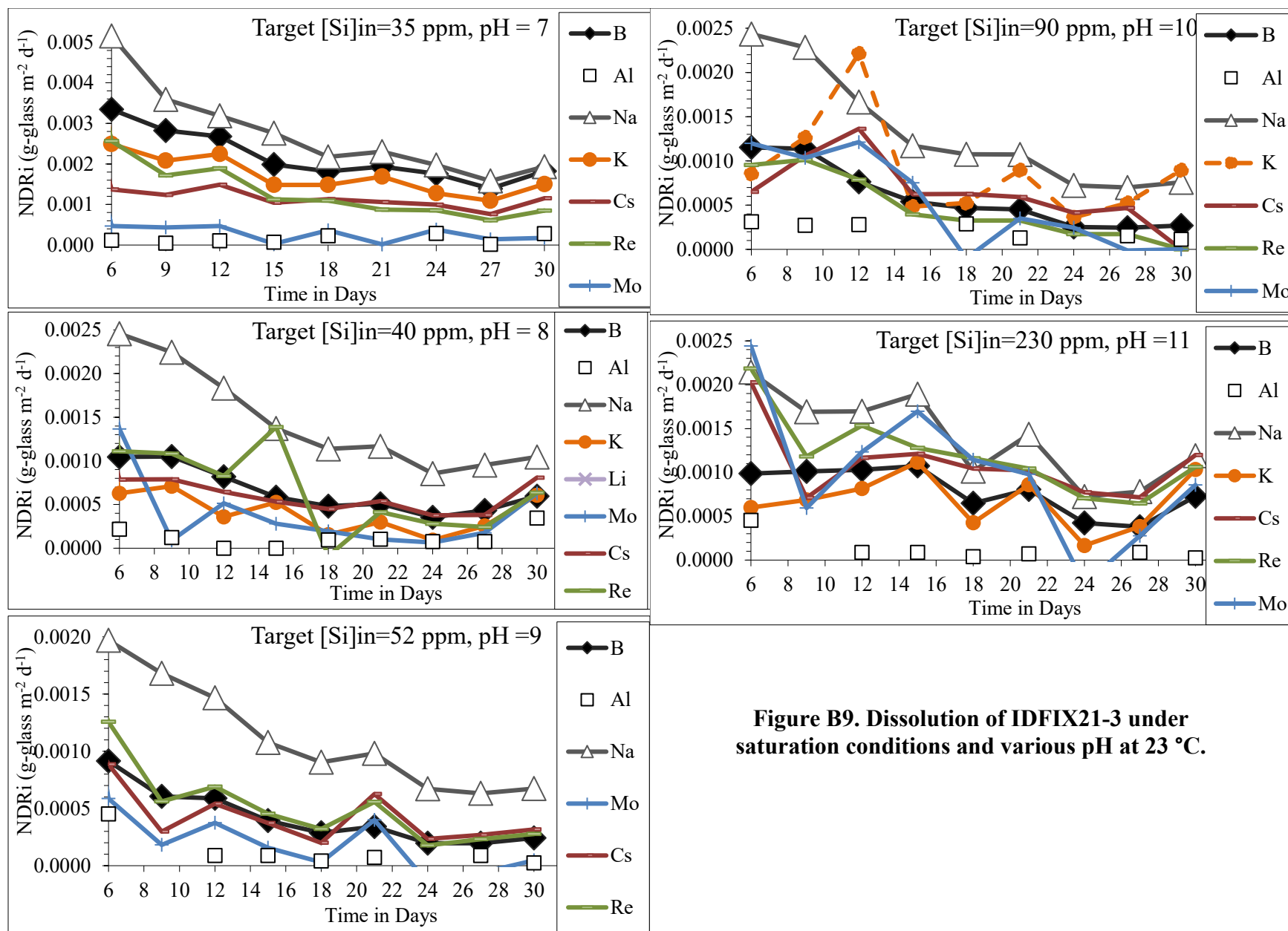
**Figure B6. Dissolution of IDFIX21-2 under saturation conditions and various pH at 23 °C.**



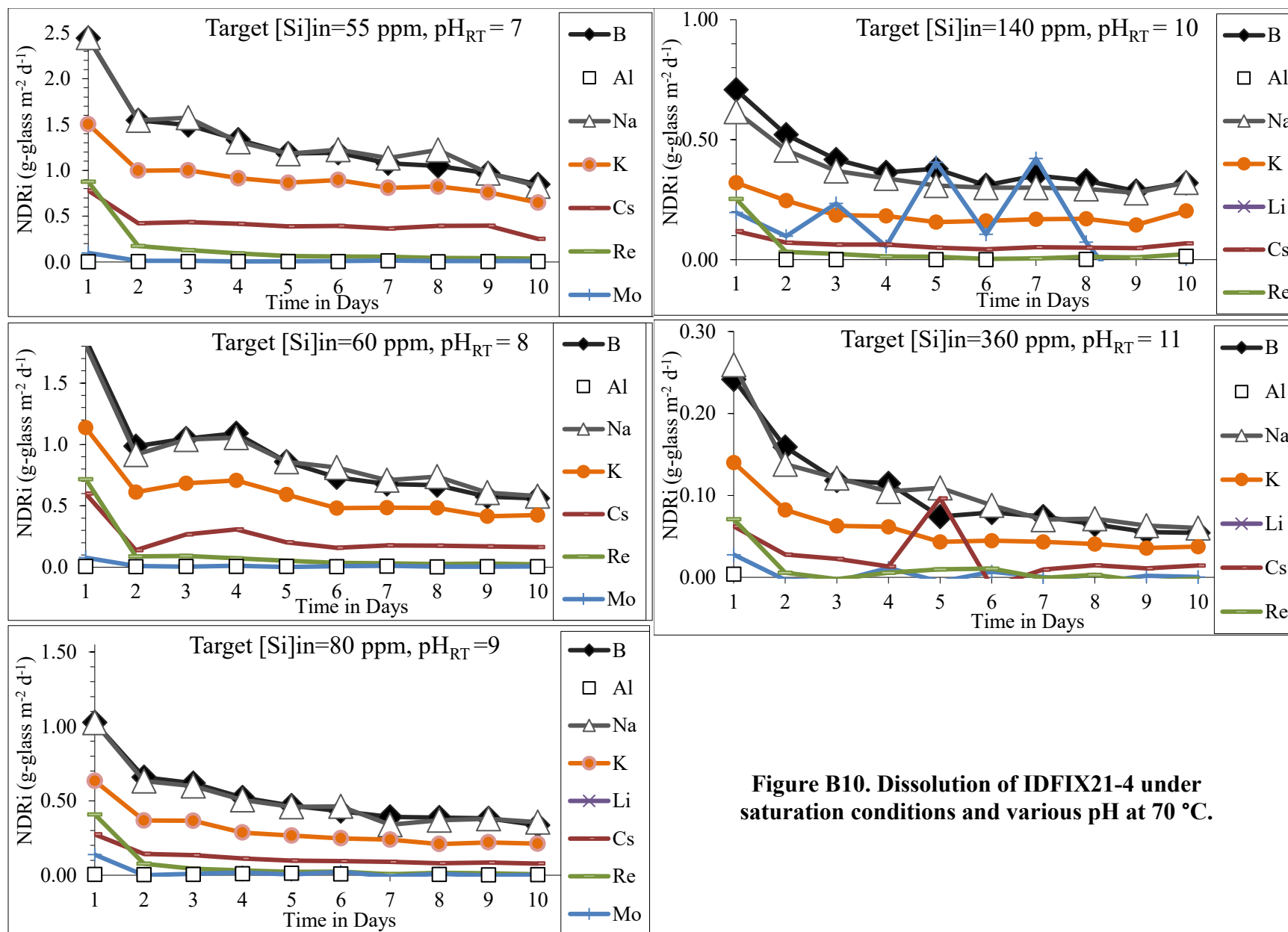
**Figure B7. Dissolution of IDFIX21-3 under saturation conditions and various pH at 70 °C.**



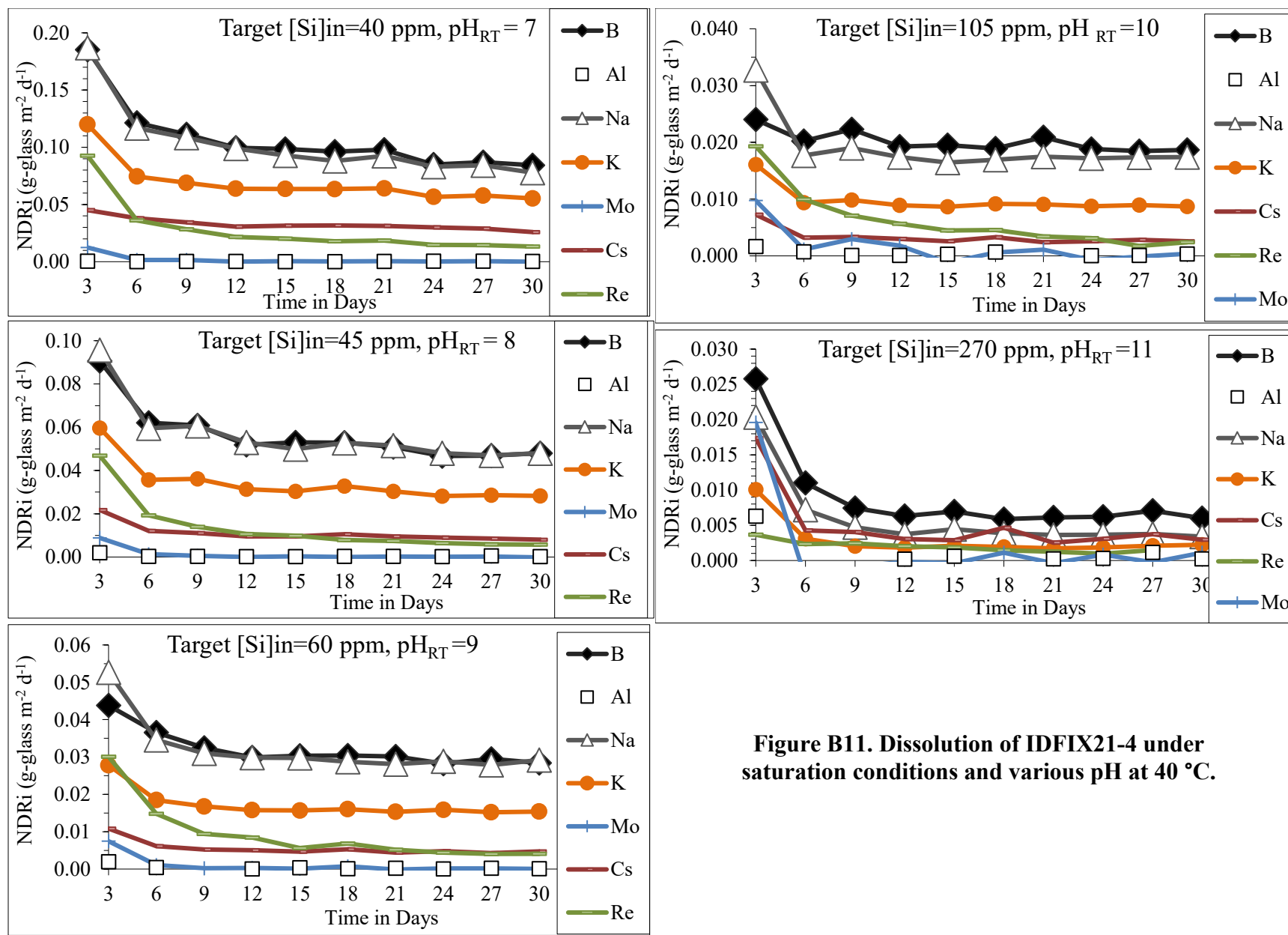
**Figure B8. Dissolution of IDFIX21-3 under saturation conditions and various pH at 40 °C.**



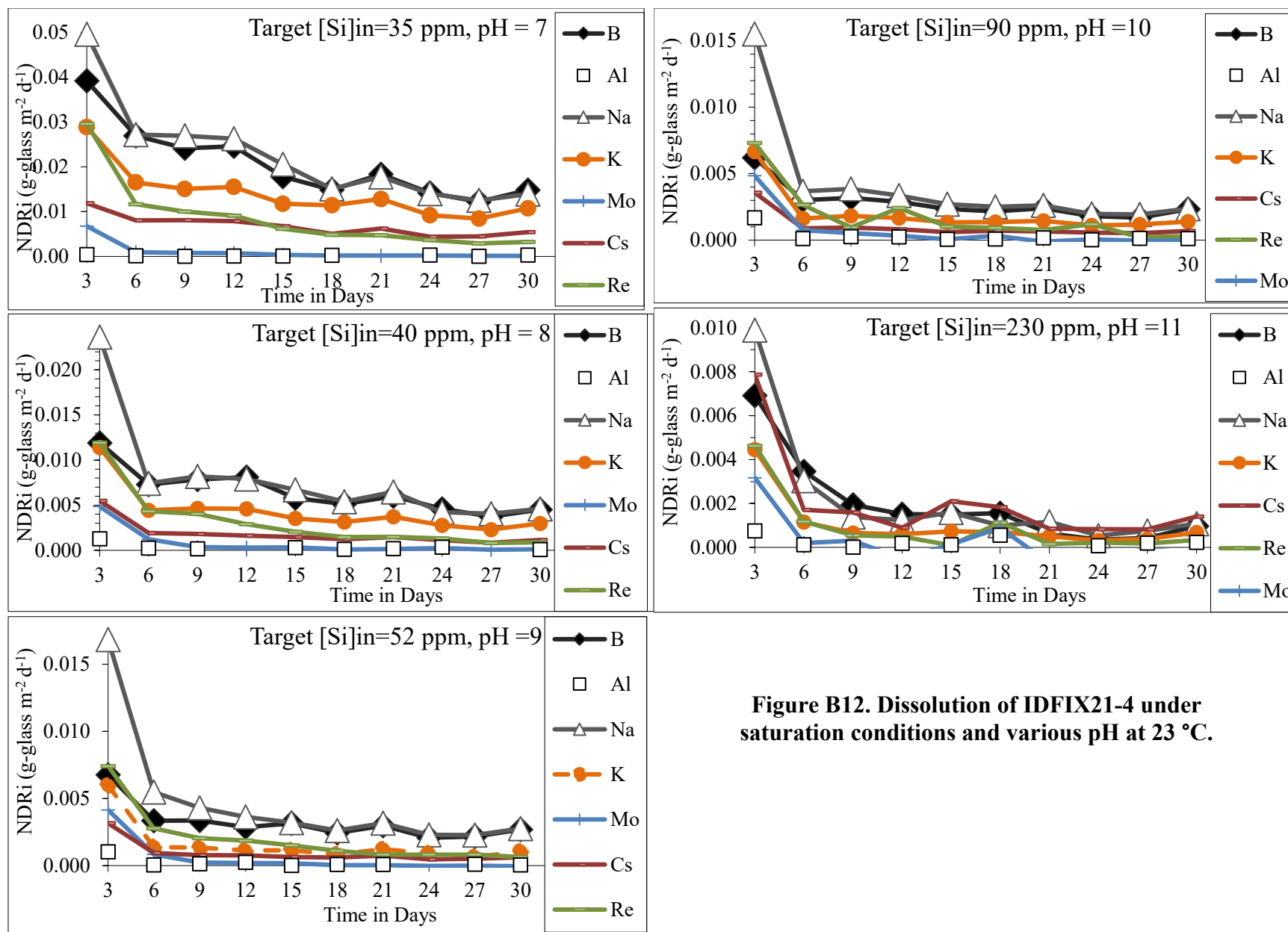
**Figure B9. Dissolution of IDFIX21-3 under saturation conditions and various pH at 23 °C.**



**Figure B10. Dissolution of IDFIX21-4 under saturation conditions and various pH at 70 °C.**



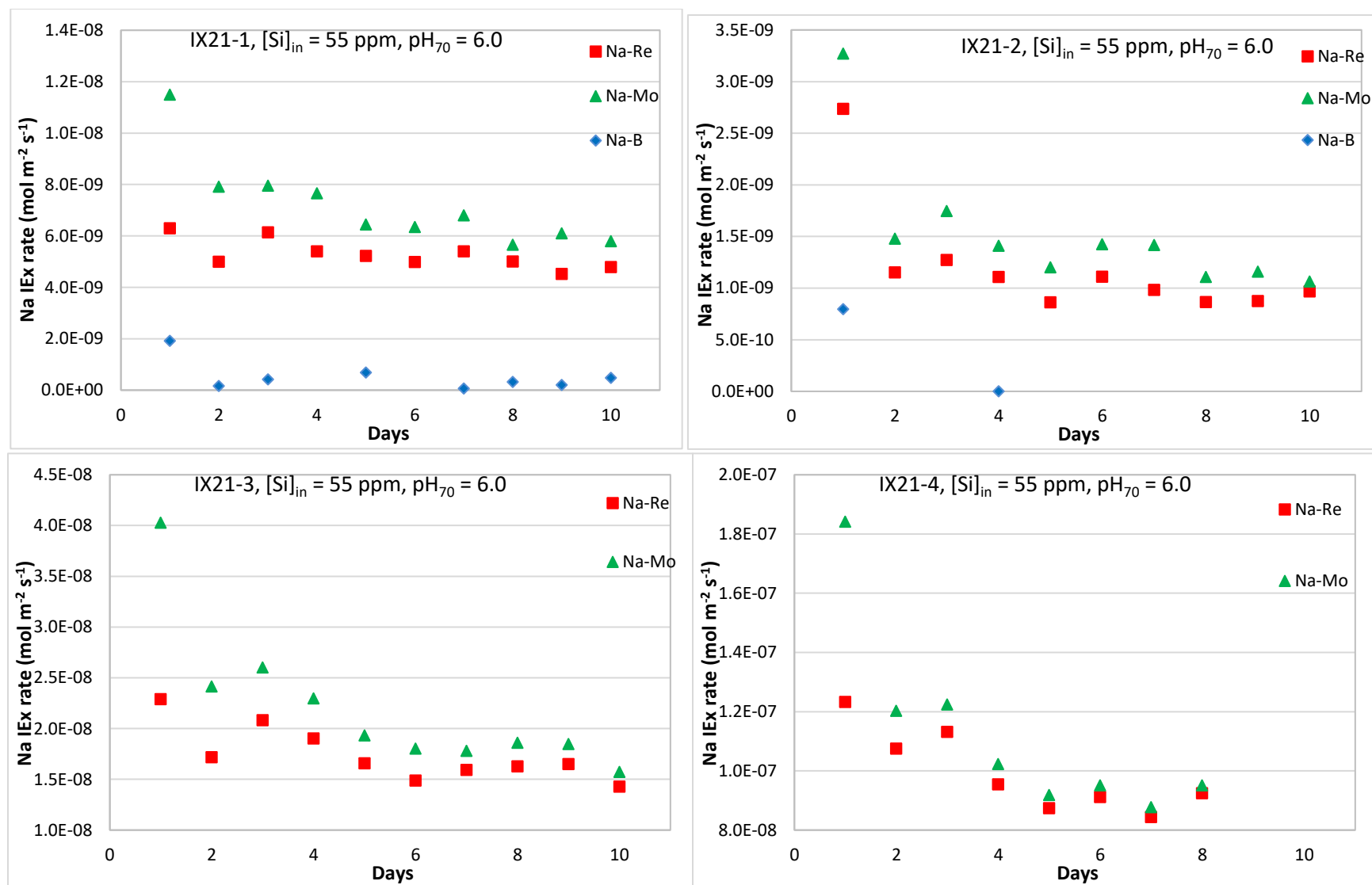
**Figure B11. Dissolution of IDFIX21-4 under saturation conditions and various pH at 40 °C.**



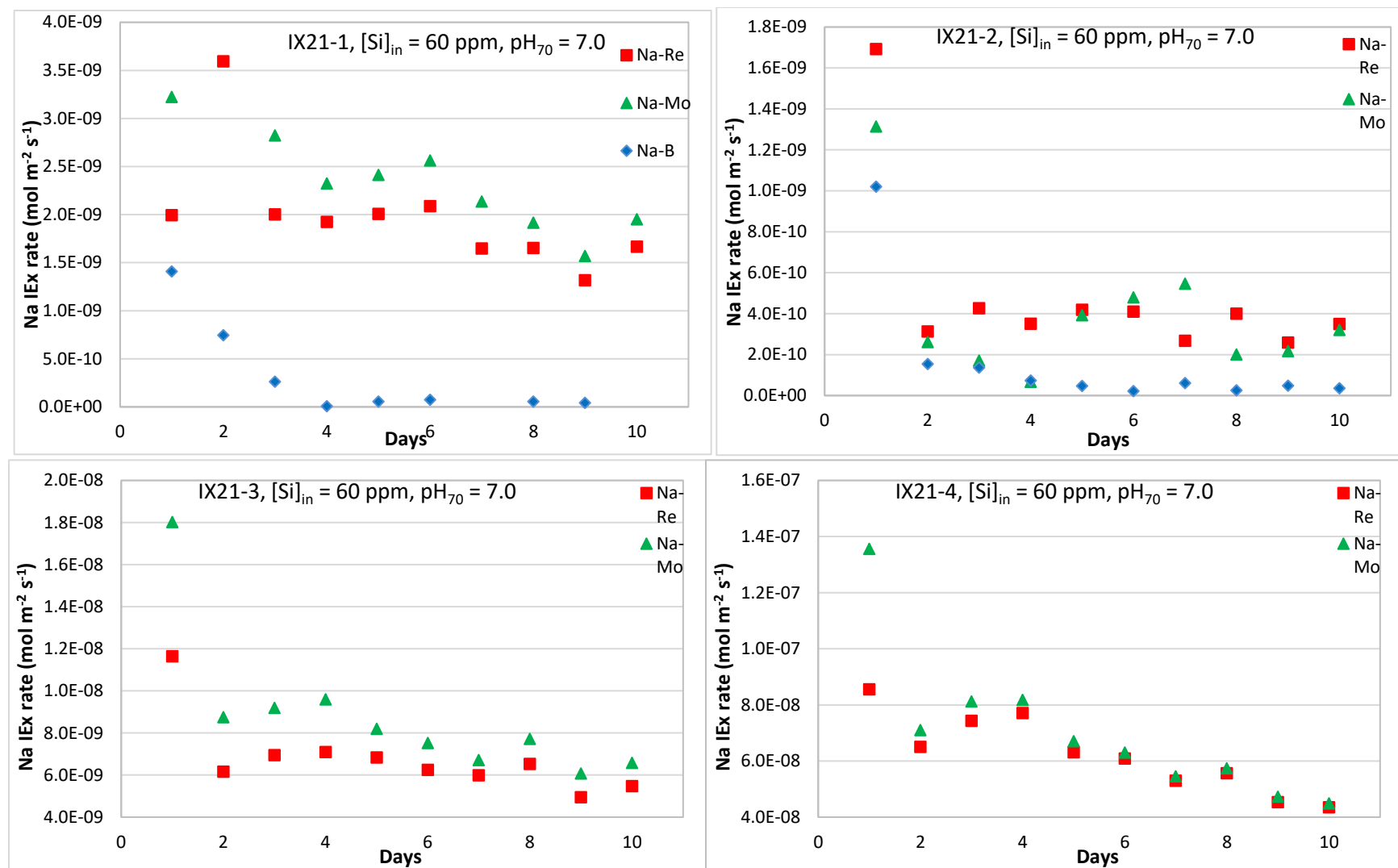
**Figure B12. Dissolution of IDFIX21-4 under saturation conditions and various pH at 23 °C.**

## **APPENDIX C**

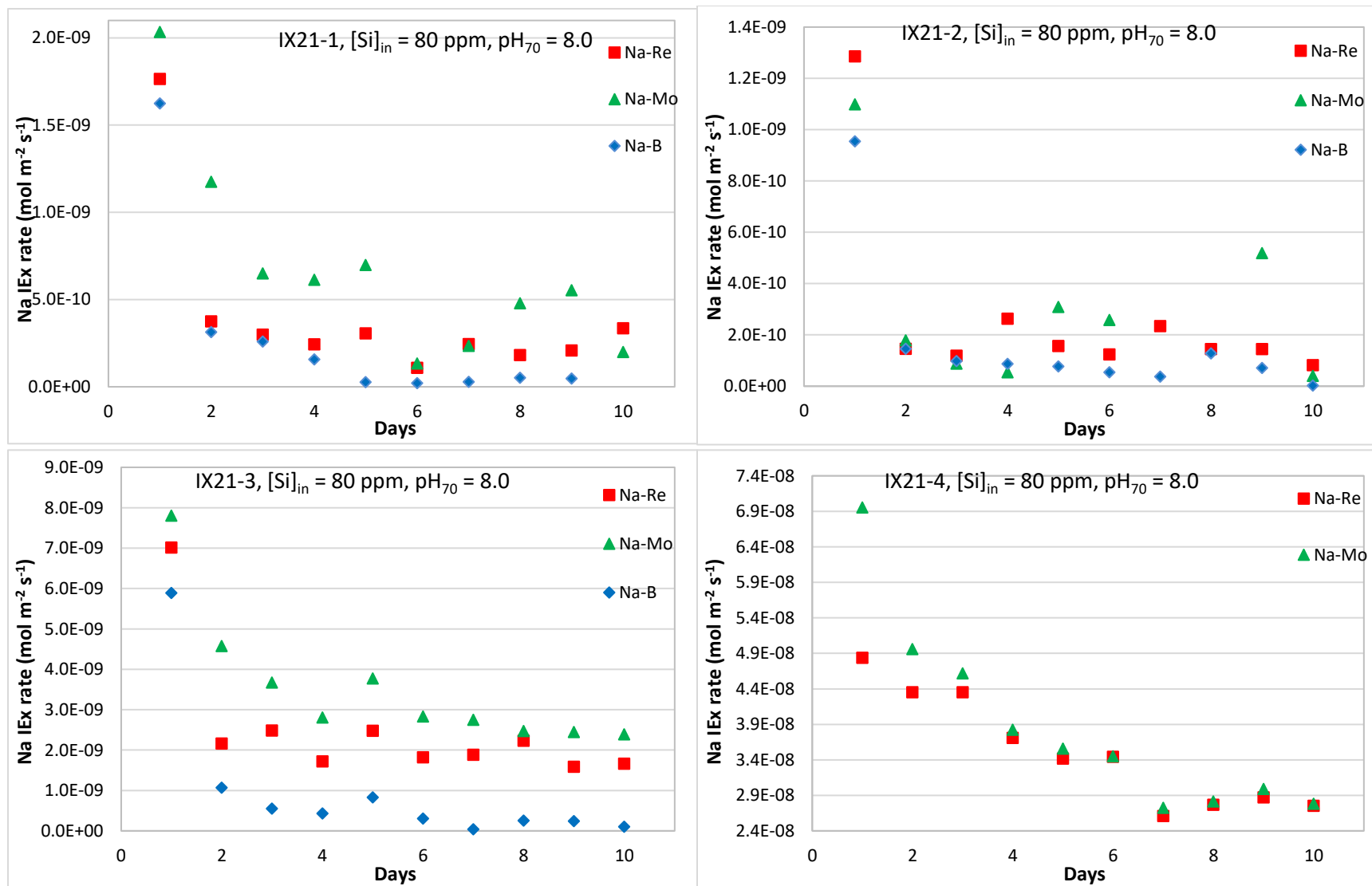
# **SODIUM ION-EXCHANGE PLOTS COMPARING THE VALUES BY DIFFERENCE OF $\text{NDR}_{\text{Na}}$ TO $\text{NDR}_{\text{B}}$ , $\text{NDR}_{\text{Re}}$ , AND $\text{NDR}_{\text{Mo}}$**



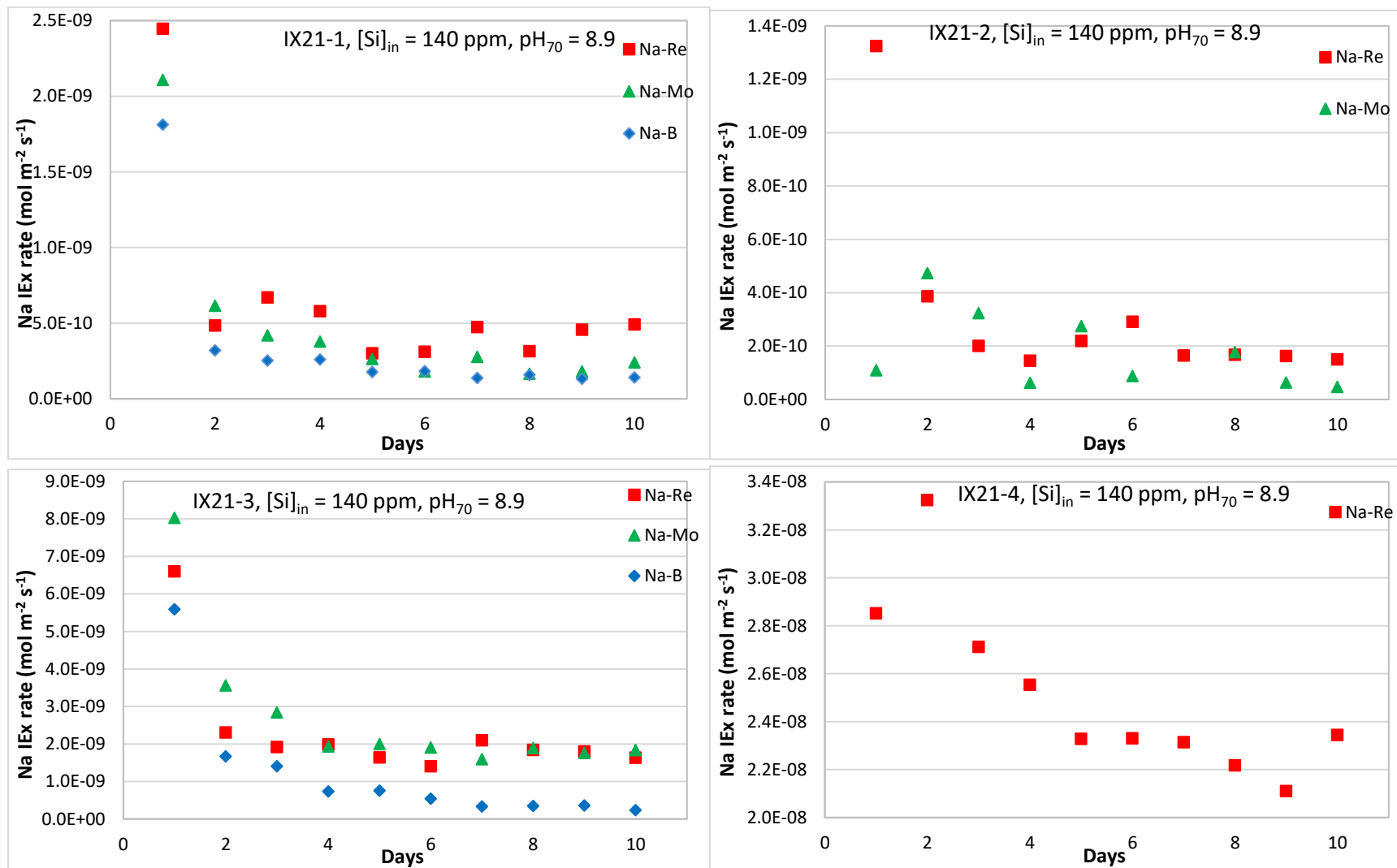
**Figure C1. Plot of sodium ion exchange rate calculated from difference of sodium normalized release rate to that of boron, rhenium, or molybdenum, at 70 °C,  $\text{pH}_{23} = 7$  ( $\text{pH}_{70} = 6$ ).**



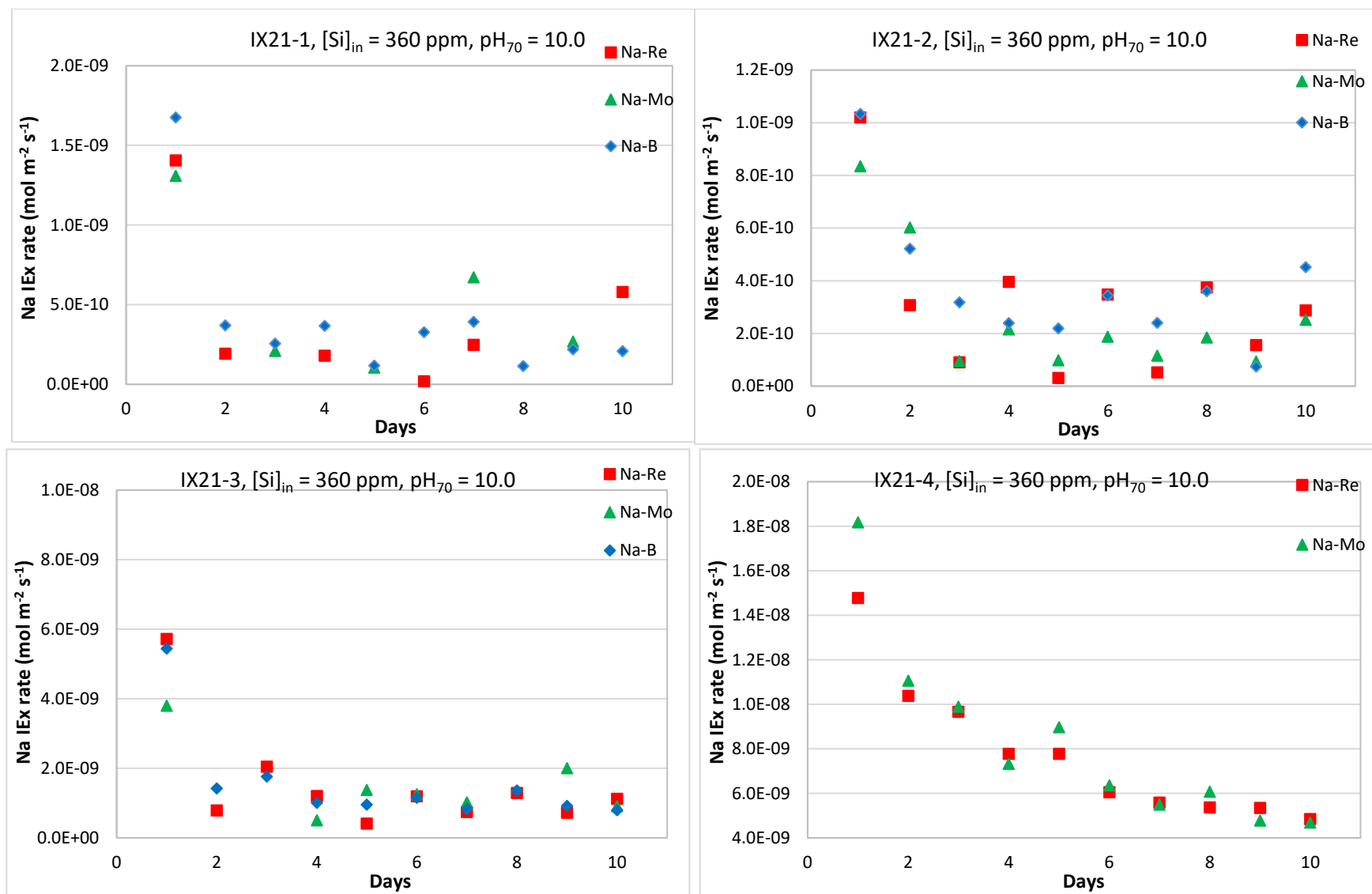
**Figure C2. Plot of sodium ion exchange rate calculated from difference of sodium normalized release rate to that of boron, rhenium, or molybdenum, at 70 °C, pH<sub>23</sub> = 8 (pH<sub>70</sub> = 7).**



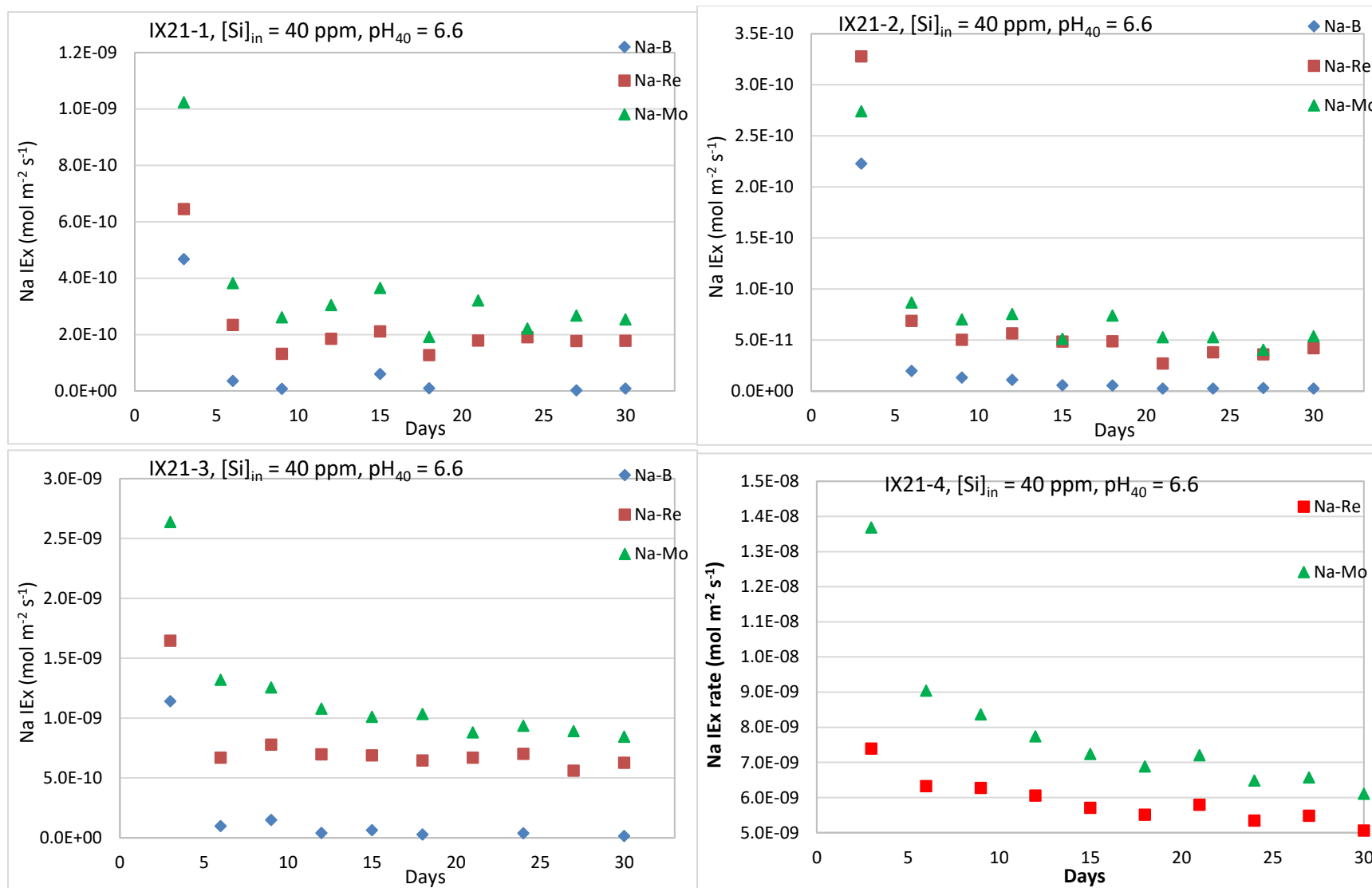
**Figure C3. Plot of sodium ion exchange rate calculated from difference of sodium normalized release rate to that of boron, rhenium, or molybdenum, at  $70^\circ\text{C}$ ,  $\text{pH}_{23}=9$  ( $\text{pH}_{70}=8$ ).**



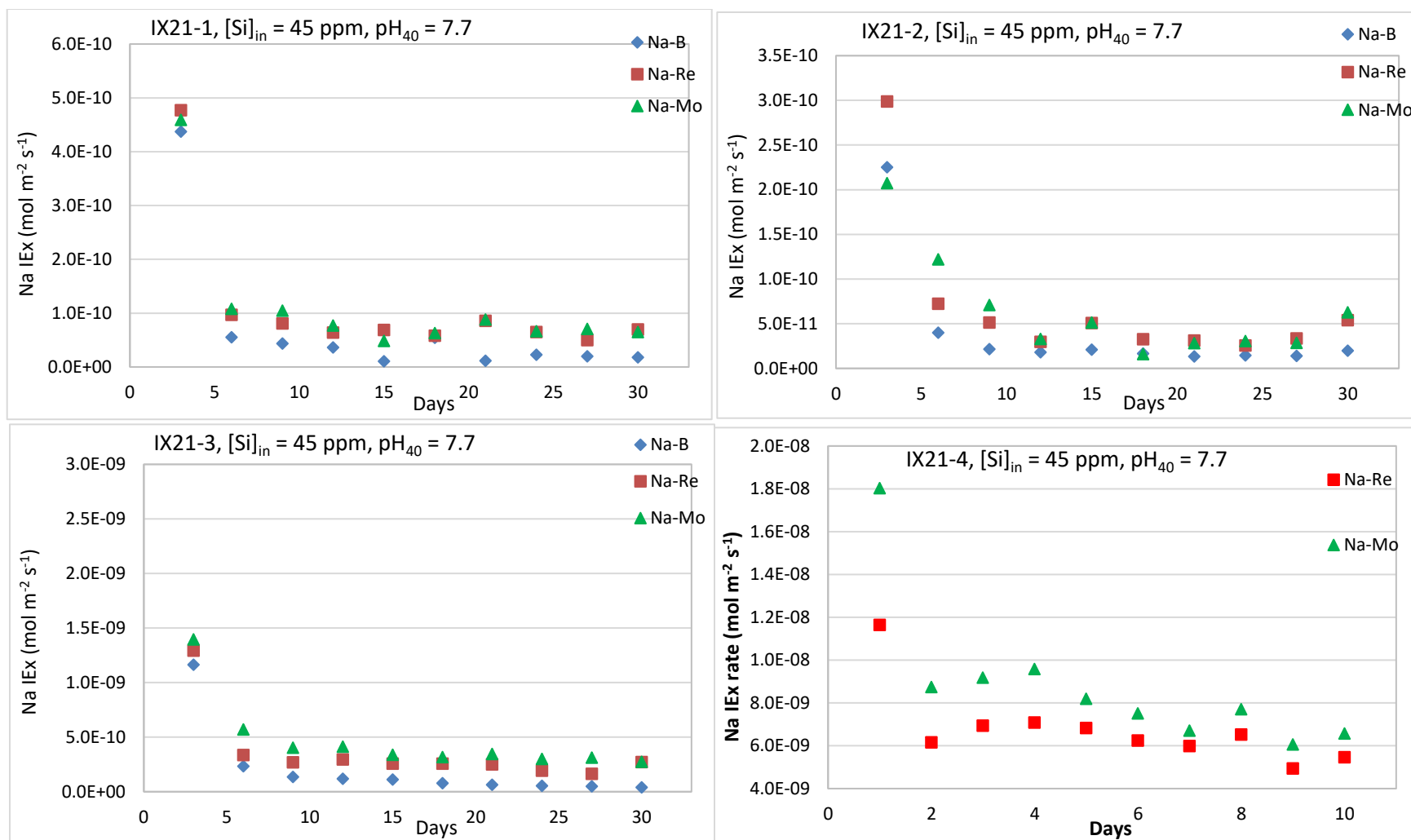
**Figure C4. Plot of sodium ion exchange rate calculated from difference of sodium normalized release rate to that of boron, rhenium, or molybdenum, at 70 °C,  $\text{pH}_{23} = 10$  ( $\text{pH}_{70} = 8.9$ ).**



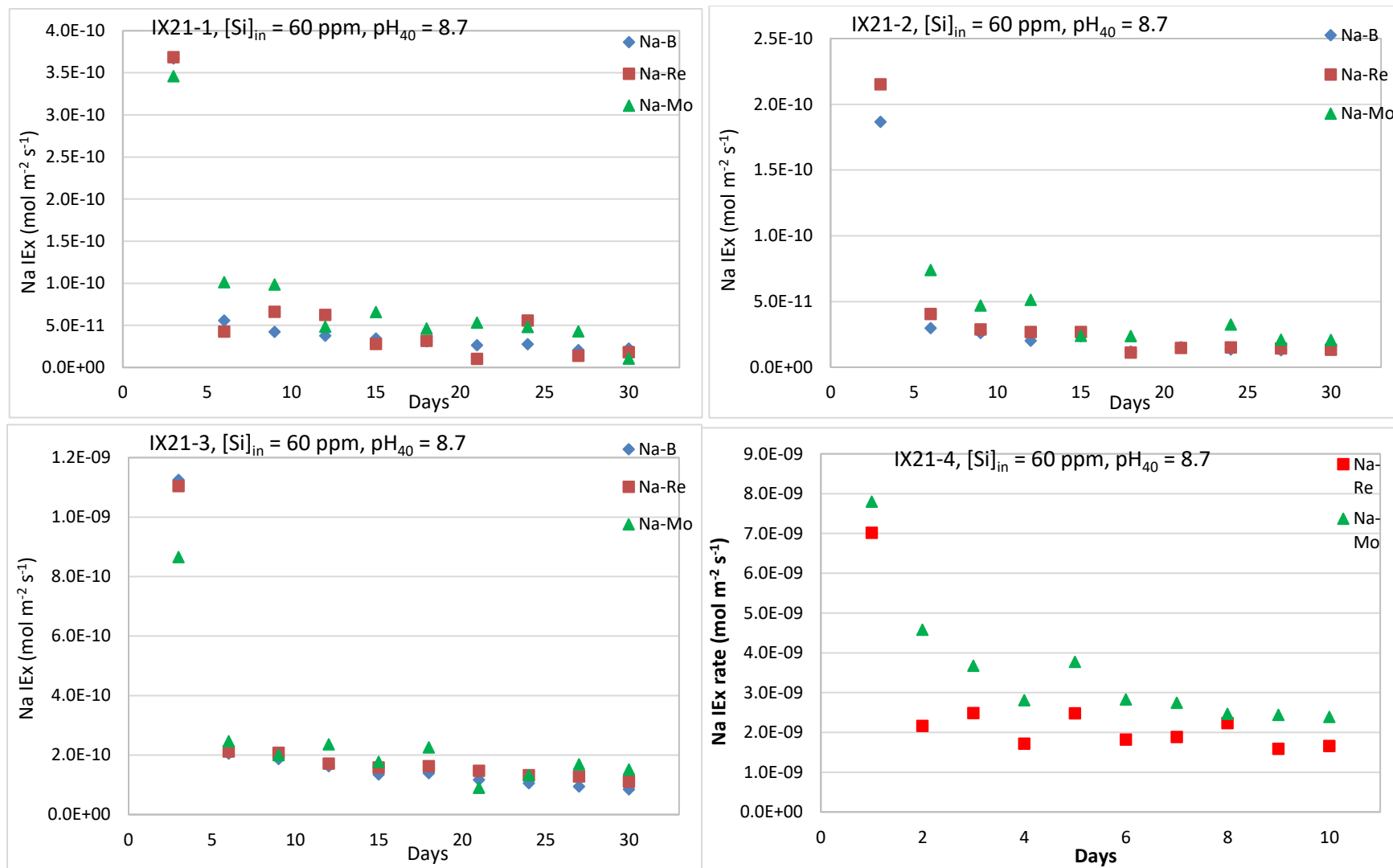
**Figure C5. Plot of sodium ion exchange rate calculated from difference of sodium normalized release rate to that of boron, rhenium, or molybdenum, at 70 °C, pH<sub>23</sub> = 11 (pH<sub>70</sub> = 10).**



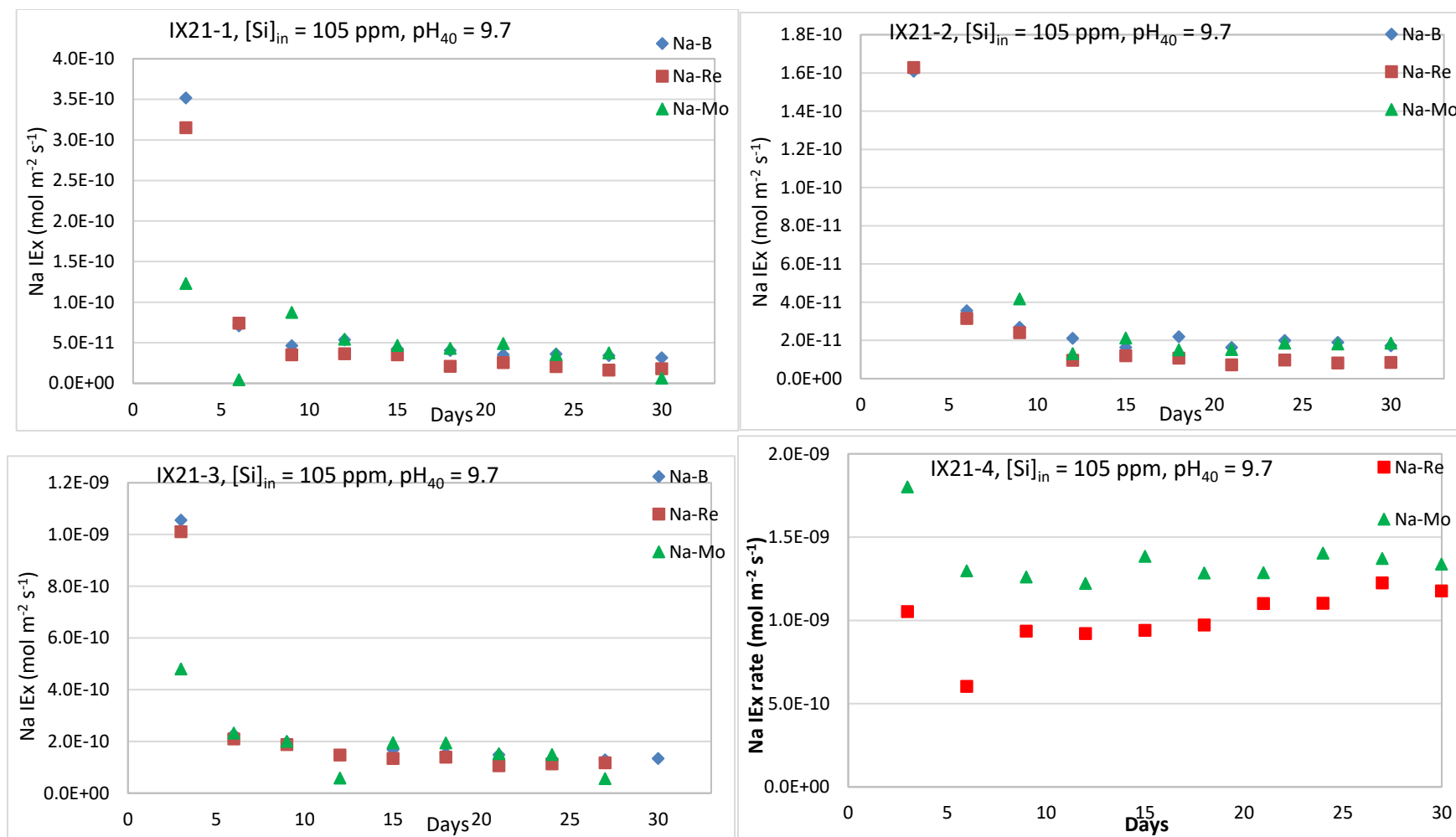
**Figure C6. Plot of sodium ion exchange rate calculated from difference of sodium normalized release rate to that of boron, rhenium or molybdenum, at 40 °C, pH<sub>23</sub> = 7.0 (pH<sub>40</sub> = 6.6).**



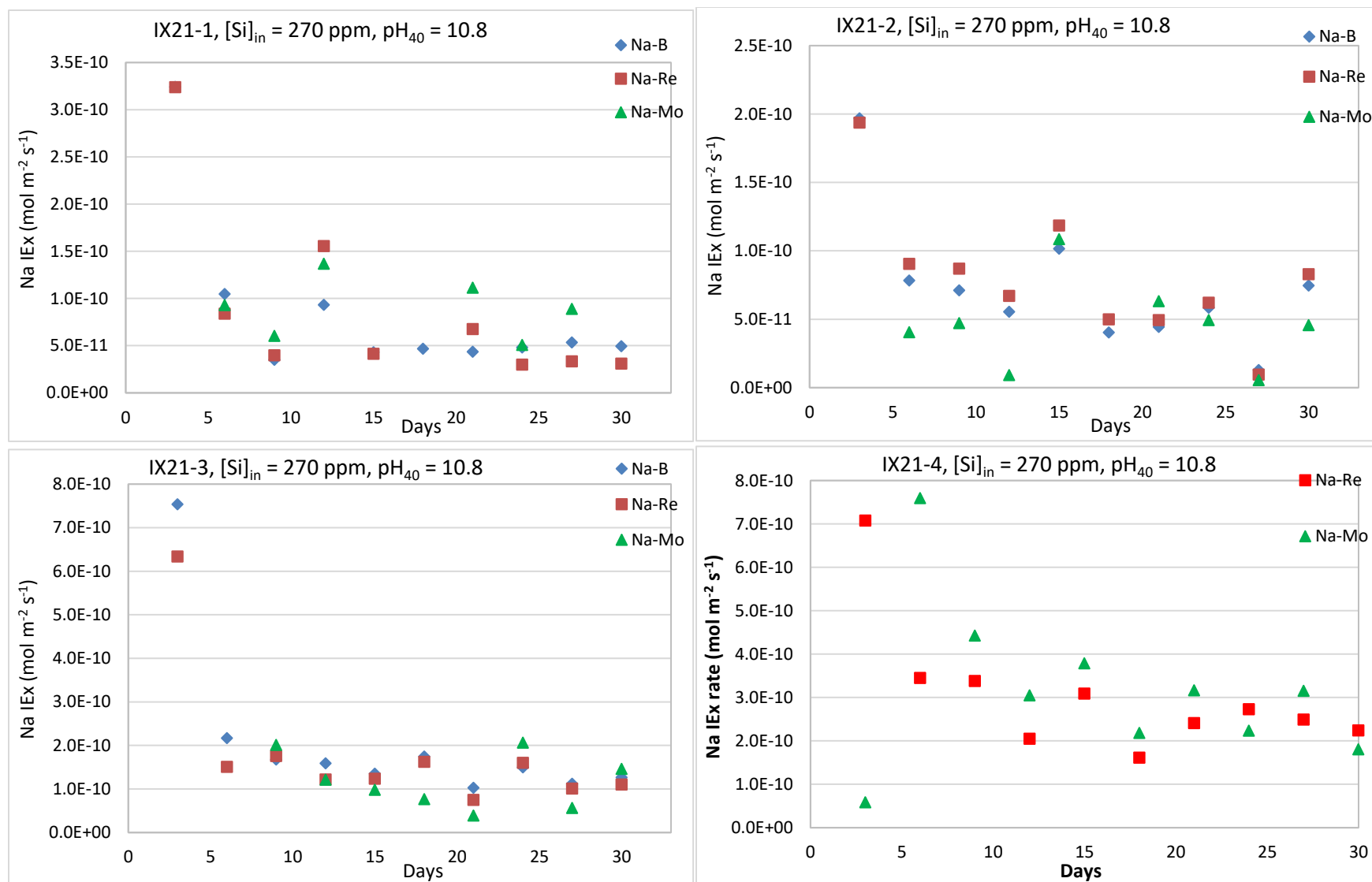
**Figure C7. Plot of sodium ion exchange rate calculated from difference of sodium normalized release rate to that of boron, rhenium, or molybdenum, at 40 °C,  $\text{pH}_{23} = 8.1$  ( $\text{pH}_{40} = 7.7$ ).**



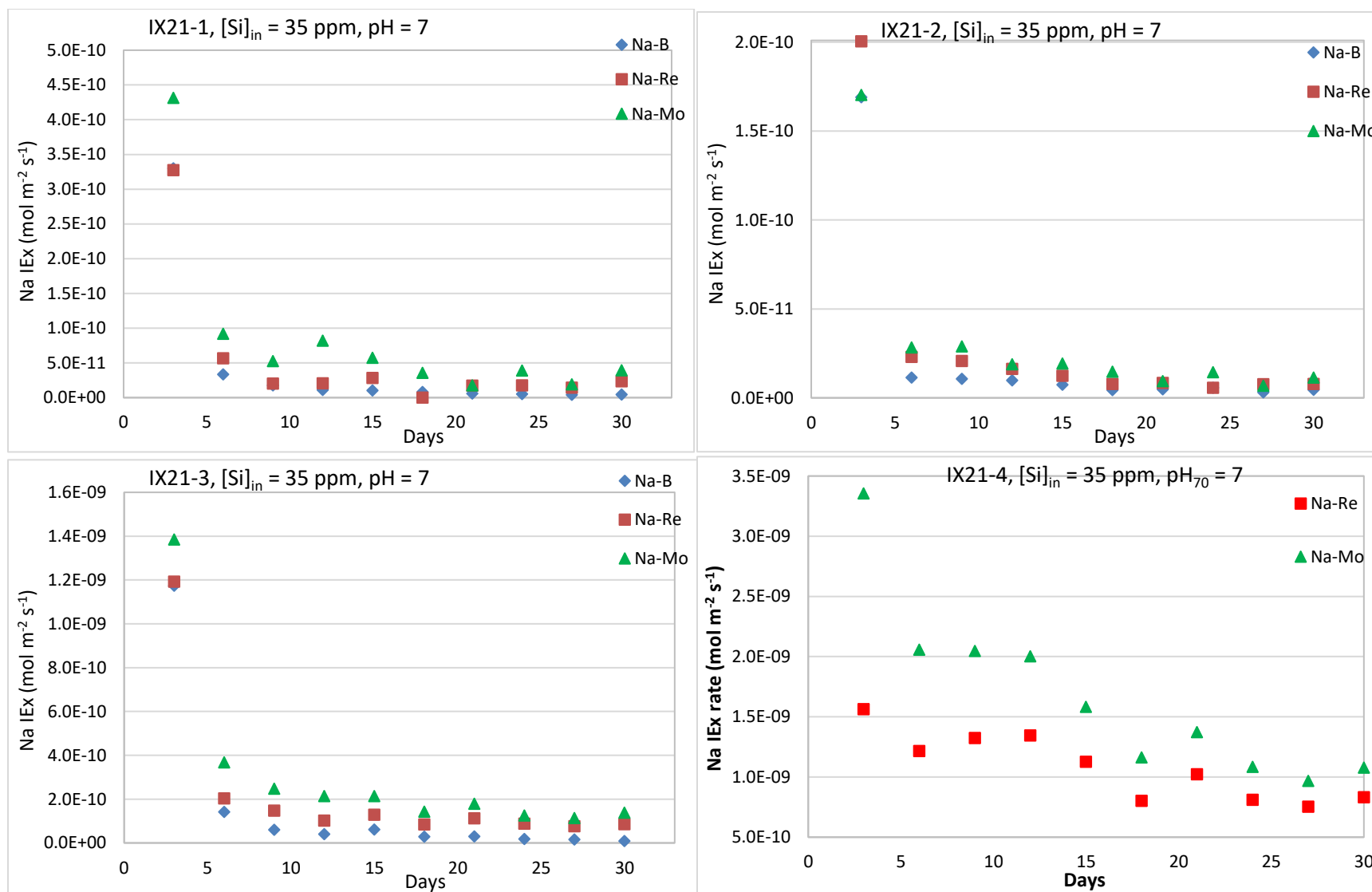
**Figure C8. Plot of sodium ion exchange rate calculated from difference of sodium normalized release rate to that of boron, rhenium, or molybdenum, at 40 °C, pH<sub>23</sub> = 9.1 (pH<sub>40</sub> = 8.7).**



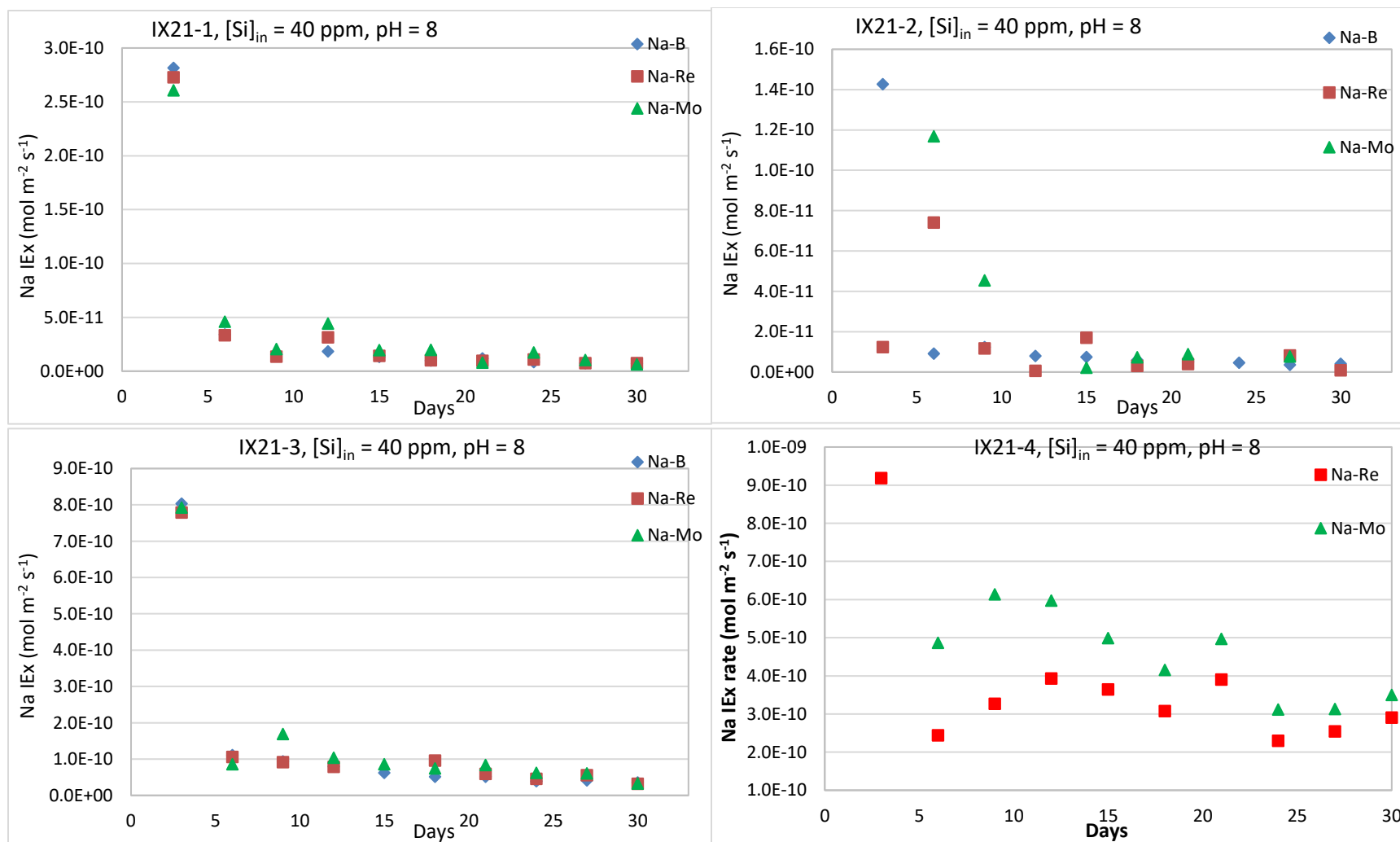
**Figure C9. Plot of sodium ion exchange rate calculated from difference of sodium normalized release rate to that of boron, rhenium, or molybdenum, at 40 °C, pH<sub>23</sub> = 10.0 (pH<sub>40</sub> = 9.7).**



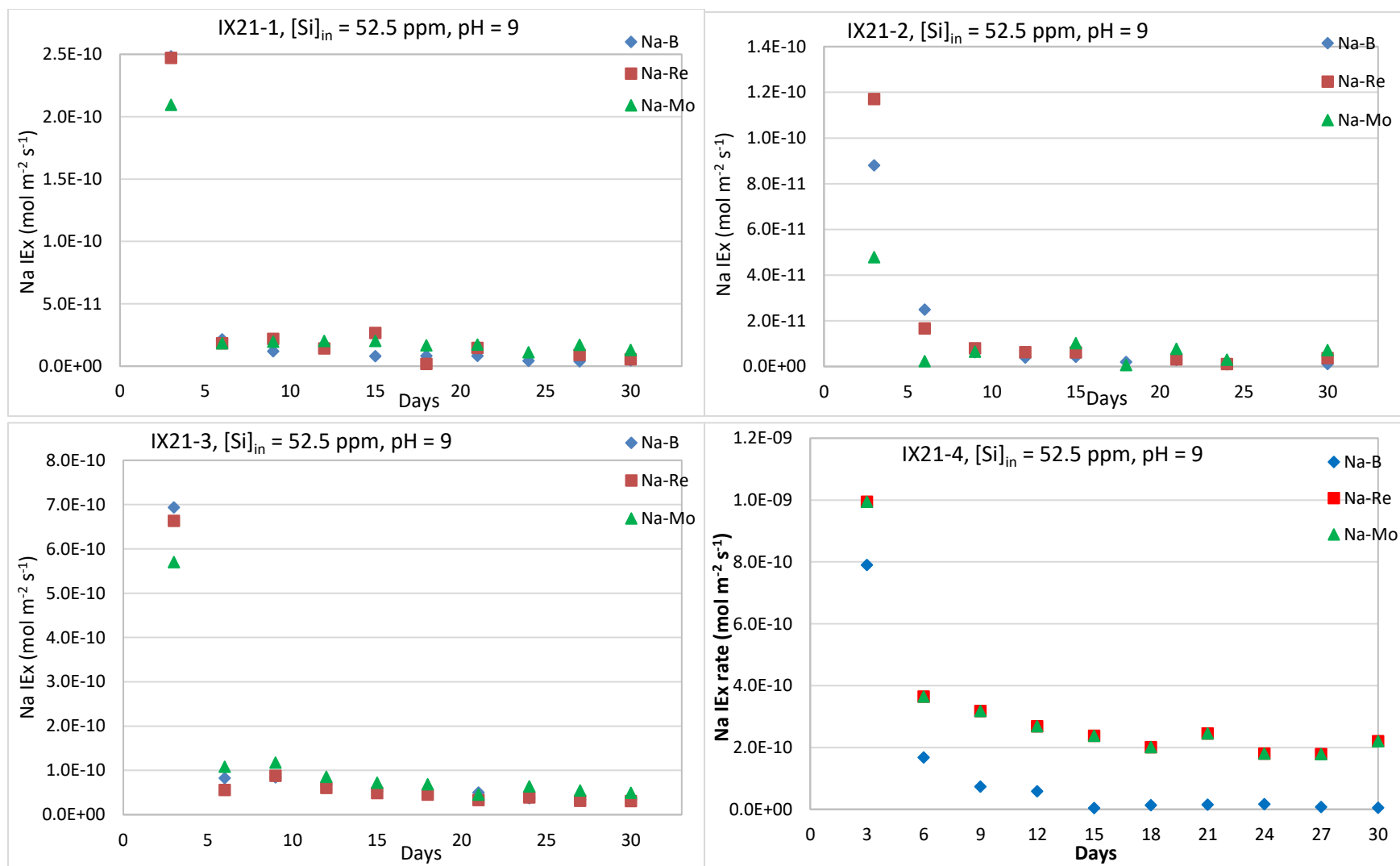
**Figure C10. Plot of sodium ion exchange rate calculated from difference of sodium normalized release rate to that of boron, rhenium, or molybdenum, at 40 °C,  $\text{pH}_{23} = 11.1$  ( $\text{pH}_{70} = 10.8$ ).**



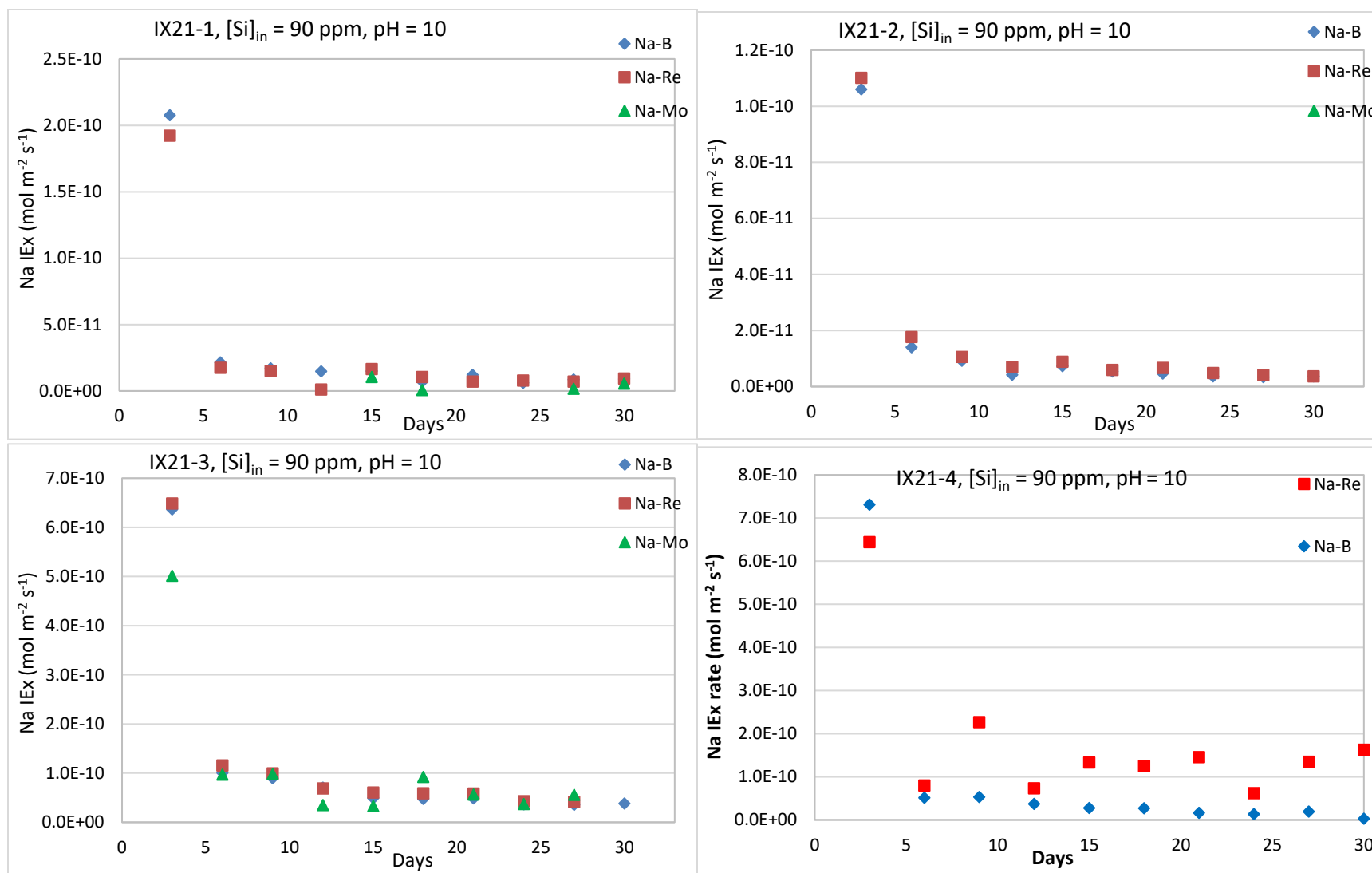
**Figure C11. Plot of sodium and lithium ion exchange rate calculated from difference of respective normalized release rates to that of boron, rhenium, or molybdenum, at 23 °C,  $\text{pH}_{23} = 7$ .**



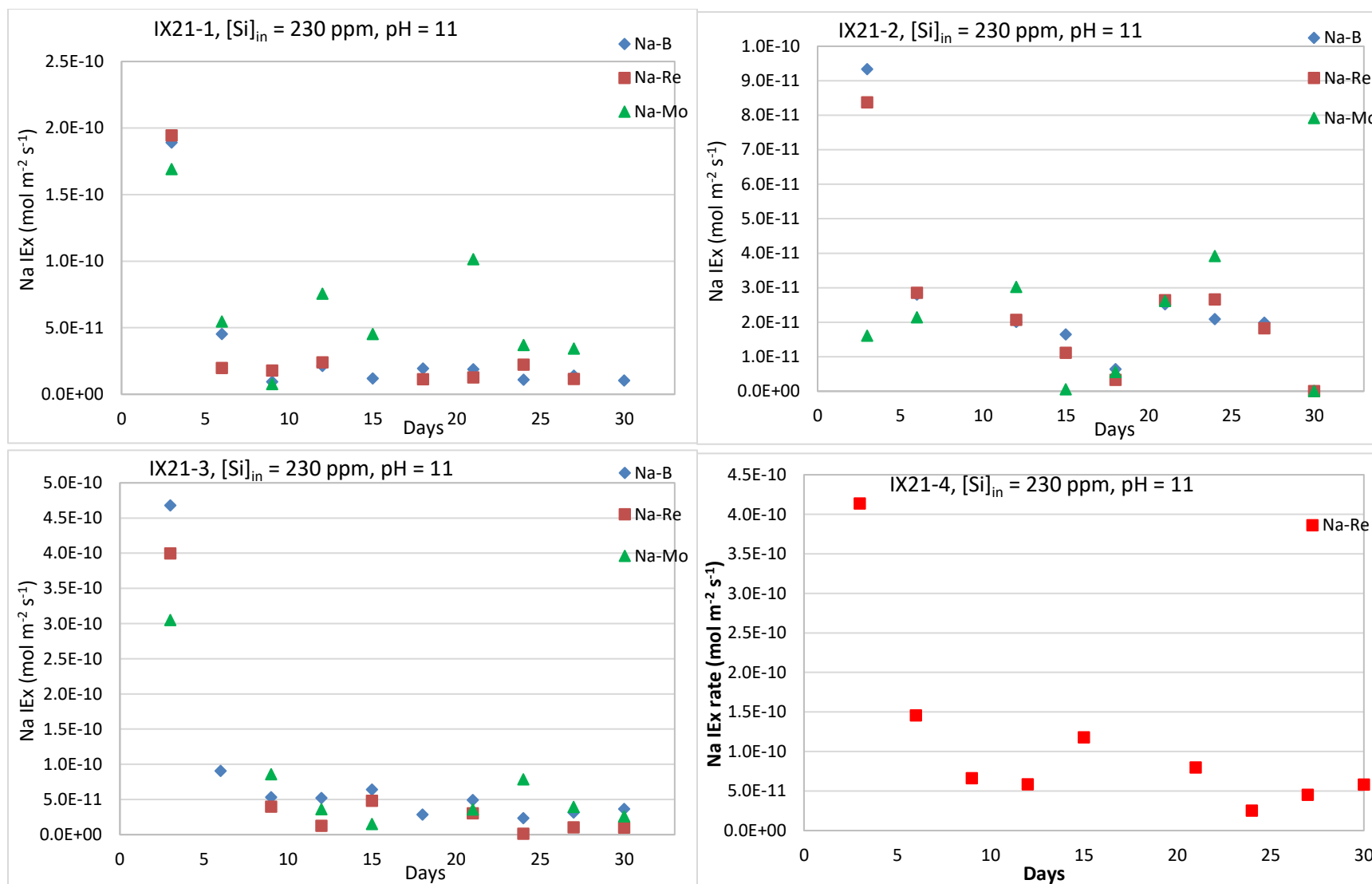
**Figure C12. Plot of sodium ion exchange rate calculated from difference of respective normalized release rates to that of boron, rhenium, or molybdenum, at 23 °C,  $\text{pH}_{23} = 8$ .**



**Figure C13. Plot of sodium ion exchange rates calculated from difference of respective normalized release rates to that of boron, rhenium, or molybdenum, at 23 °C, pH=9.**



**Figure C14. Plot of sodium ion exchange rates calculated from difference of respective normalized release rates to that of boron, rhenium, or molybdenum, at 23 °C, pH<sub>23</sub> = 10.**



**Figure C15. Plot of sodium ion exchange rates calculated from difference of respective normalized release rates to that of boron, rhenium, or molybdenum, at 23 °C, pH<sub>23</sub> = 11.**