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FY23 Status of Quality Assurance Plan for Out-of-Pile Test Data

Nuclear Science & Engineering Division

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Summary

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The DOE Advanced Reactor Technology program has supported recovery and preservation of legacy metallic fuel data collected as part of the US fast reactor program, recognizing it as essential to development and licensing activities for advanced fast reactors. Databases were established as organized collections of experimental records and data generated from in-pile experiments at EBR-II, FFTF, and TREAT as well as related out-of-pile examinations of irradiated fuels. The Out-of-Pile Transient Database (OPTD), includes records of over 150 out-of-pile furnace transient tests on metallic fuels conducted at Argonne's Alpha-Gamma Hot Cell Facility to evaluate their transient performance and characterize fuel/cladding interaction. The database is accessible to registered users from US universities, laboratories, and nuclear industry. Because the data in OPTD has not been formally qualified, its applicability and ability to support licensing activities is limited. This report outlines progress and plans to quality assure data in OPTD, maximizing its impact for model validation and verification as well as qualification of fuels for safe and effective use in advanced reactor designs.

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1 INTRODUCTION

The Integral Fast Reactor (IFR) program (1984-1994) produced a large collection of data relating to the performance of metallic fuels in sodium-cooled fast reactors (SFRs). Fuels tests were conducted under both steady-state and transient conditions to evaluate fuel/cladding compatibility. The out-of-pile furnace transient program conducted in the Alpha-Gamma Hot Cell Facility (AGHCF) tested the response of irradiated fuels to high temperature transients. The primary test materials were as-irradiated fuel pins and segments from EBR-II with prototypic fuel-clad interfaces (as-fabricated details and steady-state irradiation histories of the pins are available in FIPD [1]). The records and results from these legacy out-of-pile transient tests support advanced nuclear fuels and materials R&D by demonstrating the safety performance of the tested fuels, providing a basis for code development and validation, and informing future testing. An extensive effort was made over the past several years to collect and digitally preserve all available test records, organizing them in the web-accessible Out-of-Pile Transient Database (OPTD) [2] and producing a summary report on out-of-pile testing of metallic fuels [3].

For each of the out-of-pile tests, OPTD includes a collection of related records ranging from informal, internal memoranda to formal programmatic progress reports, conference submissions, and other publications. Records of the experiment and post-experiment examinations may include sample transport, shipping, and storage records, fuel pin sectioning diagrams, metallographic images of the sectioned samples, and experimenter notes. Furnace apparatus and test schematics, design documents, and test procedures are also included where available. Primary source post-test measurement documents such as metallography images, profilometry traces, and neutron radiographs are contained within larger records in the collection, but not separated out by measurement type and test. This set of post-test examination data, currently contained within other records, is our target for qualification.

1.1 Motivation

The collection of out-of-pile transient data in OPTD is part of an accumulated knowledge base resulting from substantial U.S. investment in advanced fast reactor research and development. The database was opened for external users in 2021 and has 18 registered users from U.S. nuclear industry, national laboratories, and the NRC.

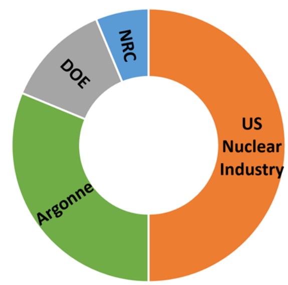

Figure 1. Registered OPTD Users (as of 9/30/2023)

Current utilization of the database by registered users is low, and as recently as Spring of 2023, some active industry researchers were unaware of its existence. While it is possible that most registered users accessed the database once or twice, downloaded relevant records, and had no need to revisit the site, less than 50% of users accessed the site in the last 18 months. Direct outreach to industry stakeholders to learn about their awareness, usage, and near-term needs, is planned for early FY24. Previous conversations have confirmed that comprehensive archival, maintenance, organization, and, most importantly, qualification of the out-of-pile test data will maximize industry utilization. *Qualified* data will be essential to support licensing of the developing advanced reactor concepts and fuels. It will also serve as benchmark data for verification and validation of the codes and models used to predict fuel performance. Because the applicability of this data set will be limited without qualification and there is an expected need to support industry and NRC in design and licensing discussions in the relative near-term, we have developed a plan and process to begin qualifying data in OPTD in accordance with nuclear industry and stakeholder priorities.

1.2 Status of OPTD Content

The online database is now populated by hundreds of documents and record collections scanned and saved in pdf format, and it functions primarily as a well-organized and curated online document library. Each record (associated with a particular pdf file) has various metadata tags assigned to allow a user to search and sort for records by test, record type, or included content. In its current state, a single pdf record in OPTD is likely to contain records of multiple tests and/or a mix of written documentation with different measurement data from pre- and post-test examinations.

While the data in OPTD has not been formally reviewed and quality assured, a preliminary review of all available test records was conducted and informal notes were made on single page test summary sheets to indicate the relative expected reliability of reported quantitative FCCI results as "Good," "Discarded," "Questionable," or "Preliminary." This information is available in a published summary report that is linked directly from the web-accessible database [2, 3]. As a temporary measure, it points existing and prospective users to recommended data sets for reference, but it makes no formal assurances. "Good" tests have results that were reported publicly and exhibit good agreement between original test records and later published values. "Discarded" tests were those with unfavorable or unanticipated test conditions and are not recommended for use. “Questionable” tests exhibited unresolved discrepancies between original test records and published results, and “Preliminary” tests are those that were unpublished. Test data in the last two categories should be used with caution until formal quality assurance (QA) is completed. While this initial binning was made by reviewing only reported FCCI depths, it will help inform our QA prioritization for metallography data.

1.3 Preparatory Steps

So that we can clearly and efficiently deliver qualified data to users as it is available, we will need to design a portion of the database that will accommodate individual files for each unique piece of PTE data (for a given test pin and measurement type) and make them clearly available to users. For example, the qualified image of the neutron radiograph for a given test pin will be stored separately from its profilometry trace. The newly-created, smaller records containing only the relevant data for that sample & measurement may be pulled into a highlight list on the test summary page (as is done in FIPD) or listed in a separate “data” section of the site. If we are to also provide qualified, digitized data for export, we’ll likewise need a section to store and, optionally, display plotted digitized data. Each piece of data will also need a tag to indicate whether it is qualified or not (and an associated display icon). The particulars of this implementation haven’t yet been decided and are pending further discussion with OPTD users and other Argonne database managers; we will prioritize structural consistency with FIPD.

The first step in processing the records for qualification is to pull out the experimental measurement data from within the records for each test and create separate “data” files and associated entries in the database so their qualification status can be independently tracked and recorded. For some records, such as metallography and NRAD images, very high-resolution scans of the quality one might use for digital image analysis can also be obtained. An indicator tag can be added to the (lower-resolution) data set in the web-accessible database to indicate that higher-resolution images are available by request from the database manager, as their size makes them impractical to provide for direct download.

1.4 Quality Assurance Program Plan

A Quality Assurance Program Plan (QAPP) was developed for FIPD and approved for use by the NRC [4, 5]. Review of this plan found it to be broadly applicable and suitable also for the data sets within OPTD. However, implementation of the existing QAPP will require the development of supplementary specifications describing the unique OPTD data sets. These specifications will provide the needed context and explanation for interpretation and use of the raw experimental data. They may provide details about the measurement instruments, techniques, and standard procedures. They will also define key features in the measurement data, like sample labels on images or the units for a table of numeric data. Without an appropriate specification for each type of measurement, the data will not be qualified. Utilization of the existing QAPP for OPTD data therefore requires development of a collection of out-of-pile data specifications.

2 AVAILABLE PTE DATA

Preliminary lists of the primary source data available in our collection for each out-of-pile test (e.g. instrument measurements, posttest examinations) are included in the out-of-pile test summary report and in OPTD on an at-a-glance information page for each out-of-pile furnace test. These one-page summaries also include information about the tested fuel samples, test conditions, purpose of the tests, and key results [3]. The pre-test, as-fabricated pin characterizations, irradiation histories, and as-irradiated characterization of test pins prior to their furnace transient exposure can be found in FIPD. While OPTD contains some pre-test records, users will need to register as users of FIPD to access additional data sets describing the pre-test conditions of the furnace test pins. All post-test examination data for the out-of-pile furnace tests will be qualified and stored separately.

Thus far, we have identified need for specifications to support qualification of the following out-of-pile furnace test data:

Experiment Data:

- Pre-test sample pin segment characterization (size, weight, axial location on pin)
- Transient Instrument Measurements (thermocouples, fission gas detector)

Post Test Examination (PTE) Data:

- Neutron Radiography (NRAD)
- Profilometry (including direct caliper measurement and contact profilometry)
- Metallographic images (micrographs)
- Reported FCCI depths (quantitative values derived from analysis of micrographs)

The PTE data is of primary importance as it is a direct analog to the PIE data in FIPD and has the highest value for benchmarking. We will focus on qualification of the out-of-pile PTE data.

2.1 Types of PTE Data

There are two types of tests archived in OPTD:

1. Whole Pin Furnace (WPF) tests on intact, irradiated fuel pins from EBR-II, and
2. Fuel Behavior Test Apparatus (FBTA) tests conducted on ~8mm tall segments cut from along the length of EBR-II irradiated fuel pins.

Different types of PTE data are available for each test.

Neutron radiography (NRAD) is a non-destructive way to examine the internal structure and composition of the fuel pin. NRAD images show the size, shape, and position of the fuel slug in each pin pre-irradiation, post-irradiation, and in some cases, post-furnace test. Comparing these images provides information on irradiation- and transient-induced fuel motion and swelling. NRAD imaging was conducted on whole fuel pins.

Contact profilometry and manual micrometer measurements are non-destructive ways to measure the external diameter of the cladding. Comparisons of axial profilometry traces or measurements before and after a transient exposure are used to reveal the induced diametral cladding strain. Additional profilometry records from the as-irradiated pins, conducted in HFEF, are available in

FIPD for comparison with posttest cladding diameters of furnace-tested pins. The whole pin furnace pins have a combination of manual micrometer and contact profilometry measurements taken before and after each test at the AGHCF. Some post-test FBTA pin segments were measured manually with a micrometer, but this data is not expected to be valuable except as possible confirmation of the axial pin position of the tested segment.

Metallography data is arguably the most crucial for understanding transient effects on the fuel pins. The metallography data in OPTD is primarily optical microscopy images, though there are a few supplemental scanning electron microscopy (SEM) records. Micrographs were captured of cross-sectioned fuel pins to reveal the inner microstructure of the fuel and cladding. These post-test micrographs can be compared to those of sibling fuel pins (irradiated but not transient tested) to identify transient effects. The nature, degree, and rate of fuel cladding chemical interaction (FCCI) is a key indicator of transient fuel performance. The extent of cladding wastage can be measured directly from appropriately scaled and marked micrographs. The original experimenters reported maximum depths and rates of cladding penetration by liquid eutectic at the fuel-clad interface and approximate areal percentages of fuel liquefaction. The body of metallography data includes both the metallographic images (micrographs) as well as the quantitative FCCI data, which are measurements obtained through interpretation and analysis of the images.

2.2 PTE Data Status

The post-test examination data available in OPTD is currently contained within multi-page scanned document records (as pdfs). The image quality in these scanned records is variable, and in some cases, recovery of the original materials for re-scanning with better resolution is needed. Searches for higher-quality original NRAD, profilometry, and metallography records were conducted over the past year and new scans collected for some NRAD and profilometry records. Additional efforts will be needed to replace yet-to-be-discovered poor image scans.

For the FBTA tests (conducted on fuel pin segments), the relevant PTE data is limited to posttest microphotography images and the quantitative values reported based on analysis of those images, e.g. reported depths and rates of eutectic penetration into the cladding and areal fraction of fuel liquefaction. The microphotos are microscopy images of the cross-section of the tested fuel pin segment; they sometimes include very high magnification images of a particular interaction region at the fuel-cladding interface to help characterize the nature of the interaction. We have not yet made a formal accounting of the raw image records to determine whether they have good resolution (we expect many will not), but we have scanned metallography records in OPTD for all successful FBTA tests.

An extensive effort is underway to recover original records and scan high-resolution metallography image files for data in FIPD. This effort will be extended to the metallography data in OPTD as needed. The improved spatial and tone resolution is expected to reveal further microstructural details in the scanned images and enable more advanced image analysis, including the use of digital image analysis software. The raw images do not have scale bars or sample labels and will need some secondary processing to add this information and/or additional documentation before they can be useful to an end user. The recovery, processing, and qualification of high-resolution metallography images and the quantitative data gleaned from their analysis is expected to require substantial sustained investment.

Posttest examination of the whole pin furnace samples likewise included capture of optical micrographs. Because these tests were conducted on intact, whole pins, more extensive posttest examinations were conducted to determine the impact of the transient exposure on the overall integrity of the fuel pin, including fuel swelling, fission gas pressure loading, and resulting cladding strain. According to experimenter records, posttest NRAD was performed on WPF pins FM-3, FM-4, and FM-6. We conducted an extensive search and located the NRAD data for FM-3 and FM-6, but not FM-4. Data reporting posttest cladding diameter or strain is available for all WPF tests to support understanding of transient-induced cladding strain, although the form and extent varies by test. Profilometry of the as-fabricated and as-irradiated pins was conducted at HFEF. Additional measurements were made at AGHCF by contact profilometry and/or manual micrometer measurement. We are missing some records, but have at least one pre-test and one post-test data set that can be used to estimate cladding strain for each WPF test.

Table 1 lists the PTE that was conducted on the WPF test pins. The marker "X" indicates that we have located the relevant PTE records for review, "-" indicates that to the best of our knowledge, the measurement was not collected. As noted in the table, were unable to find raw data records of cladding diameter for tests FM-6 and FM-7, but we recovered computed strain results reported by the original experimenters. The list of "other" PTE data that should be available for WPF tests is based on the original review of the records at the time the database was built and has not yet been verified with additional reviews of the collection.

Table 1: PTE Data for WPF Tests

WPF Test	NRAD	Cladding Diameter					Metallography	Other**
	Pre - and Postest	*Pretest*			*Posttest*		*Posttest*	
		HFEF Profilometry	AGHCF Profilometry	AGHCF Micrometer	AGHCF Profilometry	AGHCF Micrometer	Microphotos*	
FM-1	-	X	X	-	-	X	X	Gamma Scans, FG analysis
FM-2	-	X	X	X	-	X	X	Gamma Scans, FG analysis
FM-3	X	X	-	-	-	X	X	Gamma Scans, FG analysis
FM-4	not found	X	-	X	-	X	X	Gamma Scans, FG analysis, Microhardness
FM-5	-	X	-	X	X	-	X	Gamma Scans, Microhardness
FM-6	X	X	strain	-	strain	-	X	Gamma Scans, FG analysis
FM-7	-	X	8-pos avg diam, strain	-	strain	-	X	Gamma scans, FG analysis

* Microphotography scan resolution & quality varies

**Extent and quality of these data sets have not yet been verified

3 QUALITY ASSURANCE OF DATA

Quality assurance of all legacy out-of-pile data will need to be completed by peer review, since we are not able to establish that it was collected and recorded by an NQA-1 equivalent plan and process. Peer review of each piece of PTE data by a subject matter expert (SME) will include review of the primary source/raw data records together with supplemental documents that describe the processes and procedures used for collecting the data. While the collection of supplemental records for OPTD was thought to be complete, we located additional documentation in the last year as more comprehensive quality assurance reviews revealed the need. The newly-found records were scanned and will be added to the web-accessible database. As our review process for further data sets gets underway, we may find it necessary to seek out additional supporting records or information.

3.1 Data Specifications

Raw legacy data does not include the necessary context information to allow for it to be interpreted reliably. The raw records may be missing key information like a sample label, the data collection modes or conditions, a scale bar, or units. A data specification is meant to fill these gaps by describing the full context for each type of data collected. The specification serves as an interpretation guide and legend for the raw data. Establishing the full context for each piece of data is essential not only to complete the formal peer review and associated data qualification reports, but also to give the end user a comprehensive understanding of the data so they can independently evaluate its applicability for their use case.

Some specifications have been developed for PIE data in FIPD. As written, they do not apply to data in OPTD. New or revised specifications are needed to apply to the analogous OPTD PTE data. This year, we revised and extended an NRAD data specification to apply to the OPTD NRAD data [6]. We have begun drafting a standalone contact profilometry specification for the contact profilometry data collected at AGHCF (it is distinct from the data in FIPD, which was collected at HFEF). The AGHCF profilometry specification is expected to be complete by the end of CY 23. We also plan to draft a comprehensive metallography image specification that applies to both FIPD and OPTD micrographs in the coming year. These specifications are developed by collecting and referencing multiple primary source procedural documents and consulting with multiple SMEs. Publication of these specifications requires a significant collaborative effort, but these documents are essential to ensure the legacy data is well understood and used.

3.2 Steps to Delivery Qualified Data to OPTD Users

Quality assured data is stored in a dedicated, secure GitLab repository managed by Argonne IT services. Deposit of a completed data qualification package in our GitLab repository completes our data qualification process. Multiple steps are required to convert a binder of hard copy experiment records into discrete pieces of individually quality assured PTE data in the repository. Once original hard copy records are located, they need to be appropriately sorted and identified before scanning, titling, and labeling them with the appropriate records metadata. Those scanned records will then be reviewed and the included PTE data separated out by test and data type. New database entries will be created for the isolated data scans. Supplementary documents relating to the data will be collected and used to inform the creation of a data specification. The data specification, together with the raw data for qualification and all supporting documentation, will be delivered to one or more SMEs to conduct a quality assurance peer review. The peer review may reveal a need for additional records and documentation or modification of the data specification, so this process is expected to be iterative. The peer review will culminate in the completion of a data qualification report that describes the provenance and quality of the data, citing all supporting documents. The SME review will be comprehensive, and completion of the data qualification report indicates the SME's professional assessment that the data is as described and usable (within bounds that may be specified and explained in the data qualification report). The data qualification report will then be reviewed by additional quality assurance representatives and may be sent back for revision before it is finalized. When the final, signed data qualification report is submitted to the Gitlab repository together with all cited references including the data specification and the original data/measurement record, the data is considered qualified in accordance with the QAPP. This general workflow, absent any iterations, is shown in Figure 2.

Figure 2: Steps to qualify data.

The process is additionally complicated when we want to qualify digitized data. Some data, such as profilometry data, is most useful when it's available to the user as a table of data rather than an image of a plot. As in FIPD, we have utilized in-house software to convert scanned OPTD profilometry records to digitized plot data. This digitized data will have to go through its own analogous quality assurance process including peer review before it can be considered qualified. It is most efficient to conduct reviews of the raw and digitized data at the same time, but justification must be made to qualify each.

Once data has been qualified in accordance with our QAPP, we can designate it as "qualified data" in OPTD. We can upload the isolated pieces of PTE data pre- or post- qualification, but we will need to create new entries for the isolated, qualified data sets and assign tags to indicate their qualification status. We also intend to create standalone pages with listings of the FBTA and WPF tests with direct listing and link to the PTE data and indicator icons that signify "qualified" status. For the sake of clarity and efficiency, we plan to upload isolated data to OPTD only as it is qualified, but this could change pending discussion with industry representatives. It is important to note that the official record and repository of the qualified data and all necessary accompanying records is the Gitlab repository. OPTD is the delivery vehicle to provide qualified data to end users and does not communicate directly with Gitlab.

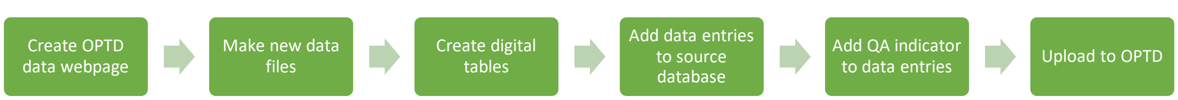

Figure 3: Steps to put quality assured data on the OPTD website.

3.1 Data Qualification Status and Progress

WPF tests represent a small test set with a variety of PTE, so we are using them as a starting point. The WPF NRAD data has served as a test case for qualification of OPTD data. We recovered new and better-resolution images and scanned them into our digital collection. We then located additional legacy operations guides and used them to write an applicable NRAD data specification. The specification was used to review the NRAD data for FM-3 and FM-6 pins and complete a data qualification report with citations to supplementary documents. All materials were uploaded to an out-of-pile section of the SFR Database Gitlab repository in accordance with the QAPP, so we have officially qualified the available WPF NRAD data. Once we have finalized and built the accommodation for "data" into OPTD, we will add it to the web-accessible portion of the database and add an indication that it has been quality assured.

Profilometry data for the WPF tests has been collected and digitized. Postprocessing of the digitized data and comprehensive reviews are underway to develop the AGHCF profilometry data specification as well as quality assure the available profilometry data for each of the WPF tests.

We haven't yet isolated the metallography images for priority tests from the larger documents or collected high-resolution images as needed. We also need to complete a comprehensive metallography image specification before we will be able to qualify the microphotography data.

While very little OPTD data has yet been quality assured, we are confident we have a sound process and plan, as evidenced by the qualification of the NRAD data. User engagement will be important as we determine how and when to add qualified data to the web-accessible OPTD. Progress and immediate next steps planned to deliver qualified PTE data are shown in Table 2. The remaining spaces in the table will be scheduled based on the expressed priorities of nuclear R&D stakeholders and funding availability.

Table 2: PTE data qualification & delivery process.

WPF PTE Data	Recover & isolate high-quality data	Complete Specification	Qualify Data	Upload QA Data to OPTD
NRAD	X	X	X	
Profilometry	X	In progress	In progress	
Metallography (images)	FY24*	FY24*	FY24*	
FCCI				
FBTA PTE Data				
Metallography (images)	FY24*	FY24*		
FCCI				

* FY24 plans include working toward qualification of a high-priority set of tests. We do not expect to complete metallography QA for all out-of-pile tests in the next year.

4 FUTURE ACTIVITIES

The OPTD contains a valuable set of data describing the transient performance of metallic fuels. Qualifying this data will maximize its impact on next-generation nuclear reactor R&D. One focus for the coming year will be engaging with industry stakeholders including ARC Clean Energy, Oklo, and Terrapower/GE-Hitachi to inform our next steps and priorities. We will continue to develop specifications, isolate data for review, qualify it, and deliver it to users via OPTD.

Anticipated activities in the coming year:

- Locating data in scanned records.
- Writing data specifications for profilometry and metallography.
- Qualifying priority PTE data in accordance with the QAPP.
- Engaging with industry to inform our prioritizations.
- Additions and improvements to the record collection.
- Maintenance of the website and user support.

5 ACKNOWLEDGEMENT

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