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Revision 1

Post-Halden Reactor Irradiation Testing for ATF: Final Recommendations

C. Jensen, D. Wachs, N. Woolstenhulme,
S. Hayes, N. Oldham, K. Richardson,
D. Kamerman

December 2018

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SUMMARY

For decades, the Halden Boiling Water Reactor (HBWR) in Norway has been a key resource for assessing nuclear fuels and materials behavior to address performance issues and answer regulatory questions. Halden contributions to modern global Light Water Reactor (LWR) technologies have been expansive and crucial to an industry with decreasing financial resources and fewer available test facilities. With increasing technical, financial, and political challenges, the HBWR has ceased operations and will undergo decommissioning with the loss of significant experimental capabilities for prototypical irradiation testing. This loss represents a great challenge and opportunity for swift response by the research and development community to fill the resulting capability gaps that are needed to sustain the current LWR fleet and development of advanced LWR technologies.

The primary objective of this report is to identify the core fuels and materials experimental capabilities available at the HBWR, assess potential capability gaps specifically related to the Department of Energy (DOE) Accident Tolerant Fuels (ATF) program, and provide recommendations for a path forward for the program. Since ATF technologies are intended for use in LWRs, the primary capabilities required for ATF are also highly aligned with broader LWR testing needs. The near-term ATFs and materials concepts have a goal of core batch reloads in commercial power plants by 2025 while the timeline for more revolutionary concepts extends to 2028 and beyond. Both timelines place urgency on a commitment to establishing necessary experimental infrastructure.

In general, particularly in regard to the ATF program, compensating for the loss of the Halden reactor appears to be feasible. However, the development of new capabilities will require significant investments in infrastructure and human resources within the DOE laboratory complex. No major transportation or waste issues have been found for the irradiation testing programs with the major exception of current political issues in Idaho (#5 below). Lead test materials will play a crucial role to the success of in-pile testing for LWR fuels. The primary recommendations for addressing post-HBWR testing gaps and providing capabilities that will sustain the U.S. nuclear fleet are summarized as follows:

1) **Knowledge transfer:** Halden possesses unique technologies and knowledge for testing, refabrication, and instrumentation of nuclear fuels and materials. Transfer of Halden expertise to relevant facilities should be an immediate effort going forward through collaborative partnership with DOE irradiation testing facilities.
2) **Expand LWR irradiation capacity in test reactors:** The DOE needs to increase its capacity for steady-state and *operational transient testing* capabilities for fuels within its complex. The first priority to fill the mission space voided by Halden will be the design and installation of at least two I-Loops in the Advanced Test Reactor (ATR), to be available by 2022. The in-pile loss-of-coolant accident loop in the TREAT Facility will be unique in the western world and should continue as planned to be available by 2021.
3) **Fuel rod refabrication and reinstrumentation:** Advanced fuel rod refabrication and reinstrumentation should be established to support DOE test facilities. This will allow researchers to take full advantage of Lead Test materials irradiated in commercial nuclear power plants to obtain sufficient irradiated material data in a timely manner.
4) **Reliable in-pile instrumentation to complement in-pile testing facilities:** Qualify Halden instrumentation technology as baseline capabilities to support integral fuel rod measurements.
5) **Domestic center(s) of excellence:** Consolidating irradiation testing activities to a limited number of "continental" facilities reduces schedule and shipping costs and simplifies data qualification efforts for fuel vendors, while ensuring no facility becomes a single point of failure for needed capabilities. A "U.S. Center of Excellence" requires transporting fuel from commercial reactors to INL for testing in the TREAT Facility and ATR. Therefore, the current moratorium by the state of Idaho on the receipt of research quantities of commercial spent fuel must be resolved to allow delivery of experiment sample irradiated in commercial reactors.

CONTENTS

FIGURES

TABLES

ACRONYMS

ATF	Accident Tolerant Fuel
ATF-1	Dry capsule irradiation test
ATF-2	Water loop irradiation test
ATR	Advanced Test Reactor
BR-2	Belgian Reactor 2
BWR	Boiling Water Reactor
CABRI	transient reactor facility in France
CALLISTO	Water loop testing device used at BR-2
CANDU	Canadian Natural-Uranium, Heavy-Water-Moderated-and-Cooled Power Reactor
CASL	Consortium for Advanced Simulation of Light Water Reactors
CEA	French Alternative Energies and Atomic Energy Commission
CIC	Core Internals Change-out
CIP	CABRI International Project
DBA	Design Basis Accidents
DOE	U.S. Department of Energy
ECP	Electrochemical Corrosion Potential
EIS	Electrochemical Impedance Spectroscopy
EPRI	Electric Power Research Institute
F&M	Fuels and Materials
FFRD	Fuel Fragmentation, Relocation, and Dispersal
FGR	Fission Gas Release
GAIN	Gateway for Accelerated Innovation in Nuclear
HANARO	Research reactor in Korea
HBWR	Halden Boiling Water Reactor
HFEF	Hot Fuel Examination Facility
HFIR	High-Flux Isotope Reactor (ORNL)
HFR	High Flux Reactor in Petten
HPG	Halden Program Group
HRP	Halden Reactor Project
HTTL	High Temperature Test Laboratory
IASCC	Irradiation-Assisted Stress Corrosion Cracking
IFE	Institute for Energy Technology
IGR	Impulse Graphite Reactor
INL	Idaho National Laboratory
IPT	In-Pile Tubes
JHR	Jules Horowitz Reactor
LECA-STAR	Hot cell facility in France
LOCA	Loss-of-Coolant Accident
LT	Lead Test
LTA	Lead Test Assembly
LTR	Lead Test Rod
LVDT	Linear Variable Differential Transformer
LVR-15	Research reactor in the Czech Republic
LWR	Light Water Reactor
MIT	Massachusetts Institute of Technology
MITR	Massachusetts Institute of Technology Reactor
MTR	Material Test Reactor
NEA	Nuclear Energy Agency
NEAMS	Nuclear Energy Advanced Modeling Simulation

NEI	Nuclear Energy Institute
NPP	Nuclear Power Plant
NR	Naval Reactors
NRC	Nuclear Regulatory Commission
NRG	Nuclear Research and Consultancy Group (Netherlands)
NSRR	Nuclear Safety Research Reactor
NSUF	Nuclear Science User Facilities
ORNL	Oak Ridge National Laboratory
PALLAS	Research reactor under development in the Netherlands
PALM	Powered Axial Locator Mechanism
PBF	Power Burst Facility
PCMI	Pellet-Cladding Mechanical Interaction
PIE	Post-Irradiation Examination
PIRT	Phenomena Identification Ranking Table
PWC	Pressurized Water Capsule
R&D	Research and Development
RIA	Reactivity Initiated Accident
RIAR	Research Institute of Atomic Reactors
SCK-CEN	Belgian nuclear research center
SPERT CDC	Special Power Excursion Reactor Test Capsule Driver Core
SS MTR	Steady-State Materials Test Reactor
TREAT	Transient Reactor Test Facility
TRISO	Tristructural Isotropic
TRL	Technical Readiness Level
TTR	Transient Test Reactor

Post-Halden Reactor Irradiation Testing for ATF: Final Recommendations

1. Introduction

For decades, the Halden Boiling Water Reactor (HBWR) in Norway has been a key resource for assessing nuclear fuels and materials behavior to address performance issues and answer regulatory questions. Halden contributions to modern global Light Water Reactor (LWR) technologies have been expansive and crucial to an industry with decreasing financial resources and fewer available test facilities. With increasing technical, financial, and political challenges, the HBWR will not be restarted again and will undergo decommissioning with the loss of significant experimental capabilities for prototypical irradiation testing. This loss represents a great challenge and opportunity for swift response by the research and development (R&D) community to fill resulting capability gaps in order to sustain the current LWR fleet and development of advanced LWR technologies.

One promising strategy to capture the Halden Reactor Project (HRP) capabilities to support LWR technology R&D would be direct transfer of HRP program scope to facilities with strong irradiation testing capability through the HRP joint program and/or bilateral projects (note that the HRP is an international, collaborative research program that is separable from the HBWR). In some cases, scope (i.e., tests) under the HRP program could be directly transferred to the Department of Energy (DOE) or international facilities in the near term with minimal changes to current DOE plans. Preliminary discussions with HRP leadership have been favorable toward this strategy. Accommodating other scopes would require developing capabilities, best worked collaboratively with HRP to leverage their testing experience and engineering designs and for direct knowledge transfer. *While DOE irradiation capabilities can cover many of the potential gaps created by loss of the HBWR relative to the needs of its Accident Tolerant Fuels (ATF) development program, some capabilities will require significant infrastructure and human capital investments.* The primary capabilities required for ATF are also highly aligned with broader LWR testing needs. *However, the volume of testing performed in HWBR will likely be difficult to backfill even if multiple facilities are used to fill all of the gaps, especially for the needs of the broader LWR community. Moreover, technology transfer through direct personnel collaboration should be a key part of the strategy to reduce risk and accelerate the transition from Halden to other facilities.*

The HBWR has been performing (or was planning) testing to support some aspects of the DOE's ATF program. The purpose of this report is to evaluate potential testing gaps created by the loss of the HBWR for the ATF development program and provide recommendations for filling irradiation testing capability gaps to support ATF program needs and objectives. This report represents an extension of a preliminary report [1] to provide deeper evaluation and reinforced recommendations for filling Halden gaps.

To accomplish these goals, this report summarizes key Halden reactor missions and capabilities while exploring existing international capabilities offering potential solutions to filling residual gaps, and giving special focus to irradiation testing and supporting technologies. Finally, detailed descriptions of the preliminary recommendations follow with final recommendations to ensure availability of testing facilities to support the ATF program. The ATF recommendations align with general broader LWR testing needs.

Two supporting workshops were held at Idaho National Laboratory in the summer of 2018 to address: (1) in-pile irradiation test devices at international test reactor facilities, with participants from many international irradiation testing facilities, and (2) a workshop to address the Halden Capability Gap Assessment, with diverse participation from U.S. national laboratories, Halden, DOE, fuel vendors participating in the ATF program, the U.S. Nuclear Regulatory Commission (NRC), the Nuclear Energy Institute (NEI), the Electric Power Research Institute (EPRI), the Organization for Economic Co-operation and Development (OECD), Nuclear Energy Agency (NEA), SCK-CEN (Belgium), NRG (Netherlands), and Massachusetts Institute of Technology (MIT).

1.1 Goals

The goals of this report are to:

1. Identify key R&D gaps created by the loss of the HBWR, with particular emphasis on needs of the ATF program.
2. Assess potential irradiation facilities, domestic and abroad, that can fill those gaps.
3. Provide the consensus results of a multi-organizational, international workshop on credible paths forward to fill gaps.
4. Describe relevant descriptions and preliminary detailed evaluations for credible options to fill HBWR gaps for the DOE ATF program.
5. Summarize findings and list final recommendations.

1.2 Approach

The strategy to achieve the goals of this report has been focused on the following key activities:

- Active discussions with HRP representatives including multiple reciprocal onsite meetings focusing on preservation and possible transfer of components of the HRP program, expertise in fuels and engineering, and key experiment technologies and their implementation.
- Solicitation of broad U.S. and European R&D communities with several discussions addressing potential gaps with U.S. DOE headquarters, U.S. laboratories, NEI, U.S. NRC, EPRI, and U.S. fuel vendors active in developing ATF concepts.
- Development of consensus tables that address test reactor capabilities worldwide (relevant to HBWR missions) and identification of credible experimental facilities to fill HBWR gaps. As will be shown, the framework for the latter table is derived from identifying key HBWR capabilities and the test reactor surveys. Representatives from most test reactor facilities shown in the tables provided feedback, confirmed the table input, and participated in the Gap Assessment Workshop at INL.
- Two international workshops were held at INL to receive broad input and consensus on the approach, information, and conclusions regarding the Halden reactor gap assessment including:
    - The Irradiation Rig Development, Instrumentation, and Qualification Workshop held on July 2, 3, and 5, 2018.
    - The Halden Capability Gap Assessment Workshop on July 9-10, 2018 with participation from U.S. national laboratories, Halden, DOE, NRC, NEI, EPRI, NEA, SCK-CEN, NRG, MIT, and industry teams from Westinghouse, GA, GE, Framatome, and Lightbridge (see Appendix A for the meeting objectives, agenda, and list of participants).
- Develop detailed evaluations of each identified option to fill HBWR gaps, including context and feasibility, to inform final recommendations for the ATF program.

2. Overview of the Halden Reactor Project

The Halden Reactor Project is the largest OECD NEA joint project with major R&D activities in two specific focus areas, including Fuels and Materials (F&M) with subcategories of nuclear fuel safety and operational margins and plant aging and degradation, and man-technology organization (plant monitoring and control and human factors). Since 1958, the HBWR has provided high-quality experimental results across a wide variety of fuels and materials testing objectives utilizing:

- Unique capability to perform in-reactor fuel rod measurements and to monitor the behavior of fuel and structural materials
- Flexibility and responsiveness to changes in R&D needs
- An international organization spanning 20 countries and more than 130 organizations.

The decommissioning of the HBWR particularly threatens the F&M mission, though some aspects of the program could survive utilizing out-of-pile facilities and other irradiation facilities with limited capabilities.

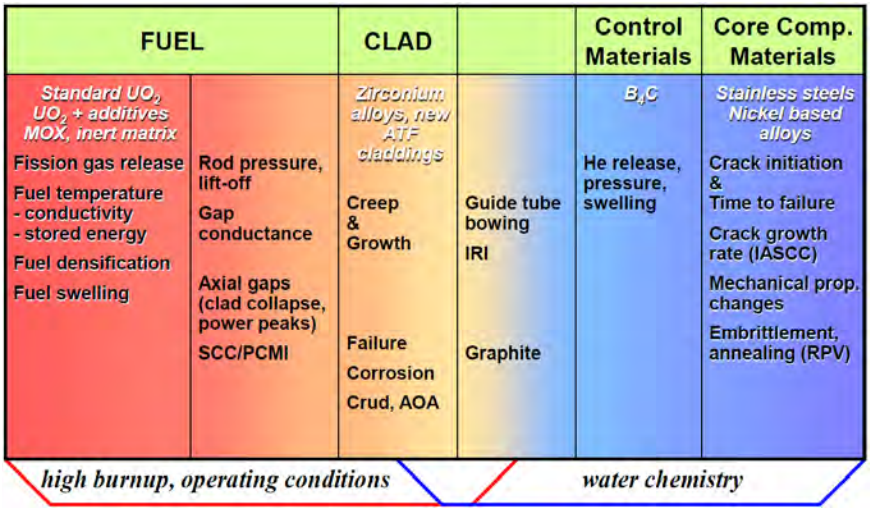
2.1 Halden Reactor Project Structure

The HRP is formally part of the Institute for Energy Technology (IFE) in Norway with 35% of its funding coming from the Norwegian government. It is administered by IFE on behalf of its international partners. The HRP utilizes an internationally comprised Board of Management to oversee responsibility for research priorities under the Joint Program while execution of the research is the responsibility of the IFE. The Halden Program Group (HPG) is an international “technical steering” committee formed from project members to provide technical evaluation and assist in preparing research programs. Since its inception, the HRP makes agreements using a three-year research program framework to commit international members to economic contributions and technical participation in the project (60% funding). Bilateral agreements made directly with specific institutions, funded in whole by those specific institutions, also play an important role in HRP activities (40% funding), although the reduction of such agreements in recent years has led to financial pressure for the HBWR under IFE.

2.2 Halden Capabilities for Fuels & Materials Testing

The HRP has developed and established unique expertise for performing reactor test irradiations on nuclear fuels. An overview of Halden capabilities presented by a representative of the IFE is found in Appendix C. In addition, other core components have been studied extensively to understand the effects of irradiation, thermal-hydraulics, and coolant chemistry. As a result, HRP personnel are highly regarded for their experience and knowledge regarding in-pile fuel experiments F&M performance insights. Along with that expertise, the unique capabilities offered by the HRP are rooted in the test reactor, which is capable of simulating prototypic operational conditions of commercial nuclear reactors, reliable and versatile in-pile instrumentation, and refabrication and instrumentation of pre-irradiated fuel rods. The HBWR is a natural circulation boiling heavy water reactor with approximately 30 experimental positions and as many as 11 experimental loops operational in the core at any given time. The thermal neutron flux is relatively low in the experimental loops at $1\text{-}5\cdot10^{13}$ $n\cdot cm^{-2}\cdot s^{-1}$.

Fuel experiments in the HBWR encompass steady-state testing for chronic dose effects (though it is not a high flux reactor) with extensive measurements of unique nuclear-thermal-mechanical-chemical-hydraulic behaviors and transient testing of fuels. Transient testing examples range from power ramps on fuel to establish fuel preconditioning guidelines, margin-to-failure testing, power-to-cooling mismatch, and Loss-of-Coolant Accident (LOCA) simulations. Important material testing capabilities well-established at the HBWR are Irradiation-Assisted Stress Corrosion Cracking (IASCC) experiments and material creep testing. Figure 1 presents an overview of the variety of testing performed at HRP.



FUEL		CLAD		Control Materials	Core Comp. Materials
Standard UO_2 UO_2 + additives MOX, inert matrix		Zirconium alloys, new ATF claddings		B_4C	Stainless steels Nickel based alloys
Fission gas release Fuel temperature - conductivity - stored energy Fuel densification Fuel swelling	Rod pressure, lift-off Gap conductance Axial gaps (clad collapse, power peaks) SCC/PCMI	Creep & Growth Failure Corrosion Crud, AOA	Guide tube bowing IRI Graphite	He release, pressure, swelling	Crack initiation & Time to failure Crack growth rate (IASCC) Mechanical prop. changes Embrittlement, annealing (RPV)

Figure 1. Spectrum of HRP fuels and materials investigations, illustration from [2]

A main feature of the HRP capability at HBWR is the in-pile LWR loops developed and refined over years of operation at Halden. The current loop design supports both Boiling Water Reactor (BWR) and Pressurized Water Reactor (PWR) prototypic thermal-hydraulic and chemistry environments. In addition to independent loop systems, the reactor operates with a coolant temperature of 240 °C, compared to most research reactors (ATR, BR-2, JHR) operating sub 100 °C, which lessens the challenge (engineering and cost) of creating prototypic thermal boundary conditions for many LWR experiments. The success of the HRP online instrumentation is closely linked to HRP capability to re-manufacture, equip and repair/refurbish instrumentation on pre-irradiated fuel rods, frequently coming from commercial power reactors. This approach allows access to data from specific fuel specimens of interest and the state of fuel at nearly any point in its lifetime. For simplification, the principal capabilities that make up the fundamental platform for HBWR testing are classified below as In-Pile Irradiation Testing Capabilities and Enabling Technologies.

2.2.1 In-Pile Irradiation Testing Capabilities

2.2.1.1 Water Loop Systems

A main feature of the HRP capability at HBWR is the in-pile LWR loops, developed and refined over many decades of use. The current loop design supports both BWR and Pressurized Water Reactor (PWR) (and Water-Water Energetic Reactor (WWER or VVER) and Canada Deuterium Uranium (CANDU) reactor designs) prototypic thermal-hydraulic *and* chemistry environments. The HRP water loop systems have a proven record of being robust and reliable. The HWBR typically operates 10 loops in the facility containing experiments. In addition to the thermal-hydraulic controls, chemistry control is a vital component of loop experimentation. The HRP has a well-established chemistry laboratory to support the loop systems.

The loops are designed to accommodate special experimental requirements including long-term burnup accumulation vs. short-term transient tests. The loops can be operated with fuel failures. Loops used for transient testing have oversized cleanup systems. Fuel secondary degradation experiments are carried out in a specific dedicated loop. As mentioned in the previous section, a variety of experiments are carried out in the HBWR loops. These experiments encompass fuel and cladding behavioral studies over long-term, steady-state irradiations looking at thermo-mechanical behavior (thermal conductivity, Pellet-Cladding Mechanical Interaction [PCMI], fuel and cladding dimensional stability), fission gas release (FGR), and cladding corrosion and creep behaviors. These experiments extend into fuel safety margin studies such as rod overpressure “lift-off,” secondary degradation, dry-out cooling transients, and power transients for

PCMI. The LOCA test facility was the only remaining in-pile capability left in the western world, critical to highlighting and investigating fuel fragmentation, relocation, and dispersal (FFRD) behavior of high burnup fuels. These loops are also commonly used to perform materials tests such as IASCC and creep testing.

2.2.1.2 Experiment Power Control for Flexible Operations (Ramp Testing and Load Following Experiments)

The ability to control specific experiment power is a key capability closely linked to the experiment design. At HBWR, a He-3 coil surrounds the fuel specimen in test devices to manipulate the local power level experienced by a fuel rod through pressure control of the He-3 gas. With this capability, power transients for experiments can be performed, supporting flexible operations (ramp testing and load following) in commercial power plants to study PCMI, FGR, and PCI-SCC. Such transients are typically responsible for fuel failures that occur and represent some of the key limitations of LWRs. The ability to maneuver specimen power is not unique to the HBWR, nor is the engineered device. Few facilities have carried out such experiments in recent times, therefore, flexible power control represents a key capability in addressing testing gaps.

2.2.2 Enabling Technologies

2.2.2.1 In-Pile Instrumentation

The HRP is renowned for success in online, in-pile measurements under prototypic LWR conditions. Key to its success is making the HRP instrumentation strategy central to all irradiation testing capabilities, from ex-reactor testing to in-reactor testing and experimental devices to interim exams, and hot-cell refabrication.

The primary instrumentation utilized in the HBWR includes thermocouples for temperature measurement (especially inside fuel for centerline measurement), Linear Variable Differential Transformer (LVDT) sensors for fuel temperature (expansion thermometer), fuel rod plenum pressure, cladding and fuel elongation measurements, and differential transformer for rod diameter measurement. The materials irradiation experiments utilize customized and well-proven techniques to measure chemistry in coolant and specimens including electrochemical corrosion potential (ECP) and electrochemical impedance spectroscopy (EIS). In addition, mechanical property measurements are made using specially-designed and proven crack propagation and irradiation creep measurement rigs. Fuel rods may also be directly connected to gas flow lines to allow online fission product monitoring or active control of gas composition in a fuel rod.

2.2.2.2 Interim Exams, Fuel Rod Refabrication and Instrumentation, and Post-Irradiation Examination

Interim inspections of experiments at the HBWR is an important and routine component of the experimental approach. Fuel rods may be removed from irradiation rigs and moved into inspection rigs in a dry handling compartment in the reactor hall. These inspections allow for several measurements to be made on the fuel samples. They also provide opportunities to recalibrate, repair, and replace instruments on the fuel and in the test device. This flexibility of frequent inspection and maintenance engineered into the HBWR experiment process is unrivaled and is key to successfully executing long-term experiments producing unique, high-value data.

The fuel rod refabrication approach is another essential ingredient in the success of the program for collecting high value data in irradiation tests. It also allows testing of fuels coming from commercial reactors for a variety of experimental needs. This capability allows preparing fuel rods from nearly any source and burnup into a form amenable to placing into irradiation test rigs. The “re”-instrumentation capability allows measurements to be made on fuel at any state of its life, alleviating the high burden on instrument technology to survive the lifetime of fuel to high burnups. For example, fuel may come from a commercial power plant or a long-term experiment irradiation that has any level of burnup. The rod is remanufactured to the desired length while installing instruments. The rod may then be reinserted into a steady-state irradiation environment or a transient test (e.g. LOCA) where measurements may be taken on the current state of the fuel.

Capabilities for hot cell examinations at the Kjeller facility are limited to basic nondestructive examination. The cells are used principally for refabrication of irradiated fuel rods into test segments and installation of instrumentation for irradiation in the HBWR. HRP may also use the Kjeller cells in the future for LOCA testing and crack growth rate measurements (IASCC) on irradiated materials. HRP currently partners with Studsvik for detailed Post-Irradiation Examination (PIE), including electron microscopy. Fuel shipments between Halden, Studsvik, and Kjeller are routine.

See Appendix C for an overview of HBWR testing capabilities.

3. Testing Considerations for ATF

This report does not intend to capture the entirety of ATF program needs or individual material needs for specific fuel and/or cladding designs. The variety of materials developed under the ATF program encompasses a wide range of Technical Readiness Levels (TRL) and, therefore, also a broad range of associated timelines for licensing and eventual commercial applications. To provide perspective, it is worth noting that the nearest-term fuel/cladding concepts generally have the goal of 1/3 core batch reloads by approximately 2025 (~5+ years), while more revolutionary concepts look to 2028 and beyond (~10+ years). The process of performing experiments, PIE, data analysis and synthesis, and regulatory assessments makes these timelines aggressive, placing urgency on identifying appropriate experiment pathways and executing experiments as expeditiously as possible. However, it is important to note that considerable experimentation for the ATF program has already been initiated and is ongoing at several DOE reactor/hot cell facilities. Also, Lead Test (LT) material insertions in commercial power reactors are now beginning.

With a variety of fuel concepts each at varying TRLs, it is also critical to point out that the development of modern LWR fuels resulted from a host of experiments ranging from out-of-pile to in-pile, separate effects to integral effects, spanning many decades of R&D. Due to the advanced understanding and advanced state of modern LWR fuels, current R&D for LWR fuels and materials testing is concentrated on highly prototypic experiments that provide continued reduction of uncertainties. Historical experimental programs were developed to provide a variety of testing configurations, from narrow separate effects to highly integral, allowing for efficient, cost-effective, high throughput experimentation to study a wide range of phenomena and experiment parameterization. For example, the SPERT CDC program, focused on Reactivity Initiated Accident (RIA) behavior, performed hundreds of experiments in less than three years, studying effects of energy deposition, rod length, cladding materials, cluster effects, and low burnup irradiation effects. This testing formed the foundation for the initial regulatory criteria for LWR fuels and provided the key understanding of fuel behaviors under these conditions. Later testing in NSRR and in highly prototypic tests in PBF, extended the database and continued refinement of models and uncertainties. With higher TRL materials, the push for higher burnups, and the loss of the prototypic PBF facility, RIA testing needs evolved to requiring more prototypic testing conditions, which resulted in the installation of the PWR water loop at CABRI.

The push toward prototypic experiments is extremely important for optimizing technology performance but naturally leads to higher costs and slower execution of experiments. Out-of-pile tests have always and continue to play an important role in bridging the experiment gap for separate to integral effects. Still, the need for in-pile facilities that can play a similar role of rapidly assessing various performance variables, as was done historically, for lower TRL technology should be a recognized testing gap for ATF materials, evidenced by the historical record. To achieve similar high-performance to modern LWR fuels, ATF materials will also need highly prototypic testing environments coupled with state-of-the-art and advanced diagnostics and modeling and simulation tools. Prior to the closure of the HBWR, the DOE was already working on this strategy with experiment capabilities being developed at the Transient Reactor Test

(TREAT) Facility and the Advanced Test Reactor (ATR). As described in later sections, the loss of the HBWR has created gaps and, in other cases, has placed greater emphasis on the acceleration of preexisting plans. This report does not detail all developing capabilities but focuses on crucial gaps left by the HBWR loss.

When considering potential testing gaps created by the loss of HBWR, distinguishing between specific data streams, experiment and data objectives, infrastructure, strategy, and process can be quite difficult and confusing. In this report, the primary focus is on core capabilities that are unique to the HBWR testing program that are foundational to enabling similar data objectives. These capabilities were identified, classified, and described in Sections 2.2.1 and 2.2.2.

Specimen quantities (total experimental capacities) for ATF is an important consideration not fully captured in this report, but it is the subject of ongoing planning. As a test reactor that has been totally dedicated to an LWR testing mission, the HBWR has a large testing capacity, including 10-11 LWR loops and up to a total of approximately 30 other testing positions, that will be a challenge to replace even across multiple test facilities for broader LWR R&D needs. However, for the ATF program, an important conclusion is the critical importance of LT fuel rods and associated materials, not only to provide operational data, but also to serve as a source of irradiated fuel rods available for PIE and for follow-on experiments such as power ramping and design-basis accident experiments. With the reduction in volume of irradiated fuel specimens caused by the loss of Halden, the utilization of LT materials for subsequent testing must be a fundamental component of developing a detailed strategy for fuel qualification going forward.

This document does not provide detailed specification of all experimental programs needed by all ATF developers. With Phenomena Identification Ranking Table (PIRT) studies beginning during this past year by different organizations, it is recommended the experimental programs form on the basis of the PIRT results. Since the preliminary evaluations were performed, the OECD has also released a State-of-the-Art Report for Accident Tolerant Fuels that also provides detailed overview of the ATF technology, useful for planning strategies [3]. Instead this report focuses on the general capabilities, particularly HBWR gaps, needed to satisfy testing needs. These capabilities will provide the primary foundation to meet the needs of the ATF program, which is also congruent with broader LWR fuel testing needs.

4. Post-HWBR Irradiation Testing Gap Assessment for ATF

One of the primary goals of this study was to develop a consensus on capability gaps (especially relative to ATF needs) and potential credible approaches to fill those gaps that will require more detailed investigations. This section summarizes the results of a detailed evaluation of testing capabilities at HBWR and potential facilities that can fill gaps of capabilities required for the ATF program. The approach used to arrive at the consensus table is described in Section 1.2.

Figure 2 presents a mapping of the core capabilities provided by the HBWR identified in Section 2.2 to corresponding testing categories to meet experimental needs. The categories on the right side of the table include capabilities that are not specific to the HBWR. These additions deviate a bit from the stated purpose to address HBWR gaps but are included here for the sake of representing some of the breadth of testing available. Many of those are already being used as key capabilities that can aid in meeting ATF objectives and represent classifications of capabilities available at various research reactors.

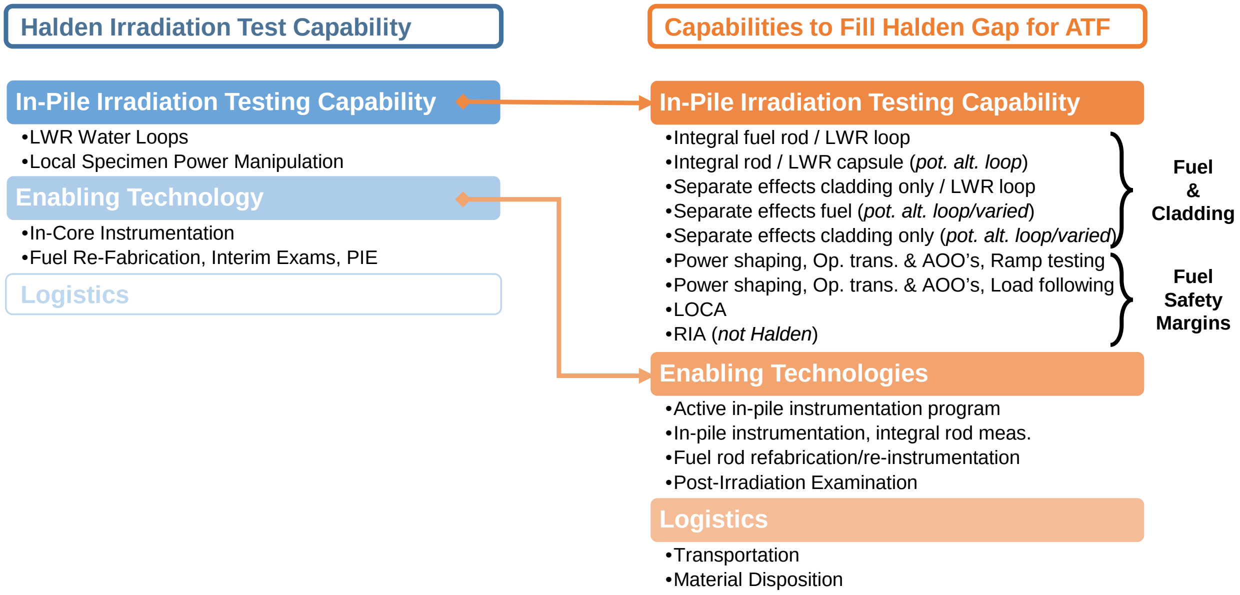


Figure 2. Mapping irradiation capability at Halden to categories for evaluating material test reactors.

A breakdown and descriptions of the categories shown in Figure 2 (used in the consensus table introduced later) follows.

- In-pile Irradiation Devices

  The primary device used for testing fuels and materials at HBWR are the ~10 LWR loops used in the reactor at any given time (see Section 2.2.1.1 for HBWR loop overview). The consensus table includes a category corresponding directly to this capability. It also highlights specific capabilities supporting various levels of testing integrality as capability sub-tiers. Capabilities needed for long-term fuel and cladding studies are included in the first five rows in this category (some may also couple with power-manipulating devices in the next category). Important distinctions are made between integral rod and separate effects fuels and cladding testing. In addition, distinctions are made between the thermal-hydraulic boundary conditions provided by different capabilities such as loops, capsules, and other separate effects devices. The last four categories represent capabilities needed for evaluating fuel behavior in power-cooling mismatch scenarios, which enables research in fuel safety margins, scenarios encompassing a range of transient conditions from operational transients, to Anticipated Operational Occurrences (AOO), to Design Basis Accidents (DBA). Ramp-testing and load-following capabilities are separated into distinct categories to represent a subtle difference in preconditioning and/or testing duration. Ramp testing may be viewed more as individual transient events, whereas load following would be more cyclic and long-lasting in overall duration.

- Enabling Technologies

  This category covers several unique capabilities that are essential complements to the in-pile testing strategy. In-pile instrumentation is a broad category with many nuances related to particular experiment objectives and approaches. Most test facilities evaluated here have some level of advanced instrumentation capabilities as will be seen in the consensus table. A second category was created to provide distinction for instrumenting integral fuel rods, as that represents a core capability distinction of the HRP, and is of particular interest for ATF.

- Logistics

  Logistics details related to the HRP are not presented in this report, except that fuel shipments between Halden, Kjeller, and Studsvik facilities are routine. The objective in this area was to capture specific nuances related to the individual test facilities. In reality, the logistics required for the ATF program are a complex issue that should not be overlooked. Some aspects of relevant logistical considerations are described in Section 6.4.

As described in Section 1.2, the approach used in this study focused on establishing an accurate compilation of key characteristics of existing irradiation facilities worldwide that could feasibly be used in support of the DOE-sponsored ATF program. The focus of this survey was on steady-state material test reactors and transient test reactors with capabilities that are relevant to HBWR and ATF testing capabilities. These tables were both verified and expanded by representatives from most of the listed facilities. They were also reviewed by participants at the Halden Capability Gap Assessment workshop held at INL. The resulting tables are shown in Appendix B. Table B1 focuses on steady-state material test reactor specifications while Table B2 provides a brief overview of crucial supporting technologies, transportation, and waste considerations. Table B3 shows information related to the transient test reactors.

The resulting consensus table (based on feedback and consensus at the Halden Capability Gap Workshop described earlier) was formulated from the previously mentioned description of HBWR capabilities, ATF testing needs, and international Steady-State (SS) Material Test Reactor (MTR) and Transient Test Reactor (TTR) capabilities. Table 1 presents the resulting evaluation of Halden capability gaps relative to ATF and corresponding reactor facility evaluations. A table key is shown in the upper left corner, and is used to evaluate each facility's capability for a given mission. The table key is divided into five categories to distinguish whether a capability is currently available, not available, designed or in design, used historically but not currently operational, or remains uncertain. Other categories could exist but were not included to avoid excessive complication in the table. Two caveats are also given with asterisks denoting some limitations relative to comprehensive, "state-of-the-art" capability and a special note highlighting out-of-pile capability at the same site.

Lead Test materials (LTR/LTA) are represented in the table as they are increasingly recognized as crucial means to obtaining more specimens for PIE and fuel safety testing. The reactors are shown corresponding to distinct classifications. Primary reactors considered in the table include the ATR, the High Flux Isotope Reactor (HFIR), the Massachusetts Institute for Technology Reactor (MITR), the Belgian Reactor-2 (BR-2), the High Flux Reactor in Petten (HFR), the LVR-15 reactor, the Hanaro reactor, the TREAT Facility, the CABRI reactor, the Nuclear Safety Research Reactor (NSRR), and the Impulse Graphite Reactor (IGR). To be more comprehensive, future test facilities, the Jules-Horowitz Reactor (JHR) and the Pallas reactor, are also represented in the table, though they are not viewed as feasible options for near-term ATF needs due to the timeline associated with their startup and eventual availability for fuel testing. Certainly for longer-term consideration, they hold very important potential, and establishing more than a single solution should be considered paramount by all materials-testing stakeholders. After completing the table using the metrics described, credible capability options for ATF were highlighted in yellow in the table.

Table 1. Consensus table for capabilities to fill post-HBWR R&D needs with capabilities utilized by ATF. Highlighted boxes represent credible capability pathways. Note: see bullets in preceding text for a description of capability categories.

Table Key

Available	Y
Not available	N
Designed or in design	D
Historical	H
Unknown/Uncertain	?

* Limited (capacity, size, etc.)
** Out-of-pile capability

			Operating SS MTR							**Not Yet Operating**		**TTR**			
		LTR/ LTA	**ATR**	**HFIR**	**MITR**	**BR-2**	**HFR**	**LVR-15**	**HAN-ARO**	**JHR**	**PAL-LAS**	**TREAT**	**CABRI**	**NSRR**	**IGR**
In-Pile Irradiation Testing Capability	• **Integral fuel rod / LWR loop**	Y	Y,D	N	N	D	H	N	Y	D	D	D	Y	Y	N
	• **Integral rod / LWR capsule (*pot. alt. loop*)**	n/a	N	D	N	Y	Y	N	N	D	D	Y	n/a	n/a	H
	• **Separate effects cladding only / LWR loop**	Y	Y,D	N	Y	D	H	Y	Y	D	D	n/a	n/a	n/a	n/a
	• **Separate effects fuel (pot. alt. loop/varied)**	n/a	Y	Y	Y	Y	Y	N	Y	D	D	Y	n/a	n/a	n/a
	• **Separate effects cladding only (pot. alt. loop)**	n/a	Y	Y	Y	Y	Y	Y	Y	D	D	n/a	n/a	n/a	n/a
	• **Power shaping, Op. trans. & AOO's, Ramp testing**	N	H,D	N	N	Y,D	H,D	N	N	D	D	Y	Y*	N	Y
	• **Power shaping, Op. trans. & AOO's, Load following**	N	H,D	N	N	Y,D	H,D	N	N	D	D	N	N	N	N
	• **LOCA**	N	N	N**	N	H,D	H	N	N	D	N	D	D	N	N
	• **RIA (*not Halden*)**	N	N	N	N	N	N	N	N	N	N	Y,D	Y	Y	N,H
Enabling Tech.	• **Active in-pile instrumentation program**	N	Y	Y	Y	Y,H	Y	Y	Y	D	D	Y	Y	Y	Y
	• **In-pile instrumentation, integral rod meas.**	n/a	H,D	D	N	H,D	H	N	Y	D	D	Y	Y	Y	N
	• **Fuel rod refabrication/re-instrumentation**	n/a	D	D	N	Y	N	N	Y?	Y	N	D	Y	Y	N
	• **PIE**	n/a	Y	Y	Y*	Y	Y*	Y*	Y	Y	Y	Y	Y	Y	N
Logistic	• **Transportation/Shipping**	-	Requires further evaluation for individual facilities and specific requirements — see text discussion							-	-	-	-	-	-
	• **Waste/Disposition**	-								-	-	-	-	-	-

The consensus table shows capability coverage over all categories listed in the table. In fact, the table shows good coverage across all categories by continental regions for U.S., European (even greater considering JHR and PALLAS), and Japan/South Korean facilities. The ATR and BR-2 reactors show wide-ranging capabilities, but especially crucial capabilities in the area of integral fuel rod testing, the primary HBWR gap and an important area for the ATF program. Capacity limitations in these facilities (not fully addressed here and expanded when considering beyond ATF needs) mean that testing needs would likely be best distributed among facilities, matching needs with unique strengths.

In the category of In-Pile Irradiation Testing Capabilities, some conclusions from the table are:

- ATR currently has the only operating pumped PWR loop for integral fuel testing; note that pressurized water capsules have inherent physical limitations, but can serve an important role, though researchers will be limited in terms of testing goals
- Nearly all test reactors in the table can do separate effects cladding testing
- Few reactors have LWR loop capability (probably representing only half of the HBWR capacity combined)
- No facility is currently capable of performing operational transients, though BR-2 has a capability that they expect to recommission in the near-term
- No in-pile LOCA testing capability exists today, although a few are in design and could be available in the near-term. Oak Ridge National Laboratory (ORNL) (and Studsvik) have out-of-pile LOCA testing capability that should be used in concert with complementary testing from in-pile facilities. The in-pile capability is expected to be especially important for testing related to extending margins or unknown behaviors related to new materials.

In the second category, Enabling Technology, the following deductions are made:

- All facilities show capability for use and availability of advanced instrumentation, though the distinction related to integral rod measurements provides some differences. Still, no facility has an in-pile instrumentation capability as mature as that of HRP.
- Fuel rod refabrication is available or is planned to be available at several essential facilities.
- PIE capabilities are generally available at reactor testing facilities but generally correspond to the type of irradiation capability available at a given facility. In the U.S., INL and ORNL provide comprehensive capabilities.

The last category in the table, Logistics, requires further investigation and detailed consideration, especially when making final recommendations (and subsequent decisions) for paths to pursue. The only facility that presented a known, potentially major issue is INL with shipping spent nuclear fuel into the state of Idaho. A more detailed summary is provided in Section 6.4.2. Important points to note include:

- The current Idaho state government has agreements in place with DOE that do not allow importing commercial spent fuel into the state. An allowance is made for "research-quantities" (sufficient for R&D) of commercial spent fuel to come into state, which is currently on hold due to DOE failure to meet obligations to begin operating a waste processing facility on the INL site. It is crucial for DOE-State of Idaho issues to be resolved in a timely manner in order to allow materials from commercial reactors to enter Idaho; this is essential for the ultimate success of the ATF development program.
- Some European facilities have expressed some limitations related to bringing "exotic" materials into their facilities due to the fact that the disposition path for them has not been resolved. In these cases, unless the quantity is small, generally the material cannot be retained by the facility.

- The availability of shipping casks represents a concern for some facilities but ultimately depends on the types of materials that are desired for testing. A summary of recommended shipping casks for different classifications of shipping will be included in the final report. The shipping of materials within the U.S. is not expected to be an issue, except possible cask or receiving limitations of a given facility. Preliminary findings indicate that capabilities at facilities align with shipping capabilities (e.g. full-length rods would be shipped to and utilized at INL and ORNL where handling facilities and casks are available).
- A strategy relying on routine international shipping is of considerable concern due to the potential high costs and long-lead times, and country-specific logistical issues associated with such an approach.

The strategy of forming irradiation testing centers by continent (i.e. a North America-based platform with ATR and the TREAT Facility as the foundation, and BR-2, JHR, and CABRI facilities forming the European base) is an important recommendation for ATF and broader LWR R&D needs, shared by many vested parties. This approach minimizes international shipments and simplifies the logistics of testing. It also creates a redundancy in testing capabilities to prevent single point “failures” or losses in international testing capabilities. Accident tolerant fuel vendors specifically recommended this approach and the OECD NEA also shared similar ideas about addressing post-HBWR testing needs internationally. No party has expressed a differing opinion about this idea. Of particular importance to the DOE ATF program, U.S. fuel vendors have emphasized the desire to build and maintain relationships with key test facilities in the U.S., with interest in consolidating the organizations involved to encourage strong technical relationships and to minimize the burden of data supplier qualifications across multiple organizations.

5. Preliminary Recommendations

Based on the previous sections, a list of preliminary recommendations was created for further evaluation. A preliminary finding of the study was that the closure of the HBWR does not represent a significant threat to the goals of the DOE ATF program, though without action, it could lead to difficulty in achieving the performance potential of ATF. The following list of recommendations resulted from the preliminary study with detailed discussion to follow in Section 0.

Partner with HRP to transfer expertise and technology for experiments and instrumentation in each of the following areas:

1) Establish fuel rod refabrication and reinstrumentation capability as Lead Test materials are crucial for the success of experimental programs at the national laboratories
2) Expand testing capability in prototypic loops for increased experimental capacity
3) Investigate capability for flexible power operations for experiments in ATR and BR-2
4) Accelerate development of TREAT LOCA capability
5) Develop overall instrumentation strategy for in-pile testing while continuing qualification of Halden sensor technology for use in U.S. test reactors
6) Expedite resolution of state of Idaho moratorium for bringing research quantities of commercial spent fuel into the state for experiments conducted in commercial reactors.

6. Discussion of Recommendations

6.1 LWR Fuels Testing and Program Structure

The Halden Reactor Project under the NEA has evolved into the beacon of collaboration for industry, and an in-pile testing R&D provider. The risk of losing the program structure and IFE staff would arguably be the greatest loss as they are a primary reason for the great success of the program. The HRP evolved to become an efficient testing program, with appreciated and respected interaction throughout international R&D facilities, fuel vendors, utilities, and regulators worldwide. Even within DOE programs, organization principles embodied by the Halden model could serve to pave a path toward greater collaborative success in the U.S. nuclear energy community. Programs such as the Light Water Reactor Sustainability (LWRS), ATF, and Consortium for Advanced Simulation of Light Water Reactors (CASL) and Nuclear Energy Modeling and Simulation (NEAMS) programs are examples of great success of DOE and segments of the LWR industry working together. The Gateway for Accelerated Innovation in Nuclear (GAIN) and Nuclear Science User Facility (NSUF) programs have created opportunities for industry to have access to unique R&D facilities and valuable scientific expertise. However, the HRP provided a unique technical bridge between the R&D, regulatory, technology development and technology user communities. The DOE could facilitate a similar program structure that can fill this integration and leadership gap for the U.S. LWR in-pile fuels and materials technology development enterprise.

Halden led such an effort by working closely with its many participants to ensure meaningful and challenging questions and needs were met for the industry. Joint project participants could individually and independently contribute to the program direction and benefit from the results without revealing trade secrets or proprietary technology. This structure also allowed the NRC to actively participate in the joint research projects. These projects are considered independent enough to limit the amount of confirmatory testing required to support regulatory approval of new technologies or methods, thus accelerating their acceptance and deployment.

These participants gained a confidence in Halden that also sowed the seeds for many bilateral projects to support proprietary needs. No current DOE program is tasked with providing such a framework that enables the public/private partnership at this scale, especially for non-ATF LWR fuels and materials studies such as burnup and enrichment extension R&D. The U.S. DOE has the technical resources (independent expertise and unique facilities) to provide the organization and leadership for such a program that would recover a crucial gap created from the HBWR loss and meaningfully strengthen the competitive position of for the U.S. nuclear industry for decades to come.

6.2 Lead Test Materials

Over the past several decades, commercial nuclear power plants (NPP) have provided the source materials for much R&D that has been crucial to technology development, especially since the 1980s. To gain operating experience and investigate fuel compatibility, LT programs have typically been used by utilities to introduce new fuels into NPP. In the U.S., the LTR or LTA must undergo a safety evaluation governed by the requirements of 10 CFR 50.59 to evaluate the impact of the limited use of a new technology or performance on the overall safe operation of a plant. For ATFs, irradiation and evaluation of LTA materials have long been seen as significant measures of success for the DOE ATF program. This goal has already been accomplished with LTA materials and will continue to be fulfilled with a variety of ATF program fuel concepts, beating the original target of insertion by 2022. To fully conduct this evaluation, these materials will be required to undergo subsequent in-canal examination, post-irradiation hot cell examination, and safety testing.

The irradiation performance data collected using the LTs is critical to complete technology development and to establish a licensing basis for its routine use. Even with the HBWR, the availability of sufficient data without LT materials is questionable due to the short timelines and limited testing capacity and resources around the world. Halden began ATF irradiations, but tests were cut short or postponed following the reactor closure. ATR is currently irradiating materials in dry capsules (ATF-1) and in a flowing water loop (ATF-2). A variety of separate effects experiments on fuels and claddings are being carried out at ATR, the TREAT Facility, HFIR, and MITR already. Still, the need for integral fuel rods irradiated to various burnup levels for PIE and follow-on testing creates a clear need to capitalize on LT materials.

The technical R&D programs for ATF concepts are led by ATF vendors. Still, in the context of limited resources, the necessary involvement of DOE facilities, and the high importance of LT materials to ATF schedule success, the following recommendations are made regarding planning for LT programs:

1. ATF vendors must coordinate closely with DOE R&D facilities that are planned for follow-on experimental programs and/or PIE as soon as possible.

Coordination should extend to the level of experiment design to ensure that LTA materials are compatible with existing handling and experimental devices. Specimen dimensions, material types, planned burnups, and availability schedules are crucial to assuring readiness of experimental facilities including test reactor facilities and required instrumentation capabilities. This discussion should extend to transportation planning as will be discussed in Section 6.4.1. DOE program leadership in the laboratories should be provided with information to form a consolidated list of this information from all fuel vendor participants.

2. LT materials can provide data through a variety of means, but online instrumentation is not considered a major priority for NPP installation for DOE due to planned availability of refabrication equipment.

LT materials should be considered for a variety of follow-on experimental activities beyond PIE. Interim inspections and PIE will provide needed data following the “cook-and-look” approach to irradiation testing. Online measurement should be obtained from refabricated fuel rods that will allow access to view the state of fuel rods at any point of their lifetimes. Lead Test materials and materials from ATR can be refabricated for continued irradiation in ATR, the TREAT Facility, or out-of-pile experiments. Focused in-pile instrumentation capability in test reactor applications should be the first priority. The refabrication and reinstrumentation capability is discussed in detail in Section 6.3.1.

3. Post-NPP irradiation experimental programs for LT materials should consider operating conditions used in the LT programs.

Most LT programs involved placing materials in non-limited core power locations to show existing fuel bounds the LT materials. The planned operational power history of the fuel should be considered for the planned data outcomes, as they may not result in the bounding results that are desired for drawing operational or safety limits. For example, the initial power history can play a significant role in following experimental studies such as transient fuel performance, depending on the case, to improve or to degrade performance. This recommendation should also be considered in the context of #1 (above) in working with DOE experimental facilities.

4. Planning should consider strategic use of materials irradiated in MTRs (ATR) in conjunction with materials coming from LTs.

With limited availability of materials, comparative testing of materials from independent sources can provide meaningful improvement in understanding and reducing uncertainty in material behavior. The ATF-2 experiment is planned to include baseline UO2/Zry rods for reference for the experiment. Of course, with this approach, there is a risk that results may not coincide, though such risk should be viewed as unavoidable and desirable. This approach will provide greater confidence in results coming from NPPs and MTRs, providing an improved and accelerated basis for qualification of combined data coming from each source.

To address these recommendations, ATF vendors and DOE should develop a joint test plan that demonstrates the integration of the LTA irradiation testing strategies to ensure timely execution of complex multiorganizational, multifacility activities.

6.3 Experimental Capability Gaps

The primary experimental capability gaps created by closure of the HBWR have remained the same since preliminary evaluations performed earlier this year. This section provides a more detailed evaluation of the approaches recommended following the joint workshop and document in INL/EXT-18-46101 and summarized in Section 5.

6.3.1 Fuel Rod Refabrication

The high importance of LT materials to the goals of the ATF program aiming for full batch reloads from 2025-2030 are discussed in Section 6.2. In some cases, it may be possible to design LT configurations that are directly compatible with experiment devices. However, this approach is not preferred due to the inflexibility it provides over a multiyear, multiorganization program. Therefore, a crucial capability to supporting testing of ATFs includes the ability to process preirradiated fuel rods of any length to achieve the desired form factor and include instrumentations providing online measurements. Figure 3 provides a description of the refabrication process that links preirradiated rods to further in-pile testing in SS MTR or TTR with online measurements.

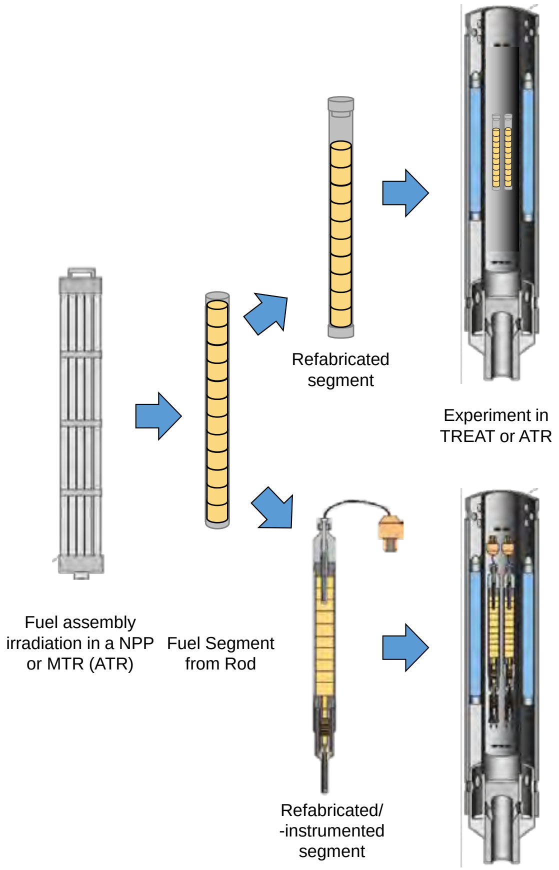


Figure 3. Refabrication process for testing rods previously irradiated rods. (Figure adapted from presentation by Thoresen, H., Halden Capabilities Gap Workshop, 2018, see Appendix C).

For more than four decades, fuel rod refabrication has played a major role in advanced LWR fuel R&D. Many early fuel experimental programs relied heavily on follow-on testing of materials irradiated in test and prototype reactors. In the U.S., the Special Power Excursion Reactor Test Capsule Driver Core (SPERT CDC) program performed transient experiments (RIA type) on rods that were irradiated in ETR that provided means to measure fuel and cladding expansion [4]. Later, by the mid-1970s, the Power Burst Facility (PBF) was performing transient experiments on rods from the Saxton PWR. These experiments included configurations containing fresh rods, previously irradiated and repressurized rods, and previously irradiated and repressurized rods instrumented with rod internal pressure sensors, rod plenum temperature sensors, cladding elongation sensors, and cladding surface thermocouples [5]. Several other test reactors have utilized similar experiment designs requiring remanufacturing of fuel rods since the early testing programs. In many cases, the specimens were largely kept intact (prefabricated to the desired length) but utilized a variety of instruments attached after base irradiation. Section 6.3.5 provides a more detailed overview of in-pile instrumentation.

The Risø reactor in Denmark forged the capability to refabricate fuel rods including insertion of instruments into the fuel for follow-on experimentation. Their process represents an elegant solution to the problem of minimizing impact on delicate high burnup structures and constituents [6]. This “reinstrumentation” approach engineered at Risø was transferred to Halden in the early 1990s with the closure of Risø imminent and tested extensively for qualification between those programs. It has since been used on hundreds of rods at Halden, and the technology has been transferred to other international facilities. At its core, the Risø process utilizes a process of filling and freezing the rod with CO2 to drill the central hole in the fuel. The state-of-the-art Halden reinstrumentation process entails the following:

- Neutron radiography to identify desired test segment and pellet locations for setting the depth of thermocouple hot junction into a pellet center
- Cutting the rod to length and drilling the fuel out at the ends of the rod
- Removing oxide layer from the cladding inner and outer end surfaces
- Filling the rod with liquid CO2 and freezing in liquid N2
- Drilling the central hole in the fuel and insertion of chemically-compatible molybdenum tube
- Slow return to room temperature, outgassing in vacuum at 300°C
- Insertion of centerline thermocouple into fuel stack
- Welding rod end plug into place, followed by multiple cycles of evacuation and refilling of the rod with inert gas, with a final specified pressurization and seal weld
- Helium leak check and thermocouple checkouts
- Neutron radiography of the assembly.

Variations of the technique have evolved over time. The French Alternative Energies and Atomic Energy Commission (CEA) have also developed an approach to reinstrumentation at the LECA-STAR Hot-Cell Facility with the objective of avoiding the cryogenic freezing process [7]. Still, no facility except Halden has accumulated the experience in the refabrication process and in-pile testing of irradiated rods. For this reason, Halden has designed and produced multiple refabrication and reinstrumentation systems that have been sold internationally. The primary instrumentation utilized in refabricated fuel rods includes fuel centerline thermocouple, rod pressure sensor, cladding or fuel elongation sensor, cladding thermocouples, and gas flow lines into the rod to control internal pressure and composition.

6.3.1.1 Overview of Refabrication Strategy to Support U.S. Testing

Fuel rod refabrication and reinstrumentation facilities are a recognized capability gap supporting major DOE fuel irradiation testing facilities. Fuel rod refabrication capabilities are an enabling technology supporting follow-on integral testing. For this reason, it is most desirable to have required facilities collocated with the testing facilities to avoid additional logistics and shipping requirements. SCK-CEN (Br-2) has purchased refabrication capabilities from Halden but they have not yet been installed. The CEA in Cadarache (CABRI and JHR facilities) have facilities that have been used to prepare the current series of CABRI International Project (CIP) experiments. They will likely be used to prepare specimens for future experiments in CABRI and JHR as well. Recently, ORNL successfully demonstrated aspects of refabrication for in-cell mechanical testing of pre-irradiated materials and plans to use the process to support integral LOCA experiments on a rod from the North Anna NPP with average burnup of 67.3 GWd/MTU [8]. The demonstrated process is adapted for the needs of the LOCA test facility at ORNL without the step of repressurizing and sealing the rod, a requirement for many other types of tests.

For in-pile testing (Halden program) and the emphasis of programs at ATR and the TREAT Facility, fuel rod refabrication capabilities are not currently available. These capabilities have long been planned as part of the ongoing program to restart the TREAT Facility [9]. The uncertainties addressed by this report provide further emphasis and prioritization for establishing advanced capabilities to support testing at the TREAT Facility but to also provide means for refabrication with state-of-the-art instrumentation and re-irradiation in the ATR.

6.3.1.2 Recommended Refabrication Strategy

Refabrication and reinstrumentation technology should be established as a core capability needed to support advanced irradiation testing programs at the TREAT Facility and ATR, and possibly HFIR and other out-of-pile integral testing (e.g. LOCA furnace at ORNL). This capability extends beyond the context of the Halden mission to support other advanced fuels and materials R&D as well. Since the announcement of the closure of HBWR, an accelerated collaboration between INL and Halden technical staff has evolved to provide a sound technical path toward this goal.

Preliminary technical evaluations of refabrication requirements, potential customer objectives, and existing hot-lab facilities has resulted in dividing refabrication into “basic refabrication” and “advanced reinstrumentation” facilities (also see Figure 3, above). Figure 4 shows a high-level breakdown of the complementary systems at HFEF and MFC-723. Figure 4 shows the potential locations of these facilities relative to one another. This strategy will leverage existing capabilities in HFEF to perform basic operations for near term applications requiring refabricated rods.

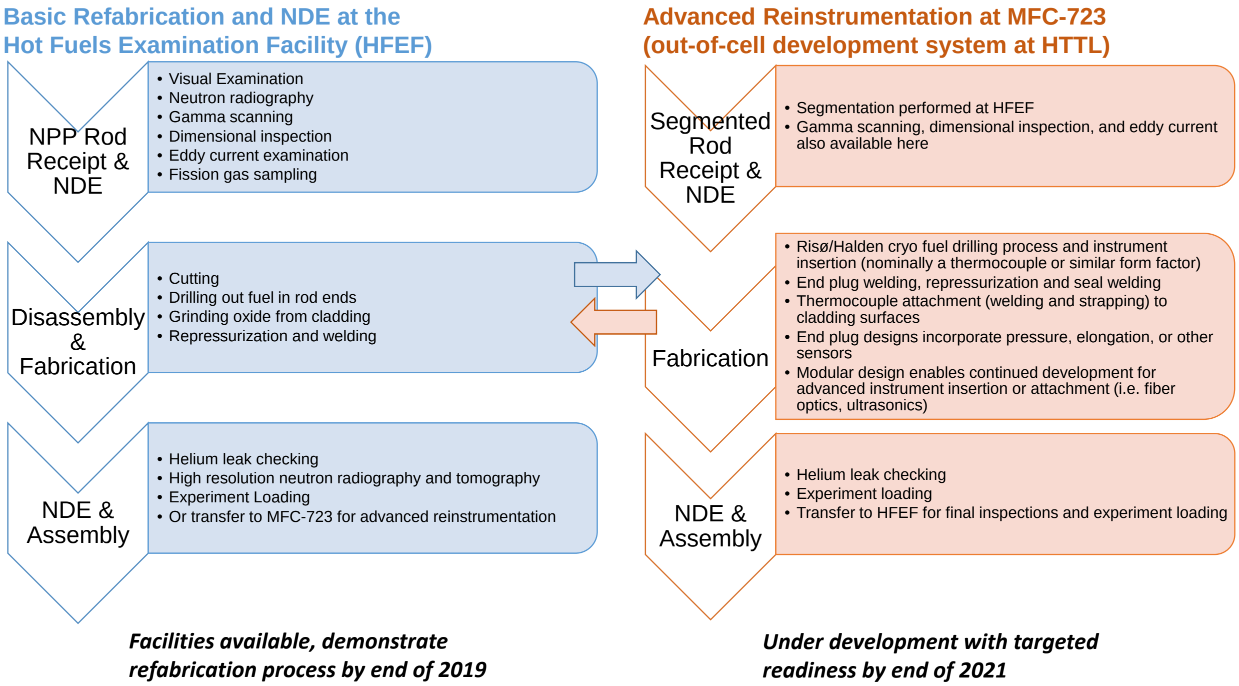


Figure 4. State-of-the-art refabrication capabilities strategy to support in-pile testing. Requires a basic refabrication capability in HFEF to receive full-length NPP fuel rods, process to length and reseal, using existing facilities. Advanced reinstrumentation capability is under development with Halden for installation at MFC-723 to receive segments from HFEF and instrument for experiments.

A scheme for basic refabrication is currently being developed for HFEF. After initial nondestructive evaluation of the rod, including neutron radiography, this basic refabrication would involve cutting parent fuel rods into desired lengths using a slow-speed saw located in the argon cell. Metallographic samples would be created using small sections adjacent to the daughter rod locations in order to determine starting microstructure. The daughter fuel rod would then proceed through a “defueling” process where approximately 1.25 mm of fuel would be removed from both ends of the rod. This would be done in conjunction with a vacuum system equipped with a HEPA filter in order to minimize contamination spread in the cell. After defueling, a specially designed lathe and reamer would be used to remove the oxide layer on the inner and outer surface of the clad in the defueled region in order to enable welding of new end plugs.

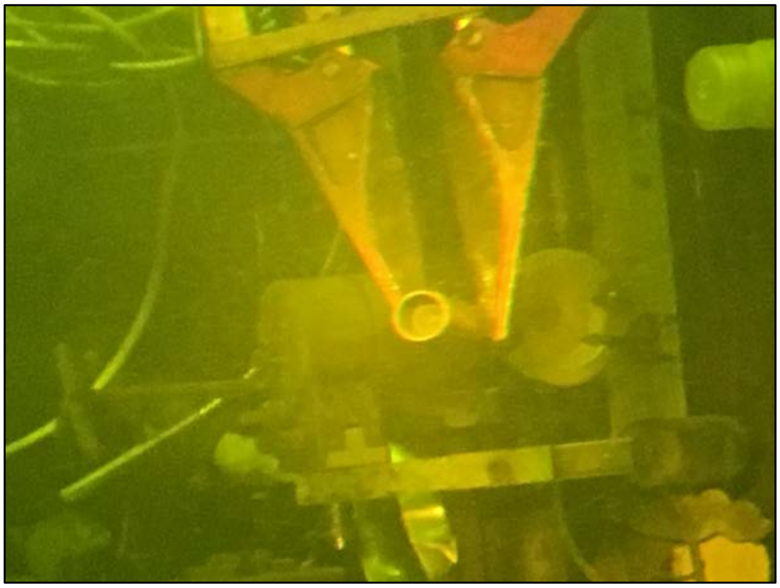


Figure 5 Example of daughter rod after defueling and oxide removal at ORNL, image from [8].

After defueling and oxide layer removal, two customized end plugs are inserted into the ends of the daughter rod. The bottom plug is welded first and then the rodlet is pressurized to prototypic end of life pressures using helium and/or argon while the top plug is welded. The rodlet is then He leak-tested to verify tightness of the rod.

For advanced rod measurement designs, a complementary reinstrumentation system is under development in collaboration with Halden that will provide a modular and flexible platform for performing precision operations and handling delicate instrumentation. A modular shielded cell concept similar to that used at Halden is being developed for potential installation at MFC-723 next to the TREAT Facility. The cell design is being leveraged off of design work previously completed for the Thermal Properties Cell that was designed and recently installed in the Irradiated Materials Characterization Laboratory (IMCL) at MFC. Figure 6 presents an overview of the planned reinstrumentation cell at MFC-723. The cell design is based on separate shielding and confinement boundaries for ease of access to instruments. Manipulators penetrate the front wall of the box while the confinement boundary (glovebox) is accessible through the back wall. This design will provide improved opportunity to troubleshoot and upgrade equipment as testing needs evolve. At the same time, a duplicate benchtop system (non-shielded) will reside in the High Temperature Test Laboratory (HTTL), the primary INL instrument laboratory. Instrument mockups and system upgrades may be evaluated and demonstrated there for eventual implementation in the remote hot-cell system. The proposed relative location of all major facilities is depicted in Figure 7.

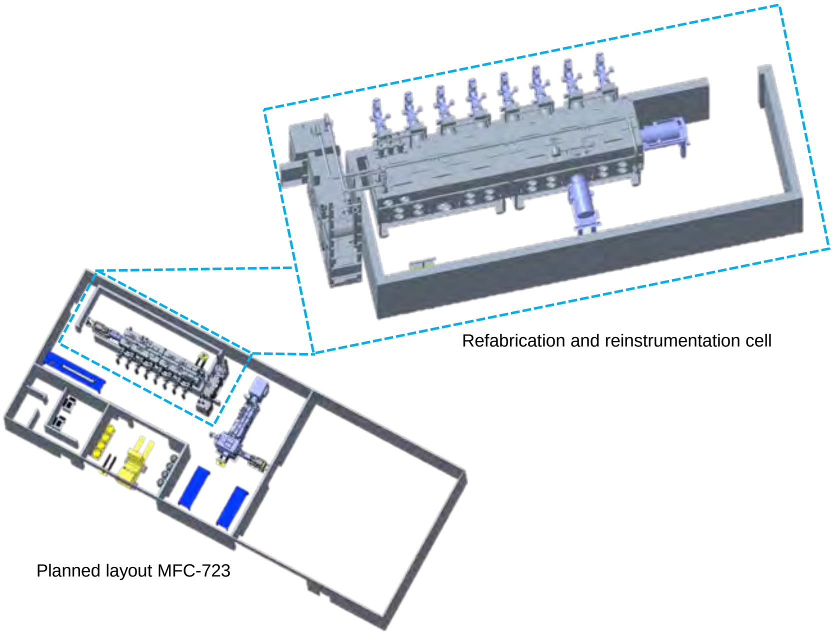


Figure 6. Planned reinstrumentation cell at MFC-723.

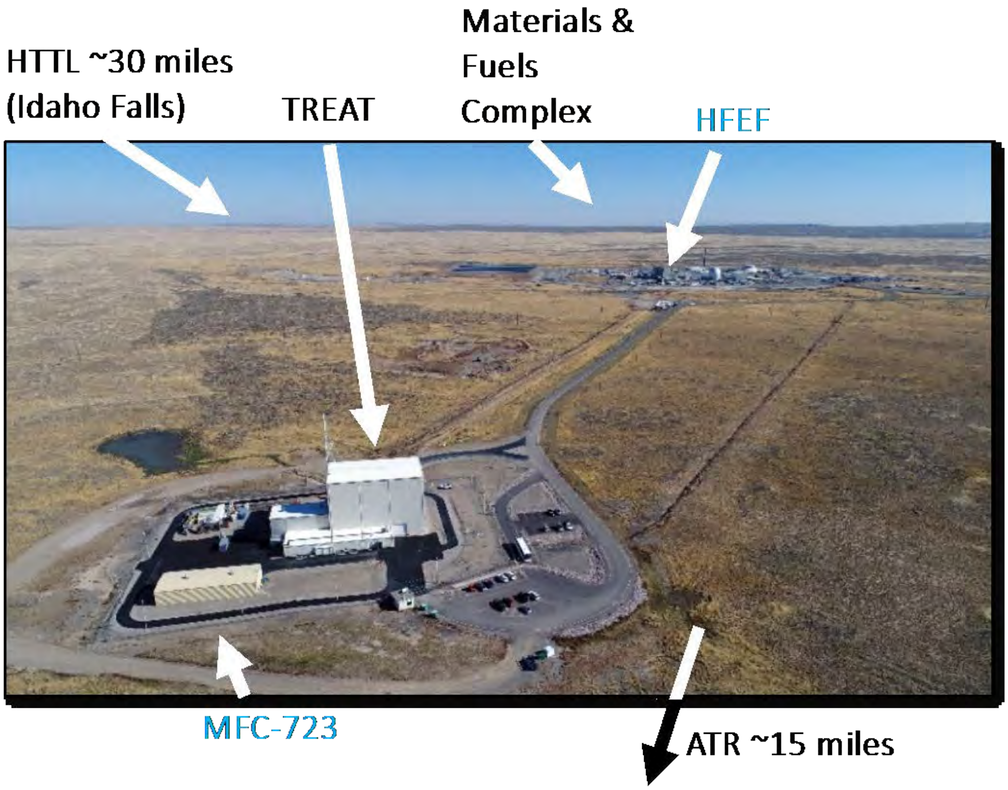


Figure 7. Locations of refabrication facilities at major INL complexes.

Significant experience has been gained over many years of refabrication development and usage. Still, most experience resides with standard LWR fuel forms (UO2 fuel in Zry Cladding). Accident tolerant fuel materials may present important challenges to traditional refabrication techniques since they have been primarily developed fuel forms of cylindrical geometries with a metallic cladding. For example, material joining for nonmetallic materials such as SiC cladding to end plugs or more non-traditional designs such as Lightbridge fuel will likely present challenges to state-of-the-art approaches. Such challenges will need to be assessed as designs mature sufficiently to require refabrication. In any case, each new material will require careful consideration of the approach to refabrication and detailed characterization of the material effects. In the meantime, alternative approaches may be available to provide a means of measurement access such as rod end caps that include features allowing for inserting and attaching instruments without disrupting rod hermeticity as discussed in Section 6.3.5.3. Otherwise, materials with refabrication limitations should be considered in designed LT programs (as recommended in Section 6.2), such that segmented rods could be available, allowing insertion into experimental devices without refabrication.

6.3.2 Prototypic Water Environments

The most significant capability gap created by the loss of the Halden reactor may be the ten pressurized water loops that, with the closure of other similar facilities across Europe, have become primary capabilities for highly prototypic LWR fuel testing for the past decade. Light water reactor loops for fuel testing are missing from the landscape though major facilities have existed in the early phases of LWR R&D. The alternatives assessment in Section 4 found that the only domestically-available prototypic water environment testing facilities are currently located at ATR and MITR. The MITR has operational LWR loop facilities which are already being used by ATF vendors. It is a great resource for prototypic testing that can support in-pile instrumentation, but access is likely limited for the purposes of prototypic fuel rod experiments, like those done at Halden. The ATR is currently the only facility (outside of Russia) that holds an in-pile PWR loop for integral irradiation testing of fuel rods for civilian programs. In addition, it is collocated with the TREAT Facility, planned refabrication facilities, and a full suite of PIE capabilities.

The ATR was originally equipped with nine in-pile tubes capable of replicating PWR coolant conditions. These PWR loops resided in the nine “flux-traps” of the reactor, and the experiments within were directed by Naval Reactors (NR) in support of the U.S. nuclear Navy fleet. Currently, ATR is equipped with one PWR loop available for DOE experiments, known as Loop 2A. It is in considerable demand by the ATF-2 experiment for the foreseeable future. It is capable of simultaneously irradiating more than 30 standard diameter, 15-cm long PWR fuel pins in one of five tiers. However, the loop is being used to irradiate fresh fuel samples that will require years to meet the experiment objective. Thus, open positions in Loop 2A experiments will be limited, and use of these positions will typically require negotiations within the ATF program, in terms of schedule and even operating parameters. This position is capable of thermal neutron fluxes in the range of $2\text{-}3{\cdot}10^{14}$ $n{\cdot}cm^{-2}{\cdot}s^{-1}$ (too high for many applications).

However, as described above, ATR now has three flux trap positions, not currently allocated for use by the Navy which could be reconfigured to add (reintroduce) PWR loops. One of these, the northeast flux trap, is in particularly high demand for non-loop experiments (e.g. TRISO fuel qualification) due to its large irradiation volume and the prerogative to exercise control over the lobe power; and it would be difficult and ill-advised to preempt this other program. The other two flux trap positions (south and east) have also been used frequently for high-value irradiation testing, but it is feasible that one of them could be returned to its original PWR loop configuration. Note, however, the flux traps have positive void coefficients, probably making BWR loop conditions almost impossible to implement in these ATR locations.

In addition to the flux traps, there are a number of lower flux positions in the ATR reactor, which are not in such high demand as the flux traps (i.e. “B” and “I” positions), which could accommodate installation of a PWR or BWR loop. The unperturbed thermal flux in the I-positions is approximately $2\text{-}9{\cdot}10^{13}$ $n{\cdot}cm^{-2}{\cdot}s^{-1}$ (similar to LWR or HWBR). Finally, the B positions (and I-positions to a lesser extent) often suffer significant flux swings near the end of an operating cycle due to outer shim rotations during operation of an ATR cycle.

Variations of LWR water conditions are also an important consideration alluded to above. The testing capacity of the HBWR included specific testing capability matched to reactor coolant designs, requiring specific thermodynamic and chemistry conditions, including PWR, BWR, VVER, and CANDU. For U.S.

interests, the PWR and BWR testing platforms are required. PWR operating conditions are typically near 15.5 MPa coolant pressure with an inlet temperature of around 280°C, while BWR conditions are about 7 MPa with inlet temperature of 280°C. In addition to thermodynamic influences, the impacts of water chemistry are of great importance for irradiation testing R&D. These R&D interests encompass mitigating stress corrosion cracking, controlling radiation fields (e.g. transport of radioactive isotopes), and avoiding fuel performance issues (e.g. cladding corrosion, crud buildup and induced power shift) [10]. With the closure of the HBWR, no BWR testing platform is available to the LWR community and is therefore a recognized gap that is considered in final recommendations.

A method of conducting LWR loop experiments recently proposed (and tested out-of-pile) by researchers at ORNL could help eliminate some of the difficulties posed by the B and I positions. ORNL has proposed a "thermosiphon" system, which is essentially a heat pipe device with the pressure controlled remotely by a source of inert gas supplied to the condensation zone of the heat pipe. The principle of the device is similar to capability used at the BR-2 and HFR-Petten reactors. The advantage of a system such as this is that PWR or BWR thermodynamic conditions may be obtained without the necessity of the loop water leaving the reactor vessel. The loop flow is driven by the convective forces inherent in a heat pipe system. The thermosiphon arrangement also makes it much easier to discharge a fueled test from the reactor for PIE and isolates possible contamination to in-reactor components. However, the system will still likely need to be disassembled in the canal area to extract the test samples and enable dry transport in currently-qualified casks. This test approach does reduce prototypicality in some regards such as chemistry control and flow rates. Therefore, it could be a complement to full loop capabilities.

The BR-2 reactor (currently an NSUF partner facility) should be considered as a possible partner facility based on its history with LWR loop capability (now out of commission) and capsule testing capabilities. The CALLISTO loop performed irradiations of fuel rods under prototypic coolant conditions until 2015. The Pressurized Water Capsule (PWC) device used at BR-2 is similar to the aforementioned thermosiphon device. Experiments have successfully been performed in this device to intermediate burnups ending in ramp testing controlled by a He-3 screen layer. The facility is currently working to bring a loop and various capsule devices online over the next couple of years.

Materials testing is generally a less restrictive activity due to lesser handling requirements. Multiple facilities possess capabilities to support this mission. The loop systems in the ATR described in this report could be used, though capacity is a likely a concern to fulfilling all needs. The HFIR facility is a great option for general dose accumulation but lacks prototypic thermal-hydraulic loop capability, though the thermosiphon device may be a possible approach for fuel testing (to provide a heat source). The MITR has both PWR water loop facilities (BWR also possible). These loops are purposed for studies of coolant chemistry, mechanical testing of materials, and corrosion testing. Some limited fuels testing has also been performed for the ATF program. The HFR-Petten and BR-2 reactors also perform materials tests, though HFR does not currently have prototypic LWR environment options.

In the light of all factors, additional in-pile water loops with options for operational transient testing should be the focus of investments, especially with promising options at ATR. The I-Loops in ATR are the first priority.

6.3.2.1 ATR Loop Expansion: Preliminary Design of I-Loops

The Advanced Test Reactor's unique serpentine-shaped arrangement for its curved-plate type driver fuel creates nine relatively large flux traps which continue to be highly subscribed for several materials and fuels test programs. While the existing LWR loop in the center flux trap provides ample flux for both prototypic and accelerated burnup accumulation in approximately 30 test rodlets, a handful of which can be comprehensively instrumented, this loop alone cannot satisfy the capabilities left by the HBWR's closure for the following reasons:

- Inability to tailor coolant chemical environment to a specific test (all 30 rodlets share the same cooling water).
- Complications with coolant-voiding conditions (e.g. BWR, dry out) due positive void coefficients of reactivity in flux trap-based loops.
- Overall limitations in specimen capacity, particularly for instrumented specimens whose electrical lead routing typically limits them to the uppermost positions in a test train.

Additional LWR loops, which are not subject to some of the constraints present in flux trap-based loops, will be needed in order to address Halden capability gaps using ATR. While useful for other capsule-based and instrumented-lead type experiments, positions within ATR’s neck shim housing and inner reflector have less desirable useable diameters to implement LWR loops. Only the Large and Medium I-positions, which reside outside of the reactivity control cylinders in the outer beryllium reflector, have adequate volume for LWR loop installation (see Figure 8). These I-positions are ideal for LWR loop systems, hereafter referred to as I-Loops, for the following reasons:

- Relatively high availability for nuclear energy experimenters
- Weak reactivity interaction with the main core, thus enabling coolant voiding and actively-controlled specimen flux manipulation
- Neutron flux which is similar to the HBWR and well-thermalized for fuel testing.

Typical flux trap-based loops have annular return flow paths in the core and are composed primarily of stainless steel in-pile tubes (IPT), and yet still often require flux shrouds in test train hardware (e.g. hafnium) to reduce flux in order to achieve LWR prototypic heating rates. For I-positions the objective is different and requires greater neutron economy. A non-annular loop layout with the test section oriented toward the core, and using nuclear grade Zr-2.5Nb alloy (which has been used extensively in high fluence pressurized water conditions in CANDU reactors) work to accomplish this aim in the I-Loop design (see Figure 9). Thermal neutron flux in medium-I positions are slightly higher than the large-I positions at $4{\cdot}10^{13}$ $n{\cdot}cm^{-2}{\cdot}s^{-1}$ during typical ~50 day ATR cycle powers (five lobes each at ~25 MW lobe power, ~125MW total core power); making medium-I positions the preferred location for I-Loops. Each I-Loop enables a 2×2 rodlet array (giving up to 16 total 30cm rodlets across ATR 1.2 m active core length per loop). The I-Loop design is also compatible with other test train configurations such as a cross section with two or three individual rodlets in discrete flow tubes for varying thermal hydraulic conditions within a single test assembly, or a single rodlet cross section to reduce rod-to-rod self-shielding for increased nuclear heating with additional volume for instrumentation.

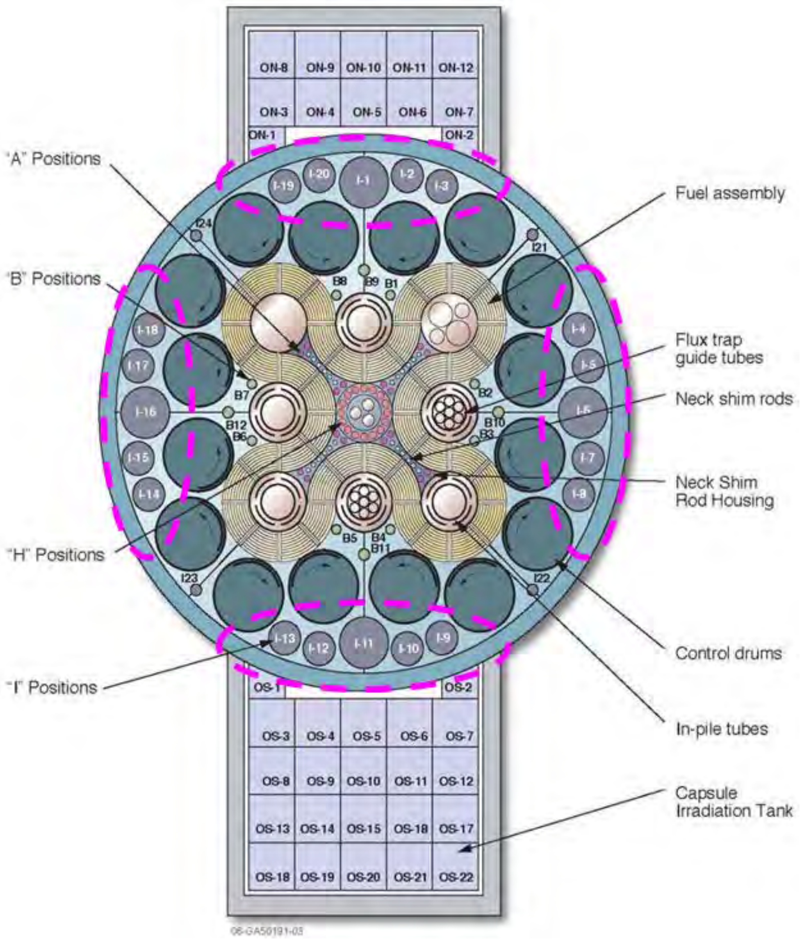


Figure 8. ATR core map (Large and Medium-I positions highlighted)

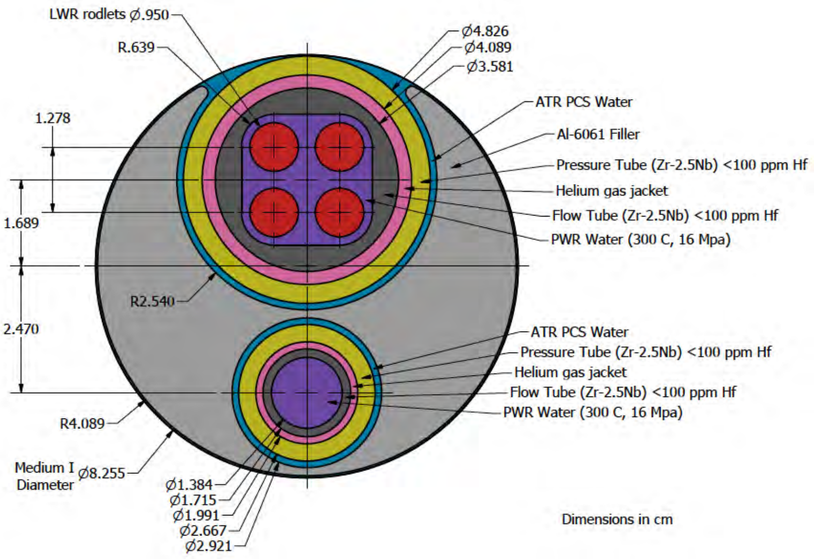


Figure 9. ATR I-Loop design cross section

Monte Carlo investigations have been performed and have demonstrated that inclusion of a standard ATR driver fuel assembly in a large-I position can increase neutron population in the outer reflector while placement of a standard beryllium plug between this “booster fuel” and the I-Loop moderates the spectrum for a 10-15% thermal neutron flux increase in the fuel specimen (see Figure 10). This novel, yet straightforwardly-achievable, approach to ATR core management can elevate thermal neutron flux to the same level available in the HBWR at $5{\cdot}10^{13}$ $n{\cdot}cm^{-2}{\cdot}s^{-1}$ during routine ATR cycles. This flux level also scales with adjacent lobe powers; enabling it to be at least doubled ($\geq 1{\cdot}10^{14}$ $n{\cdot}cm^{-2}{\cdot}s^{-1}$) during high-power cycles. These high-power cycles typically last ~10 days and occur roughly once or twice per year at 50-60 MW lobe power. Infrequency of high-power ATR cycles does not make them practical for accelerated steady burnup accumulation, but use of the center flux trap loop or beyond-commercial specimen enrichments are better-suited for this purpose anyway. Rather, I-Loop tests performed in high-power ATR cycles provide headroom for ramp testing via actively-controlled flux suppression as described further in Section 6.3.3. Table 2 presents a summary of nuclear heating predictions for a few key I-Loop configurations.

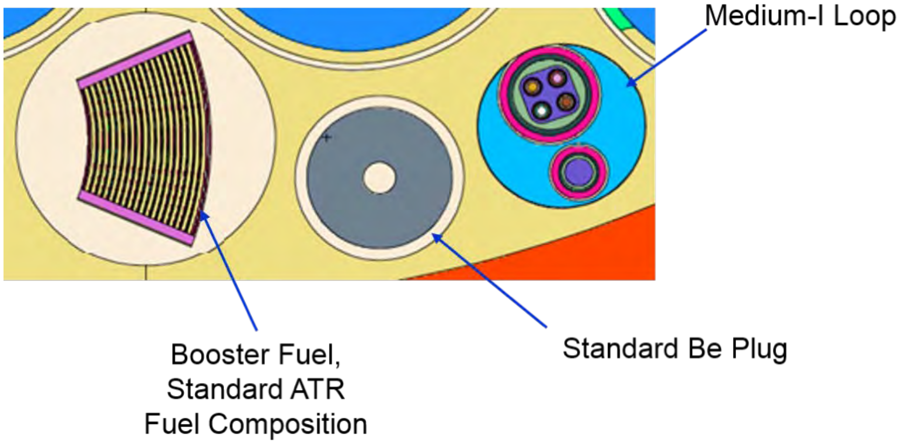


Figure 10. Monte-Carlo model of I-Loop system

Table 2. Calculated nuclear heating results for I-Loop design

Cross Section	Booster Fuel	Lobe Power (MW)	kW/m*	kW/ft*
4 rod	None	23 (typical cycle)	17	5.3
1 rod			19	5.9
4 rod	Yes		19	5.9
1 rod			21	6.6
4 rod	None	50 (high power cycle)	37	12
1 rod			41	13
4 rod	Yes		41	13
1 rod			46	14
*Peak Linear Heating Rate, Fresh UO2, 4.9% enriched				

ATR's native facility design is heavily based around the nine flux trap loops as manifest in existing penetrations through the pressure vessel and shielding structures for high-pressure plumbing and test train extraction via overhead casks. Facility modification to include these new I-Loops, however, is a retrofit operation with some key mechanical constraints. First, the reactor pressure vessel's existing top closure plate will be replaced so that eight new peripheral penetrations exist in addition to the current nine for the flux traps. This closure plate is a relatively small part of the pressure vessel head (1.2m diameter) and was already planned for removal during the upcoming core internal change-out (CIC), planned in 2021. This would create a rare opportunity for this modification without perturbing planned operations. Structural calculations have shown that these new penetrations will not compromise the reactor pressure boundary.

Second, new IPT will be installed so that test train extraction and instrument leads route through the top closure plug while permanent plumbing will penetrate through the side of the reactor pressure vessel in existing L-flanges in a manner typical for many successful lead-out type experiments performed at ATR. The slight offset (~20cm offset over ~6m length) of these in-pile tubes will require that test trains are designed with some compliance to facilitate insertion and extraction (see Figure 11). Test train extraction in this fashion also permits the transport of irradiation tests to ATR's sizeable spent fuel storage pool, the adjacent dry transfer cubicle hot cell, or to a variety of off-site hot-cell for several options in between-cycle and post-irradiation examinations.

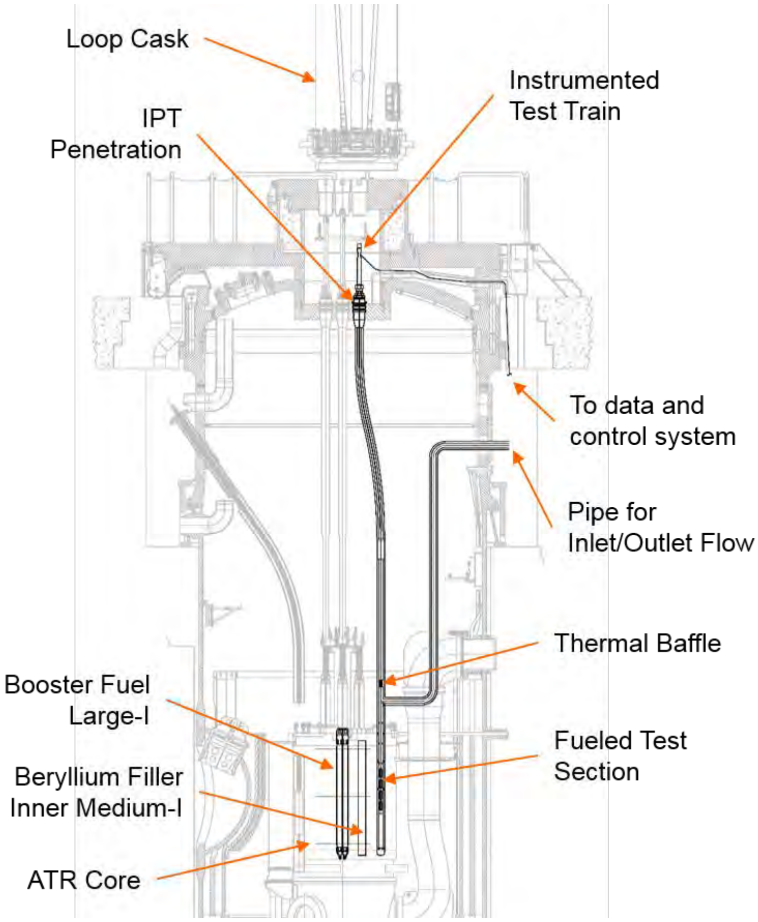


Figure 11. Layout of I-Loop design in ATR pressure vessel

Lastly, CIC marks a major transition for some existing experiment facilities at ATR, a few of which are not planned to be reinstalled (e.g. Advanced Gas Reactor test support equipment). Removal or repurposing of this equipment will enable I-Loop hydraulic support equipment (e.g. pressurizers, line heaters, pumps, heat exchangers, ion exchangers, and coolant chemical conditioning) to be placed in existing shielded cubicles for connection to I-Loop IPTs. While these modifications combined would permit up to eight total I-Loops in the ATR, the current plan is to install two I-Loops initially during CIC in order to provide markedly increased LWR test capacity and the ability to discretely control two coolant conditions for various tests. While the project is ambitious, preliminary design and safety evaluations have been performed and show that this effort is a viable strategy to address LWR fuel irradiation testing capability gaps left by the HBWR closure.

6.3.2.2 PWR Loop in BR-2

The BR-2 reactor is the primary MTR facility currently available in Europe and is also a NSUF partner facility. It is provides high neutron flux irradiation possibilities and is light-water cooled with coolant temperatures of < 50°C. The reactor serves isotope production and fuels and materials irradiation missions, with a variety of irradiation test positions and devices available. The reactor has recently been refurbished with a new beryllium matrix with renewed 20 years of life. Since the 1990s, BR-2 used the CALLISTO water loop device for irradiation testing at prototypic LWR conditions. The water loop was connected to three in-pile experimental rigs which executed a variety of experiments, including integral fuel rod experiments with flux detectors, centerline thermocouples, and pressure transducers. In 2015, the loop was decommissioned and dismantled after more than 20 years of operation.

Currently, a pressurized water loop based on the in-core rig used for CALLISTO is under design. The closure of Halden has resulted in a greater emphasis for accelerating its development for availability by mid-2020 [11]. The current concept is to leverage Halden designs for the ex-core loop support equipment, replicate the in-pile CALLISTO device to minimize implementation risks, and design the instrumented fuel test train at BR-2. Figure 12 presents a schematic of the in-pile device used in CALLISTO.

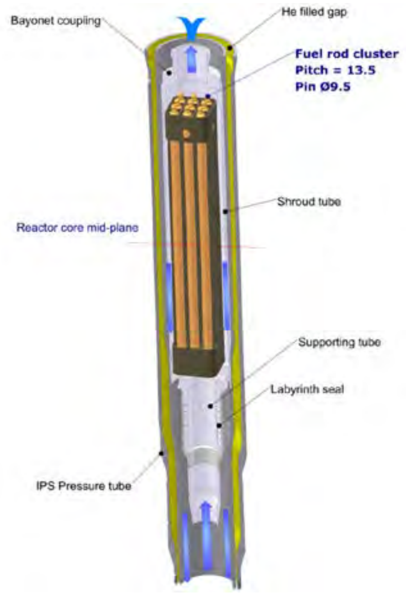


Figure 12. Image of now decommissioned in-pile section of the CALLISTO device used at BR-2 [12]. Currently, designs for a similar system are underway for targeted deployment by mid-2020.

6.3.2.3 Pressurized Water Capsule

Pressurized water capsules (PWC) have been used at various testing facilities around the world to serve LWR testing needs. The devices have the advantages of providing representative heat transfer conditions to test fuel and to provide containment of any potential contamination. Still, the device does suffer from some limitations in terms of operating conditions due to a passive thermal control mechanism. In general, PWC can complement testing in loops, though installation of loops is still the most desirable capability to provide overall testing options. The flexibility and prototypicality of in-pile flowing LWR loops is a primary testing gap since the HBWR loss. The BR-2 reactor has a PWC design used in the past and planned to be available again by 2020. The High-Flux Isotope Reactor has performed significant out-of-pile demonstration work for a fully self-contained thermosiphon device for testing fuel rods. A PWC could also be designed for use at ATR, if expanded capacity were needed beyond existing Loop-2A and recommended additional I-Loop installations, though expansion of I-loop systems is the preferred approach. Pressurized water capsule devices could serve an important mission for water testing. Still, investments in expanded capabilities should be focused on additional in-pile water loops.

6.3.2.3.1 HFIR

At ORNL, HFIR is an 85 MW reactor and is a primary MTR in the U.S. along with the ATR. Recent investigations of a two-phase thermosiphon capsule have been carried out for applicability to testing advanced fuels and materials in HFIR. The device is closed-loop with no moving parts and self-contained to maintain any contamination within. In principle, the concept is similar to other water capsule devices used by other reactor facilities and currently at BR-2 (next section). Figure 13 illustrates the physical mechanism for thermal hydraulic operation of the thermosiphon, where the inner tube bearing a fuel specimen is heated, with buoyant forces driving flow upward. This forms steam into the condenser region where the coolant condenses on the walls, then flows back down the outer annulus to form recirculation. The capsule is cooled by the reactor primary coolant on the exterior.

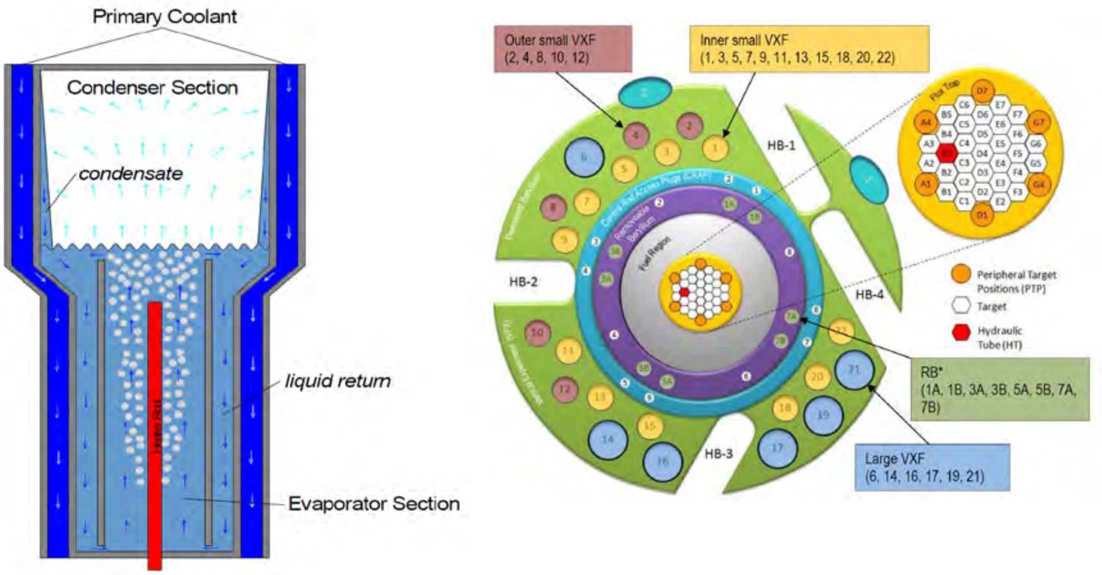


Figure 13. (Left) Schematic of HFIR thermosiphon illustrating the principle of operztion. (Right) HFIR core cross section with test positions, figures from [13]

The High Flux Isotope Reactor has a variety of test positions available to irradiation as seen in Figure 13, with very high flux positions ($1.1 \cdot 10^{15}$ $n \cdot cm^{-2} \cdot s^{-1}$) in the center flux trap. In the permanent reflector, the VXF positions have a significantly reduced fast flux with thermal flux ranging from $2\text{-}5 \cdot 10^{14}$ $n \cdot cm^{-2} \cdot s^{-1}$. The small and large positions have diameters of 40.2 mm and 72 mm. The largest holes have been considered the primary targets for the thermosiphon to allow greater space within the vehicle to facilitate heat transfer design.

The design of the thermosiphon is shown in Figure 14. It is made of several concentric rings where the heat source would be fuel rods with an active rod length up to 51 cm. Figure 14 also shows the overall physical representation of the device made up of the two main zones, the evaporator (heated by fuel) and the condenser. The surface area of the condenser is the primary performance design variable for the device.

A design prototype of the facility was built at ORNL with several experiments performed and compared with thermal-hydraulic models demonstrating performance and validating modeling assumptions. The current design is capable of operating at a maximum pressure of 15.5 MPa. The maximum nominal operating power is approximately 75 kW. Ultimately, the power limit is dependent on specific experiment design specifications.

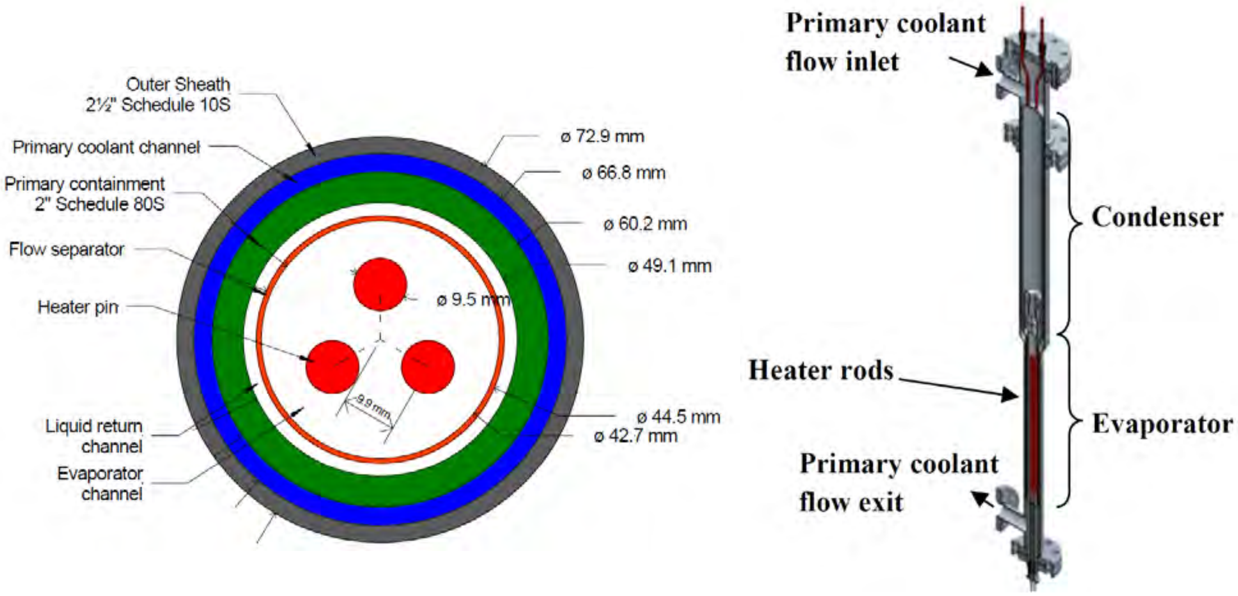


Figure 14. (Left) Cross section of in-core region of HFIR thermosiphon. (Right) Representation of thermosiphon design in test facility, figures from [13])

The thermosiphon design is a potential candidate for irradiating integral fuel rods in HFIR. It has the potential to be adapted for chemistry control and in-pile instrumentation. No evaluation of power ramp performance has been made.

6.3.2.3.2 BR-2

The BR-2 facility has developed a PWC device available for testing fuel of 20 cm to 100 cm in length, depicted in Figure 15. The PWC is designed to provide representative LWR conditions to perform steady state and transient testing. The device is similar to the HFIR thermosiphon design, a passive heat transfer design that capitalizes on boiling and condensation heat transfer at high power levels. The capsule can operate to 16.0 MPa with rod power levels up to 75 kW/m and heat rates of 10 kW/m/min. In previous times, power manipulation was accomplished by manipulating pressure in a He-3 jacket, as has been done at several other facilities.

One PWC device is currently available at BR-2. A second device is planned to be available for testing by the end of 2019, with expanded capability for water chemistry control. Additional capsule systems are planned to be available in 2020 through 2021, including a potential option to allow diameter change on a fuel rod, similar to the approach used at Halden. The He-3 system used for specimen power manipulation in these devices is also planned to be reimplemented in 2020 as well.

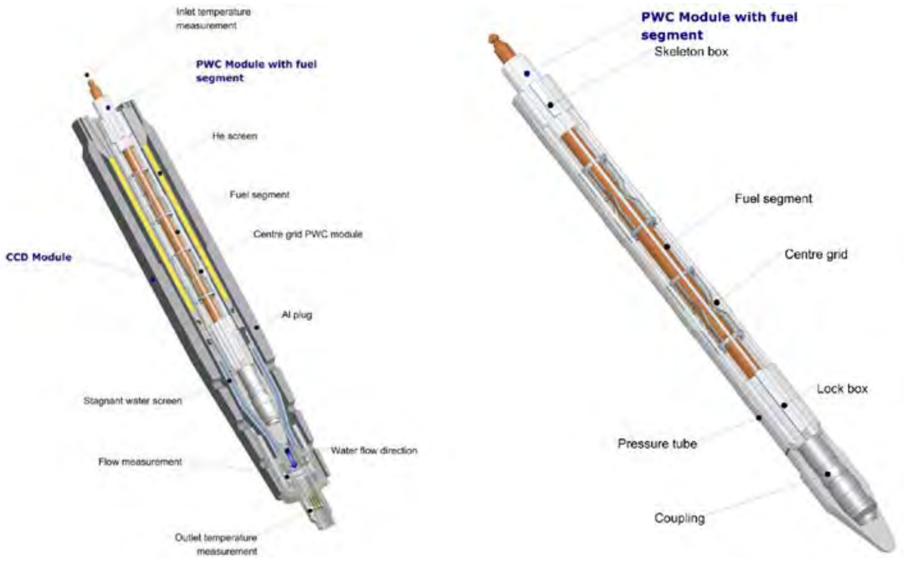


Figure 15. Schematic overview of BR-2 PWC device. Currently, the PWC is undergoing refurbishment with planned availability by early 2020, figures from [12].

6.3.3 Operational Limits Testing

Experimental capabilities to support operational transient studies were identified as primary testing gaps for ATF from preliminary evaluations [1]. Understanding the performance of fuels during operational transients is particularly crucial for fuel technology qualification since they typically define operating limits for the reactor. Transient events of interest, or what are sometimes called power-cooling mismatch conditions, include fuel conditioning, power ramps, load following, Departure from Nucleate Boiling (DNB) and dry-out, and margin-to-fuel melting. This category of testing also includes other potential design limits such as rod overpressure investigations, which have been done at Halden. In particular, ramp testing has been recognized as important to ATF qualification and licensing and is an experimental capability gap left by the closure of the Halden reactor.

Operational transient testing has always been important to the development of nuclear technology. More than two decades ago, the HFR reactor and the now-shutdown Studsvik R2 reactor both performed testing that has become crucial to reducing uncertainties that drive the magnitude of required operational and safety margin [14]. Since the closure of the R2 reactor, the ramp-testing experiment technology was transferred to Halden in 2005, along with rod overpressure testing [15], while the HFR has since dismantled their ramp-testing capability. The BR-2 reactor has had power ramp capability to allow utilization of the PWC device by incorporating a He-3 filter to control specimen power. The device is currently out of commission but is planned to be made available by 2020. In the meantime, some ramp testing can be done in BR-2 by manipulating the power in the entire reactor core. The JHR is designing the Adeline device to support transient testing using a displacement system. While the merits of out-of and in-pile testing are not the purpose of this document, in-pile testing represents an important Halden capability gap – a gap that needs to be filled in order to study improved creditable material performance for ATFs.

For in-pile experiments, the necessary heat transfer boundary condition on the fuel rod requires prototypic heat loss behaviors. In some transient cases, the coolant response plays a crucial role in limiting fuel response. Therefore, the ideal configuration for performing these tests is in a prototypic thermal hydraulic device. Pressurized water loops and capsules are two options, though neither approach is available today with power control. The recommended strategy is to integrate the design of such an experimental configuration into the design of new loop facilities at ATR. Section 6.3.2 describes potential thermal hydraulic capabilities in more detail.

6.3.3.1 Planned Fuel Failure

Limits assessment testing requires pushing fuel performance to failure in order to define fuel performance and safety criteria. It is crucial for assessing and confirming available margin. Such testing has special considerations due to the implications it carries with shielding requirements for the ex-core thermal hydraulic support facilities and for cleaning loop systems of contamination. Due to the importance of such testing, the HBWR has routinely operated loops that experienced release of fission products into the coolant. Of the ten loops used in their facility, some loops have oversized clean-up systems and one loop is dedicated to fuel secondary failure studies. In planning transient testing capabilities into a new design at ATR, planned experiment fuel failures will be a requirement, with supporting loop clean-up systems and shielding designs to allow it. The Halden experience with these conditions should be used to help guide these considerations through direct collaboration on system designs and processes for loops at the ATR.

6.3.3.2 Ramp testing experimental test train design

Transient testing of various power-to-cooling ratios is among the most valuable of functions performed by the HBWR, leaving a meaningful capability gap. The recently-restarted TREAT Facility offers capabilities for these types of studies, but the physics that govern its operation limit such testing to more extreme overpower conditions ranging from milliseconds to a few minutes in operation to simulate postulated plant accidents. Steady state material test reactors are better suited for studying operational transients and similar conditions ranging from several tens of seconds to several days. The ATR has a rich history of transient testing in its pressurized water loops using the Powered Axial Locator Mechanism (PALM) device, which mechanically drives fuel specimens in/out of the core and across within ATR axial neutron flux gradients. This approach is compatible with the existing LWR loop in the center flux trap and can be implemented for some types of ramp testing but is still constrained by the same voiding reactivity complications present in flux trap-based loops. In order to enable ramp testing with coolant voiding, as well as to increase the overall capacity and condition-tailoring test flexibility, a different approach is needed to enable ramp testing in I-Loops.

Based on the successful approach to ramp testing performed in the HBWR [15] and Studsvik R2 [14], the preferred method for manipulating specimen power is a local flux suppression via gaseous neutron absorber. This approach uses a gaseous neutron poison, preferably ^{3}He due to corrosion complications that would arise using boron gas compounds (e.g. BF_3), in a gas jacket or tubing coil surrounding the specimen position of an I-Loop test train. Varying pressure of the ^{3}He gives spatially uniform, rapid response, and fine adjustability of flux suppression over a wide range. Use of this system in reflector-based I-Loops minimizes the addition of reactivity in the event of accidental system depressurization. This approach can be paired with adjustment of hydraulic conditions via I-Loop pump variable frequency drives to give enormous flexibility in ramp-testing parameters; particularly when performed during high-power ATR cycles. Historic ATR system design [16] shows both the viability of such an approach and the orders of magnitude specimen power adjustment possible with a ^{3}He system in medium-I tests as shown in Figure 16 and Figure 17. Experience with both historic and current ATR experiments having related design constraints provide a successful base of engineering solutions to deal with in-pile gas control systems and associated tritium management. While ^{3}He gas is both scarce and rather expensive, such a system should be manageable as it takes a relatively small amount of this gas to create such a system likely to be satisfied by the ^{3}He supply currently at INL, the possible acquisition of the HBWR's existing ^{3}He gas, and/or new acquisition from the U.S. isotope program at a much-reduced cost for government-sponsored research (compared with ^{3}He price for commercial use).

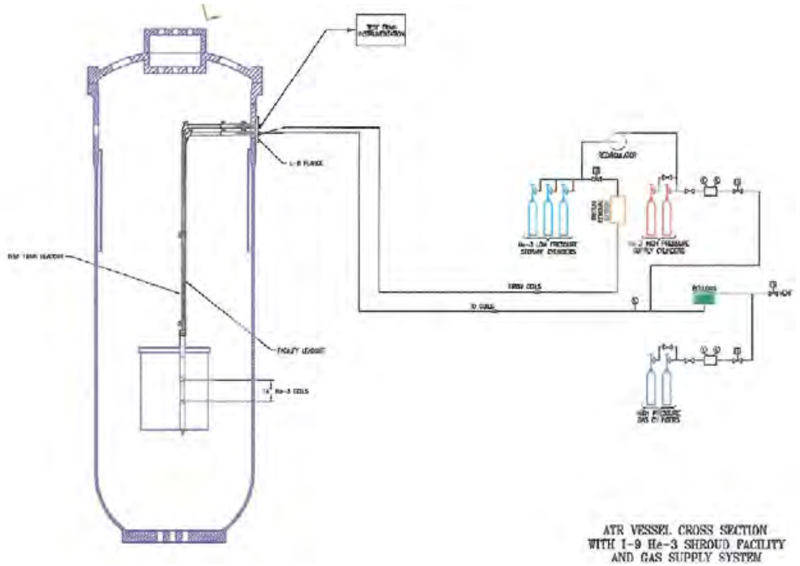


Figure 16: System layout for historic ATR ^{3}He design [16]

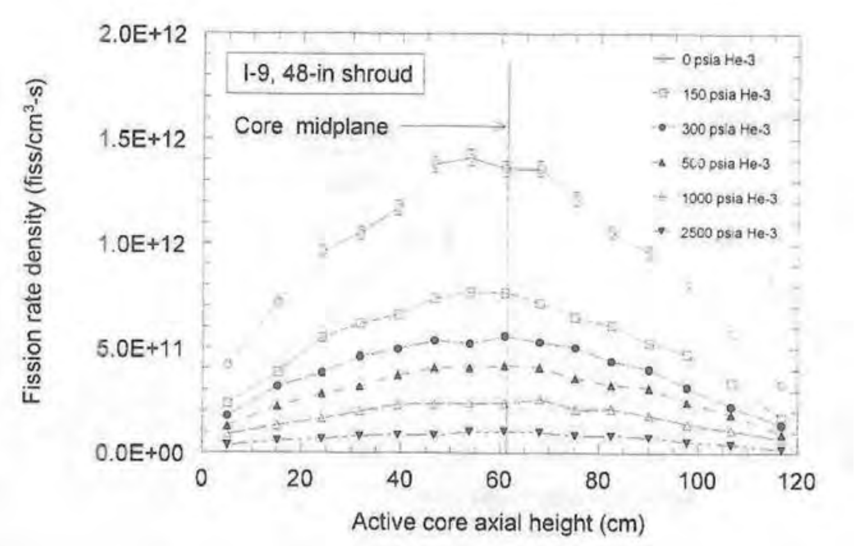


Figure 17: Flux suppression predictions for historic ATR ^{3}He design [16]

6.3.4 Design Basis Accident Studies

Accident testing is another fundamental capability for development and qualification of reactor fuels. The testing requirements for a given fuel form depend on its TRL and likely its relative behavior to well-described fuel forms. Separate effects testing provides much of the information necessary for filling knowledge gaps and developing behavioral models, while integral effects testing becomes the primary confirmatory basis for qualification of a new design or function. The primary events of interest include an overpower event, RIA, and an undercooling event, LOCA. A wide variety of ATF testing is already planned or underway across multiple institutions. Integral RIA testing is not a Halden testing area but is already beginning at the TREAT Facility. CABRI and NSRR are also active programs supporting RIA testing.

In-pile LOCA testing has been performed at several facilities in the past. For over a decade, Halden has become the only remaining in-pile LOCA test facility with the exception of the Research Institute of Atomic

Reactors (RIAR) in Russia. The main objectives of the in-pile LOCA tests have been to investigate fuel fragmentation, relocation, and dispersal for high burnup LWR fuels. At the same time various out-of-pile “integral” LOCA testing facilities are still available around the world. Notably, Studsvik has active LOCA testing capabilities and programs under the OECD NEA joint Studsvik Cladding Integrity Program (SCIP). Japan Atomic Energy Agency (JAEA) also has active integral LOCA facilities. Recently, ORNL has demonstrated an out-of-pile integral LOCA testing capability on high burnup fuel, which will be available to the ATF program. The loss of the Halden in-pile LOCA testing capability leaves a void for the LWR R&D community. The ATF program has been progressing toward establishing LOCA capabilities at the TREAT facility for the past few years.

6.3.4.1 In-Pile LOCA Testing

The Transient Reactor Test (TREAT) Facility is a graphite-based test reactor whose nimble transient control rod system and negative temperature characteristics enable it to safely perform various power excursions ranging from milliseconds-long power pulses to minutes-long shaped transient events that simulate postulated reactor accidents, notably including LWR LOCAs. The TREAT Facility’s unique design does limit its ability to support burnup accumulation, but its collocation and purpose-built shielded shipping infrastructure enable it to accept specimens which are irradiated in other reactors and assembled into a TREAT experiment vehicle (e.g. capsule or loop) at the Hot Fuel Examination Facility (HFEF). In order to simulate both the nuclear and thermal hydraulic boundary conditions present in postulated LOCAs, the TREAT Facility will use pressurized water-environment capsules or loops with the capability to depressurize in synchronization with power transient shaping. A recently-performed LOCA transient test, shown in Figure 18, provides an example. Several seconds of high-power operation established the desired specimen thermomechanical state just prior to test environment depressurization, reducing reactor power to a few minutes, where lower-level fission heating simulates decay heat in the specimen. A similar approach to LOCA research was used successfully in historic transient test reactors such as the Power Burst Facility [17]. The transient shown below, although not yet performed on fuel specimens, is calculated to provide prototypic nuclear heating in high burnup LWR fuel specimens (70 MWD/kgU) for simulation of a full design basis LOCA and beyond.

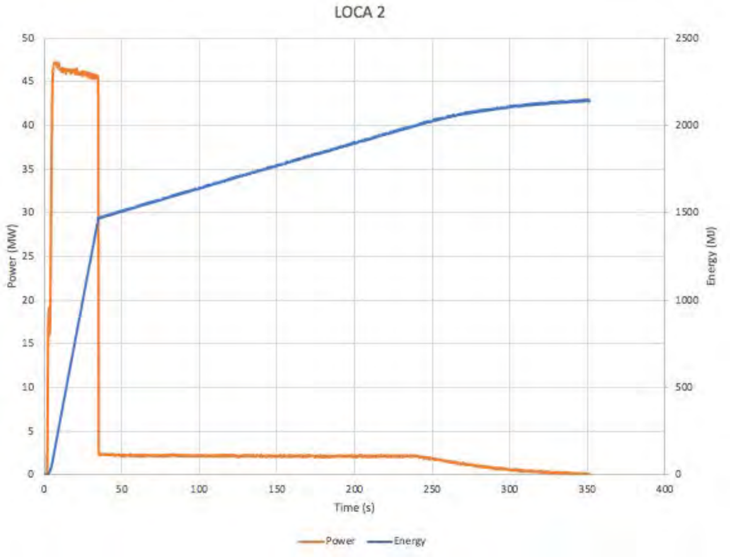


Figure 18: TREAT Facility LOCA-type transient shape

TREAT’s dry core and concrete-block shielding greatly facilitate in-situ instrumentation gathering specimen-focused real-time data during transient irradiations while its fast neutron hodoscope provides real-time spatial monitoring of fuel motion to help ascertain LOCA phenomena such as fuel fragmentation and relocation within ballooned cladding areas. Pressurized water environment testing capabilities are currently being developed primarily under the ATF program with near-term deployment for LOCA-capable static-water capsules in 2020 and bundle capable, forced-convection loops a couple years thereafter (see [9]). Both irradiation vehicles possess expansion tanks, remote blowdown valves, and reflood lines to simulate a LOCA. In addition to providing prototypic LOCA nuclear heating to the fuel specimens, both of these irradiation vehicles contain electrical heater rods. The heater rods surround the specimens to simulate neighboring fuel rods in LOCA conditions and to preheat the test environment prior to nuclear heating. These efforts were already well underway before the HBWR closure was realized and are now receiving increased emphasis both to support ATF and to fill in-pile LOCA testing capability gaps. With these capabilities, TREAT will be uniquely capable of simulating the full evolution of nuclear and thermal hydraulic boundary conditions associated with LWR LOCA.

6.3.5 In-Pile Instrumentation

Even with significant difficulties, many in-pile instrumentation capabilities have been developed over more than five decades of irradiation testing experiments worldwide. For a detailed review of in-pile instrumentation at international irradiation facilities see [18][19]. In the U.S., several historical programs utilized significant in-pile instrumentation, though prototypic testing of LWR fuels and materials has not been a major component of the DOE R&D portfolio since the 1980s. Still, modern coordinated development of in-pile instrumentation for test reactor applications has been underway at INL for more than a decade [20]. Transient test reactors do not suffer from very difficult issues with high dose material performance effects and have demonstrated a greater variety and quantity of in-pile measurements. Major R&D has been devoted to instrumentation capabilities for reestablishing transient testing programs in the U.S. at the TREAT facility through projects at INL and a variety of university and national laboratory projects [21]. In addition, a recent DOE program has started to provide support to specific R&D for in-pile instrumentation development [22].

The primary objectives of all experimental programs are closely tied to the planned data streams. For irradiation testing, the experimental data streams may be classified as online, in-pile measurements of critical performance parameters and PIE characterization (a third classification could be midcycle examinations and measurements). Performing reliable and accurate measurements in any in-pile environment is a formidable challenge. Some specific challenges include:

- The irradiation effects of interest for material experiment objectives also impact the performance of sensor materials with evolving microstructures and material compositions. Semiconductor devices have extremely limited performance for most material irradiation tests. Metallic structures experience significant evolution of microstructure impact properties and performance.
- Experimental test trains are typically high-aspect ratio devices with relatively small cross sections which require insertion into small holes in test reactors while avoiding significant neutronic interference. Thus, sheer quantities of lead wires and space for sensor placement is limited.
- Much instrumentation requires intimate interaction with the measurement target, frequently raising challenges of interference with specimen performance. For radioactive materials, installation access can be quite limiting and may require a glovebox or hot cell.
- Most reactor environments are quite harsh, striving for high thermodynamic efficiencies through high temperature operations, utilizing a variety of working fluids that can be challenging for chemical compatibility reasons. Chemical compatibility in LWR environments can be a significant limitation for much instrumentation.
- All reactors, including test reactors, have a fission product containment and/or pressure boundary, typically consisting of a thick metallic wall. Experimental assemblies may contain multiple containment and/or pressure boundaries. Routing cabling through these individual isolated

environments, from a specimen to the data acquisition, typically requires hermetic seals, which may also be challenged by the extreme thermodynamic or chemical conditions of an environment.

- The typical remote location of a reactor core requires long lengths of extension cables, passing through, or near, a variety of structures and potential sources of electromagnetic interference.
- The lifetime of an experiment can be quite long, requiring multiple installations and removals from the test reactor. The harsh environment and handling provide frequent opportunity for damaging delicate lines while irradiation effects will impact calibration of measurement devices.
- Recalibration and troubleshooting in-pile devices is generally quite difficult due to limited access once installed into a reactor facility, or in devices containing highly radioactive materials.

6.3.5.1 Review of Existing In-Pile Instrumentation

As detailed in references [18] and [19], a wide array of instrumentation capabilities exists at irradiation testing facilities around the world. Two classifications of instrumentation are needed to support in-pile testing: specimen instrumentation (e.g. measure fuel rod parameters directly or characterize local radiation flux) and loop or irradiation device instrumentation (monitor and control environment, e.g. measure coolant temperature, pressure, chemistry). Oftentimes, this instrumentation is categorized by the targeted measurement parameter. Primary parameters of interest include temperature, flux and fluence, dimensional, and fission gas (quantity and composition). In some cases, specialized devices have been designed to measure important physical properties and material responses such as crack growth or material creep under loading.

A review of all available in-pile instrumentation used at facilities around the world reveals an important conclusion:

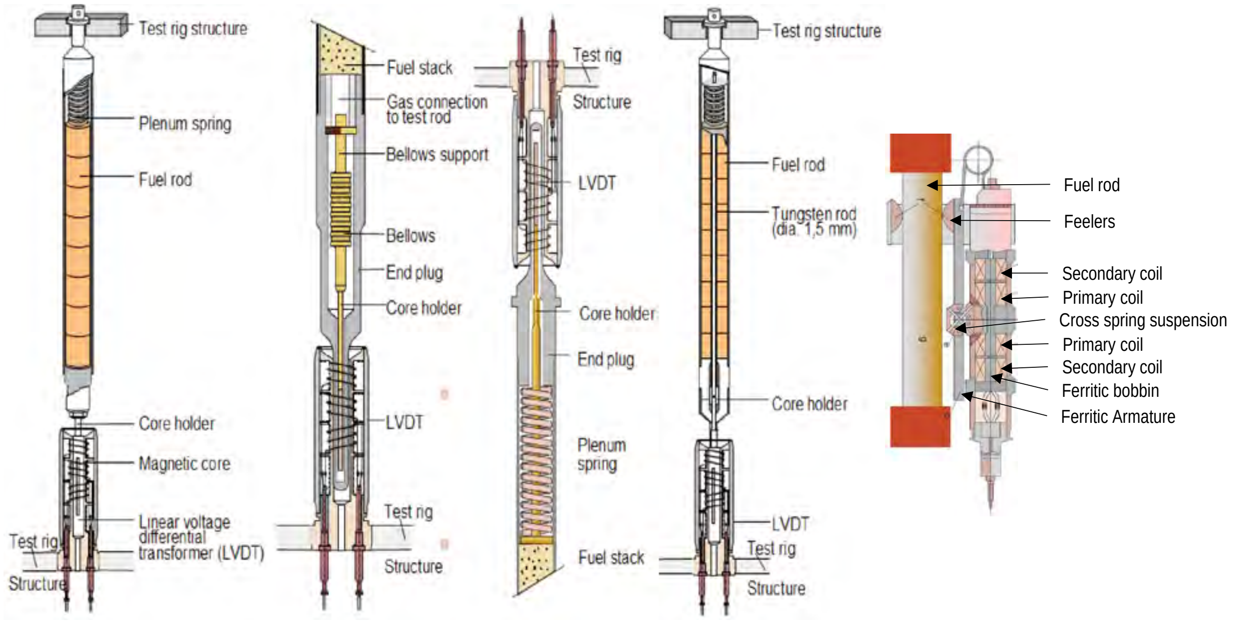
The variety of instrumentation considered widely mature, successful, and diversely applicable is relatively small including: thermocouples, LVDT-based sensors, and self-powered detectors (SPD) (or for neutrons, SPND, and for gamma, SPGD).

This conclusion does not imply that other devices have not been successful for particular applications. The use of these devices provides access to the most commonly desired fuel performance parameters, listed above. In fact, as stated previously a wide range of unique, novel technologies have been developed and demonstrated. Still, most advanced in-pile instrumentation devices have a very particular application and corresponding operational envelope, given the challenges listed in the previous section. The Halden suite of instrumentation is highly tailored toward LWR testing needs. For general ATF testing requirements, the needed technologies are not lacking at facilities around the world. The primary gap in DOE facilities exists in experienced integration of instrumentation into fuel rods (refabrication), test devices, and specific reactor facilities and related instrument qualification.

Thermocouple technology: Thermocouples remain the most common temperature measurement device for in-pile experiments. Several standard-type thermocouples are available commercially, though the most common types used for in-pile applications, include type K or N (nickel based, use to ~1300 °C), Type S or R (platinum based, use to ~1800 °C), and Type C (tungsten based, use to ~2300°C). Pt-based and W-based thermocouples suffer from issues from significant transmutation effects causing decalibration. Ni-based alloys show excellent performance even to high fluence, though they do suffer from high temperature drift. Unique thermoelement designs using Mo-Nb, also called the High Temperature Irradiation Resistant (HTIR) thermocouple, have been developed for high temperature measurement up to 1600 °C and have shown favorable low drift performance in ATR. This design has been developed and tested for several years at INL, showing good performance. Similar designs have been developed at CEA since the 1970s [23]. Halden has used Type C, W-based, thermocouples for temperatures up to 1800°C. For long duration experiments, transmutation effects on drift are compensated based on material studies.

LVDT technology: Linear Variable Differential Transformer technology has long been a primary sensor used for in-pile applications around the world, due to good performance in high flux radiation environments. Halden's LVDT devices have become a standard for irradiation testing since they have refined their design over the lifetime of their facility. Essentially, the LVDT is used to convert mechanical displacement of a ferritic rod to an electrical signal. This LVDT technology design consists of a center, primary coil with two outer secondary coils connected in opposition. The device provides high resolution sensitivity to the displacement of the ferritic core. Halden LVDT's have been developed routinely for applications up to 350 °C. In the last decade, working with INL, Halden has developed LVDT designs that can perform well up to 700°C, the differences primarily being material compositions used in the design.

The device is a common commercial product used for a variety of applications. Though not unique to Halden, the LVDT adapted into a variety of measurement configurations to allow transduction of temperature, pressure, deformation of fuel rods, flow rates in non-intrusive flow meters, and has been extended to a variation of the measurement principle to make a unique device to measure rod diameter, called a diameter gauge. The device has been used to provide information about cladding deformation, oxide growth, and crud deposition. Figure 19 shows representations of the LVDT-based fuel rod measurement designs used by Halden.



Cladding Elongation

Internal Pressure

Fuel Elongation

Fuel Expansion Thermometer

Diameter Gauge

Figure 19. Various LVDT configurations used at Halden. Similar approaches have been used at several other facilities. Diameter gauge design (far left) is based on LVDT measurement principle with similar construction features. Figures from presentation by Helge Thoreson, Halden Capabilities Gap Workshop, 2018, see Appendix C.

Self-Powered Detectors: SPDs have been developed since the 1960s and are widely used in NPPs and MTRs around the world. The sensor is based on concentric design having a central emitter region, acting as the primary interaction with the radiation field, surrounded by an insulating layer and an outer sheath that conducts current. A variety of sensor types are available depending on application needs. Notably, both prompt and slow-response SPNDs are available to support various transient characteristics of experiments. Experiments in both the ATR and TREAT Facility are currently using SPNDs and are working on detailed characterization and calibration of sensor output in those facilities. Halden test trains have used SPNDs for decades to monitor local flux for in-pile experiments.

Other Instrumentation of Note for ATF: Halden has experience with a wide range of other instrumentation devices as mentioned previously. Creep-testing rigs and methods remain of great interest for some ATF materials. Though not currently a major focus for ATF research, crack growth rigs at Halden have also served the LWR community. Options are available to perform such tests at ATR, HFIR, and MITR already exist. Water loop chemistry-monitoring devices such as electrochemical potential probes have been used at Halden and elsewhere to monitor in-pile chemistry conditions and can serve future water-based testing needs.

6.3.5.2 In-Pile Instrumentation for ATF

Typically, the demands for in-pile instrumentation increase with the TRL and overall technical maturity of the material technology. Early development of LWR materials did not rely heavily on in-pile, online instrumentation. Over nearly five decades, the technology has continued to mature as needs have evolved with emphasis on high burnup, improved fuel economics with longer fuel cycles, and the need for flexible power operations. These demands have driven additional testing with increased focus on improved online measurement strategies to explore new regimes and to continue to reduce uncertainties in technology performance while developing and validating new modeling and simulation tools.

With significant challenges described in the previous section, in-pile instrumentation can be an expensive prospect and, for some sensors, can be entirely limiting. Therefore, measurement needs should be defined early in the experimental design process to allow sufficient development and qualification of components, systems, and compatibilities with environment and facilities (see Section 6.3.5.5).

The in-pile instrumentation needs for ATF are likely to vary widely and depend heavily on the desired performance level. It is anticipated that most ATF technologies will first attempt to show at least equivalent performance to current fuel systems. With several ATF designs driving towards enhanced performance, it is expected that experiment needs will evolve to expand performance margins while striving for minimized uncertainties in experimental results. This goal will require state-of-the-art or advanced instrumentation strategies, as was used in the HBWR for modern LWR fuel technology. Because the needs of each fuel type and vendor will vary, this report will address general in-pile instrumentation needs based on state-of-the-art approaches.

In-pile instrumentation R&D has been a major focus of TREAT Facility experiment development. Researchers have made significant progress in providing online instrumentation for the ATF-2 experiment in the ATR, and the Advanced Gas Reactor (AGR) program has developed advanced successful designs for ATR experiments. Several ATF experiments have been ongoing for a few years now. Drop-in capsule experiments continue to be irradiated under ATF-1 with no online instrumentation, to perform basic screening of fuel irradiation performance and fuel-cladding compatibility. The ATF-2 experiment is operating under prototypic thermal hydraulic conditions. The top tier of rods (several axial tiers) has been designed to accept instrumentation lead-out cabling. Currently that option is not employed with specimens in the loop, but it will be available once instrumentation designs are qualified by demonstrated adequate performance in out-of-pile thermal hydraulic facilities (see Section 6.3.5.5).

6.3.5.3 Accessing Rod Performance in a Pre-Irradiated State

Access to preirradiated fuel rods from LT programs is an important strategy to generating data needed for ATF, as discussed in Sections 3 and 6.2. Similar needs exist for rods that are currently under irradiation in the ATR. Refabrication capability will serve both. A second approach is to incorporate design features into appropriately-sized specimens that can be inserted into experimental devices. An example of an enabling feature is a rod end cap design that allows for sealed insertion of instrument taps without slicing a rod, as shown in Figure 20. This design is currently being developed for future ATR insertions. Similar features could potentially be installed on rods that are likely to pose difficulties for refabrication, such as

SiC-cladded fuel. Other options that should be considered include incorporation of markers that can be detected through fuel rod end caps, e.g. ferritic cores within the cladding that can be measured between cycles with an LVDT that indicate pressure or dimensional information. Some developmental work is also ongoing through DOE-funded work for wireless sensors that could eliminate the need for penetrations through fuel cladding, though their ability to survive long term irradiation still needs to be evaluated.

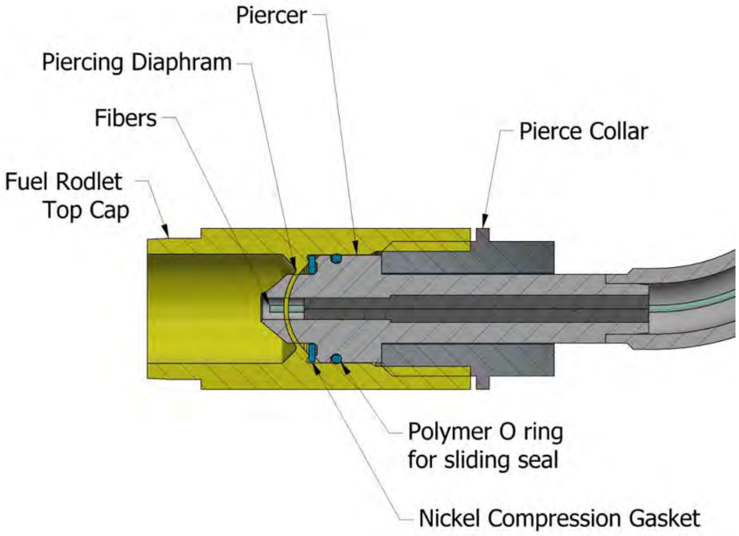


Figure 20. Cross section of rod end cap design to enable instrumentation insertion after base irradiation, for continued testing in the ATR or TREAT Facility (image courtesy of B. Durtschi, INL, 2018).

6.3.5.4 Innovative Measurement Technology

For near-term needs, innovative sensing technologies are not considered a major priority, though they certainly should serve a major role in advanced R&D. A variety of technologies are now under development under other DOE programs and research programs around the world that can greatly enhance the value of experiments and create new experiments to access phenomena in a unique manner that will contribute to the development of advanced modeling tools. The development of advanced modeling and simulation tools, and advanced instrumentation devices and processes, are key to establishing the desired framework that will enable accelerated development of fuels and materials. For example, a single optical fiber can provide access to temperature, pressure, gas composition, thermal and mechanical properties, etc. Still the technology is not well-proven in a test reactor environment and should be matured and adapted to access the many hardware layers required to reach a fuel specimen. Several technologies offer great promise [22].

6.3.5.5 Qualification

The availability of instrumentation described in the previous section is a concern for filling the Halden testing void. However, most devices are readily available and are used at multiple facilities, including INL. The primary focus for in-pile application is the specific qualification required to ensure robust and desired performance of the sensor and the supporting engineered system. In-pile experimental programs around the world have always utilized out-of-pile facilities to perform rigorous testing of measurement devices to reduce the risk of hardware failures and characterize sensor response in a nearly integral environment (excluding the neutrons). Numerous examples of such approaches are available for historic test facilities at INL and around the world. The qualification process should entail detailed laboratory studies in simplified configurations, moving toward integral environment testing in furnaces and water autoclaves, then into more representative environment and hardware configurations as found in the reactor devices. Only when functional and operational requirements are shown to be adequate with known measurement uncertainties should instrumentation be installed in-pile. For a prototypic LWR in-pile loop, an out-of-pile equivalent is needed to do these evaluations and provide opportunities for troubleshooting by irradiation testing engineers. Ultimately, even with significant instrumentation capability available and proven for a variety of applications around the world, reliable instrumentation must be qualified to specific testing devices and applications, a significant effort for any in-pile experiment.

6.3.5.6 Summary Recommendations

As new in-pile devices and refabrication facilities come forth, qualification of instrumentation will be a major focus. Significant capabilities for in-pile instrumentation exist in DOE (and internationally). The primary measurement approaches used at Halden will likely continue to develop, and will be available when needed. To ensure success in the near term while advanced instrumentation continues to mature, the DOE should continue to prioritize and support in-pile instrumentation R&D and qualification at major test facilities to fill the Halden gap. Bolstering the development of standardized measurement devices, like those used at Halden (and many other facilities) and growing the experience of staff for support of LWR testing should also be a priority. In the near term, a pointed effort should be made to work toward technology transfer of Halden LVDT technologies to INL in support of continued production and the use of proven designs. In addition, the DOE should leverage Halden experience with water loop instrumentation to support development and operation of new water loops at ATR. In all cases, the Halden experience should be cited as much as possible to facilitate efficient maturation of these capabilities. Finally, the focus on prototypic LWR environments for in-pile testing requires an out-of-pile equivalent to support qualification of instrumentation.

6.4 Logistics, Waste, & Schedule

6.4.1 General shipping considerations

The emphasis of LT materials for satisfying the need for producing irradiated materials for PIE and follow-on testing begs the necessary question about the problem of logistics and the eventual material waste streams. For U.S. national laboratories, regular material waste streams are available to support research materials. In Europe, the requirements vary by institution but generally seem to be a surmountable issue for research materials. This section presents a simplified summary of shipping considerations to show feasibility of transporting materials between facilities crucial to the ATF program. The primary relationships considered are commercial NPP, national laboratories, and international facilities. In Europe, shipping between major R&D laboratories such as Studsvik and NPP is relatively routine. Within the U.S., shipping irradiated fuel to national laboratories has not been as common in recent decades. Therefore, the primary shipping connections of concern involve:

- NPP to national laboratories, particularly INL and ORNL
- INL to/from ORNL
- International facilities (NPP or laboratories to INL)

Shipping casks are available to meet these shipping needs with general dimensions summarized in Table 3. The NAC-LWT cask is available to provide transport of full length fuel rods and assemblies [24]. These rods would likely originate from U.S. NPP and could be received at HFEF for further processing. This cask was used historically for similar shipping commercial fuel to INL. The BRR cask is currently used for shipping experiments on the INL site [25]. It is also considered for shipments of fuel with allowable dimensions between U.S. domestic facilities. The TN-Lab cask (or “Flying Pig”) is currently the key to enabling feasible shipments between the international facilities using air transport [26]. The cask has been under development for several years but is expected to be certified in France at the beginning of 2019. The current plan is to begin licensing in the U.S. with expected readiness near the beginning of 2020. Currently, HFEF at INL is working develop and approve procedures for handling and acceptance of the TN-Lab cask. The TN-Lab cask allows a 10 kg content payload with up to 45 grams of fissile material (U/Pu). One possible strategy for LT materials in European NPPs is to send materials to a laboratory such as Studsvik or Kjeller (IFE hot cell) to be cut to length or refabricated to a length amenable to the TN-Lab cask for shipping to the U.S. The overall length of the cask (30 cm) is a particular constraint to consider for European NPPs. Other shipping modes are doable, though are likely to come with much higher cost.

Table 3. Description of preferred shipping casks that can serve the needs of the ATF program.

	Domestic Options		**International**
	BRR	**NAC-LWT**	**TN-Lab**
Inner Cavity Diameter (cm)	40.6	34	15
Inner Cavity Length (cm)	137	452	30

With the availability of casks, the specific logistics of shipping materials requires advanced planning between facilities. A few important steps include preparation of an NRC-approved route plan, supporting analysis and documentation, arranging transportation, and additional costs associated with loading and unloading. A Certificate of Compliance (CoC) amendment may also be required to support non-standard payloads in the cask for some shipments. It is recommended that planning LT materials for insertion into NPP include preliminary planning for materials to be sent to R&D facilities. Currently, no issues are expected from the standpoint of needed hardware and processes. Still, the first planned shipments should include some schedule contingency and begin planning as soon as possible as the entire process is exercised. With LT materials already in test reactors and more expected to go in soon, shipping discussion should begin between fuel vendors, utilities, and the national laboratories.

6.4.2 Receipt in the State of Idaho

The Idaho National Laboratory (INL) site has historically played an important role in conducting in-pile irradiation testing on Light Water Reactor (LWR) fuel, including previously irradiated fuel. Historical research programs at the MTR, ATR, TREAT, SPERT, PBF, and LOFT reactors all included the use of previously-irradiated material from commercial or demonstration LWRs [27]. In 1995 the Department of Energy published a Programmatic Spent Nuclear Fuel (SNF) Management Environmental Impact Statement (EIS) to analyze its alternatives for the continued management of its SNF program [28]. The EIS separated SNF into two categories: (1) commercial SNF and (2) DOE-managed SNF. While commercial SNF management was beyond the scope of the program, DOE-managed SNF was defined to be inclusive of "special-case commercial reactor spent nuclear fuel" which includes complete or partial assemblies used to support DOE-sponsored research and development programs. In its Record of Decision (ROD) following the analysis DOE determined to manage non-aluminum clad SNF at the INL site, including the special case commercial SNF to be used in testing [29].

The state of Idaho challenged the adequacy of the 1995 EIS and a federal court subsequently issued an injunction against further shipments of SNF to the INL site. The matter was resolved in what became known as the "1995 Idaho Settlement Agreement" (ISA) [30]. The agreement limited the types and amounts of SNF that DOE could ship to the INL site (ISA§D), required DOE to meet certain milestones in its environmental remediation efforts at the INL site (ISA§B & ISA§E), and established the INL site as the lead laboratory for SNF research (ISA§F). The ISA in section K.1.a provided as its sole enforcement mechanism the complete suspension of SNF shipments to the INL site. Section D.2.e of the agreement prohibited shipments of SNF from commercial power plants to the INL. However, section F.1 seemed to imply that shipments of SNF in excess of those permitted by the agreement could be brought in if the purpose of the shipment was for testing, and that the material would be removed from Idaho within five years. In 2011, a resolution to this ambiguity in the ISA was addressed by a memorandum of agreement (MOA) between the DOE and the state of Idaho [31]. In the MOA, the state of Idaho exercised authority provided it in section J.1 of the ISA to waive section D.2.e of the ISA, thereby allowing shipments of SNF from commercial nuclear power plants to the INL site for research purposes.

Pursuant to section 6(a) of the MOA, DOE notified the state of Idaho of its intent to bring two shipments of SNF from commercial power plants to the INL site for research purposes in December of 2014 and requested additional written support for the shipments [32]. At that time, the DOE had failed to meet the milestone identified in section E.5 of the ISA to treat sodium-bearing liquid high level waste by December 31, 2012. As such, it was assumed that an additional indication of support from the state of Idaho would be required given that section K.1.a of the ISA suspends all shipments of DOE-managed SNF to the INL site, regardless of origin. While the state of Idaho provided a general indication of support for the shipments and research work, the state indicated that no waiver of section D.2.e of the ISA would be provided as long as DOE's Integrated Waste Treatment Unit (IWTU) was not operational and not processing waste [33][34]. As such, neither of the two proposed shipments of commercial SNF have been shipped to Idaho and the research associated with the SNF has either been moved to other national laboratories or has proceeded without the SNF component.

No additional shipments of SNF from commercial reactors have been requested since those proposed in December of 2014. Since that time, the IWTU at the INL site has not started operations and DOE has made no public indications as to when the IWTU may be operational and processing waste. In addition, due to the shutdown of the Waste Isolation Pilot Plant (WIPP) between February of 2014 and January 2017, DOE fell behind on its shipments of Transuranic Waste (TRU) and failed to meet milestones in section B.1 of the ISA which require a running average amount of TRU waste to be removed from the INL site each year, and will likely fail to meet the overall deadline for TRU waste removal from Idaho of December 31, 2018.

Any future shipments of SNF from commercial power plants to the INL site for research purposes such as those discussed in this report will require the state of Idaho to provide a waiver to the ISA. This will require a renewed negotiation between the DOE and the state of Idaho to identify the conditions under which Idaho would consider a waiver. If the DOE cannot meet any of the conditions required by the state of Idaho, it is highly unlikely that any work scope involving the testing of SNF from commercial power plants will be able to take place at the INL site. In-pile research at the INL site would thus be limited to testing on fresh fuels and/or irradiated experimental material that is not considered SNF, such as irradiated test rodlets from research reactors and potentially other experimental material.

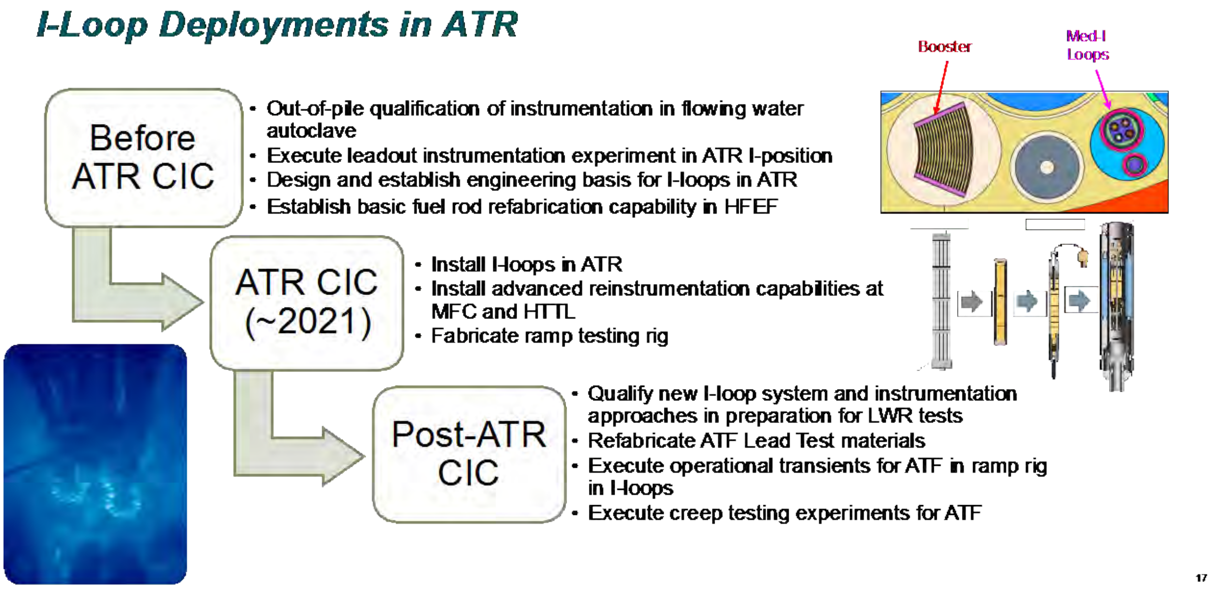
The impacts of such an impasse are significant for ATF, INL, DOE, the state of Idaho, the nuclear energy industry, and the world. The gravity is especially true given the nearly unique role that ATR, the TREAT Facility, and MFC hold in the U.S. and the world today for irradiation testing and PIE capabilities. The inability to perform R&D on ATF materials coming from NPP is a high risk to the long-term success of the program. Beyond ATF, the inability to ship research materials into Idaho represents a devastating barrier to supporting the U.S. LWR industry with world leading facilities, and even the advanced reactor community in a longer timeframe. The concerns with shipping materials from NPPs into the state of Idaho should continue to be a top priority for the entire U.S. nuclear energy community. However, the timeline for ATF needs (and for the broader U.S. LWR industry) does not allow for much delay.

6.4.3 Schedule

The loss of Halden has created some high-prioritized emphasis on establishing refabrication capabilities to complement DOE test reactor facilities and establishing a power ramp capability. These systems are complex in terms of engineering and required facilities. The strategy for bringing them online is closely tied to the needs of the ATF program. Lead Test materials will begin coming out of NPPs over the next few years. Current industry goals include full batch reloads around 2025, and full core reloads by ~2028. The earliest testing and PIE may begin with LT materials is at their removal and shipping from NPPs. Individual fuel vendors are responsible for specific schedules for licensing.

To simplify the discussion, test capabilities that support ATF will target deployment of 2021-2022 to support LT material from NPPs. Meanwhile, testing should continue to build toward the availability of LT materials over the next few years to ensure efficient experiment programs to obtain data crucial for licensing. The ATR Core Internals Changeout (CIC), a process where all internal core materials are replaced, is an important serendipitous event planned to occur in 2021, which facilitates installation and integral start-up testing of new LWR loops in the reactor facility. By 2022, a complete LWR testing platform would be available with additional in-pile water loops with in-pile instrumentation options, capable of performing power experiments in ATR and integral RIA and LOCA devices available in TREAT. The planned deployment schedules for these capabilities are found in Figure 21 and Figure 22.

The proposed schedule is aggressive but doable if funding is committed as needed. In planning specific test programs, researchers should consider the entire material lifetime when planning data needs, including: 1) LT insertions; 2) desired burnup; 3) cooldown and shipping of materials; 4) rod refabrication; 5) experiment; 6) PIE and analysis. Experiment planning is recommended to begin as early as possible at this point to ensure timely availability of plans and facilities (e.g. claim experiment hardware and schedule). The potential high demand on key facilities will require INL to play a strong central coordination role to ensure efficient throughput. If well-planned, upon receipt of materials, it is likely that data outputs would become available approximately 1-2 years later (steps 4-6 above).



I-Loop Deployments in ATR

Before ATR CIC

- Out-of-pile qualification of instrumentation in flowing water autoclave
- Execute leadout instrumentation experiment in ATR I-position
- Design and establish engineering basis for I-loops in ATR
- Establish basic fuel rod refabrication capability in HFEF

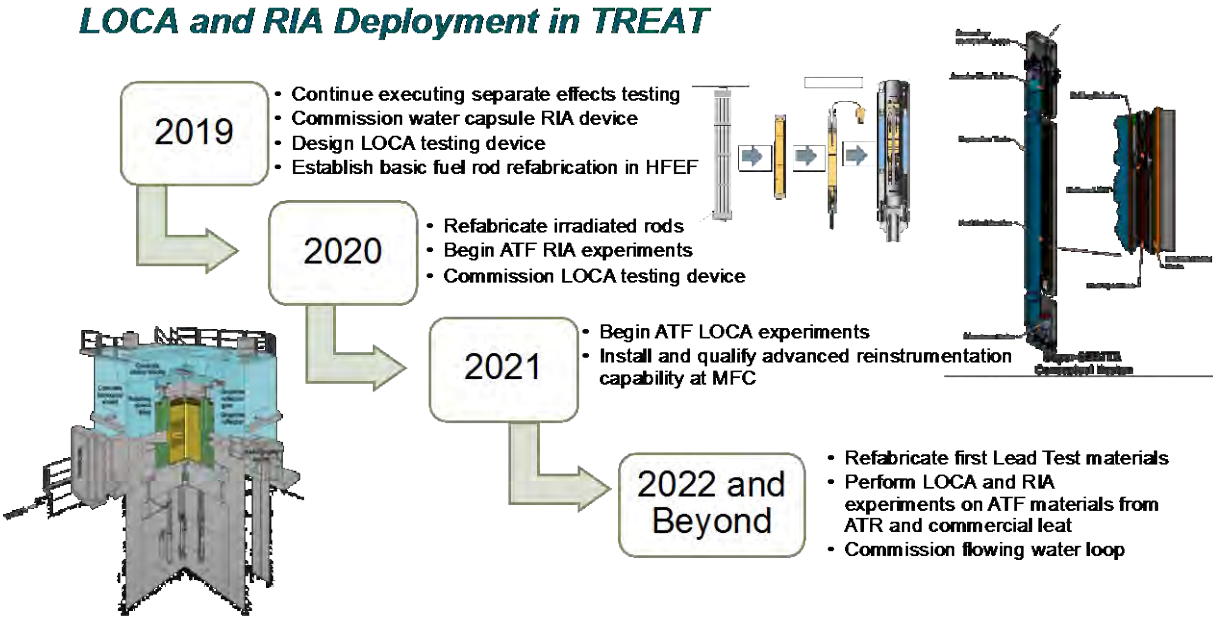
ATR CIC (~2021)

- Install I-loops in ATR
- Install advanced reinstrumentation capabilities at MFC and HTTL
- Fabricate ramp testing rig

Post-ATR CIC

- Qualify new I-loop system and instrumentation approaches in preparation for LWR tests
- Refabricate ATF Lead Test materials
- Execute operational transients for ATF in ramp rig in I-loops
- Execute creep testing experiments for ATF

Figure 21. Targeted development strategy for expanded LWR loops with ramp testing capability in ATR.



LOCA and RIA Deployment in TREAT

2019
- Continue executing separate effects testing
- Commission water capsule RIA device
- Design LOCA testing device
- Establish basic fuel rod refabrication in HFEF

2020
- Refabricate irradiated rods
- Begin ATF RIA experiments
- Commission LOCA testing device

2021
- Begin ATF LOCA experiments
- Install and qualify advanced reinstrumentation capability at MFC

2022 and Beyond
- Refabricate first Lead Test materials
- Perform LOCA and RIA experiments on ATF materials from ATR and commercial leat
- Commission flowing water loop

Figure 22.Targeted development strategy for expanded design basis accident testing capabilities at the TREAT Facility

7. Conclusions and Final Recommendations

The closure of the Halden reactor is a major loss to the LWR fuels and materials R&D community, especially at a time when such test facilities are increasingly scarce worldwide. The unfortunate loss represents potential reawakening for DOE facilities to better utilize major existing infrastructure to meet the needs of the modern LWR industry in addition to the advanced reactor community. Significant irradiation testing capabilities are available and being used at major U.S. testing facilities including ATR, HFIR, the TREAT facility, and MITR. Revitalized LWR testing capabilities at BR-2 and construction at JHR are promising European complements to expanded DOE capabilities, while Russia maintains a full suite of LWR R&D capabilities. The ATR and TREAT Facility (and MFC) have the necessary key capabilities to absorb the breadth of the Halden mission gaps (though probably not the full testing capacity desired by the international community) and are conveniently situated within 25 km of each other. Still, additional scientific infrastructure is necessary to meet the needs of the ATF program and continue sustaining the current LWR fleet. Immediate partnership between DOE laboratory and Halden technical staff will ensure efficient development and maturation of these capabilities. The integrated technical program coordination for broader LWR fuels and materials irradiation testing (beyond ATF) provided by the HRP is a potential program gap that could be addressed through DOE and industry cooperation.

The recommendations provided in this report are promising to support the existing reactor fleet and advanced LWR testing needs. With limited alternatives, the recommendations provided herein will not only take advantage of world-leading irradiation testing and hot lab capabilities in the DOE complex, but will also allow the U.S. to more fully command its nuclear energy destiny.

The final recommendations of this study are consistent with preliminary recommendations (Section 5).

Experimental Infrastructure

- The primary capability gaps left by the Halden reactor program are the prototypic in-pile LWR loops that provide operational transient testing and in-pile LOCA testing capabilities.

  The first recommendation is to continue initiated design and installation of additional LWR in-pile loops in the ATR with standardized instrumented test trains to perform operational transient testing on integral fresh and previously-irradiated fuel rods. Along with Loop 2A, a minimum of two additional I-Loops will provide options (among others) for (1) power ramp testing and (2) testing in BWR conditions. The INL has already established bilateral projects with IFE for water loop and power ramp test train design. These capabilities are proposed to be installed during the ATR CIC in 2021 for availability in 2022. The BR-2 facility is also working towards availability of a pressurized water loop and capsule devices within the next two years. Similar capsule devices could also be considered for installation at HFIR and/or ATR. In-pile LOCA testing facilities are planned to be available for the TREAT Facility by 2021.

  Engineering work to design and install the I-loops and experiment test trains is urgently required. Additional funding is required no later than for the beginning of FY2020 to meet the crucial installation window in ATR corresponding to CIC.

- Advanced refabrication and reinstrumentation facilities are required to enable testing materials irradiated in commercial NPPs at DOE facilities.

  A refabrication strategy has been developed to fully capitalize on LT materials. Aspects of a basic refabrication process have been successfully exercised at ORNL to support out-of-pile LOCA testing (unpressurized rod). A basic refabrication process is planned to be exercised using existing facilities in HFEF by 2020. Meanwhile, a modular hot cell and a Halden reinstrumentation system are both under design to enable integration of advanced instrumentation with previously-irradiated fuel rods at MFC by the end of 2021. The reinstrumentation system will be jointly designed with INL and fabricated by IFE Halden staff.

Additional funding is required as soon as possible to procure and install the modular hot cell needed to support the advanced reinstrumentation system.

- Reliable instrumentation for key fuel performance measurements and materials testing is needed to take full advantage of these facilities.

  DOE is currently investing in a comprehensive in-pile instrumentation program that will provide the technical oversight to deliver mature sensor technologies that can be integrated with previously-irradiated fuel. The technologies optimized by Halden are already a major focus of near-term qualification efforts for ATR and the TREAT Facility to fulfill the post-Halden mission. Significant progress has already been made under the ATF, Advanced Gas Reactor (AGR), and National Science User Facility (NSUF) programs in the past decade. INL is working with Halden in these areas. In addition, companion out-of-pile thermal hydraulic facilities are required (and under construction) to support efficient qualification. Coupled with the irradiation testing and PIE infrastructure in DOE laboratories at INL and ORNL, these capabilities will provide ATF with the necessary tools for success and will give make the U.S. world leaders in LWR fuels and materials R&D.

  The DOE is currently supporting qualification of needed baseline instrumentation for in-pile experimental devices including future I-Loop experiments. Continued support is required to standup in-pile capabilities by 2022.

Transportation and Waste

- Though non-trivial, evaluations of transportation and waste issues have found no major gaps in existing infrastructure. In fact, the TN-Lab cask may greatly facilitate opportunity for international cooperation.
- *The current moratorium on shipping commercial spent fuel as it relates to receipt of experimental materials into Idaho is a crucial near-term issue that must be resolved for the success of the ATF program and continued industry collaboration.* Accident Tolerant Fuels LT materials must be shipped to Idaho for PIE and follow-on testing in ATR and the TREAT Facility.

Relationships

- The DOE laboratories should continue partnership with HRP to transfer expertise and technology for experiments and instrumentation in all technical areas discussed above.
- Technical programs for addressing in-pile R&D needs of modern LWR fuels and materials (fuel reliability issues, improved fuel cycle, extended fuel burnup, core material lifetime issues) is a programmatic gap in DOE that could be filled through direct collaboration with industry, having much in common but not fully addressed by the ATF program.
- Finally, the Halden joint program could serve as an R&D model for a U.S.-based joint project where DOE program leadership organizes and executes a technical program that is derived, reviewed, and consumed by the U.S. LWR community (fuel vendors, utilities, and regulator).

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Appendix A - Halden Capability Gap Assessment Workshop

Idaho National Laboratory (INL) led a month-long assessment of LWR fuel testing gaps created by the recent announcement of the permanent shutdown of the Halden Reactor in Norway. The assessment activity culminated in a workshop in Idaho Falls (July 9-10) in which representatives from the U.S. national laboratories, Halden, DOE, NRC, NEI, EPRI, NEA, SCK-CEN, NRG, MIT, and industry teams from Westinghouse, GA, GE, Framatome, and Lightbridge met to review the assessment and explore how as a community to accommodate future testing needs. Needs for testing and qualification of Advanced Tolerant Fuels currently under development by DOE in partnership with industry was the most urgent topic at the workshop.

The agenda for the workshop is shown below along with the list of attendees.

U.S. DEPARTMENT OF ENERGY

INL Idaho National Laboratory

Halden Capability Gap Assessment Workshop

July 9 - 10, 2018 - Idaho Falls, Idaho
Energy Innovation Laboratory Meeting Center Room 102A
775 University Blvd.

WORKSHOP PURPOSE:

Evaluate national, and possibly international, irradiation capabilities to replace fuel testing services historically provided by the Halden reactor, in the event of a reactor shut down. Recommendations will be included in the Halden Mitigation Plan being prepared by DOE.

WORKSHOP OBJECTIVES:

1. Identify Halden capabilities needed to support the LWR testing program. If they exist at another facility today, identify the facility.
2. Identify the subset of capabilities, unique to Halden, which must be developed to support ATF testing and licensing.
3. Establish a common, high-level understanding of alternative facilities that may provide a pathway for filling the critical ATF capability gaps.
4. Identify and discuss preferred pathways to develop capabilities critical to ATF.

DESIRED OUTCOMES:

1. Consensus on Halden capabilities needed to support the LWR testing program.
2. Consensus on capabilities unique to Halden and critical for ATF testing and licensing.
3. Consensus on credible pathways to fill the capability gaps critical for ATF testing and licensing.
4. Consensus on next steps for creditable pathways (i.e. conduct feasibility study, conduct an alternatives analysis, implement).

PREREQUISITES:

- A preliminary list of Halden capabilities needed to support the LWR testing program and those that are critical to ATF testing and licensing.
- A preliminary assessment of alternative facilities that may fill critical capability gaps for ATF testing and licensing.

Preliminary information provided prior to the workshop will serve as a starting point. Stakeholder participation will be key to developing and recommending credible pathways to fill capability gaps.

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Idaho Falls, Idaho

Monday, July 9, 2018

ENERGY INNOVATION LABORATORY (EIL) MEETING CENTER – ROOM 102A

8:00 **Welcome** .... J. Wagner / S. O'Kelly

8:05 **Background / Objectives** .... S.Hayes / K.Richardson

8:15 **Overview of Halden Capabilities** .... Halden Rep

9:00 **Identification and Consensus on Halden Capabilities needed to support the LWR Testing Program and Capabilities Critical for ATF Testing and Licensing** .... Facilitated Discussion

10:00 **BREAK** .... ALL

10:30 **Alternatives Discussion for Developing Capabilities Critical to ATF** .... Facilitated Discussion

- *Validate/Inform Strawman Alternatives Assessment for Materials Test Reactor and Transient Test Reactors*
- *Gain common understanding of alternatives*

12:00 **WORKING LUNCH** .... ALL
Topic: Overview of BR-2 Sven van den Berghe

1:00 **Alternatives Discussion for Developing Capabilities Critical to ATF (cont.)** ... Facilitated Discussion

2:30 **Transportation / Waste Considerations (NRC Points of Contact by Phone)** .... ALL

Material at Halden may need to be sent elsewhere for testing. As the pros and cons of shipping Halden fuels vs. restarting irradiation of new fuels elsewhere, discuss insights such as time frame for adding a new fuel form to a CoC, which packages are approved for "research quantities, etc.

3:00 **BREAK** .... ALL

3:30 **Alternatives Discussion for Developing Capabilities Critical to ATF (cont.)** ... Facilitated Discussion

4:30 **Summary** ....

4:45 **Group Photo** .... ALL

5:00 **ADJOURN**

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Tuesday, July 10, 2018

ENERGY INNOVATION LABORATORY (EIL) MEETING CENTER – ROOM 102A

8:00 **Consensus on Credible Pathways and Next Steps** .... Facilitated Discussion

- *Identify Credible Pathways*
- *Recommend Next Steps*

10:00 **BREAK** .... ALL

10:30 **Moving Forward** .... ALL
Discuss how to move forward in a coordinated manner.

11:30 **WRAP-UP**

11:30 **ADJOURN**

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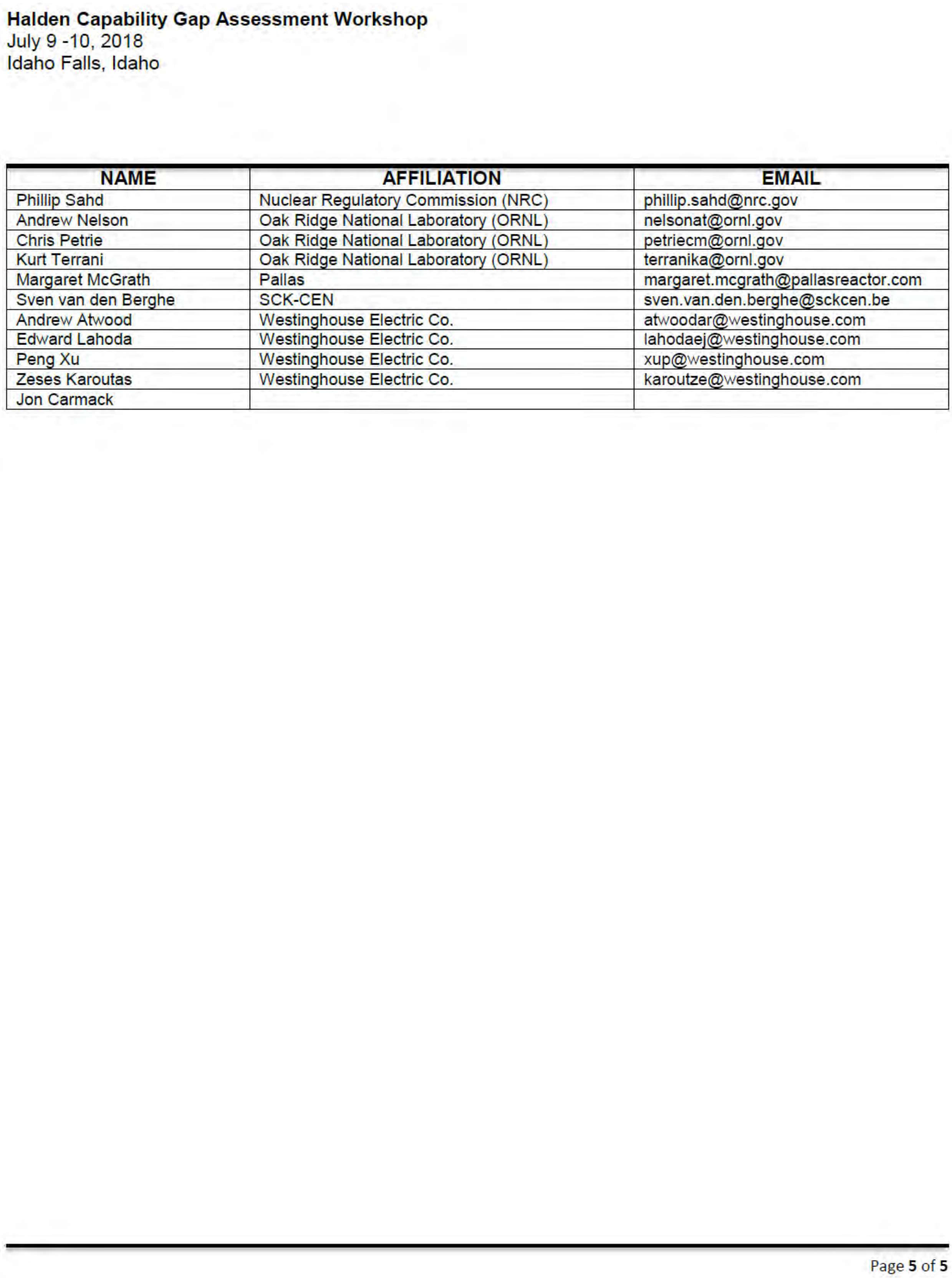

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Appendix B - International Material Test Reactor Survey Tables

The following tables were created to provide a database of information regarding material test reactors that may be considered to fill testing gaps created by the HBWR shutdown. The list is not meant to be comprehensive for test reactors world-wide but to capture facilities with high relevancy to HBWR missions.

Test facilities in Russia and China are not captured in these tables.

Table B1. Steady-State Material Test Reactor Overview – Reactor Data

	Operating Facilities									Not Yet Operational	
Reactor	**HBWR**	**ATR**	**HFIR**	**MIT-II**	**MURR**	**BR-2**	**HFR-Petten**	**HANARO**	**LVR-15**	**JHR**	**Pallas**
Maximum Thermal Flux (10^{14}n/cm2/s)	1.5	10	30	0.7	6	10	3	4.5	1.5	30	3
Maximum Fast Flux (10^{14}n/cm2/s)	0.8	5	11	1.7	1	7	5	2	3	10	3
Cycle (days), #/year		~50, 4	24, 7			~25, 6	~31, 9	~25, 4			>300
Core Height (cm)	80	120	61	60	61	80	60	70	58	100	60
Origin	IFE, Norway	DOE, USA	DOE, USA	MIT, USA	U of Mo, USA	SCK-CEN, Belgium	NRG, Netherlands	KAERI, South Korea		CEA, France	PALLAS, Netherlands
PWR loop	11 total loops available (PWR/BWR)	6 total, 1 used for DOE, Scoping studies for i-positions underway	capsule device designed (thermosyphon)	1 loop (removable if needed)	none	capsule device available, working to reconstruct historical loop	capsule device available	1 loop	1 loop, status unknown	2 loop types known (LWR), qty unknown, capsule type devices	1 planned
BWR loop	11 total loops available (PWR/BWR)	Scoping studies for i-positions underway	capsule device designed (thermosyphon)	1 loop, alternate to PWR	none	capsule device available, loop under design	capsule device available		1 loop, status unknown	see above	1 planned
Other positions	40 in-pile 5 reflector	1 rabbit (removed) 47 in-pile 60 reflector/pool	3 rabbits 37 in-pile (2 instrumented) 42 reflector 4 beamports	2 rabbits 3 in-pile 9 reflector 9 beamports	2 rabbits 3 in-pile 15 reflector/pool 6 beamports	40 in-pile 50 reflector	17 in-pile 12 reflector some beamports	1 rabbit 7 in-pile 17 reflector		10 in-pile 26 reflector	2 in-pile 4 reflector
Fuel tests	Routine	Routine	Routine, PWR geometry and reduced size/separate effects	limited, (2 recently completed tests, 1 planned)	Not common	Routine	Routine	Routine	Not common	Strong LWR-focused mission, also Gen IV	planned to be routine
Power transients for fuel experiments	He3 coil screen used to control power locally	Mechanical PALM facility used in flux traps, other strategies under consideration	n/a	n/a	n/a	Ramp reactor power in dedicated experiments; He3 coil used on PWR capsule device, Tritium issue needs resolution - solvable	Done historically, Design for PWR/BWR ramp-test ready	unknown	n/a	displacement system in reflector for flexible power control, planning for room for ~20 experiments	considering variable power capability using horizontal displacement system in reflector region (akin to at HFR) but not to fuel failure

Table B2. Steady-State Material Test Reactor Overview – Enabling Technology and Logistics Information

	Operating Facilities								Not Yet Operational	
Reactor	**HBWR**	**ATR**	**HFIR**	**MIT-II**	**BR-2**	**HFR-Petten**	**HANARO**	**LVR-15**	**JHR**	**Pallas**
In-pile Instrumentation	most mature program in the world for LWR experiments, LVDTs for many crucial measurements, TCs, SPNDs, EIS, ECP	many varieties used, much under development, experience using HRP sensors	various capabilities, active development	experience in crack growth measurement, and Halden Electrochemical Corrosion Potential probes, strong INL partner, working with AMU/CEA on in-pile calorimetry	active instrumentation group, currently limited reactor use, good experience with classical irradiation instrumentation, experience with HRP	thermocouples, LVDT-based (pressure, dimension change), SPND/activation monitor, capacitor-based dimension change, off-gas monitoring	standard instrumentation approaches, TC, LVDT, SPND	?	much under development, strong experience	expect some standard and Halden-LVDT type instrumentation
PIE	necessary operations at , relies on Studsvik for advance diagnostics	state-of-the-art, continued upgrades	state-of-the-art	limited, non-fuel, increasing (new hot cell and instruments funded by DOE	state-of-the-art capabilities, full suite of classical LWR fuel PIE, collaborates w/ Studsvik	strong capabilities	strong capabilities	Assumed limited	state-of-the-art at Cadarache/ Saclay	expect limited NDE at reactor hot cell, with reliance on transport to NRG hot lab or off-site hot labs for PIE
Refab/Instrum	most experience, designs/sells systems	working with Halden for hot cell installation by 2021	under development	no	equipment available (HRP), installation planned in refurbished hotcell, experience with refabrication, but not instrumentation	Yes, for materials irradiations	unknown	no	yes	no
Shipping/ Transportation	…	Current issue with ID state gov, research quantities expected to be allowed, commercial spent fuel may have near term solution as well	No major issues	No major issues	No major issues. TN-106 most used container for 1m fuel rods, 4m fuel rods by R-72 package	No major issues, depending on cask availability	?	n/a	No major issues	expect to use international shipping agent to send fuel for PIE
Disposition/ Waste	…	No major issues	No major issues	No major issues? (DOE material is typically shipped back to a national lab)	No major issues for non-exotic materials, special materials can be "shipped back"	No major issues	?	n/a	No major issues	expect to send expt. fuel for PIE and that facility to waste it
Comments		Wide range of experimental conditions available, US Navy is primary customer, PWR loop installed for DOE ATF use, additional loops feasible in outer positions, advanced instrumentation used in-pile by a variety of test programs		one water loop available with PWR or BWR chemistry (2 were operated historically), no fueled tests in water loops, historical experience with in-pile heating and boiling	strong mission in isotope production, but sufficient spare capacity thanks to highly flexible core configuration	strong mission in isotope production, several positions available for fuels/materials R&D	recently resumed operation		Advertised startup 2022, uncertainty remains, key longer-term solution for testing	Construction start advertised as 2020 with 5 year completion time, longer term potential

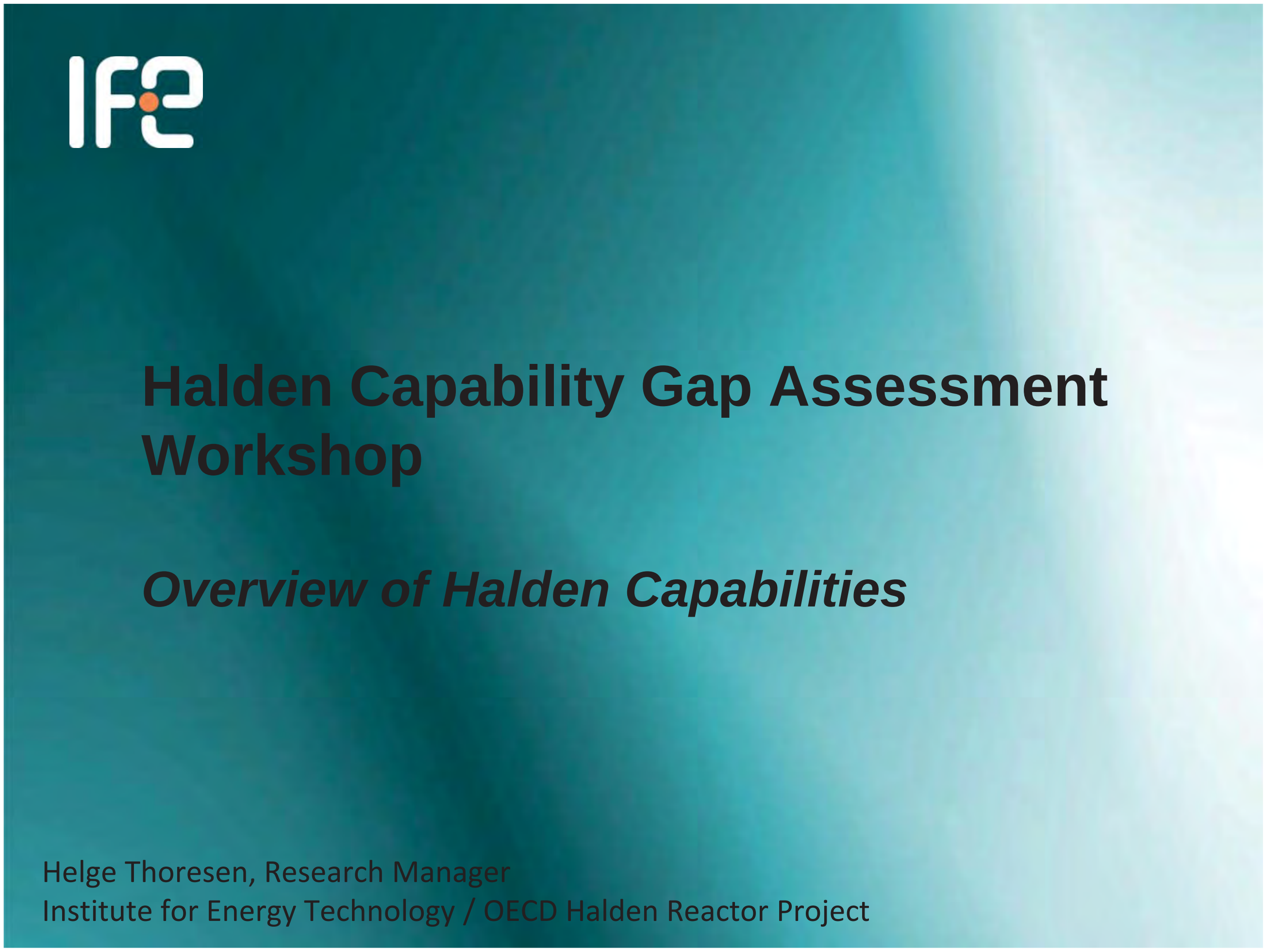
Table B3. Transient Material Test Reactor Overview – Reactor Data, Enabling Technology, Logistics

Reactor	**Operating Facilities**				**Not Yet Operational**
	TREAT	**CABRI**	**NSRR**	**IGR**	**JHR (also SS MTR)**
Core Height (cm)	120	80	38	80	100
Organization	DOE, USA	CEA/IRSN, France	JAEA, Japan	NNC, Kazakhstan	CEA, France
RIA	Capability suite under development for ATF, beginning commissioning capsules	Prototypic PWR flowing loop	Stagnant capsule, limited flow, up to BWR pressure	performed RIA experiments for Russia historically	no
LOCA	Capability suite under development for ATF, beginning commissioning capsules	Prelim. design underway	n/a	n/a	planned
Power ramping	possible, though limited capability for fuel preconditioning, already under study	n/a	n/a	n/a	?
Instrumentation	Facility provides flexible access, wide variety being developed	Good suite of instrumentation, limited flexibility	Good suite of instrumentation, limited flexibility	Using instrumentation	See SS reactor: JHR
Refabrication/PIE	See SS reactor: ATR	See SS reactor: JHR	State-of-the-art	limited	See SS reactor: JHR
Transportation/ Disposition	See SS reactor: ATR	See SS reactor: JHR	?	unknown, DOE sensitive country	See SS reactor: JHR
Comments	Close proximity to ATR, PIE, and fuel fab, facilities allow flexible and diverse testing strategies (Na, H2O, gas, etc)	close proximity to future JHR, sodium loop no longer available, waiting for first PWR test results	not so easy to introduce exotic materials, new capability for high temperature/pressure testing	Historical RIA testing, no current established capability for LWR testing, experience in	See SS reactor: JHR

Appendix C - Overview of Halden Capabilities

Presentation given at the Halden Capability Gap Assessment Workshop held at Idaho National Laboratory on July 9-10, 2018.

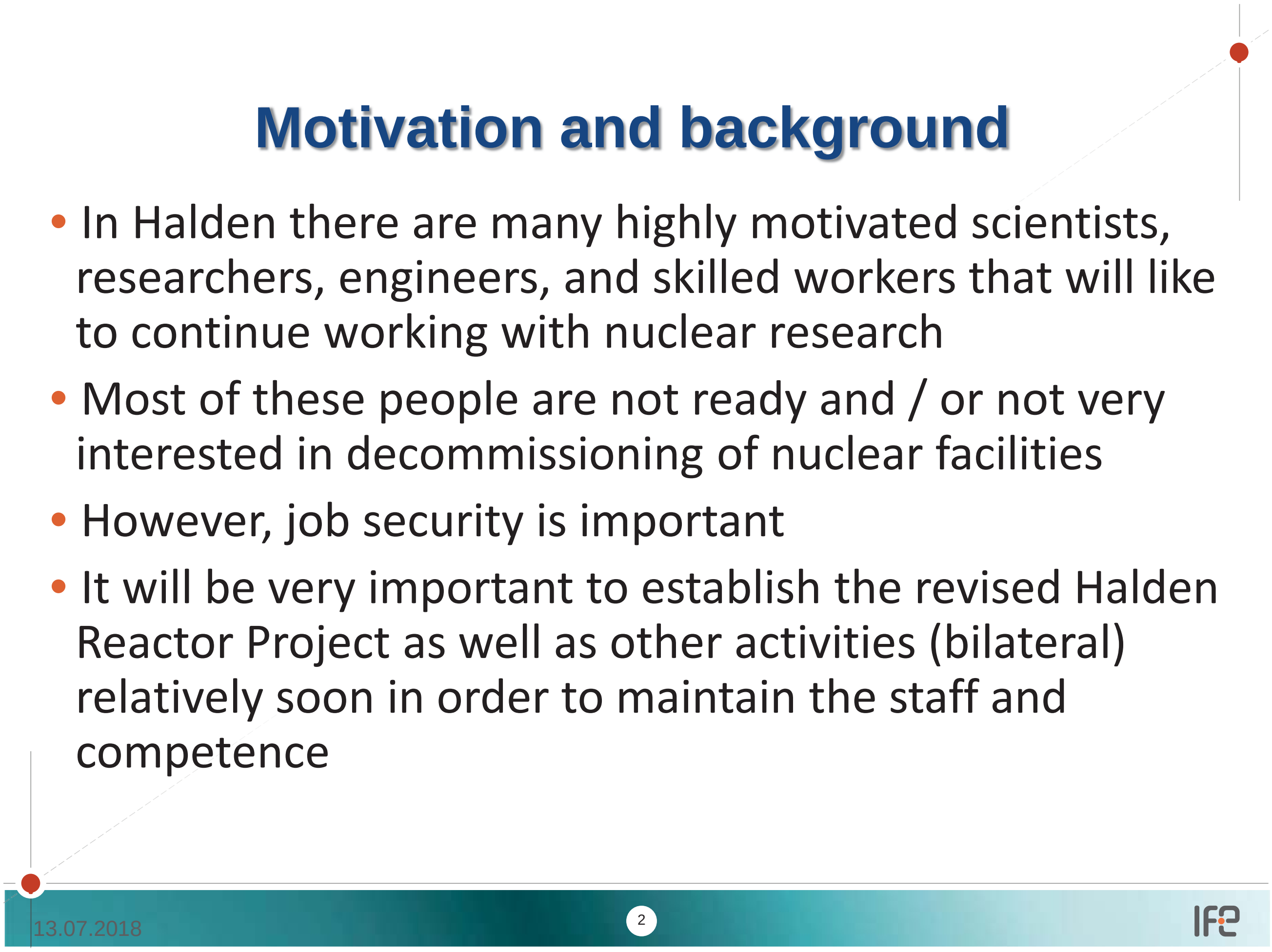
Presentation by: Helge Thoresen, Research Manager, Institute for Energy Technology / OECD Halden Reactor Project



Halden Capability Gap Assessment Workshop

Overview of Halden Capabilities

Helge Thoresen, Research Manager
Institute for Energy Technology / OECD Halden Reactor Project



Motivation and background

- In Halden there are many highly motivated scientists, researchers, engineers, and skilled workers that will like to continue working with nuclear research
- Most of these people are not ready and / or not very interested in decommissioning of nuclear facilities
- However, job security is important
- It will be very important to establish the revised Halden Reactor Project as well as other activities (bilateral) relatively soon in order to maintain the staff and competence

13.07.2018

2

Contents of the presentation

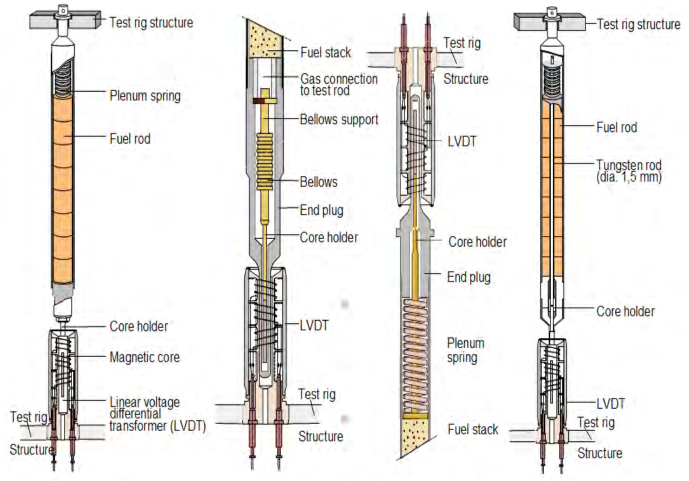
- In-core irradiation rigs and instruments :
  - Basic LVDT-based instruments (and read-out systems)
  - Diameter gauges and hydraulic systems
  - Loading systems and displacement monitoring systems
  - Crack-growth monitoring systems
  - Other instruments – ECP sensors etc.
- Water loop systems and out-of-core systems :
  - Water loop systems (especially loops for failed fuel)
  - Re-fabrication and re-instrumentation systems
  - Re-fabrication and re-instrumentation for LOCA
  - Interim inspection systems (including gamma-tomography)
  - Other systems

Basic LVDT-based instruments (and read-out systems)

- Several series / types of Linear Voltage Displacement Transformers (LVDTs) have been developed
- The standard LVDTs are used for fuel rod inner pressure, fuel stack elongation, fuel rod cladding and fuel temperature measurements
- LVDTs have also been developed for high-temperature (up to 700 deg. Celsius) applications (have been tested out-of-core in super-critical steam, molten salt and liquid metals)
- Unique read-out systems have been developed (constant current AC systems – eliminates noise in a good way)
- Transfer of technology for production of LVDTs may take some time

Making In-Pile Fuels Measurements

- All test assemblies are equipped with in-pile instruments to monitor fuel behavior:
  - ✓ Pressure in fuel rods
  - ✓ Fuel temperature
  - ✓ Elongation of fuel and clad
  - ✓ Change of cladding diameter
- Test assemblies create a controlled testing environment within the Halden Reactor

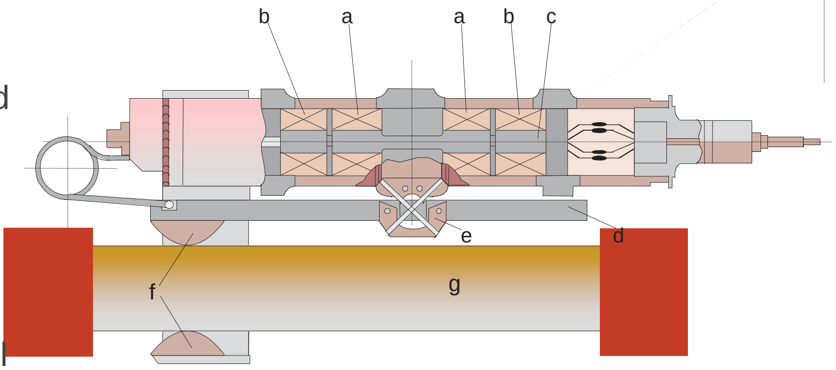


Cladding elongation detector | Fuel rod pressure transducer | Fuel stack elongation detector | Fuel expansion thermometer

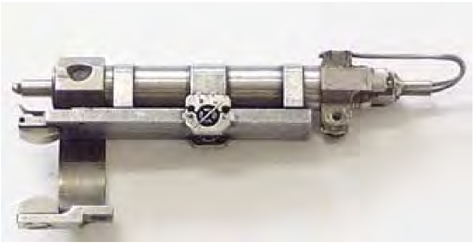
‘On-line’ measurements are the speciality of Halden’s experimental work: reliable instrumentation provides direct insight into phenomena while they develop

Diameter gauges and hydraulic systems

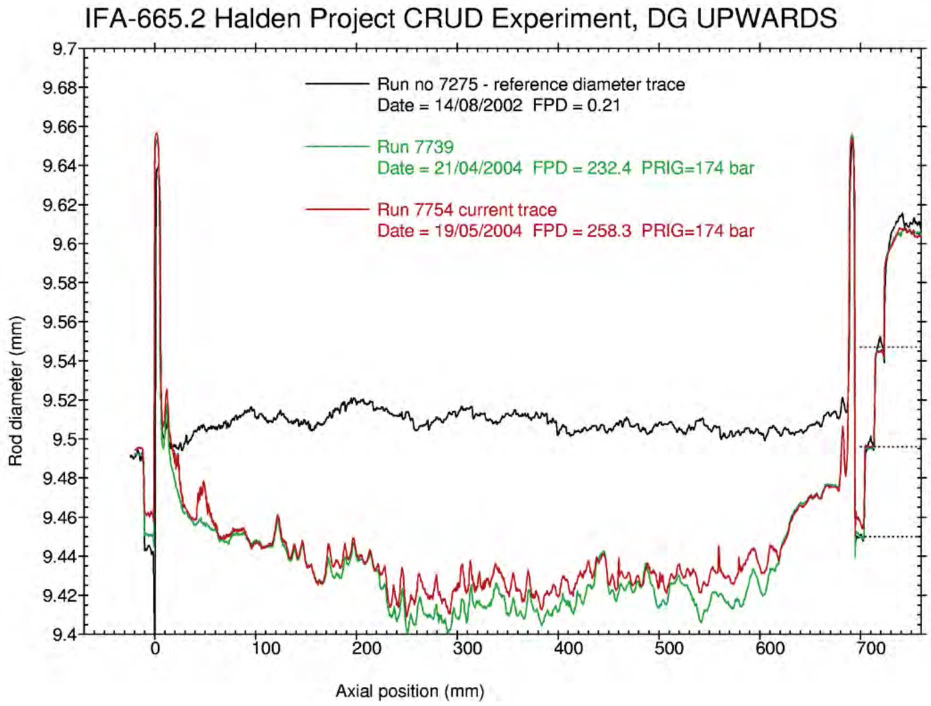
- Provides data on fuel rod diameter profile.
- Instrument based on the LVDT principle.
- Differential transformer with two feelers on opposite sides of the fuel rod.
- DG moved by hydraulic system while a position sensor senses the axial position along the rod.
- Operating conditions: 165 bar, 325°C



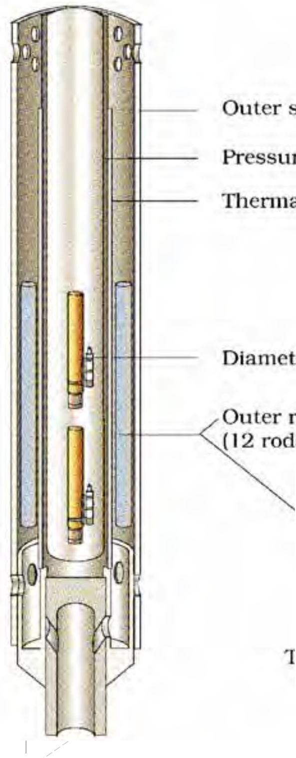
a: Primary coil
b: Secondary coil
c: Ferritic bobbin
d: Ferritic armature
e: Cross spring suspension
f: Feelers
g: Fuel rod



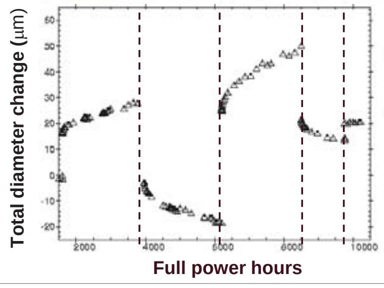
On-line evidence for crud loading by use of DG measurement



Cladding Creep Testing

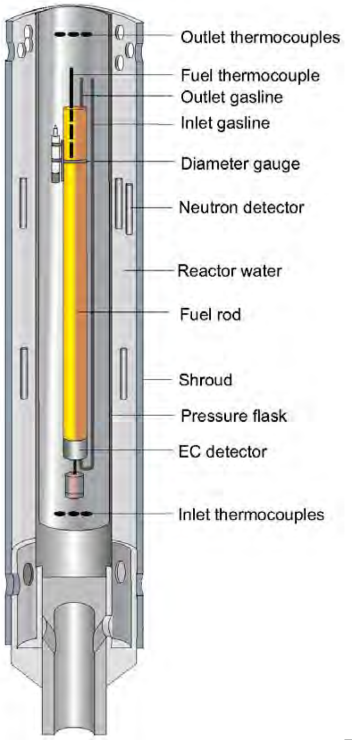


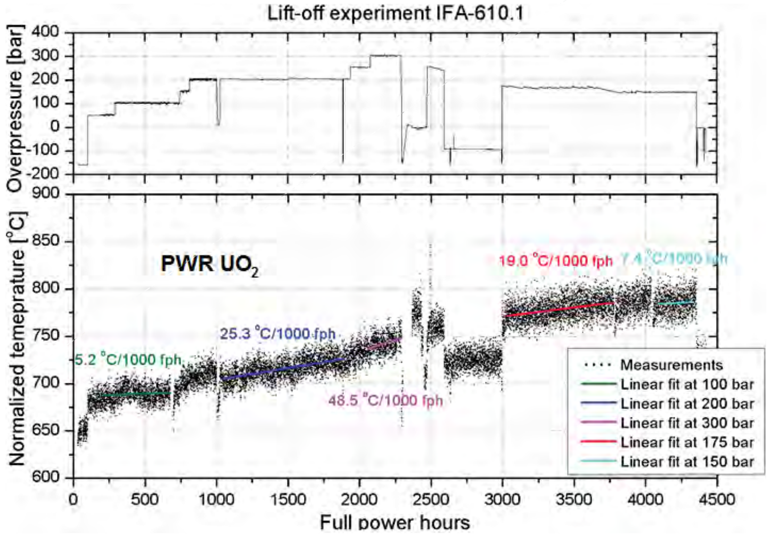
- Cladding OD change monitored on-line with diameter gauge
- Fuel rods with large gap to avoid PCMI connected to gas system for internal pressure change (hoop stress control)
- Hoop stresses of up to ~130 MPa (tension and compression)
- Booster rods to increase local fast flux to ~3-4 n/cm2/s



- Recent and future focus on:
  - Opt. Zirlo, E110-M, M5, M-MDA
  - ATF claddings

Combined in-core instrumentation and advanced analyses





To study fuel temperature rise with gas overpressure
(> coolant pressure)

Other instruments – ECP sensors (or oxygen sensors in liquid metals)

Iron/ Iron-oxide membrane reference electrode

Potential on SHE scale calculated up to 650 C (see paper)

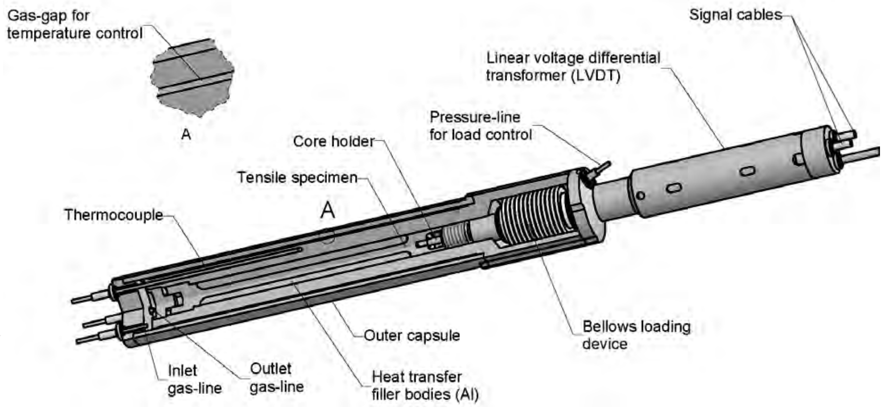
reference electrode
(mechanical seal)

reference electrode
(brazed seal)

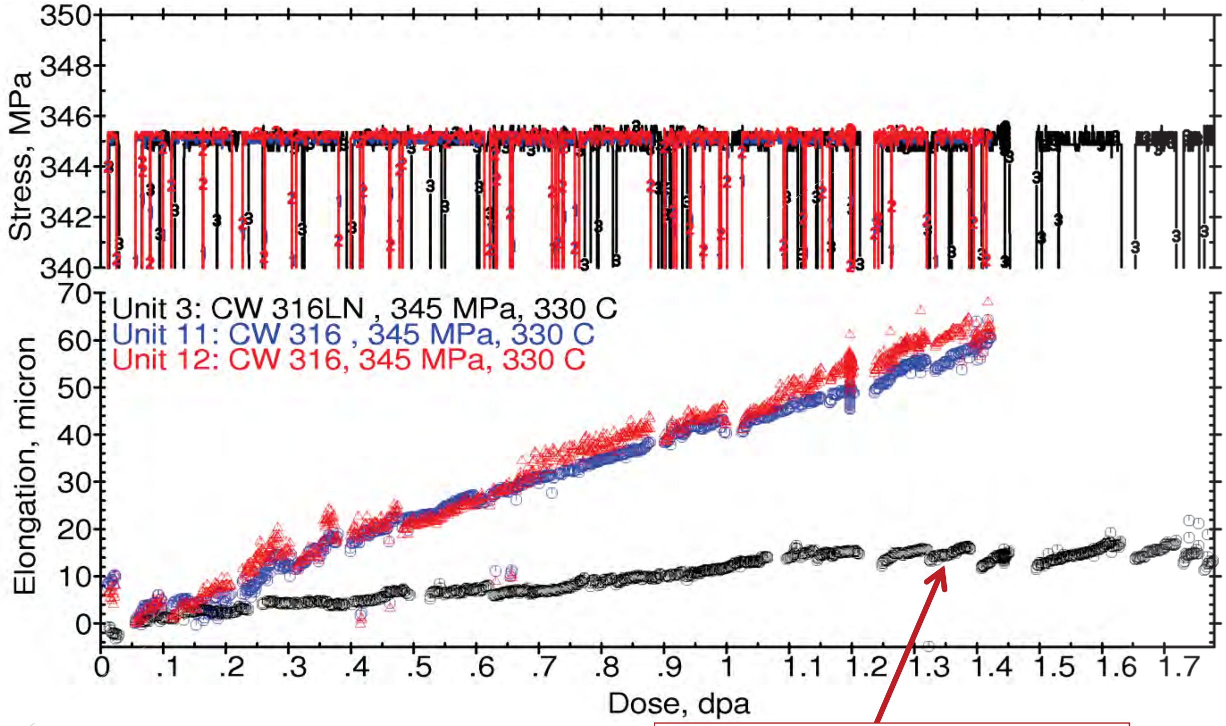
Tested successfully
at VTT under SCW conditions

Loading systems and displacement monitoring systems

- Aim is to provide baseline creep and stress relaxation data
  - core component materials
  - materials proposed as more accident tolerant
  - inert gas conditions with gas gap for temperature control
  - gas lines connected to bellows for applying tensile stress and LVDT for minitoring length change



Comparitive testing to aid better-for-purpose materials selection: irradiation creep of CW 316 SS and CW 316LN

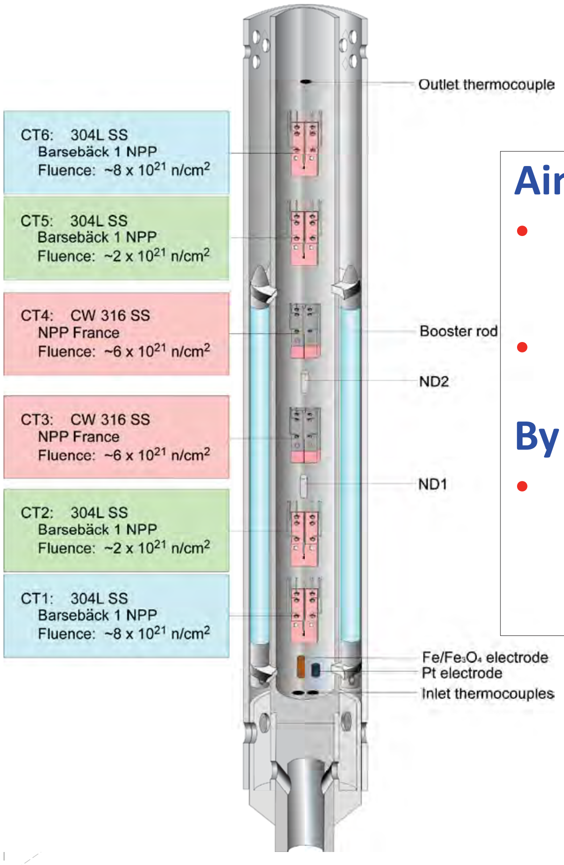


CW316LN has lower creep/relaxation rate

Crack-growth monitoring systems

- Systems for monitoring crack-growth rates in-core have been developed by Halden
- Compact Tension (CT) specimens fabricated from either fresh or pre-irradiated materials are utilized
- System for spot-welding of external current and potential electrodes to CT specimens made from fresh or pre-irradiated materials have been developed
- CT specimen loading system is based on pressurized bellows connected via gas-lines to an external control room
- Algorithms and software optimized over several years and include compensation for temperature effects (thermocouple effects) etc.

IASCC Studies

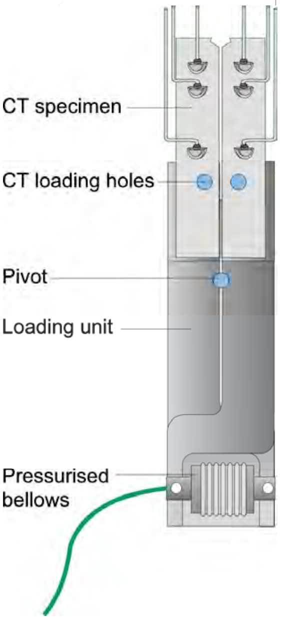


Aimed at:

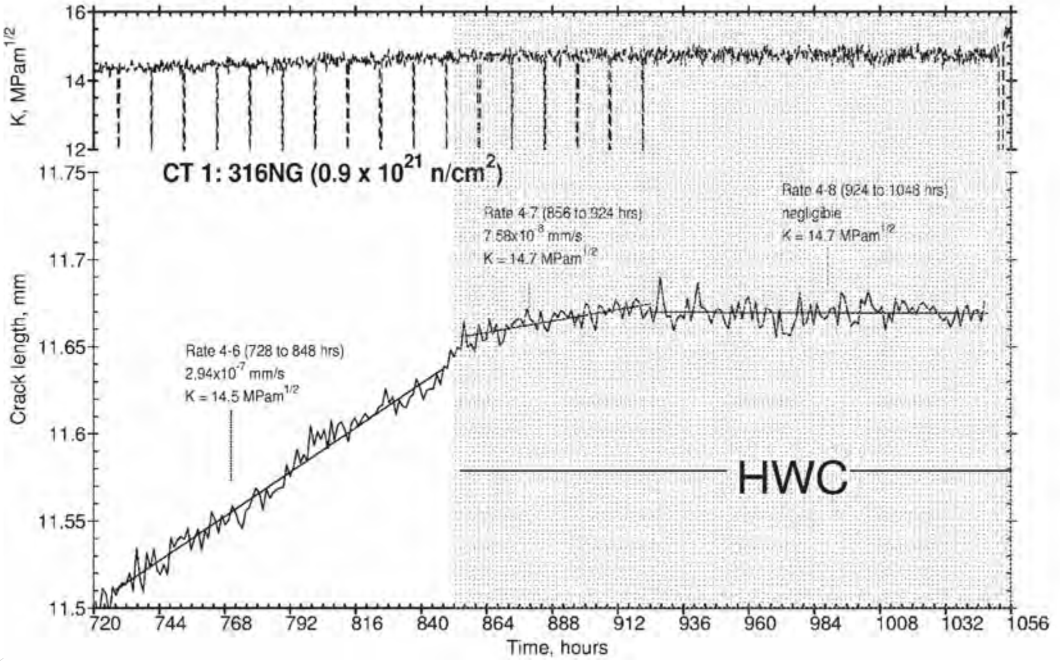
- develop understanding of key parameters affecting material cracking behaviour
- assess benefits of countermeasures

By making:

- online measurement of load, flux, temperature, chemistry, crack initiation and growth rate



Low fluence material showing benefit of HWC



Water loop systems (I)

- The coolant in the Halden Boiling Water Reactor is D_2O, at 235°C and 34 bar
  - Not suitable for corrosion studies and materials testing in general
- Test rigs can be positioned in a pressure flask and connected to a dedicated water loop systems, and hence isolated from the main coolant
- Loop systems allow testing of fuel clad and materials under BWR, PWR, VVER or PHWR conditions:
  - Coolant pressure
  - Coolant temperature
  - Water chemistry
- The Halden water loop systems have proven to be very robust and reliable

Loop systems (II)

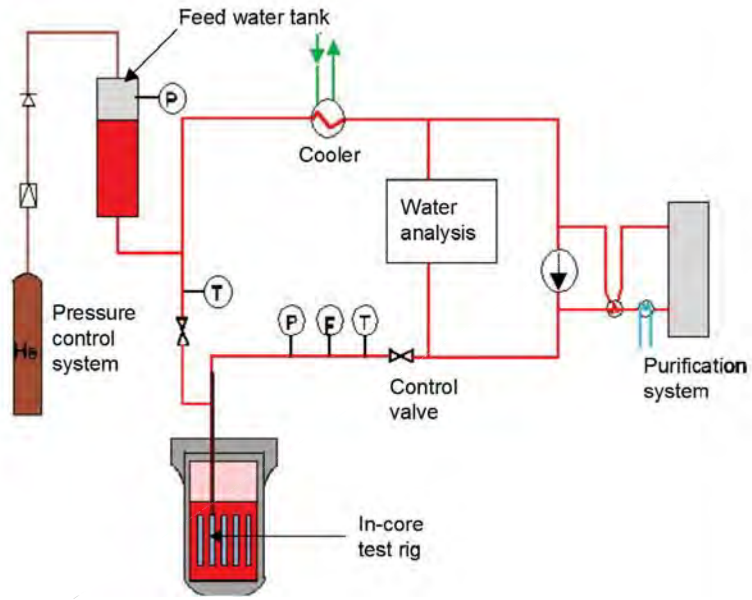
- Some loop systems are designed for long-term irradiation tests while other loop systems are designed for shorter-term transient tests
- All loop systems can be operated with fuel failures but the loop systems used for transient testing (e.g. for PCI / power ramps or LOCA) have «oversized» clean-up systems
- One loop system is available for fuel degradation (fuel secondary failure) studies
- Currently 10 loops in operation

- Each loop can be used under any LWR conditions, but usual to assign each loop to either BWR, PWR, VVER or CANDU conditions

Typical loop conditions

Loop type	Thermal-hydraulic conditions	Water chemistry additions
BWR	288°C 72 bar	H_2 or O_2 (Pt, ZnO, TiO_2, ...)
PWR	290 - 340°C 150 - 160 bar	LiOH B(OH)3 H_2 (ZnO, ...)
CANDU (D_2O)	290 - 340°C 150 - 160 bar	LiOH H_2 (TiO_2, ...)

Loop schematic



Vol: 60 – 120 l

Flow: 100 l/h -
10000 l/h

Pressure: 200 bar

Temp: 350°C

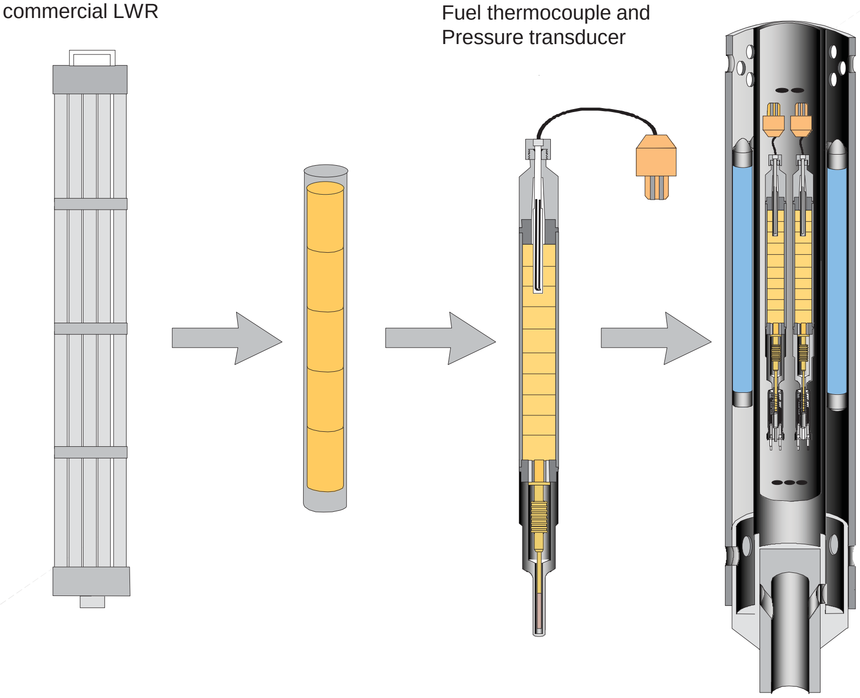
On-line measurements

- **In the test rigs**
  - Neutron flux (for power determination)
  - Coolant temperature
  - Crack length
  - Crack initiation
  - ECP (electrochemical corrosion potential)
  - Sample elongation
  - Fuel properties
- **In the loop system**
  - Coolant pressure
  - Coolant flow
  - Coolant temperature
  - Hydrogen, oxygen concentration
  - Conductivity

Re-fabrication and re-instrumentation systems

- The re-instrumentation equipment is designed and manufactured by IFE / HRP (based on principles demonstrated by RISØ in Denmark)
- Re-instrumentation equipment revised and updated several times since 1991
- Complete packages of re-instrumentation equipment have been delivered to SCK / CEN in Mol Belgium and to RIAR in Russia
- The resent delivery of re-instrumentation equipment to RIAR in Russia was of a compact and modular system (small footprint in the hot-cells)
- Delivery of re-instrumentation equipment to other laboratories is possible (covered by bilateral agreements)
- First re-instrumentation in 1991
- >130 rods re-instrumented since then

Re-instrumentation of fuel rods



Fuel assembly irradiated in a commercial LWR

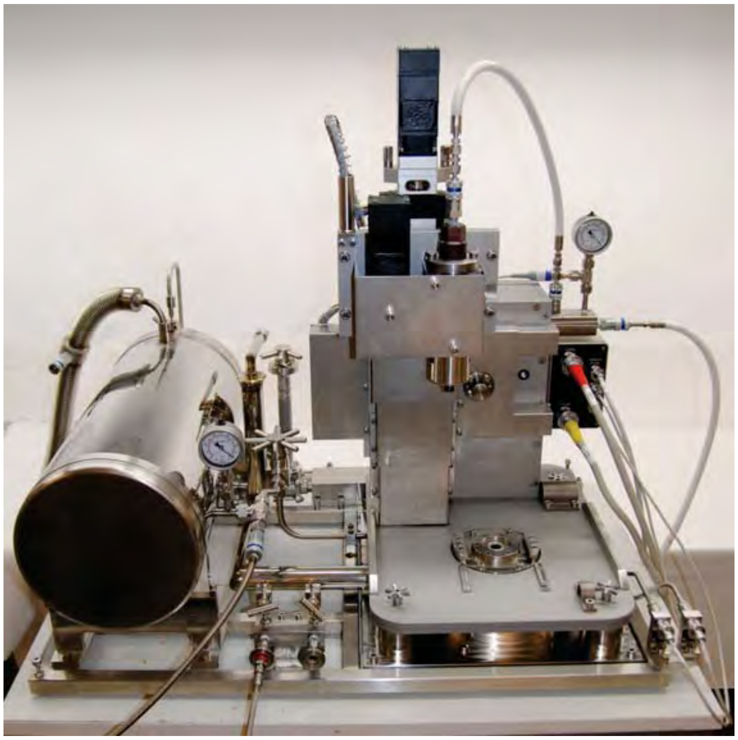
Fuel rod segment

Re-instrumented fuel rod segment with Fuel thermocouple and Pressure transducer

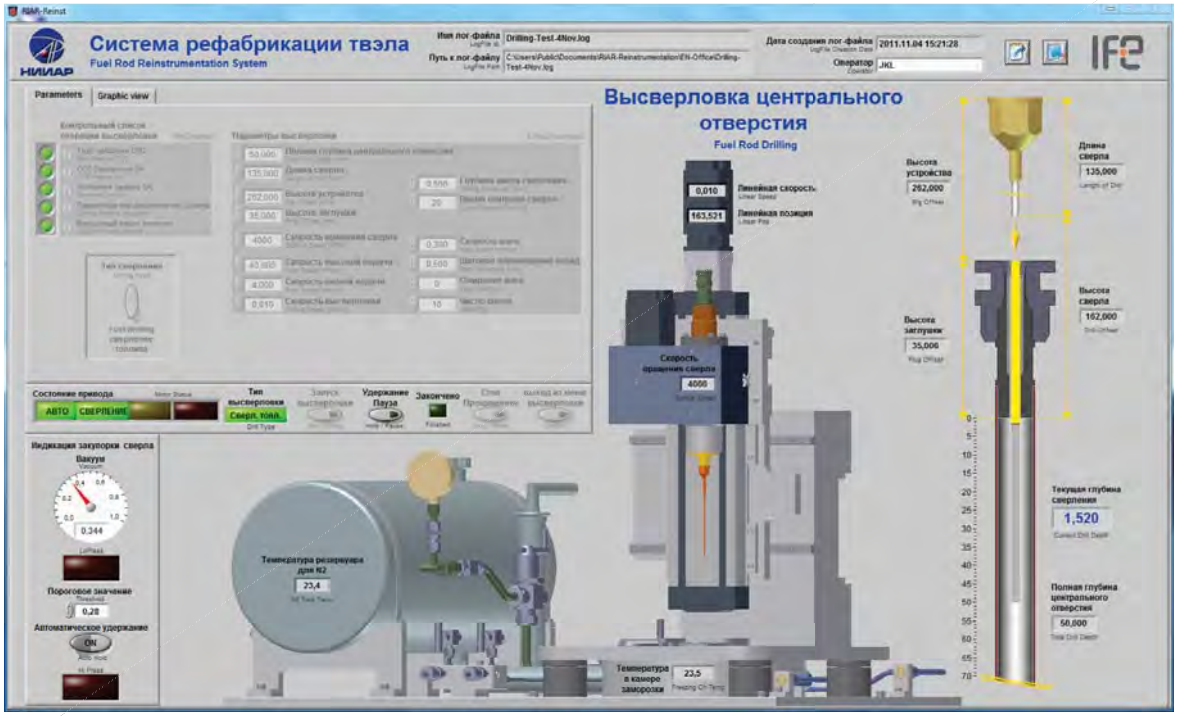
Re-irradiation in LWR-Loop

Re-instrumentation equipment - frame

Re-instrumentation equipment – drilling unit



Re-instrumentation equipment - screen



Имя лог-файла: Drilling-Test-4Nov.log

Дата создания лог-файла: 2011.11.04 15:21:28

Оператор: JKL

Линейная скорость: 0,010

Линейная позиция: 163,521

Скорость вращения сверла: 4000

Температура резервуара для N2: 23,4

Температура в камере заморозки: 23,5

Высота устройства: 262,000

Длина сверла: 135,000

Высота сверла: 162,000

Высота заглушки: 35,000

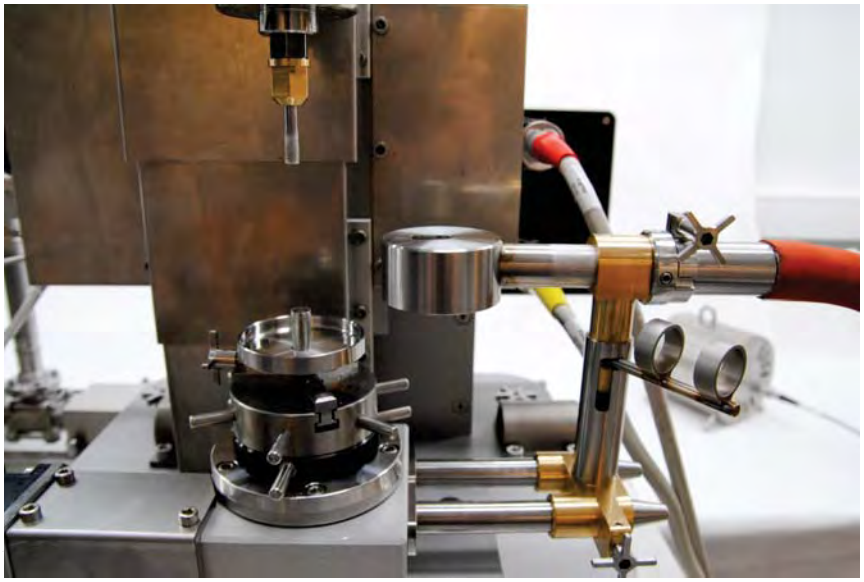
Текущая глубина сверления: 1,520

Полная глубина центрального отверстия: 50,000

Вакуум: 0,344

Пороговое значение: 0,28

Re-instrumentation equipment - defuelling



Re-fabrication and re-instrumentation for LOCA

- Preparation of fuel rods for in-core LOCA tests is demanding
- Based on standard re-fabrication and re-instrumentation techniques and equipment
- Equipment and procedures modified for handling of more complex fuel rods and for attachment of cladding thermocouples to high burn-up fuel rods
- Equipment also developed for 2-D gamma-scanning and for gamma-tomography of fuel rods after the LOCA transient

- The water loop system also differs from the other loop systems (that are not expected to operate with significant fuel failures)

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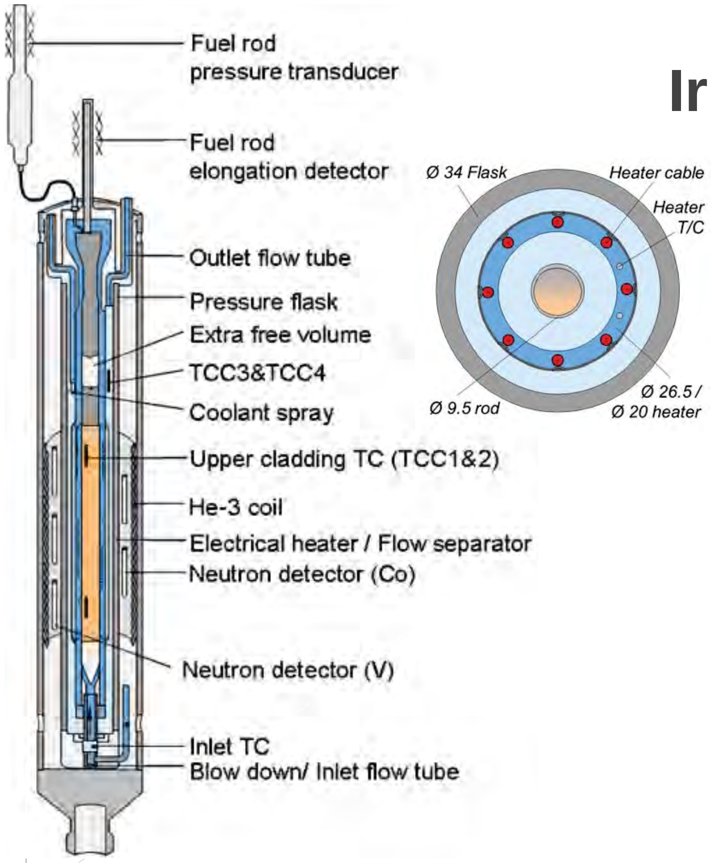
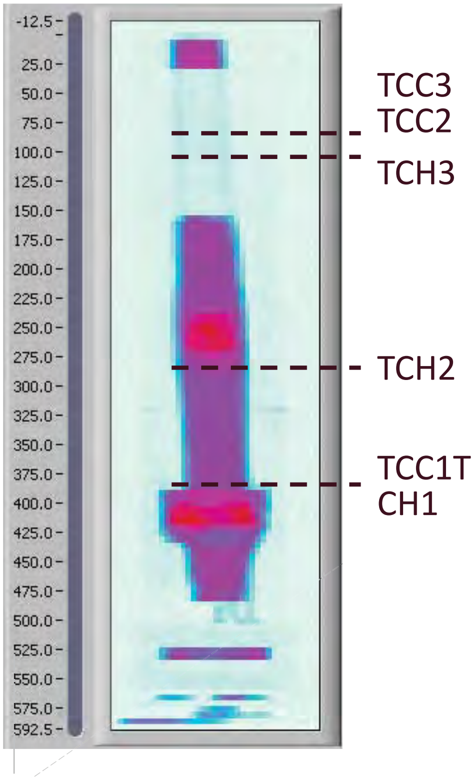
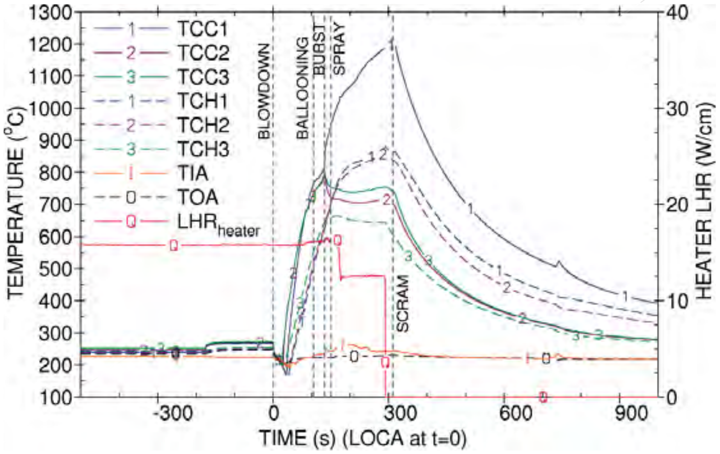


Irradiation Rig

- Single fuel rod in a pressure flask connected to a water loop
- Low level of nuclear power simulates decay heat
- Electrical heater surrounding the rod simulates the heat from neighbour rods
- Rod instrumented with
  - 2 – 3 cladding thermocouples
  - Pressure sensor
  - Cladding elongation detector
- Thermocouples in the heater
- Neutron detectors for power distribution

Fuel relocation and temperature increase





Ballooning and fuel relocation can cause the cladding temperature to increase as observed in IFA-650.9

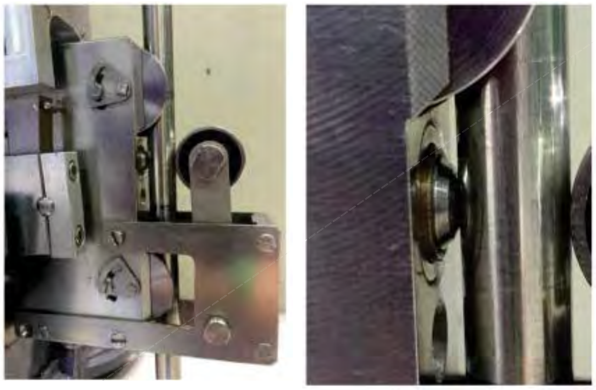
Interim inspection systems (I)

- All interim inspections performed in dry conditions in a relatively simple handling compartment
- Fuel rods removed from the irradiation rigs and installed in different purpose-built interim inspection rigs (fuel rods with thermocouples typically will not be removed from the irradiation rigs unless “in-core connectors” are used)
- Inspections also performed on the irradiation rigs and repairs / upgrades performed as required - e.g. replacement of turbine flowmeters and / or LVDTs (spare LVDTs and “in-core connectors” are installed in the irradiation rigs when they are built)

Interim inspection systems (II)

- *Typical fuel interim inspections at Halden :*
  - Visual inspection
  - Measuring of diameter profiles, length changes and rod bowing
  - Crud-brushing and crud sampling
  - Oxide thickness measurements (also developed for FeCrAl)
  - Eddy-current measurements for defects detection
  - Gamma-scanning and gamma-tomography
  - Neutron radiography (not a standard interim inspection item)
  - Re-calibration (or replacement) of instruments as required (typically thermocouples and pressure gauges)
  - Re-configuration of test matrix as required

Oxide thickness measurements



- Fischer probe and Fischerscope electronics (~2.5 MHz)
- IFE measurement head, retractable probe
- Zeroing and calibration by representative cladding materials and foils
- IFE applications for post-processing and visualization

Motivation and background – cont.

- Halden technology is more than just the LVDTs, other instruments and hardware
- There is highly skilled staff that design instruments, irradiation rigs and all other types of equipment
- There is highly skilled staff that operate and maintain the loop systems, perform experiments, and analyzes the data from the experiments
- After the decision was made to permanently close down the Halden Boiling Water Reactor – this highly skilled staff is very interested in sharing their knowledge with others in order to benefit nuclear research and development