



FY-22 Progress Report for Advanced Re-fabrication / Re-instrumentation Capability Development

September 2022

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ABSTRACT AND ACKNOWLEDGEMENTS

In support of performing follow-on irradiation experiments with previously irradiated materials, the Halden Reactor Project developed unique and state of the art capabilities to refabricate and re-instrument previously irradiated materials. Such materials were used in in-pile tests at the Halden reactor, and out-of-pile tests for example using furnaces as a heat source. The decision to close the Halden Reactor Project results in the loss of this refabrication and re-instrumentation capability. As a result, the United States (U.S.) Department of Energy (DOE) has determined to develop refabrication and re-instrumentation capability at the unique shielded facilities at Idaho National Laboratory (INL). The development of refabrication capability has been completed and demonstrated. This report focuses on the complementary aspects of re-instrumentation and the progress to-date. Halden spent nearly 30 years developing both refabrication and re-instrumentation. Collaboration with Halden is allowing Idaho National Laboratory (INL) to develop this capability much more rapidly.

In FY-21 the results include development of the capability to drill annular center holes in ceramic UO_2 fuel pellets, development of fuel rod end caps with feedthroughs for centerline instrumentation inside the rodlet, The procurement of both fuel drilling and welding demonstration equipment from Halden, evaluation of surface thermocouple attachments to support better understanding of temperature measurement uncertainties, and finally, the conceptual design of a new shielded enclosure where advanced refabrication and re-instrumentation equipment can be housed.

In FY-22, the results include

- Completing set up of the drilling and welding modules procured from Halden, and early experimental trials using that equipment.
- Completing set up of an out-of-cell circumferential weld system to allow for further weld development to take place and support fabrication of fuel for fresh fuel experiments.
- Evaluation of the Hot Fuel Examination Facility (HFEF) infrastructure to support future installation of advanced re-fabrication/re-instrumentation equipment, specifically related to necessary infrastructure for cryo-drilling.
- Developments in dry-drilling alternative. Including experimental studies showing cordierite is the most suitable surrogate for UO_2 for performing drilling studies. That drilling performance is enhanced when a fuel-clad bonding condition is simulated.
- Conceptual design completed for attaching surface thermocouples to irradiated fuel in support of TWIST capsule experiments.

The authors would like to thank the numerous colleagues at INL and Halden who provided support in accomplishing this work. Their support both material and intellectual is invaluable in advancing the state of the art and establishing the capabilities for refabrication and re-instrumentation at INL.

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CONTENTS

ABSTRACT AND ACKNOWLEDGEMENTS	iii
ACRONYMS.....	viii
1. INTRODUCTION.....	1
2. HALDEN FUEL DRILLING AND WELDING MODULES	4
2.1 Historic Case for Cryo-Drilling and Why Halden Used This Method.....	4
2.2 Technology Transfer from IFE to INL.....	4
2.3 Halden Equipment Checkout and Practice Conducted in FY22	5
3. OUT-OF-CELL CIRCUMFERENTIAL WELD SYSTEM	9
4. EVALUATION OF INFRASTRUCTURE TO SUPPORT ADVANCED REFABRICATION/RE-INSTRUMENTATION	9
5. DEVELOPMENTS IN DRY-DRILLING ALTERNATIVE.....	9
5.1 Material Drilling Study	10
5.2 Drill Bit Optimization Study (March 2022).....	11
5.3 Pellet Backer/Stack Drilling Study	12
5.4 Standardized Crack Development in Cordierite.....	12
5.5 Cracked Surrogate Drilling Study.....	14
5.6 Unirradiated UO ₂ Cracking and Drilling Study	17
5.7 HFEF Incell Concepts for Supporting Center Holes in Fuel with Incell Equipment.....	17
6. Conceptual Design for Attaching Thermocouples to Previously-Irradiated Rodlets.....	19
7. CONCLUSIONS.....	20
9. REFERENCES.....	21

FIGURES

Figure 1. Shows the distinction between basic refabrication activities and advanced re-instrumentation.	2
Figure 2. The fuel rod segment after defueling the ends of the segment to make space for new end caps to be inserted.....	2
Figure 3. Defueling module removing surrogate pellet material from rodlet mockup.	5
Figure 4. Defueling module with protective cover and fines collection system added.	6
Figure 6. Lining up tungsten electrode prior to closing welding chamber and performing a practice weld.....	8
Figure 7. Welds made in the welding chamber.....	8
Figure 8. Irradiated fuel from Tarapur Atomic Power Station at 5x magnification. (<i>Roy and Sah, 1985</i>).....	9

Figure 9. Bradpoint (Left) and 118 pt. (Right) drill bits side-by-side at 50x magnification.....	11
Figure 11. (Left) 5000 lbf Dillon Force Gauge used for measuring force applied before fracture. (Right) Setup for crushing pellet stack. Pellet positioned between the two flat plates was crushed axially 1–4 times in order to achieve visual similarity to cracking observed in irradiated UO ₂	13
Figure 12. Top and bottom surfaces of sample 15 (A&B respectively) and sample 16 (C&D respectively) post-drilling.....	16
Figure 13. Exploded view of conceptual drilling method.....	18
Figure 14. A representation of the prototype fixture used to weld TCs to the surface of rodlet cladding.	19

TABLES

Table 1. Machining parameters for dry-drilling of surrogate and actual UO ₂ fuel.	10
Table 2 Ceramic drilling study results.*	10
Table 3. Sample crushing recipes for simulating cracks within surrogate UO ₂ fuel meat.	13
Table 4. Samples 9-14 in their pre- and post- drilled state along the exit-hole surface as a function of mill feed rate. L.C.= light cracking, M.C.=moderate cracking, H.C.= heavy cracking.	15
Table 5. Gage pin results for drilled holes in surrogate pellet stack ups.....	17

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ACRONYMS

ATF	accident tolerant fuel
ATR	Advanced Test Reactor
CEA	
COMSOL	
CT	computed tomography
DOE	U.S. Department of Energy
EFF	Experimental Fuels Facility
EIL	
EPIC	Experiment Preparation and Inspection Cell
FCCI	
FCMI	
FCPI	
FY	fiscal year
GTAW	Gas Tungsten Arc Welding
HAAS	
HBWR	Halden Boiling Water Reactor
HFEF	Hot Fuel Examination Facility
HIP	hot isostatic press
HRP	Halden Reactor Project
IFE	Institute for Energy Technology
INL	Idaho National Laboratory
LI	Laboratory Instructions
LWR	light-water reactor
OD	outer diameter
PCD	
PWR	pressurized-water reactor
SAR	Safety Analysis Report
TC	thermocouple
TREAT	Transient Reactor Test Facility
TWIST	
UHP	
WUPS	Weld Under Pressure System

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1. INTRODUCTION

The Halden Boiling Water Reactor (HBWR) in Norway and its international collaborative research program, the Halden Reactor Project (HRP), were, until their recent closure, a key resource for assessing nuclear fuel and materials behaviors to address issues and answer regulatory questions supporting the light-water reactor (LWR) community. HBWR and HRP included significant experimental capabilities and knowledgeable staff developed over decades to perform this challenging work. Recognizing a potential challenge induced by the closure of HBWR, a gap assessment was performed to identify critical capabilities historically provided by HBWR and develop recommendations for filling those capability gaps to support the ongoing Accident Tolerant Fuel (ATF) Program. (Jensen et al. 2018)

The gap assessment highlights four key capabilities/recommendations for investment:

- Acceleration of loss-of-cooling accident testing at the Transient Reactor Test (TREAT) Facility
- Expansion of the water loop and ramp testing capability at the Advanced Test Reactor (ATR)
- Establishment of refabrication/instrumentation capability
- Deploy reliable advanced in-pile instrumentation.

This report will focus on progress and development in the establishment of the refabrication and instrumentation capability at Idaho National Laboratory (INL).

Refabrication and instrumentation is considered an enabling capability that allows access to fuel materials at any point in their lifecycle. It is also critical in supporting the deployment and qualification of ATF materials, as many candidate materials are already undergoing irradiation as lead test rods in commercial nuclear power plants, and irradiation in ATR alone cannot produce the quantities of materials necessary to support qualification.

Refabrication and instrumentation allows for the use of the lead test rod materials that have been irradiated under prototypic commercial conditions, including localized phenomena like fretting, grid spacer effects, and corrosion. Specific segments of these materials can then be selected for subsequent testing under steady-state, transient, or ramp conditions. Refabrication also allows instrumentation to be added to these segments to measure parameters, such as temperature and fission gas release.

Halden first successfully re-instrumented a fuel rod segment for subsequent follow-on irradiation testing in 1991 and performed refabrication and instrumentation on more than 130 rod segments during operations over the next 25+ years. During this time, Halden further refined this capability and developed significant staff expertise. Halden had initially adapted the technology to refabricate and instrument fuel rods which was first developed by researchers at the Riso campus of the Technical University of Denmark. It is also notable, that INL had previously developed the ability to refabricate and add instrumentation of irradiated fuel rods in support of experiments that were performed in the late 1970's at the Power Burst Facility.

INL has selected a phased approach to refabrication and instrumentation in which efforts were primarily focused on establishing a basic refabrication capability initially, with initial scoping efforts for advanced re-instrumentation proceeding in parallel.

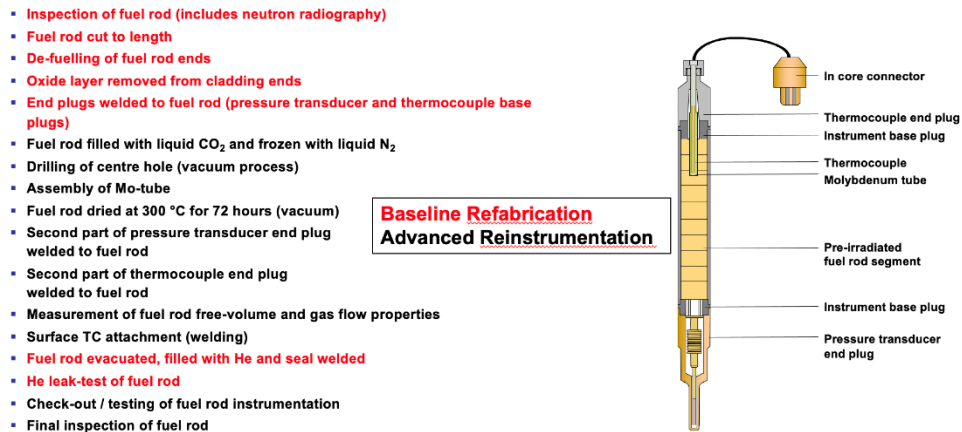


Figure 1. Shows the distinction between basic refabrication activities and advanced re-instrumentation.

During fiscal year (FY)-21, INL successfully completed the development and installation of all basic refabrication equipment into the HFEF and successfully demonstrated basic refabrication on an irradiated fuel rod from the ATF-2 experiment.

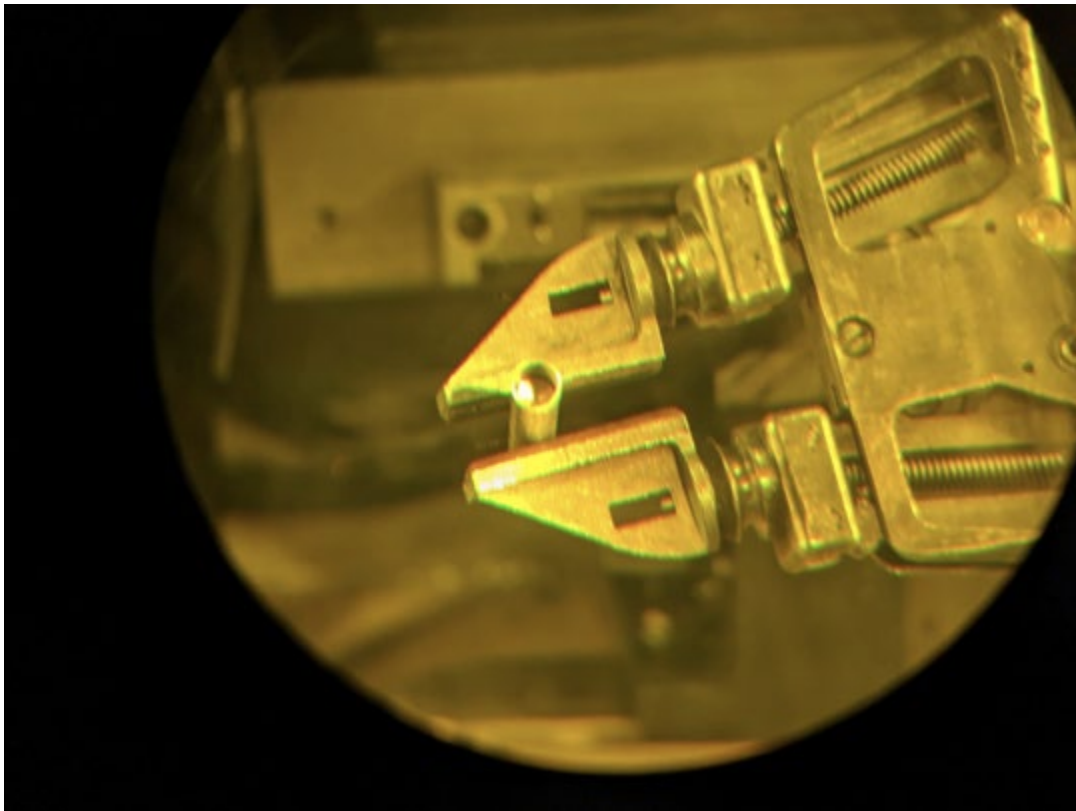


Figure 2. The fuel rod segment after defueling the ends of the segment to make space for new end caps to be inserted.

Additional work completed in FY-21 is described in the following points.

- Scoping studies for pellet drilling have been divided into two subsections and include efforts to perform dry-drilling on fresh fuel pellets and a cryo-drilling technique technology transfer via a collaboration with Halden. The demonstration of the dry-drilling technique was ultimately successful and allowed for the assembly of a first fresh fuel rodlet with a centerline hole and a thermocouple.
- Endcaps for rodlets that support instrumentation are non-trivial and are highly experiment specific. Initial scoping studies were performed to develop an endcap that could support a centerline fuel thermocouple were completed and supported the assembly of a first fresh fuel rodlet with a centerline thermocouple.
- Previous work done at both INL and Halden indicated that temperature measurements by thermocouples attached to the outer surface of fuel cladding are sensitive to a number of parameters, including attachment method, mechanical design, spacing, fin effect, two phase flow, etc. To better understand some of these sensitivities, we performed modeling of the thermocouples, and it is being used to inform work to weld thermocouples to cladding outer surfaces.
- Thermocouples mounted to the exterior surface of fuel cladding have historically proven to be some of the most useful data collected from in-pile experiments. Despite demonstrated success at INL in attaching thermocouples to cladding for fresh fuel TREAT experiments, significant challenges exist in remotely attaching thermocouples on previously irradiated fuel. Some initial scoping studies have been performed using the same circumferential welding system developed in the basic refabrication work. Initial work shows that thermocouples can be attached to cladding surfaces using this welding system. However, a method to hold thermocouple leads in place for remote welding and the optimization of the welding process remain a challenge.
- A dedicated shielded enclosure facility continues to be identified as the preferred option for the long-term use of advanced refabrication and re-instrumentation work. In support of this, preconceptual engineering design activities were continued to develop the design of a dedicated refabrication and advanced re-instrumentation cell, should funding become available in the future.

The remainder of this report will focus on FY-22 efforts to develop advanced re-instrumentation capabilities.

Each of these scoping areas to support advanced re-instrumentation will be discussed in more detail in the following sections. Key takeaways for efforts in FY-22 include:

- Completing set up of the drilling and welding modules procured from Halden, and early experimental trials using that equipment.
- Completing set up of an out-of-cell circumferential weld system to allow for further weld development to take place and support fabrication of fuel for fresh fuel experiments.
- Evaluation of the Hot Fuel Examination Facility (HFEF) infrastructure to support future installation of advanced re-fabrication/re-instrumentation equipment, specifically related to necessary infrastructure for cryo-drilling.
- Developments in dry-drilling alternative. Including experimental studies showing cordierite is the most suitable surrogate for UO_2 for performing drilling studies. That drilling performance is enhanced when a fuel-clad bonding condition is simulated.
- Conceptual design completed for attaching surface thermocouples to irradiated fuel in support of TWIST capsule experiments.

2. HALDEN FUEL DRILLING AND WELDING MODULES

2.1 Historic Case for Cryo-Drilling and Why Halden Used This Method

More than 30 years ago, the HRP (now Institute For Energy Technology (IFE)) began developing techniques based on technology originally developed by the Riso campus of the Technical University of Denmark; for refabricating full-length irradiated fuel rods into much shorter (150–400 mm) rodlets, which could then be re-irradiated in one of their pressurized-water loops. Originally, this was done by simply shortening the rods, removing a pellet from each end, cleaning the oxide off the Zr-4 cladding from each end, and welding on new Zr-4 end caps. However, there was a desire to monitor temperature during irradiation. It was recognized that this would require drilling a center hole in the irradiated UO_2 ceramic approximately 50-mm deep in order to accommodate a thermocouple.

They determined that it was possible to dry drill a hole in the UO_2 ceramic using a hollow, diamond-tipped bit. Drilling dry required that they go slow and potentially replace the bit during the process. However, the difficulty was that, once irradiated at a high temperature, the UO_2 pellets are no longer solid entities but rather severely fractured. In such a situation, the drill is not working its way through solid material but rather something akin to a gravel bed. IFE discovered that, when the bit completed its work and was removed, the gravel bed would collapse on itself, making it impossible to install a thermocouple.

IFE engineers found an ingenious solution to the collapsing bed problem. They first filled the rodlet with liquid CO_2 ,^a and then froze that CO_2 into a solid by filling the surrounding chamber with liquid nitrogen. With the liquid nitrogen surrounding the now frozen CO_2 , the rodlet pressure could be dropped to atmospheric, which would then allow drilling to take place as before. With the UO_2 bed stabilized by the frozen CO_2 , when the drill bit was removed, the hole stayed intact, and at this point, a thin-walled molybdenum tube was inserted into the hole. With the hole now sleeved, the LN_2 and CO_2 could be allowed to evaporate (technically, sublime in the case of the CO_2).

Molybdenum was selected as the sleeving material because it has a very high melting temperature and it is inert to both the UO_2 ceramic and INL's patented High Temperature Irradiation Resistant thermocouples, which are sheathed with niobium. IFE also utilized molybdenum protective sleeves between their specialty (Molybdenum/Re 47.5%) sheathed thermocouples and the UO_2 fuel.

2.2 Technology Transfer from IFE to INL

The closure of the Halden reactor was a major loss to the worldwide LWR fuels and materials research and development community, especially at a time when such test facilities are increasingly scarce. The DOE has a stated goal to capture or preserve as many of IFE's technological innovations as possible. One of these technologies is their fuel rodlet re-instrumentation process. The process consists of three major operations: defueling of rodlets (i.e., removal of a pellet from each end and removal of oxides near what will be the weld surfaces); drilling and installing a thermocouple or other relevant sensor; and filling the rodlet with inert gas and welding it closed.

IFE accomplished these three phases by developing three equipment modules: a defueling module, a drilling module, and a welding module. INL has subcontracted with IFE to fabricate and deliver copies of these three equipment modules. This procurement was supported by the DOE Advanced Sensors and Instrumentation program. The defueling and drilling modules were delivered to INL in FY-21, and the welding module was delivered February 2022.

^a This must be done inside a sealed chamber because CO_2 is a liquid at room temperature only under pressure. A pressure of 850 psi is required to maintain CO_2 in the liquid state at 70°F.

Note that, although this equipment was designed for hot cell use, the set now located in the Measurement Science Laboratory facilities in the Energy Innovation Laboratory building are not planned to be moved into a hot cell; but rather, it is being used as a test bed to first understand and practice IFE's techniques and second to develop methods for incorporating advanced instrumentation into irradiated fuel rodlets, and, hopefully, to simplify certain aspects of the IFE process.

2.3 Halden Equipment Checkout and Practice Conducted in FY-22

As described above there are three equipment modules: defueling, cryo-drilling, and welding. A description of the checkout activities performed on each of these modules is provided below.

Defueling Module Checkout Activities

- Verified customized control system communicates with the defueling module
- Verified operation of manual control pendant
- Verified all axes of the defueling module operate properly
- Verified tooling supplied was able to machine back a full ceramic pellet
- Removed oxides from inner and outer surfaces of an oxidized stainless tube using tooling supplied
- Verified operation of fines collection system.



Figure 3. Defueling module removing surrogate pellet material from rodlet mockup.

In addition to performing checkout activities described above, INL technicians also created a clear plastic shield for the defueling unit and designed and installed a fines collection system as shown in Figure 4.

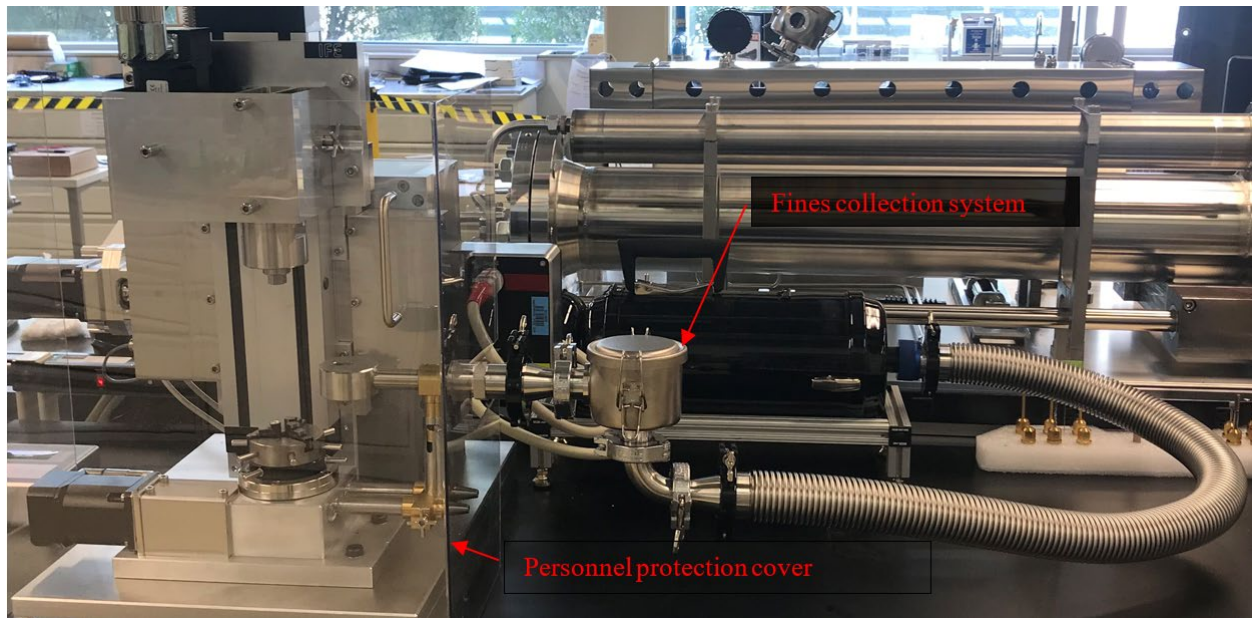


Figure 4. Defueling module with protective cover and fines collection system added.

Lessons learned from exercising the defueling module are as follows:

The mini-mill which constitutes the defueling system has more runout (wobble in the rotating chuck) than is typical for a milling machine. Despite this additional runout, the technicians were able to effectively defuel surrogate rodlets.

Cryo-drilling Module Checkout Activities

- Verified customized control system communicates with the drilling module
- Verified control system properly controls the drilling process
- Verified temperature and pressure sensors are operating correctly
- Verified cryo-freezing system works correctly
- Verified tooling supplied was able drill surrogate fuel pellets – full 50 mm drilling depth was achieved.

INL enhancements to the cryo-drilling system included a clear plastic personnel protection cover.

Figure 5 shows the drilling module with its control screen in the background at the beginning of a drilling run. The plastic guard was removed (on the floor below) to provide a clear photo of the diamond coated drill bit.

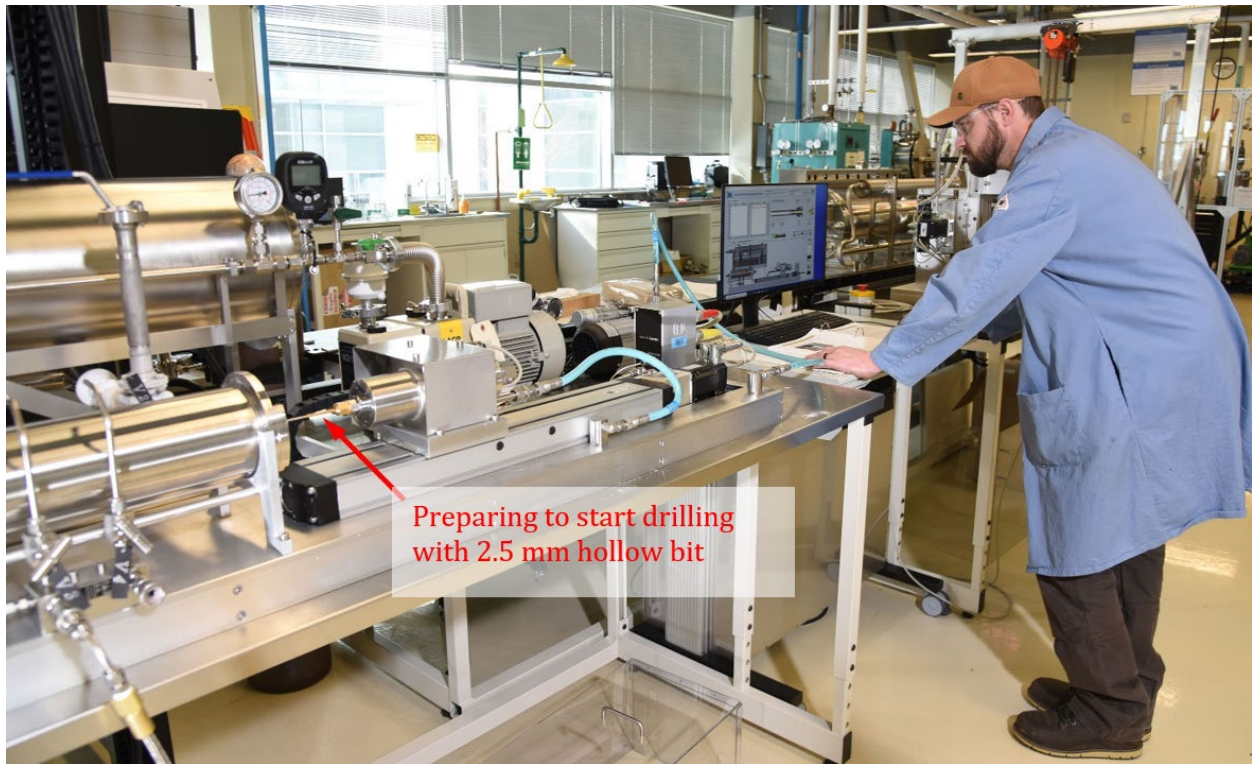


Figure 5. Drilling module lined up to begin drilling operation.

Lessons learned from exercising the cryo-drilling module are as follows:

- The hollow diamond drills supplied by Halden typically have a small braze occlusion in the bore. This must be drilled out in order to clear chips through the bore of the diamond drill.
- The LN_2 chamber surrounding the frozen CO_2 must be refilled frequently. Technicians found that by throttling the supply valve a small flow of LN_2 kept a sufficient level of LN_2 around the freezing chamber.

Welding Module Checkout Activities

- Verified control system rotates the chuck properly according to operator commands
- Verified drying system works correctly
- Verified a full penetration weld can be made
- Verified temperature and pressure sensors are operating correctly
- Verified helium leak check chamber works correctly.



Figure 6. Lining up tungsten electrode prior to closing welding chamber and performing a practice weld.

Shown below are two Zr tube (cladding) welds. On the left is a weld with insufficient oxygen cleanup in the chamber, and on the right is a weld with low oxygen content.

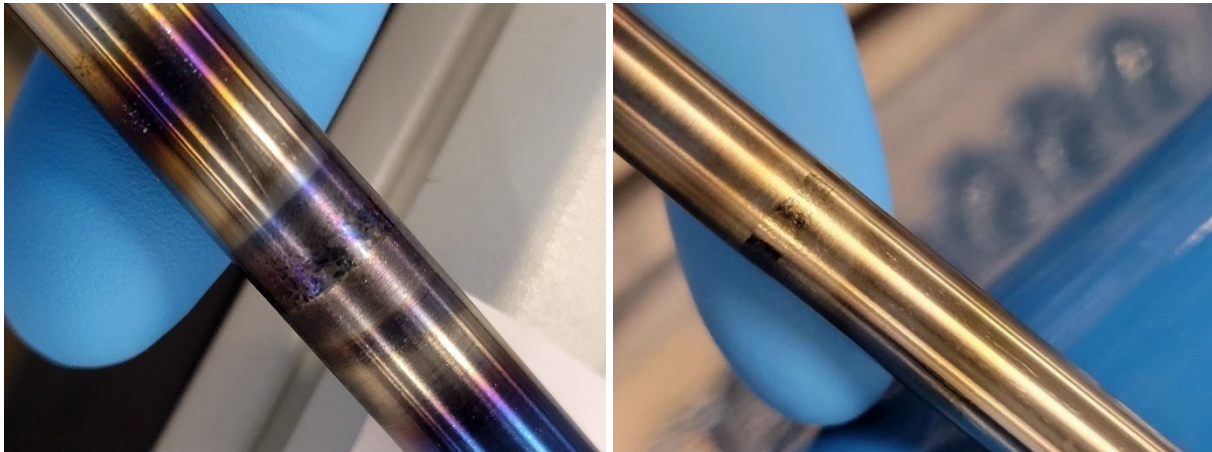


Figure 7. Welds made in the welding chamber.

The welding module was supplied without a power supply. The power supply selected was a programmable Miller Maxstar 210DX. In addition to the power supply, INL enhancements to the welding system included a high precision vacuum gauge with 1 milliTorrr low scale readout.

Lessons learned from exercising the welding module are as follows:

- A very low oxygen level is required to produce an acceptable weld on Zr cladding. Three vacuum cycles to <10 milliTorrr followed by refill with to 2 Bar with UHP gas was sufficient to clean up the welding chamber.

3. OUT-OF-CELL CIRCUMFERENTIAL WELD SYSTEM

To support further development of welding parameters and fixtures necessary for advanced refabrication and instrumentation including welding thermocouples to the cladding surface of a previously-irradiated fuel pin, a duplicate of the remote circumferential weld system was fabricated and installed into the Advanced Fuel Fabrication Facility at INL's Materials and Fuels Complex. Applicable facility modifications were made including installation of electrical power feed at the installation location and drafting and approval of work control for operation of the system (AFF-LI-007). This system can also be used to perform endcap welding or thermocouple welding of fresh fuel rodlets that can be used for experiments.

4. EVALUATION OF INFRASTRUCTURE TO SUPPORT ADVANCED REFABRICATION/RE-INSTRUMENTATION

An evaluation of the infrastructure needed to support a cryogenic drilling system inside the HFEF was performed. A comprehensive description of the anticipated infrastructure needs is discussed in PLN-6575, "HFEF Cryogenic Drilling Infrastructure to Support Advanced Refabrication of Pre-Irradiated Fuel Rodlets." Several locations in the HFEF inert-atmosphere hot cell were identified as potential locations for operation, including windows 1M, 7M, 9M, and 11M. At least one penetration into the hot cell will be required to install infrastructure to support the cryogenic liquids as well as power and instrumentation to the drilling system. The drilling system design, development, qualification, and installation is anticipated to occur over about 2.5 fiscal years.

5. DEVELOPMENTS IN DRY-DRILLING ALTERNATIVE

At the beginning of FY-22, the dry-drilling process of UO_2 was proven feasible on fresh, monolithic fuel. Despite this, the dry-drilling method utilizing a milling technique would still result in blowout upon exit of the drilled hole in UO_2 . Additionally, attempts to physically imitate what actual high-burnup fuel (exemplified below in Figure 8) would machine like were unexplored.

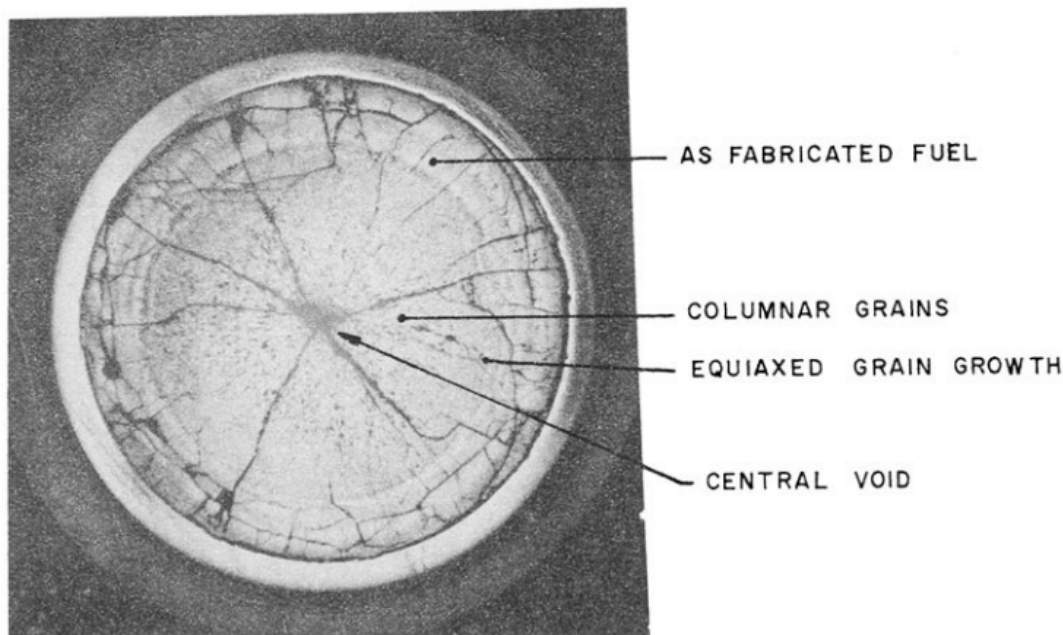


Figure 8. Irradiated fuel from Tarapur Atomic Power Station at 5x magnification. (Roy and Sah, 1985)

The goal for this FY was to create an accurate depiction of high-burnup UO_2 in a surrogate material for machining purposes. The primary factors include:

1. Interconnected cracking across the fuel meat.
2. Fuel/cladding diffusion and chemical interaction.
3. Porosity towards the center of the fuel mass.
4. Similar machineability to that of UO_2 .

All these factors were accounted for, save for induced porosity. Interconnected cracking was created by axially crushing the samples in a vice or press. The fuel/cladding physical and chemical interaction (FCPI and FCCI) was simulated by gluing surrogate pellets into a stainless-steel sleeve, and machineability was determined by a brief qualitative material drilling study of cordierite, mullite, alumina, and magnesia.

5.1 Material Drilling Study

Mullite has traditionally been used as a non-radiological surrogate for UO_2 fuel for machining and thermophysical testing purposes at INL. It was discovered during dry-drilling activities last year that mullite exhibits work hardening upon excessive feed rate or force applied during drilling, either stripping the diamonds off the bit or breaking it entirely. This is uncharacteristic of UO_2 to the best of our knowledge. To address this, four common ceramics underwent a drilling recipe matching that of the UO_2 pellets drilled in FY-21. These parameters are shown below and were utilized for all drill jobs unless specified otherwise for an individual sample(s).

Table 1. Machining parameters for dry-drilling of surrogate and actual UO_2 fuel.

Parameter	Value
Head Speed	3000 rpm
Feed Rate	0.75 in./min
Peck	0.01 in.

The pellets were visually inspected by our machinist drilling to qualitatively determine which behaved most like UO_2 . The results are included in the table below.

Table 2 Ceramic drilling study results.*

Material	Results
Alumina (Al_2O_3)	Much harder to drill than UO_2 , visual deflection in drill bit seen, along with significant wander.
Mullite ($\text{Al}_2\text{O}_3 + \text{SiO}_2$)	Similar chipping during drilling seen. Similar blowout observed upon drilling through the material. Rapid heating and work hardening observed about 0.056 in. into the drill job. Stripped the bit of its diamonds and stopped drill progress.
Magnesia (MgO)	No chipping observed on the top of the pellet. Was much softer than UO_2 , as there was no issue drilling through the material with various kinds of bits. Major blowout seen at the exit hole which was dissimilar to UO_2 behavior.
Cordierite ($\text{Mg}_2\text{Al}_4\text{Si}_5\text{O}_{18}$)	Was softer than alumina, but harder than magnesia. Similar chipping and blowout to that of UO_2 . Very similar behavior to that of UO_2 from a machining perspective.

* All drilling was performed with a 0.0625 in. brad point bit, at a feed rate of 0.75 in./min, 300 rpm mill speed, and peck of 0.01 in.

It was concluded that cordierite behaved the most like that of UO_2 and was used as the project's surrogate for the remainder of the year.

5.2 Drill Bit Optimization Study (March 2022)

Another change necessary to create an experiment that more accurately reproduces conditions that would be seen in the drilling of irradiated UO_2 is that of the drill bit itself. In FY-21 a 0.0635 in. brad point drill bit (Figure 9) was the primary type used for drilling of TC holes. However, this resulted in significant blowout of pellets upon the exit hole being made. This was not remedied even by use of a backer. A temporary solution of drilling halfway through a pellet before flipping it over and drilling the other half was implemented. This was a sub-optimal method, as machinists would not be able to do this when drilling irradiated UO_2 that has bonded to the cladding. Our machinist recommended we try using a custom 118-pt. 0.0635-in. carbide jobber drill bit with diamond coating instead. The two bits are shown side-by-side below.

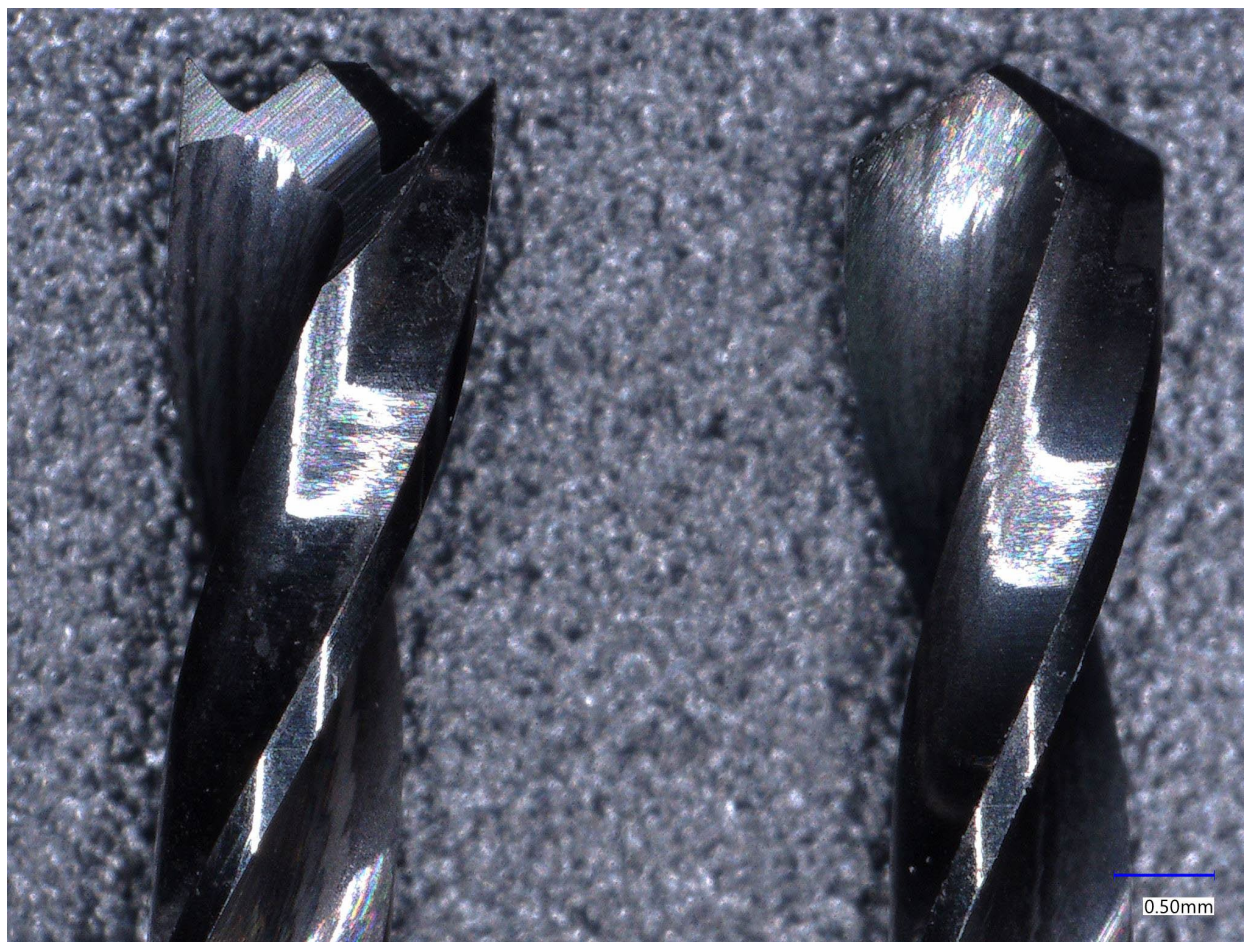


Figure 9. Bradpoint (left) and 118-pt. (right) drill bits side-by-side at 50x magnification. The 118-pt. bit has shown promise because of its drastic reduction in chipping and blowout upon exit of the drilled material.

All drilling performed this year has utilized a through-hole approach (i.e., drilling in through the top face and out through the bottom face without stopping in the middle to flip it over). This way, drilling methods can be more directly applied to researchers in HFEF if or when the time for testing on irradiated UO_2 comes.

During the material drilling study, two samplings were drilled of each ceramic: one utilizing a Bradpoint bit, and one using a 118-pt. bit. Blowout was visibly more prevalent using Bradpoint bits for the ceramics than using the 118-pt. bits. This was formalized by comparing a Bradpoint drilled cordierite sample with that of a 118-pt. drilled sample which are visualized in the Figure 10.

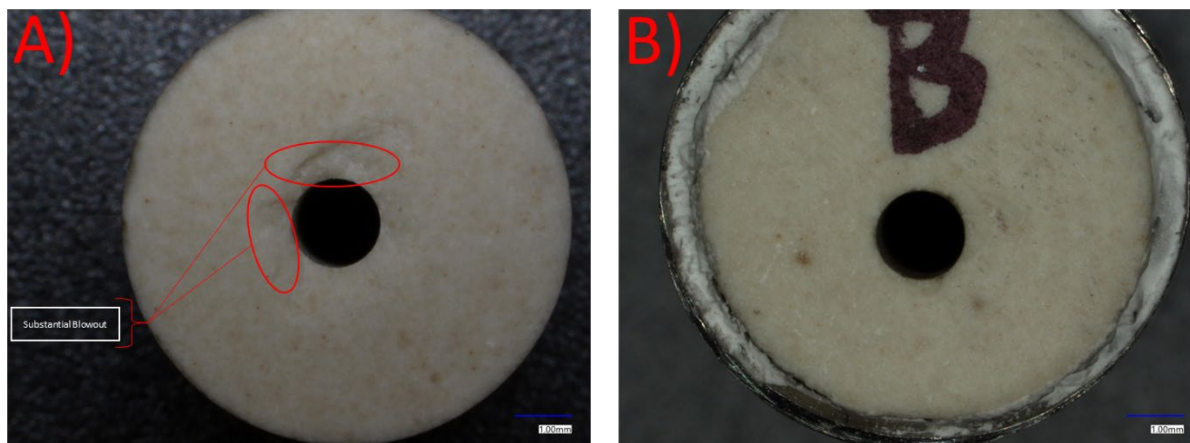


Figure 10. (A) Exit hole of a cordierite pellet drilled with a Bradpoint bit. Visible blowout is seen in the red circled areas. (B) Exit hole of cordierite pellet clad in stainless-steel tubing drilled with 118-pt. jobber bit.

Use of 118-pt. bits were used henceforth during this year's machining operations and are recommended for use on irradiated UO_2 if dry-drilling is to be pursued for those pellets.

5.3 Pellet Backer/Stack Drilling Study

The use of backers is a technique commonly used in the machining world to reduce or eliminate chipping or blowout on a workpiece. This method implements a material in front of, or behind the area of interest for machining. Last FY this was attempted by use of a polymer block under the simulated UO_2 pellet but yielded negligible success. This time, the system was two cordierite pellets stacked atop each other, with one acting as a backer for the other. This was a benefit as it allowed machinists to see backing effects with a similar material, as well as get a better understanding of drilling behavior in larger stackups of UO_2 pellets. Across several samples, blowout was reduced when stacks of two or more pellets were implemented. While quite functional for reducing blowout on sintered and minorly cracked pellets, some blowout was unavoidable in the heavily fractured cordierite, as the smaller pieces would fly out of the top and bottom. This is elaborated on further in the section below.

5.4 Standardized Crack Development in Cordierite

Once a solid groundwork was laid for drilling uncracked cordierite, and uncracked cordierite in a stack, the need for simulating the cracking of the fuel, and the FCCI and FCMI was needed. Like in FY-21, Ceramabond 671 was utilized as the rudimentary process for securing pellet stacks inside of the stainless-steel cladding tubes. A thin layer of glue was applied on the inner circumference of the tubes cut for the corresponding pellet stacks, then pellets were slid down gently and allowed to cure for ~24 hours in a fume hood. From this point the pellet stackups needed to be crushed in a manner that could be easily repeated but was not random in application of force. After several iterations, a final methodology was developed utilizing a vice, two flat plates, and a Dillon 5000 lbf compressive force gauge. The setup is shown in Figure 11.

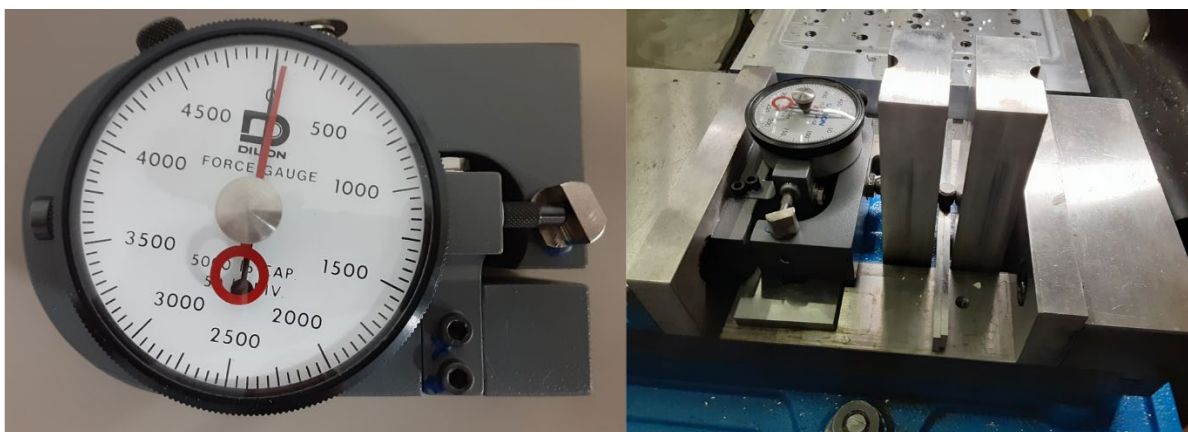


Figure 11. (Left) 5000 lbf Dillon Force Gauge used for measuring force applied before fracture. (Right) Setup for crushing pellet stack. Pellet positioned between the two flat plates was crushed axially 1–4 times in order to achieve visual similarity to cracking observed in irradiated UO_2 .

Pellet stackups were systematically crushed until audible and visual fracture was achieved, then the force was recorded, and the sample was rotated 90° before repeating the process until the desired cracking amount was observed. In the first six created pellet stacks, the force gauge method had not been implemented, and resulted in almost all the samples being over-crushed, and falling out of their sleeves during machining, or having massive dropout of material during drilling. In the second batch of samples (9-14), the two-plate + force gauge methodology was used and resulted in a more favorable and controlled experimental environment. The third batch (samples 15 and 16) implemented an additional gluing step after crushing in order to re-bond the pellets to the side of the inner cladding wall. Samples 15 and 16 will be discussed in greater depth later. The details of the forces achieved during crushing are recorded in Table 3.

Table 3. Sample crushing recipes for simulating cracks within surrogate UO_2 fuel meat.

		Number of Pellets in Stack	Maximum Force Applied (lbf)	Number of Times Crushed*
Sample Identifier	9	1	1000	3
	10	1	865	2
	11	1	860	3
	12	2	950	3
	13	2	1050	4
	14	2	1025	4
	15	2	1200	4
	16	2	2600	3

* Depicts number of times brought to force, released, rotated 90° , and repeated.





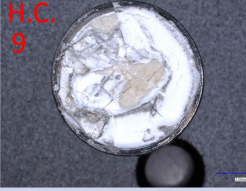







5.5 Cracked Surrogate Drilling Study

Samples 10 and 12 were drilled first with machining parameters matching that of Table 1. Sample 10 was lightly cracked to begin with and was found to drill out a clean hole on both sides quite easily, despite the uneven surfaces. Sample 12 fared less favorably and resulted in loss of the entire top pellet in the stack, and major blowout at the exit hole on the bottom pellet. Sample 12 was more fractured than sample 10, which partially contributed to the blowout. It was decided for the next four samples, we would try lowering the feed rate on the mill in order to reduce the stresses incurred on the delicate fuel meat in the center. This would hopefully prevent blowout and hole collapse long enough to perform gauge measurements or insert a sleeve to allow for thermocouple (TC) integration.

The next two samples, 9 and 14, were drilled with the same 3000 rpm speed and 0.01-in. peck rate, but with a 0.55-in./min. feed rate instead of the standard 0.75 in./min. Sample 14 was more cracked than that of 9. Sample 9 had only minor material loss on the top and bottom from loose pieces present. Sample 14 on the other hand had significant material loss at both entry and exit holes. It was thought at this point that there must be some level of fracture within the fuel that a dry-drilling method may become unsuitable due to high amounts of blowout.

The final two samples in this batch, 11 and 13, were both heavily cracked from the crushing process. The feed rate was lowered a final time to 0.45 in./min. Sample 11 underwent fracturing, but no blowout or major material loss was observed. The hole also retained its form and did not backfill after drilling. Sample 13 behaved in a similar fashion, save for the top pellet which split in two and came out of the cladding. Optical micrographs of the exit holes of each of the samples along with the machining parameters and number of pellets are shown in Table 4.

Table 4. Surrogate Cordierite samples 9-14 in their pre- and post- drilled state along the exit-hole surface as a function of mill feed rate. L.C.= light cracking, M.C.=moderate cracking, H.C.= heavy cracking.

		Single Pellet		Two Pellet Stack	
		Pre-drill	Post-drill	Pre-drill	Post-drill
Feed Rate (Inches/minute)	0.75	L.C. 10 		M.C. 12 	
	0.55	H.C. 9 		H.C. 14 	
	0.45	H.C. 11 		H.C. 13 	

Upon discussion with our machinist on these findings, these six samples pointed towards two conclusions: That lower feed rates may allow for heavily irradiated UO₂ to be dry-machined without need for cryo-drilling, and that during the crushing of these pellets, the bond (glue) is being broken between surrogate fuel and cladding inner wall. This would cause for an unrealistic scenario, in which resonance during drilling of the loose pellet could cause excessive damage to the structure in addition to loss of material.

While the issue of the bond between fuel and cladding would not be an issue with actual highly irradiated UO₂, in an effort to create as realistic of a surrogate study as possible, two more clad cordierite samples were made to address the validity of this hypothesis.

These two pellets were glued and crushed in the same fashion as the samples in batch 2, but after crushing, were glued again around their perimeter. This was done by finely painting Ceramabond 671 in the gap between the cordierite and stainless steel and allowing to cure again for 24 hours. Since the glue concealed a large amount of the pre-drilled surfaces, only micrographs of the post-drilled samples were gathered. The re-bonding greatly assisted in pellet retention during the drilling process, and hardly any blowout was seen, in addition to excellent hole retention for both samples. This is visualized in Figure 12.

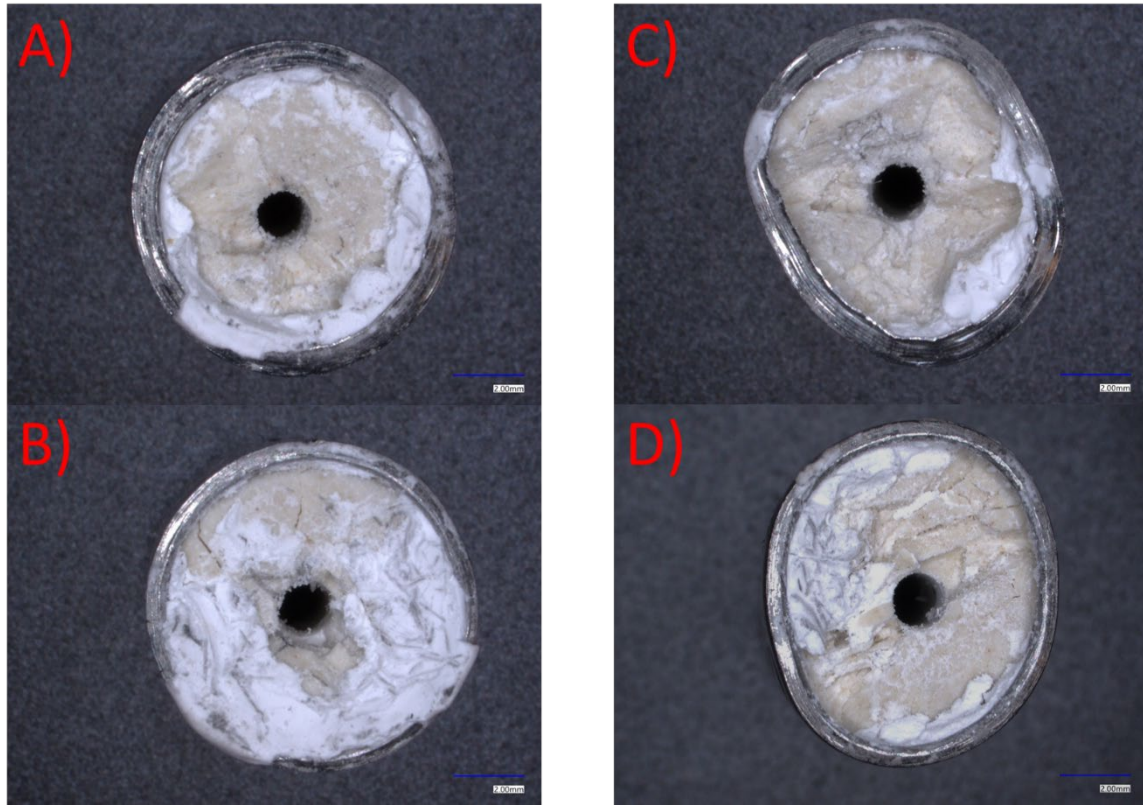


Figure 12. Top and bottom surfaces of sample 15 (A&B respectively) and sample 16 (C&D respectively) post-drilling. Both samples were two pellet stacks glued inside of stainless-steel tubing. Sample 15 was only moderately crushed, while sample 16 was heavily crushed, as noted by its visible deformation. Both samples were re-glued after crushing activities to re-bond the outer pellet surface with the cladding tube.

While it is possible that some of the glue could have improved the mechanical properties of the pellets during drilling by seeping down into and reinforcing the cracks before drilling occurred, it appears the vast majority of the glue stayed on the surface of the samples. If the stack up structure was not assisted in an unrealistic manner by the Ceramabond 671 after crushing, then drilling of irradiated UO_2 in a similarly fractured fashion should be achievable with sufficient hole retention for the implementation of a TC. Another consideration based on these results could be the implementation of a cap on the top and bottom of the drilled surface (for irradiated UO_2) in order to prevent material blowout and loss of structural integrity while drilling. This also seems to confirm the machinist's suspicion that material loss and blowout was due to inadequate bonding of the pellets to their simulated cladding. This caused increased vibration, in turn shaking large quantities of material out of the clad.

Finally, drilled hole diameter was verified using ASME B89.1.5 certified Deltronic gauge measurement pins, accurate to $+0.000040/-0.000000$ in. Gauge measurements are recorded in Table 5.

Table 5. Gage pin results for drilled holes in surrogate pellet stack ups. Drill bit used for all activities listed was a 0.0635-in. 118-pt. diamond-coated carbide bit.

		Gauge Measurement (inches)
Sample Identifier	9	0.0635
	10	<0.0613*
	11	0.0613*
	12	≥0.0637
	13	≥0.0637
	14	≥0.0637
	15	0.0635
	16	≥0.0637

* Gauge measurements smaller than the utilized bit was due to backfill of material after drilling, as recorded in FY-21 and other historical instances of dry-drilling irradiated UO₂.

Many of the drilled holes had additional clearance past the 0.0635 in. This could have been due to the loose, gravel-like pieces of the fuel were easily pushed aside to allow for larger pins to squeeze through. In all instances where ≥0.0637-in. gauge measurements were recorded, there was still a snug fit at 0.0635 in. Higher gauges were not pursued as the largest certified gage pin in the used set was a 0.0637 in.

5.6 Unirradiated UO₂ Cracking and Drilling Study

Once the investigation of the surrogate cordierite samples was complete, the next step was to implement the same methods on unirradiated UO₂ before attempting with the high-burnup fuel. Efforts primarily included the implementation of air or argon as a coolant for the mill located in the radiologically contaminated area. Since HFEF cannot utilize a water coolant in the hot cell, our efforts were to simulate that process as close to reality as possible. While hazards were addressed and work control updated, three UO₂ pellet stacks of two pellets each were glued into cladding tubes and transferred into the high-density fuels glovebox for crushing. Upon completion of work control, the pellets will be crushed under varying force conditions to see a wide spectrum of sample cracking and how it would affect the UO₂ drilling process. If favorable, then the conditions will be passed along to HFEF engineers for implementation into the mini-mill setup.

5.7 HFEF Incell Concepts for Supporting Center Holes in Fuel with Incell Equipment

Researchers at The French Alternative Energies and Atomic Energy Commission, or CEA, have been able to demonstrate the ability to drill a center hole in irradiated fuel without the needs of a cryogenic fluid system such as Halden's system. Their demonstration is documented in "*Hard Drilling Technique for Making a Center Hole of Irradiated Fuel Pellets*," written by Francis Berdoula and Karl Silberstein, which showed success of drilling in high-burnup fuels and supporting the hole with molybdenum tubing. Efforts at INL have explored methods of dry-drilling irradiated fuel within the HFEF facility. Several conceptual methods have been explored and are discussed in the following paragraphs.

High-burnup fuel has the potential to be structurally unstable due to cracks found within the fuel pellets. Drilling a center hole in the fuel poses an issue when the drill bit is removed out of the hole as the hole may cave in with the fractured fuel. This is an issue that must be considered during dry-drilling operations before a tubing can be inserted to support the fuel. This is a non-issue when the fuel is stabilized using a cryogenic fluid system to support the fuel structure. The Halden group, with their cryo-drilling system, drilled the centerline hole with a diamond hole saw and then supported the fractured fuel with a molybdenum tube. The CEA group used specialized diamond hole saws and to drill and install a molybdenum tube during a dry-drilling process. The molybdenum tube holds the drilled hole open so that a thermocouple could be inserted into the centerline of the fuel. It also serves another purpose in maintaining the fuel structure providing reliable geometry as a boundary condition when you do thermal modeling rather than having a random particle filled space.

Conceptual methods were explored to replace inserting the molybdenum tubing with another material that was ideally capable of drilling the fuel. The first concept would use a material, like tungsten carbide or polycrystalline diamond (PCD), drill the hole and leave the bit in the hole. The bit would have a hole in the center large enough to place a small 1/16-in. thermocouple. The bit would stabilize the fuel structure and provide a well for the thermocouple. However, these materials have issues that might make them unsuitable for inserting in a fuel pin and taken to very high temperature. PCD is commonly produced with cobalt which may activate during irradiations. PCD could be manufactured without cobalt, but components tend to diffuse out of the solid at temperatures around 800°C. This is a similar issue with tungsten carbide at higher temperatures. However, another issue is that these materials are not currently found in a configuration around 2.5 mm OD and 1.5 mm ID. Alternatively, stainless-steel diamond-hole saws are readily available in the desired size, but its melting point is lower than the desired temperatures for which INL plans on testing fuel pins which may result in undesirable material behavior.

A second conceptual method that is being explored is the use of a very thin-walled molybdenum tube to support the fuel structure, approximately .003-in. wall thickness. Pop rivets are a common fastener and operate by pulling a mandrel into the shank of the rivet body. The mandrel has a head on the end and is pulled into the shank which yields around the mandrel head. This deformation fastens the work pieces together. Similarly, a diamond hole saw has a small head section where the diamonds are impregnated into the bit. This piece may act as the mandrel. Likewise, a process to develop sufficiently thin-walled molybdenum tubing is being explored to create a tube that can act as the shank. In theory, the diamond hole saw can drill through the fuel and when completed, be pulled out through the molybdenum tubing that is slightly smaller than the outside cutting diameter of the hole saw. This would cause the molybdenum tubing to yield around the hole saw, leaving the tubing in the hole to support fuel.

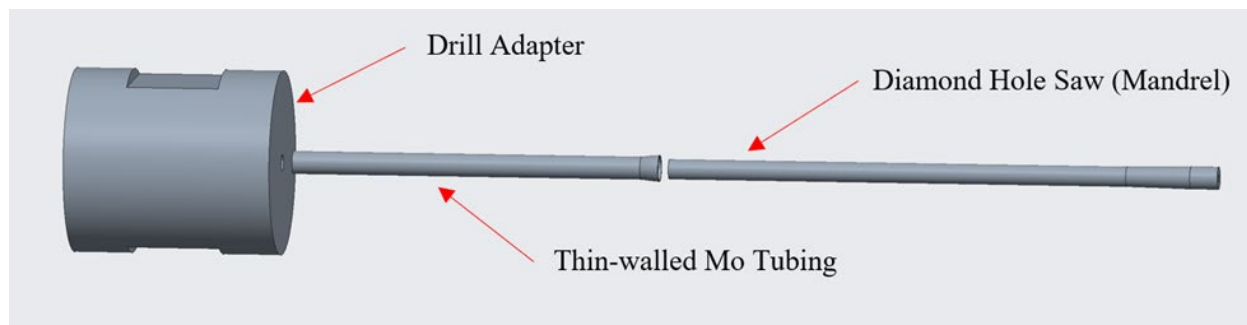


Figure 13. Exploded view of conceptual drilling method.

During refabrication work at INL in 2021, it was demonstrated that the use of an endmill can drill through irradiated UO₂ fuel at HFEF. Following this success, a similar method using the thin-walled tubing described above may also be used with a standard endmill. Before the endmill is removed from the drilled hole causing potential cave in, the tubing would be slid down the endmill if the hole is opened slightly more than the OD of the endmill. This would reduce the complexity of installing the Mo tubing and removing the diamond hole saw through the tubing. This method would provide structural support to the fuel. Though not yet demonstrated, the methods conceptualized here are planned to be further developed in FY-23.

6. Conceptual Design for Attaching Thermocouples to Previously-Irradiated Rodlets

In addition to investigation of drilling techniques for centerline TCs, a conceptual design for surface TC welding was developed and initial prototyping was started. Surface TC welding is currently utilized in fresh-fueled experiments, and this technique was adapted for remote use. However, management of thin-wire TCs completely remotely operated equipment is a major obstacle to successful completion of a TC weld on previously irradiated fuel. Direct handling of TC wire with hot cell manipulators is challenging due to reduced dexterity and wire fragility. Minimization of TC wire handling with hot cell manipulators is therefore needed to achieve consistent and repeatable surface TC welds.

Development of a modular fixture was emphasized to address these challenges, as seen in Figure 14. The TC Frame assembly can be assembled with less than size 30 AWG wire prior to integration with the pre-irradiated rodlet. The TC wires are secured to the frame with the strain relief with a slight tension. The rodlet is then mounted inside the frame and the TC wires deflect slightly to match the contour of the rodlet. A spring-loaded, pocketed heat sink is then secured to the rodlets surface around the wires. The assembly then integrates with lathe-style chuck in the Rodlet End Welding System developed in FY-21. This enables accurate angular positioning of the TC-rodlet interface relative to the tungsten electrode. Continued development and prototype testing of the fixture is aimed to continue in FY-23 using the out-of-cell weld system.

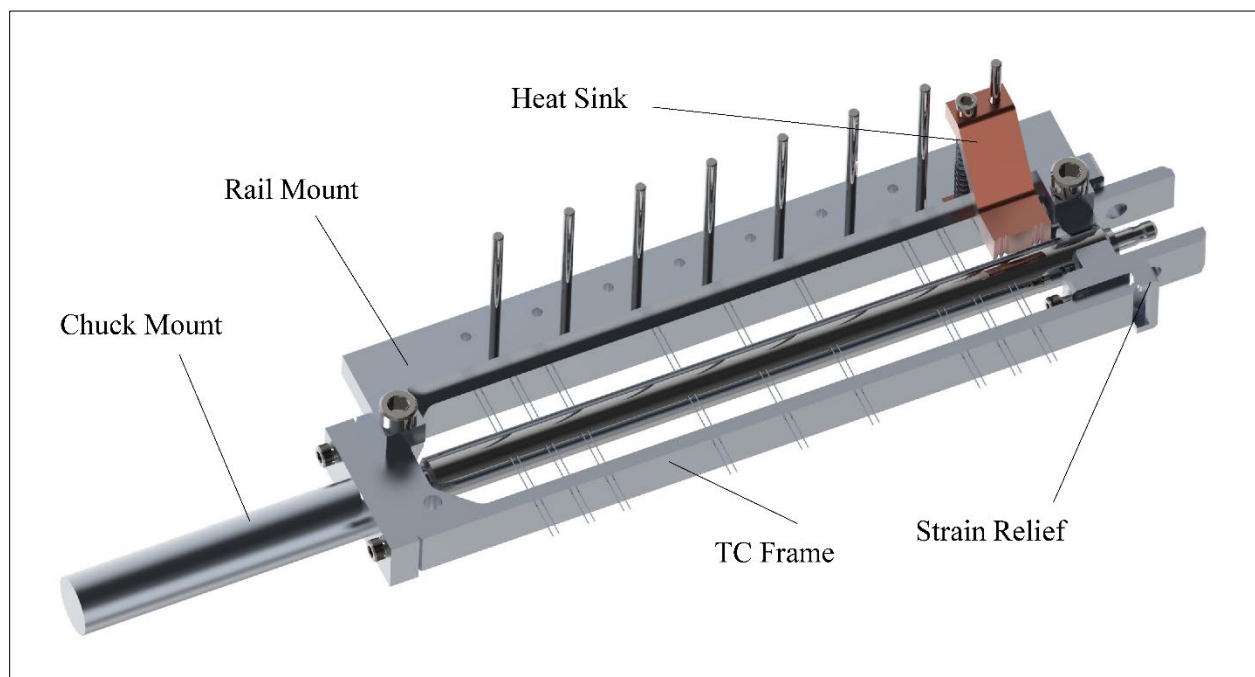


Figure 14. A representation of the prototype fixture used to weld TCs to the surface of rodlet cladding.

7. CONCLUSIONS

The loss of the Halden Reactor, and the associated knowledge and capabilities, continues to be impactful to the nuclear fuel research community. Thanks to early action and intervention, basic capabilities to refabricate fuel segments and assemble them into follow-on experimental conditions for either in-pile or out-of-pile testing is now available. As noted at the beginning of this report, Halden continued to refine and advance their refabrication and re-instrumentation capability for nearly 30 years. Embarking on this path, INL successfully developed the capability to drill centerline holes in fresh UO_2 fuel pellets to support the assembly of advanced instrumented fresh fuel rodlets for irradiation testing. INL also successfully developed a first-generation end fitting for rodlets to support fuel centerline instrumentation leads for use with fresh fuel tests.

Key takeaways for efforts in FY-22 include:

- Completing set up of the drilling and welding modules procured from Halden, and early experimental trials using that equipment. In anticipation of developing irradiated fuel drilling capabilities for centerline instrumentation in fuel rodlets, INL procured several systems from Halden including a defueling module, drilling module, and welding module. Simultaneously, INL has continued efforts to further leverage existing capabilities such as dry-drilling and the existing remote end (circumferential) welding systems to accomplish the same tasks. Learning from both systems allows for more rapid development of methods and techniques that will support eventual deployment of advanced refabrication and re-instrumentation for follow-on experiments. Notable lessons learned in this phase of development include the sensitivity of the Halden drilling system to the small braze occlusions in the bore that restricted material removal. However, it was also determined through initial engineering study, that the use of cryogenic drilling would be plausible in a hotcell environment within known facility constraints. Meanwhile, surrogate cracked fuel pellets were successfully drilled dry indicating potential for success using the existing HFEF Mini-Mill.
- Completing set up of an out-of-cell circumferential weld system to allow for further weld development to take place and support fabrication of fuel for fresh fuel experiments.
- Evaluation of the Hot Fuel Examination Facility (HFEF) infrastructure to support future installation of advanced re-fabrication/re-instrumentation equipment, specifically related to necessary infrastructure for cryo-drilling.
- Developments in dry-drilling alternative. Including experimental studies showing cordierite is the most suitable surrogate for UO_2 for performing drilling studies. That drilling performance is enhanced when a fuel-clad bonding condition is simulated.
- Conceptual design was completed for attaching surface thermocouples to irradiated fuel in support of TWIST capsule experiments. Thermocouple welding continues to be a particular challenge due to the difficulty in handling the small gauge wires. The prototype wire holder compatible with the remote end weld system has been designed and is currently being fabricated. Results of testing with this concept are eagerly awaited and will be performed during FY-23.

Space allocation for advanced refabrication and re-instrumentation remains a significant challenge. The preferred solution is the installation of a dedicated refabrication and re-instrumentation shielded cell within the TREAT Experiment Support Building. The efforts currently underway to develop the methodology and equipment to perform refabrication and re-instrumentation will facilitate more rapid deployment and readiness once space becomes available.

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