Final Report

High Temperature, High Pressure Devices for Zonal Isolation in Geothermal Wells

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1 Introduction

This report documents the technical progress achieved by Composite Technology Development, Inc. (CTD) during the 3 year program (January 1, 2009 to January 30, 2013) of DOE Award No. 10EE0002771, entitled "High-Temperature, High-Pressure Devices for Zonal Isolation in Geothermal Wells." This report is submitted to the Department of Energy (DOE) in partial fulfillment of grant requirements. It is not intended for release outside the U. S. Government.

1.1 Project Overview

The U.S. Department of Energy is leading the development of alternative energy sources that will ensure the long-term energy independence of our nation. One key renewable resource being advanced is geothermal energy. Currently, commercial geothermal reservoirs are referred to as a hydrothermal energy because the water and the heat are naturally occurring. Unlike wind and solar power, geothermal energy is not affected by changing weather and is therefore always available to meet power demands. Thus, this process offers an environmentally benign, reliable source of energy for the nation.

In the U.S., geothermal power is currently produced from relatively shallow wells located primarily in California and Nevada. In these locations, geothermal energy is produced under nearly "ideal" circumstances, which include porous rock and an ample supply of sub-surface water. For geothermal energy to be more widely utilized, and to tap into the large potential offered by generating power from the heat of the earth, deeper wells will be necessary to reach the hot, dry rock located up to 10 km beneath the Earth's surface. To utilize this resource, water will be introduced into the well to create a geothermal reservoir. This approach is known as an Enhanced Geothermal System (EGS) [1-2].

EGS reservoirs (Figure 1) are typically at depths of 3 to 10 km, and the temperatures at these depths have become a limiting factor in the applications of some technologies. For example, reliable zonal isolation for high-temperature applications at high differential pressures is needed to conduct mini-fracs and other stress state diagnostics.

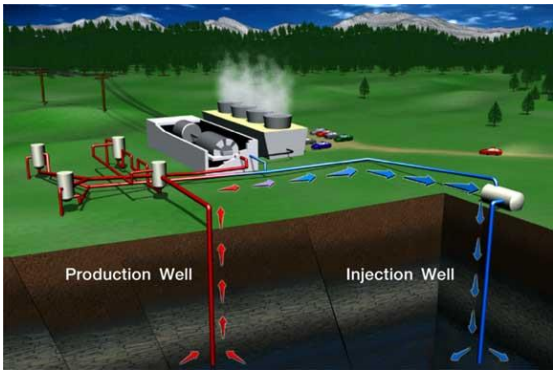

Figure 1: Geothermal power plant.

Zonal isolation is essential for many EGS reservoir development activities. To date, the capability has not been sufficiently demonstrated to isolate sections of the wellbore to: 1) enable stimulation; and 2) seal off unwanted flow regions in unknown EGS completion schemes and high-temperature (>200°C) environments. In addition, packers and other zonal isolation tools are required to eliminate fluid loss, to help identify and mitigate short circuiting of flow from injectors to producers, and to target individual fractures or fracture networks for testing and validating reservoir models. General-purpose open-hole packers do not exist for geothermal environments, with the primary barrier being the poor stability of elastomeric seals at high temperature above 175°C. Experimental packer systems have been

developed for geothermal environments but they currently only operate at low pressure, they are not retrievable, and they are not commercially available. Cased-hole isolation tools suitable for high-temperature environments are emerging, and these tools have the advantage of metal-to-metal seals, but they offer limited pressure differential capabilities.

The development of the high-temperature, high-pressure (HTHP) zonal isolation device would provide the geothermal community with the capability to conduct mini-fracs, eliminate fluid loss, to help identify and mitigate short circuiting of flow from injectors to producers, and to target individual fractures or fracture networks for testing and validating reservoir models.

In this program, CTD will utilize its expertise in high-temperature materials, shape memory composites and foams, and deployment mechanisms for spacecraft and oil tools to develop a new class of HTHP zonal isolation devices for use in EGS. The goal is to demonstrate the ability to isolate sections of an EGS wellbore to: 1) enable stimulation; and 2) seal off unwanted flow regions in unknown EGS completion schemes and high-temperature (>200°C) environments at temperatures upwards of 300°C.

The concept for a high-temperature, high-pressure zonal isolation device is to be designed for use in creating circulation paths in environments where temperatures are in excess of 300°C and differential pressures of up to 10,000 psi can be required to stimulate solid granite. This new zonal isolation device would distribute the high-pressure differential through a significant length of high temperature, shape memory polymer composite material. The development of differential pressure would be initiated by a thermally triggered actuation of a 'structural seal' that fills the cross section of the bore with the shape memory material. After this preliminary seal is made, differential pressure will begin to build through the material as the seal forces the flow to pass through pores in the shape memory material. The shape memory material is compressed into place to react the force of the internal flow, forming an effective and reliable high-pressure seal.

There are several technical and engineering challenges associated with the successful development of this EGS zonal isolation device including:

- Design of the structural seal and the method with which to store sufficient strain energy for it to deploy under any foreseeable downhole conditions and still be able to initiate the development of a differential pressure across the zonal isolation device.
- Selection and design of the shape memory material that will be used to build high pressure through restricted flow and demonstrate that it will meet the demanding requirements in a downhole, high-temperature environment
- Design of a mechanism that will enable the compressive force applied to the polymer to be relaxed to enable dissipation of the differential pressure across the packer and enable it to be retrieved.

Over the course of this program, CTD will conduct Go/No-Go reviews to downselect candidate materials, mechanism designs, and overall device concepts and solutions for continued development and testing. During these technology assessments, the best solutions will be identified for continued testing and evaluation. In year two of this program a few of the best

design approaches will be used to design, build and test demonstration units, to prove out and determine the feasibility of these approaches under simulated downhole conditions. In year three of the program, a full-scale prototype of the final HTHP zonal isolation device will be designed, manufactured, and tested. At the conclusion of the program, CTD will have designed and validated the design of a zonal isolation device that can be used for EGS.

1.2 Tasks and Objectives

The goal of this program is to develop and demonstrate reliable high-temperature high-pressure zonal isolation devices that are compatible with the high-temperature downhole environment anticipated for Enhanced Geothermal Systems. Over the course of this 3 year program, CTD will design, demonstrate, and qualify a high temperature high pressure zonal isolation device. The key elements of the work plan are described in the following sections.

1.2.1 Task 1 - Develop a Detailed Specification for Zonal Isolation Device Performance

In this task, the project team will consider the environments and the loads to which the device will be exposed. Environmental conditions to be addressed include temperature, pressure, fluids and chemicals (both abrasives and corrosives). In terms of loads, standard mechanical and thermal stresses will be considered, but more challenging cases such as impact and vibration loads associated with transportation to the well site and lowering the device into the well will also be addressed.

In addition to identifying the lifecycle requirements of the zonal isolation device, the specification developed here will also define screening test protocols that will be used to investigate candidate materials, mechanism designs.

When complete, this specification that will be used as a basis to which both material and device performance will be compared, and will also be used, in part, to establish the Go/No-Go technology assessment criteria, will be reported to DOE.

1.2.2 Task 2 - Preliminary Design Development

In this task, CTD and our collaborators will advance the conceptual design developed prior to the submission of this proposal. A preliminary design will be developed that includes component, sub-component, and material-level considerations. This design will include aspects such as the structural seal, stops and locks to maintain the position of the deployed zonal isolation device, the shape memory polymer composite that will be used for the porous high pressure seal, and release mechanisms that can be used to remove the device.

1.2.3 Task 3 - Selection of Materials and Components Designs

Task 3.1 Design and development of the structural seal

In this sub-task the design of a structural seal that will be used to initiate the development of differential pressure across the device will be developed.

Task 3.2 Design and development of the secondary seal shape memory composite material

In this sub-task the design of a secondary shape memory material seal that will be used to build high pressure through internal flow resistance in high temperature environments will be developed.

Task 3.3 Design and development of stops and locks to maintain deployment

In this sub-task the designs of stops and locks that will be used maintain the deployment of the structural and shape memory seals will be developed.

Task 3.4 Design and development release mechanisms to enable device removal

In this sub-task, the project team will collaborate to develop the design of release mechanisms that will be used to initiate the retrieval of the zonal isolation device.

1.2.4 Task 4 - Screening and Evaluation of Potential Zonal Isolation Component Designs

Task 4.1 Screening and evaluation of the structural seal

In this sub-task, CTD will characterize materials to be used in fabricating the structural seal and test engineering models and concepts to demonstrate their ability to make the necessary seal. This task will concentrate on how the reaction force necessary to hold the seal in place will be transferred to the walls of the well bore.

Task 4.2 Screening and evaluation of structural seal deployment mechanism

In this sub-task, CTD will characterize materials to be used in fabricating the structural seal deployment mechanism and test engineering models and concepts to demonstrate the deployment of the structural seal in the downhole environment.

Task 4.3 Screening and evaluation of the secondary seal shape memory composite material

In this sub-task, CTD will characterize materials to be used in fabricating the secondary seal, and test engineering models and concepts to demonstrate their ability to build high differential pressure through the device. This task will concentrate on the porosity and grain size of the material required to build significant pressure in the seal through high resistance flow paths.

Task 4.4 Screening and evaluation of stops and locks to maintain deployment

In this sub-task, CTD will characterize the materials to be used in fabricating the stops and locks required to maintain the deployment of the structural and secondary seals in the device. In addition, CTD will test engineering models and concepts to demonstrate their ability hold these seals in the deployed position.

Task 4.5 Screening and evaluation of release mechanisms to enable device removal

In this sub-task, CTD will characterize materials to be used in fabricating release mechanisms to initiate the retrieval of the zonal isolation device. In addition, CTD will test engineering models and concepts to demonstrate its ability to release the seals and enable them to be recovered for re-use.

A go/no-go decision will be made based on the successful testing of engineering models and concepts. Should the testing be unsuccessful per the specification defined in Task 1, project redirection may be necessary to either re-evaluate the specification or the tests and materials used in Task 4.

1.2.5 Task 5 – Design, Fabricate, and Test of a Zonal Isolation Demonstrator

In this task, CTD will incorporate designs, test data, and lessons learned from Tasks 2, 3, and 4 to develop the design of a HTHP zonal isolation device demonstrator. The outcome of this work will be a final demonstration unit that is designed to demonstrate the functionality of a HTHP zonal isolation device. Once produced, the demonstration devices will be tested.

A go/no-go decision will be made based on the successful testing of demonstration devices. Should the testing be unsuccessful per the specification defined in Task 1, project redirection may be necessary.

1.2.6 Task 6 - Incorporate Lessons Learned into Second Demonstration Unit

In this task, CTD will evaluate the results from the testing of the first demonstration unit and incorporate any design modifications that are needed to improve its performance. In addition, CTD will construct a second, or modify the first, demonstrator to incorporate these changes. The outcome of this task will be a revised design for a second HTHP zonal isolation demonstrator and a second device demonstrator ready for test. Once produced, the demonstration devices will be tested.

A go/no-go decision will be made based on the successful testing of demonstration devices. Should the testing be unsuccessful per the specification defined in Task 1, project redirection may be necessary.

1.2.7 Task 7 – Develop Final Design for HTHP Qualification Prototype

In this task, the project team will incorporate the results of all previous testing to finalize the HTHP zonal isolation device design.

1.2.8 Task 8 - Manufacture and Testing of Qualification Prototype

In this task, the HTHP zonal isolation device design completed in Task 7, will be fabricated by CTD. This part will incorporate the updated designs developed over the course of this program to produce a qualification unit suitable for field testing. CTD intends to contact, discuss, and negotiate such a prototype test with one of the DOE funded Enhanced Geothermal System Demonstration program teams. If a suitable arrangement with one of these awardees cannot be made, testing under simulated conditions will be performed in a similar manner to which the demonstrator units were previously tested.

1.2.9 Task 9 - Develop Pilot-Scale Manufacturing Plan

In this task, CTD will develop a pilot-scale manufacturing plan for the HTHP zonal isolation devices. The manufacturing plan will assess the requirements for a manufacturing facility, explore possible sources of toll manufacturing, arrange a supply chain for all raw materials and purchased components, and develop a cost model that will provide cost projections for these units based on manufacturing volumes.

2 Project Development Details

2.1.1 Task 1 – Develop a Detailed Specification for Zonal Isolation Device Performance

Developing the detailed metrics and functionality requirements potential products must fulfill is the first technical step in any successful new product development. It is critical to have a clear, unambiguous set of goals for the device before any subsequent development work can proceed. The CTD development team worked in collaboration with numerous entities within EGS industry and government offices to capture the customer needs for zonal isolation well operations and use this information to develop product specifications including performance, functionality and cost specifications. From these top level product specifications, particular technical design requirements were derived to aid in technical development.

In addition to identifying the zonal isolation product specifications, the derived technical requirements also defined screening test protocols that were used to investigate candidate materials, mechanism designs and component performance during product development. Developing these test protocols is critical. For example, when screening materials, it is important to test it to failure to understand the limits of a design and its failure modes. However, if a test protocol is not well planned, and it is either too severe or not severe enough, the results of the screening could provide false guidance for the device development and design process.

Due to the challenging nature of this project, in addition to the many, complex, and interactive environments and mechanical loading conditions that a HTHP zonal isolation device will be subjected to, the first step CTD took in determining the operational requirements needed for EGS zonal isolation applications was to reach out to several entities involved with the development of EGS well and energy systems. This included the Department of Energy, Sandia National Laboratory, Alta Rock, Geodynamics and several others. Spearheading this effort was drilling expert and industrial partner Bob Worrall of Brontosaurus Technologies. Mr. Worrall led efforts with CTD in several meetings with these collaborators which in turn facilitated the definition and creation of the desired zonal isolation product traits for various zonal isolation uses. From these meetings the project team derived technical and functional requirements for future HTHP zonal isolation devices. Collaboration was continuous throughout the project and provided important feedback as the technical team refined the zonal isolation device designs.

Challenges of High Temperature, High differential Pressure (HTHP) Zonal Isolation

Before further detailing zonal isolation product specifications like environments, loads and functionality, it is prudent to describe the challenges faced in various EGS zonal isolation applications and what limitations are observed using traditional zonal isolation devices.

The primary application of HTHP zonal isolation is hydraulic fraccing used in the creation of EGS reservoirs by connecting injection and production wells with long-spanning fractures in the geological formation deep under the surface. CTD found that the most common formation compositions are of granite or similar composition, indicating high pressures are necessary for hydraulic fractures to initial and propagate. According to EGS industry collaborators, well operators try to create wells in formations with steady state temperatures up to 300 °C and possibly beyond in future endeavors, but many are operating at lower temperatures currently.

Current zonal isolation technology includes a variety of tools used in oil drilling operations including inflatable designs, swelling materials and mechanical packers. These technologies all attempt to create an immediate pressure differential by design, or a perfect seal to isolate a section of wellbore. Unfortunately, expansive materials used in inflatable and swelling technology cannot survive the high downhole temperatures and extreme mechanical loads experienced when attempting this task. Mechanical packers can survive the high temperatures, however to seal the high pressures in a short length of the borehole wall, high stresses are imparted on the geological formations which can lead to fractures forming around the desired area and subsequent loss of fraccing pressure to initiate or continue the fracture to completion (See Figure 2).

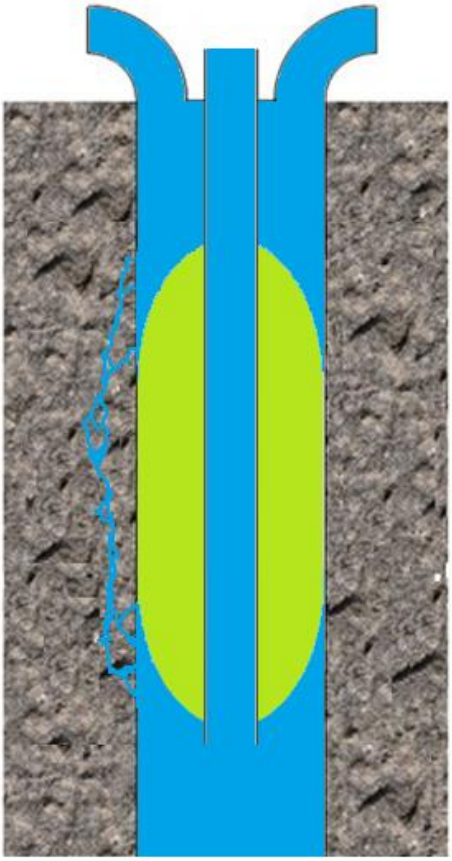

Figure 2: Illustration of wellbore formation damage imparted by the necessarily high radial pressures of an expandable packer

Additionally, it is well known that EGS fraccing operations have had seismic troubles, stemming from high energy fractures of hard formations. While much remains unknown about the science behind this issue, it would make logical sense that fraccing operation which limits fracture propagation speed may reduce undesirable perceivable seismic activity on the surface. While it is unclear what all the causes are associated with seismic activity during zonal isolation, if any, certainly there is no consideration for this in most current oil drilling based technologies.

Applications secondary to fraccing include flow control and isolation of particular zones of the EGS well reservoirs to maintain desired temperature zones. Again the likely high operational temperatures will result in failure using an inflatable or swelling zonal isolation technology due to the use of low temperature polymers. Mechanical packers may be successful in some of these applications, but still risk damage to the formation which could compromise a very expensive well development.

Overall these are two very different applications; however, both illustrate a need for a high temperature solution which will undoubtedly not cause irreversible well damage.

Environmental conditions including temperature, pressure, fluids and chemicals (both abrasives and corrosives) need to be considered. Loading conditions and standard mechanical and thermal stresses also need to be considered.

Downhole Environment

It was found that the typical EGS operational environment can vary tremendously. Temperatures can be as extreme as 300°C (572°F) or above for locations such as those in Australia where Geodynamics is attempting EGS operations. While some locations and applications can have very high steady state temperature requirements, many locations are significantly lower than 300°C. Additionally, well temperature can be cooled to a temperature range on the order of 100°C at maximum flow conditions (about 15 gal/min) before performing a fraccing operation, giving a slight relief to a device depending on time of use. However, even these environmental conditions pose challenges to the operators since typical elastomeric seals exhibit poor stability and performance at temperatures above 177°C (350°F).

Common downhole depths extend down to 2,500 m (~8,000 ft.) and may go further in the future. Once downhole, the only condition added by depth is hydrostatic pressure on devices; and having such a remote downhole location adds complexity to use and delivery of downhole devices. The variety of temperatures and pressures the device will see during downhole delivery in addition to the variation in delivery time based on depth placement, will affect the device design and material selection.

Diameter of the open hole cross section can vary from approximately 16 cm (6.5 in) to 26 cm (10 in) and can contain sections of borehole wall significantly out of round containing jagged breakout sections. For many applications the cross section may be annular when drill or production piping is run in the well, but some applications may require spanning the full open hole. This variation in cross section can greatly vary the loading conditions realized by the isolation device. Additionally, operators may also require tools to seal undesired fractured sections that would cool production temperatures or be sources of lost fluid input.

In most cases it has been found that the formation composition where the device will be located is primarily granite. Granite is known for being extremely hard and abrasive. In addition, the surface finish of the bored hole is typically extremely rough, although no specification for this roughness has been determined at this point. It is noted, however, that the well bore will not be perfectly smooth nor uniformly round as detailed above.

Additionally, downhole fluids and contaminants are to be expected. Hydrogen sulfide is a corrosive gas commonly encountered downhole and can cause premature component failure if neglected in the product requirements. Fraccing fluids and other EGS downhole fluids can often contain small sized particulates and chemicals such as benzene based chemicals. Many fraccing fluid formulations are proprietary, thus it is important that any device be as robust as possible with regard to chemical compatibility.

Based on the above information, the environmental downhole conditions are summarized below in Table 1.

Table 1: A summary of the downhole environment

Environmental Conditions	
Steady State Temperature °C (°F)	200-300 (392-572)
Operational Depth m (ft)	300-2,500 (1,000-8000)
Open Hole Dimensions cm (in)	16.5-25.4 (6.5-10) w/ breakout areas
Formation Compositions	Granite - extremely rough surfaces
Corrosives	Hydrogen Sulfide, Benzene
Particulates	Propping agents, drilling mud and particulates

Device Applications and Operational Use

The major challenge of zonal isolation in EGS operations is high pressure high temperature fraccing applications. While fraccing pressures can be as high as 10,000 psi, many fraccing operations will occur at lower pressures, as low as 3,000 psi in differential pressure. Further, zonal isolation used for flow control and isolating well regions to maintain desired temperatures will require lesser differential pressures than those required for fraccing. Some of the possible configurations of zonal isolation devices for different applications are shown below in Figure 3.

Another factor besides the specific downhole conditions that must be considered for a specific zonal isolation process are the features and specifications the operator desires or what processes are they willing to employ. What processes are the well operators willing to employ to prepare the well for the insertion or activation of the zonal isolation device or to remove the zonal isolation device? For example, is the well operator willing and able to cool the well in the region where the zonal isolation device will be installed which might allow the device to be thermally triggered.

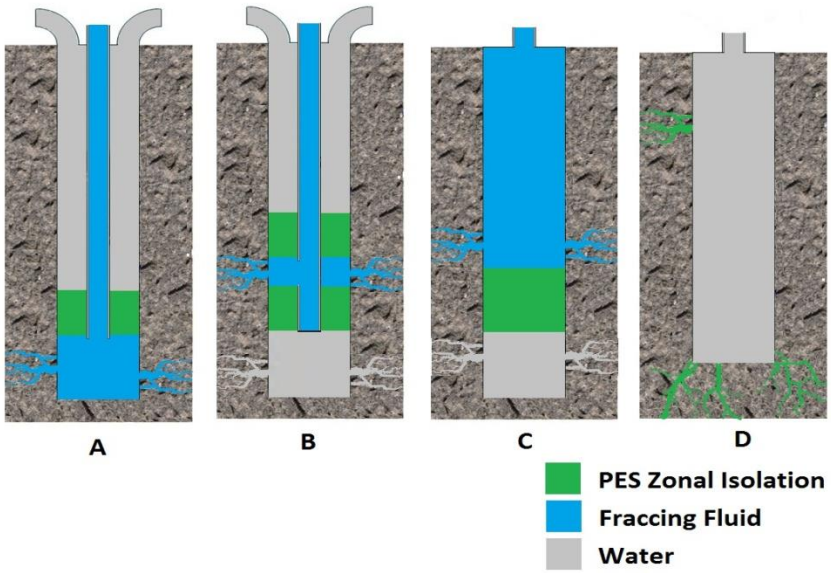

Figure 3: Different configurations of zonal isolation devices in geothermal well applications. a) a single device used in the stimulation process, b) a straddle configuration sealing of the annulus used for stimulation and pressure leak-off testing, c) a full cross-section isolation device used to control flow in boreholes, and d) loss zone mitigation.

Table 2: Process constraints desired by operators

- Function in annular sections or full cross section configurations
- Deployment to be completely controllable by the operator
- Minimize harmful or toxic materials
- Resist downhole corrosive chemicals and abrasive formations
- Minimize need for drill rig onsite for device set and use
- Reduce pressures applied to formation walls (< 500 psi)
- Device failure modes cannot cause reservoir or well damage

While traditional fraccing has become a better controlled reservoir creation tool, it is still unpredictable for advanced operations such as those found in EGS operations. EGS operators may face challenges of volatile time tables, earthquakes, and other unforeseen events which can setback operations. As such, any zonal isolation tool must be robust and highly controllable by

the operator. Tools which rely on temperature and timed deployment could fail before downhole delivery can be completed, resulting in critical time and money being wasted.

Operators need tools which can be easily removed without damage to the reservoir as any damage could require costly repair operations or loss of production value. Also, any operations which don't require the presence of drill rigs are highly desired as this can save millions of dollars - the difference in creating a financially feasible reservoir or not. Non-toxic products which are easily removed and can be safely disposed of are preferred to reduce disposal costs, reduce environmental impact and reduce safety risks. Additionally, operators prefer equipment and materials which can be safely operated by drilling personnel and those which operators are previously familiar using.

As a means to capture these requirements and their impact on the design and requirements of a zonal isolation device, Brontosaurus Technologies assisted CTD in putting together an analytical model that takes into consideration the basic well characteristics and zonal isolation needs and outputs details and requirements that can be used to design a specific device to serve a particular need. An example of this model is shown in Figure 4.

Figure 4: Example of model calculations for a specific zonal isolation application

Product Level Requirements – Level 0 and Operational Requirements

As highlighted above, the traits of desired zonal isolation device as determined by operators and various location requirements vary tremendously, while the main goal is to create a device to create differential pressures of 10,000 psi in a well that has steady state temperatures of up to 300°C. With these challenging goals in mind, the design team determined that an incrementally staged set of top level requirements and development approach was the best course of action. Listed below in Table 3 are the top level zonal isolation tool requirements as set by the design team.

Table 3: Progressive stages of zonal isolation device performance – Product level requirements

Stages	Maximum Operational Temperature (°C)	Maximum Differential Pressure (psi)
I	150	4,000
II	220	7,500
III	300	10,000

Having a variety of solutions with staged performance was determined the best fit for the desired variety in the zonal isolation market since some materials and designs might be more suited for lower temperatures and pressures, while others might make more sense for use at higher

temperatures and pressures. Additionally, the increasing temperature and pressure requirements through the 3 stages make for a smoother development path where stage I can be completed and various components of a design solution can be improved incrementally from there to satisfy the stage II and III requirements.

In addition to the performance requirements listed in Table 3, CTD determined that any potential solution must meet further technical traits to meet customer product desires. These desired product features are listed above in Table 2.

Design Level Requirements – Level 1

From the product or device level (Level 0) requirements, the technical team derived specific requirements for potential design solutions (level 1 requirements). The full list of design requirements and the parent is shown below and will be referenced throughout the report. The design itself and the components will be detailed in Task 2.

2.1.2 Task 2 – Preliminary Design Development

The design team proposed a number of design concepts to be evaluated. Each concept sought to find a solution to the questions of 1) how to best control the downhole delivery and deployment, 2) how to transfer the pressure loads into the borehole walls, and 3) how to operate under the extreme conditions amongst other technical challenges to meet product requirements.

In a traditional packer, the packer is installed as an impermeable barrier that reacts the differential pressure in a relatively short length of borehole by transferring it to the walls of the formation with a solid seal. This approach is inherently limited in the maximum pressure that can be reacted by the strength of the wellbore formation itself which may be relatively unknown. High pressure reacted against the walls of the bore can cause local fractures and spalling that create flow paths around the packer and damage to the wellbore by creating large breakout sections. Although the fractures to be created for an EGS system would typically be in granite, the geology of the well may be such that the packer needs to be set in a lower strength region above the granite, significantly limiting the maximum stress that can be applied to the wellbore.

CTD's concept for zonal isolation is different than a traditional packer.

As with many porous materials, the Poisson's effect is typically limited, so gaining expansive pressure through vertical compression is not likely to be achieved. The second goal fulfilled by having an expansive device is the ability to form a seal around uneven wellbore cross sections.

As mentioned previously, CTD has investigated the installation of a zonal isolation device for oilfield applications that is compatible with lower temperatures. This device is installed to the outside of a drill string in a compacted state, lowered into the

However, in order for this type of system to work in an EGS well, the material performance would need to be significantly different than anything previously envisioned.

The preliminary design development task selected a primary design concept deemed as the best current option by a weighted selection process.

2.1.3 Task 3 – Selection of Materials and Components Design

2.1.4 Task 4 - Screening and Evaluation of Potential Zonal Isolation Component Designs

Table 4: Properties of water as a function of water temperature

Temperature - t - (^oF)	Dynamic Viscosity - μ - ($lb\ s/ft^2$) x 10^{-5}	Kinematic Viscosity - ν - (ft^2/s) x 10^{-5}
32	3.732	1.924
40	3.228	1.664
50	2.730	1.407
60	2.344	1.210
70	2.034	1.052
80	1.791	0.926
90	1.580	0.823
100	1.423	0.738
120	1.164	0.607
140	0.974	0.511
160	0.832	0.439
180	0.721	0.383
200	0.634	0.339
212	0.589	0.317

A=annular area of the bore hole, $A = \frac{\pi}{4}\left(D_o^2 - D_i^2\right)$

Again, using the values of typical bore hole dimensions,

D_o= outside diameter of the bore hole = 0.22m (8.5 in.)

D_i=inside diameter of the drill pipe = 0.17m (6.75 in.)

Q = flow rate in the direction normal to the planar annular area A

We will set Q to 7.5 barrel/min = 1210 in^3/s. This is in an effort to keep the well at cooler temperatures and act as a fraccing system damper such that when the fracture begins to propagate, it may occur at a slower rate due to the limitation of available pumping volume by the fraccing pump. Also if a less dynamically viscous fluid than water, the hydraulic permeability will need to drop in a linear fashion just as with flow rate. The opposite is true for an increase in dynamic viscosity.

Stage I

L=45.5

κ = 467 Darcys (d)

A reduction of the flow rate to 1 barrel/min = 162 in^3/s yields,

κ = 86 d

Stage II

L=48.8

κ = 500 d

A reduction of the flow rate to 1 barrel/min gives,

κ = 49 d

Stage III

L=45.6

κ = 467 d

A reduction of the flow rate to 1 barrel/min gives,

κ = 46 d

For reference, packed sand of 1mm diameter has a hydraulic permeability of 32d and sand of 3mm has a hydraulic permeability of 284d. Therefore we can predict that the hydraulic permeability should be between roughly 100-1000.

3.) To estimate the required radial output pressure to hold the device in place a basic balance of forces calculation was done assuming that the shear stress and pressure differential are uniform over the length of the isolation device.

$F_f \equiv$ Frictional force provided by the work pipe and borehole wall

$F_p \equiv$ Force created by pressure on the plug

$P_R \equiv$ Radial output force of isolation plug on borehole walls

$\mu_b \equiv$ Coefficient of friction between plug and borehole wall = 0.9 (assumed)

$\mu_p \equiv$ Coefficient of friction between plug and work pipe = 0.9 (assumed)

A=annular area of the bore hole, $A = \frac{\pi}{4}\left(D_o^2 - D_i^2\right)$=.0153 m^2

L=6.1m (20 ft.)

$$F_p = \Delta p \cdot \frac{\pi}{4} \cdot \left(D_O^2 - D_i^2\right)$$

$$F_f = P_R \cdot \pi \cdot L \cdot \left\lfloor D_O \mu_B + D_i \mu_p \right\rfloor$$

Setting Fp to Ff and solving for PR we find

$$P_R = \frac{\Delta p}{4L} \cdot \frac{\left(D_O^2 - D_i^2\right)}{\left(\mu_B D_O + \mu_P D_i\right)} = 7.97E4Pa\left(11.6\,psi\right)$$

2.1.5 Task 5 – Design, Fabricate, and Test of Zonal Isolation Demonstrator

Zonal Isolation Demonstration Unit: an experimental flow loop

Prototype demonstration design and testing equipment were fabricated to illustration concept feasibility and compare prototype performance with models and design analysis. CTD engineers first designed and built an in-house testing machine, to show proof of concept and to test for conformity of components to required specifications. The Zonal Isolation Demonstration Unit (ZIDU) was designed to be modular and allow experimentation flexibility by simple configurationally changes. The ZIDU was fitted for multiple lines of pressure transducers, 12 lines of thermocouples, a flow meter, pump monitoring and numerous removable test units which simulate the borehole. A Masosine pump (Figure 5) was selected for flow delivery due to its ability to pass large solids without damage. Additionally a hydraulic, high-pressure pump which has been regulated with a number of valves and regulators allowed the unit to safely deliver up to 300 psi. The system also included a number of heating elements which can elevate the temperature to 80°C. This allows CTD to replicate the high pressure differentials and moderate temperatures required by this project in a shorter length. The demonstration test system allowed a number of variables to be adjusted including pressure, temperature, and delivery method.

Figure 5: Masosine pump representation illustrates how the pump can deliver large solids up to 2” in diameter

The Zonal Isolation Demonstration Unit (ZIDU) was completed as shown in Figure 6. Calibration of the data acquisition system and system controls was performed and multiple Removable Test Units (RTU) were constructed (Figure 6 & Figure 7). The different RTUs allow deployment mechanisms to be understood, and material mechanics to be readily visualized in efforts to aid proper modeling and materials selection.

The completed ZIDU stands nearly 20 feet high to accommodate RTU lengths of up to 10 feet Figure 6. RTUs which were constructed include: 3 clear units, one 7 feet in length and 6" in diameter with an annular cross section; and a high temperature high pressure heavy gauge steel unit.

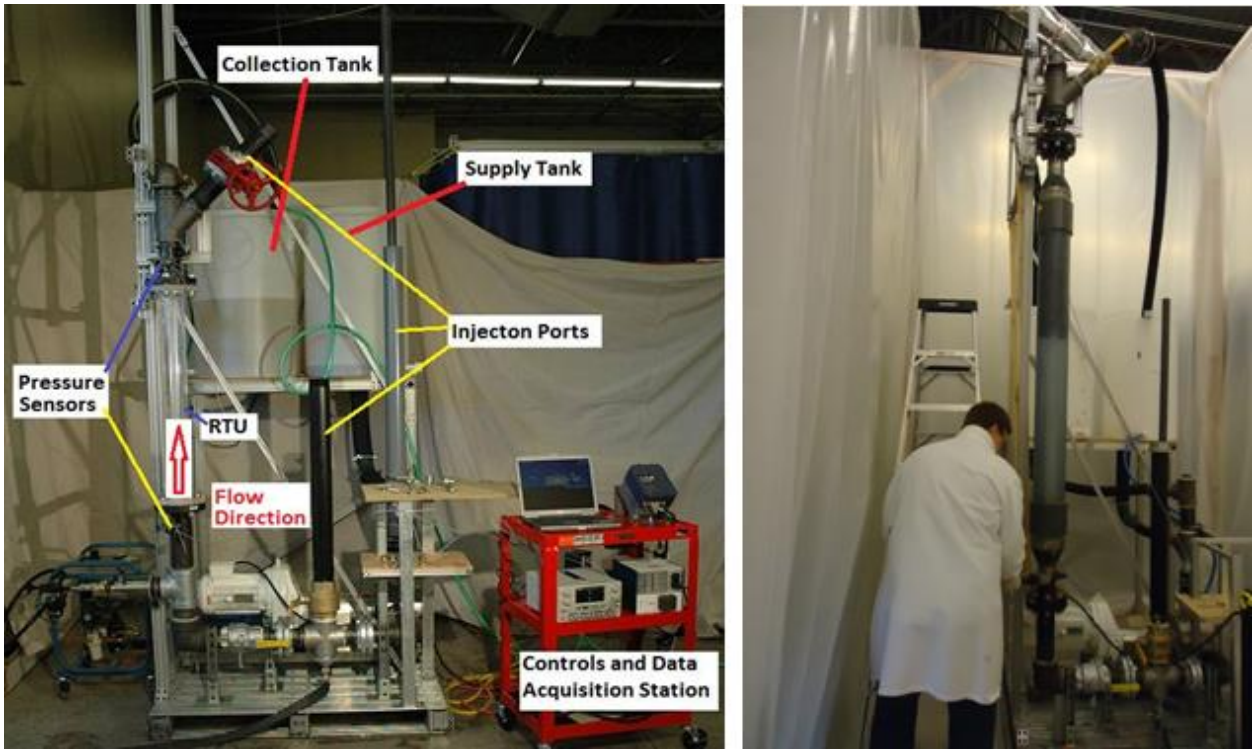

Figure 6: The Zonal Isolation Demonstration Unit (ZIDU) flow loop

Figure 7: Clear Acrylic and High Pressure Removable Test Units (RTU).

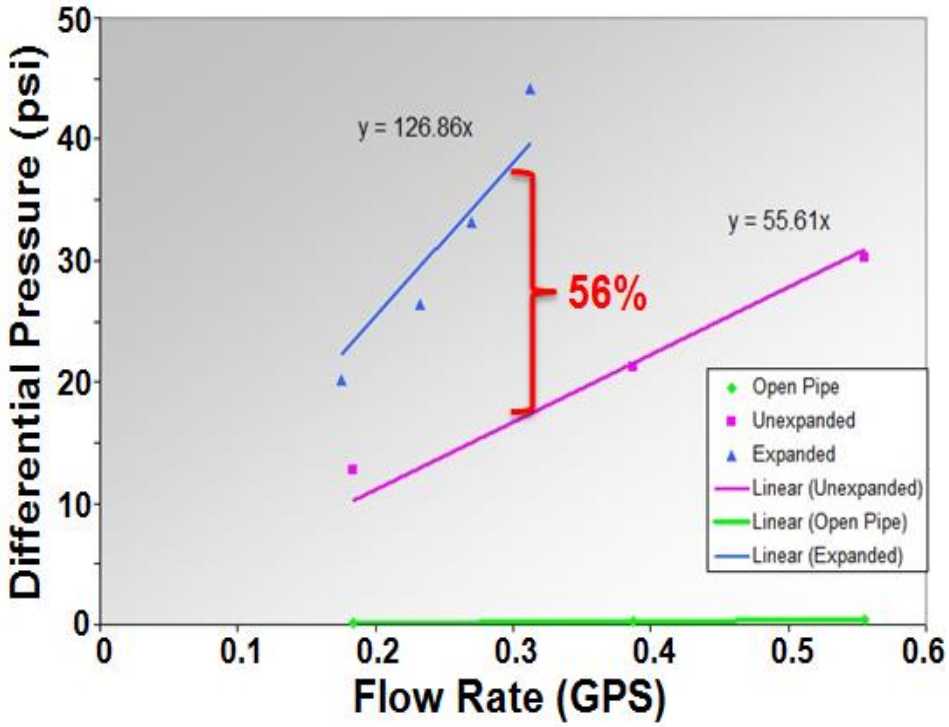

Figure 8: Pressure versus flow data gathered during the full system demonstration experiment

2.1.6 Task 6 - Incorporate Lessons Learned into Second Demonstration Unit

2.1.7 Task 7 – Develop Pilot-Scale Manufacturing Plan

Case Study

The assumptions for this case study are shown in Table 5. A mid temperature EGS well is assumed at 220°C with a standard 8.5 inch open bore hole. Brontosaurus Technologies supplied the circulation details as a 15 BBL/min flow rate used to cool the well to roughly 80°C at steady state. A 7.5 BBL/min flow rate should then have a steady state temperature of 150°C.

Table 5: Theoretical EGS well conditions

Static Temperature	Bore Diameter	Work Pipe OD	Circulated Temperature
220° C	8.5 in	7 in	80° C

2.1.8 Task 8 – Manufacture and Testing of Qualification Prototype

2.1.9 Task 9 – Develop Pilot-Scale Manufacturing Plan

References

1. "The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century," prepared by the Massachusetts Institute of Technology under DOE Contract DE-AC07-05ID14517, 2006.
2. "Geothermal Technologies Program – Multi-Year Research, Development, and Demonstration Plan" United States Department of Energy, 2008.