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Post-Halden Reactor Irradiation Testing for ATF: Preliminary Assessment and Recommendations

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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 will shut down and decommission in the near term with the loss of significant experimental capabilities for prototypical irradiation testing. This loss represents a great challenge and opportunity for swift response by the R&D community to fill the resulting capability gaps.

The primary of 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 DOE ATF. The near-term ATF fuels and materials concepts have a goal of core batch reloads in commercial power plants of ~2025 while the timeline for more revolutionary concepts extends to ~2028+. This timeline places some urgency on making decisions on experiment pathways and execution.

In general, particularly in regard to the ATF program, compensating for the loss of the Halden reactor appears to be feasible. However, not surprisingly, the development of new capabilities will require significant investments in infrastructure and human resources within the DOE laboratory complex. As a result of the preliminary assessment for the DOE ATF program, near-term recommendations to address post-HBWR testing are summarized as follows:

1) Halden possesses unique technologies and knowledge for testing, refabrication, and instrumentation of nuclear fuels and materials; a key effort going forward should be to transfer that expertise to other relevant facilities as soon as possible through collaborative partnership with DOE, including TREAT and ATR. This collaborative partnership should focus specifically on water loop technology, in-pile Loss-of-Coolant-Accident (LOCA) testing device at the Transient Reactor Test (TREAT) facility, fuel rod refabrication capability at INL, and in-pile instrumentation for integral fuel rods as well as materials testing.
2) Within the DOE complex, the potential to increase the capacity for steady-state fuel testing should be explored. Three primary targets for study should include increasing capacity in the existing ATF-2 loop in the Advanced Test Reactor (ATR), exploring the development of loops in the I-positions within the ATR, and investigating the use of pressurized water capsules in either ATR or the High Flux Isotope Reactor (HFIR).
3) Using Lead Test Rod (LTR) and Lead Test Assembly (LTA) materials irradiated in commercial reactors for follow-on testing in hot cells and transient and steady state reactors is an important strategy to have sufficient quantity of pre-irradiated materials. Given this approach, one critical need is to develop capabilities for fuel rod refabrication and reinstrumentation within existing DOE hot cell facilities
4) In-pile flexible power operations for fuel experiments (e.g. ramp testing) is a recognized capability gap desired for ATF development. Possible strategies to address this gap include using pressurized water capsules at BR-2 (Belgium), adapting methods developed at Halden to ATR loops, or using a mechanical mechanism in the ATR similar to the PALM device used by the Naval Reactors program.
5) Given the desire to send fuel from commercial reactors to INL for safety testing in TREAT and possible ramp testing in ATR, a critical issue that must be resolved is the moratorium by the State of Idaho on the receipt of research quantities of commercial spent fuel. Fuel vendors have also expressed a preference for dealing with a limited number of facilities to avoid international shipments of spent nuclear fuel.

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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 shut down and decommission in the near term with the loss of significant experimental capabilities for prototypical irradiation testing. This loss represents a great challenge and opportunity for swift response by the R&D community to fill the resulting capability gaps.

One promising strategy to retain the 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 Department of Energy (DOE) facilities in the near term with minimal changes to current DOE plans. Preliminary discussions with HRP leadership have been favorable towards this strategy. Accommodating other scope 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. However, the volume of testing performed in HWBR will be difficult to support 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 Department of Energy (DOE) Accident Tolerant Fuels (ATF) program. The purpose of this report is to evaluate potential testing gaps created by the loss of the HBWR for the ATF fuel development program and provide initial recommendations for filling irradiation testing capability gaps to support ATF program needs and objectives. A follow-on report (later this year) will address detailed descriptions of credible strategies and associated facilities to provide even more informed recommendations.

To accomplish these goals, this report summarizes key Halden reactor missions and capabilities while exploring existing international capabilities that are potential solutions to fill residual gaps. Special focus is given to irradiation testing and supporting technologies. Two supporting workshops were recently held at Idaho National Laboratory 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 Halden Capability Gap Assessment, with diverse participation from U.S. national laboratories, Halden, DOE, fuel vendors participating in the Accident Tolerant Fuels (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 both domestic and abroad that can fill those gaps (see Appendix B);
3. Provide the consensus results of a multi-organizational, international workshop on credible paths forward to fill gaps; and
4. Provide recommendations for the near-term path forward for the DOE ATF program. The report sets the stage for a more detailed evaluation and recommendations in a follow-on report later this year.

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 recent onsite meetings focusing on preservation and possible transfer 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; and
  - the Halden Capability Gap Assessment Workshop on July 9-10, 2018 with participation from US 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).

A second report will follow later this year with detailed descriptions of the credible experiment pathways identified in this report, preliminary findings on some listed recommendations, and more comprehensive recommendations for next steps.

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 and 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, the HRP and HBWR personnel are highly regarded for their experimental capabilities and F&M performance insights. Along with that expertise, the unique capability offered by the HRP is rooted in the test reactor capable of simulating operational conditions of commercial nuclear reactors, reliable and versatile in-pile instrumentation, and re-fabrication 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.

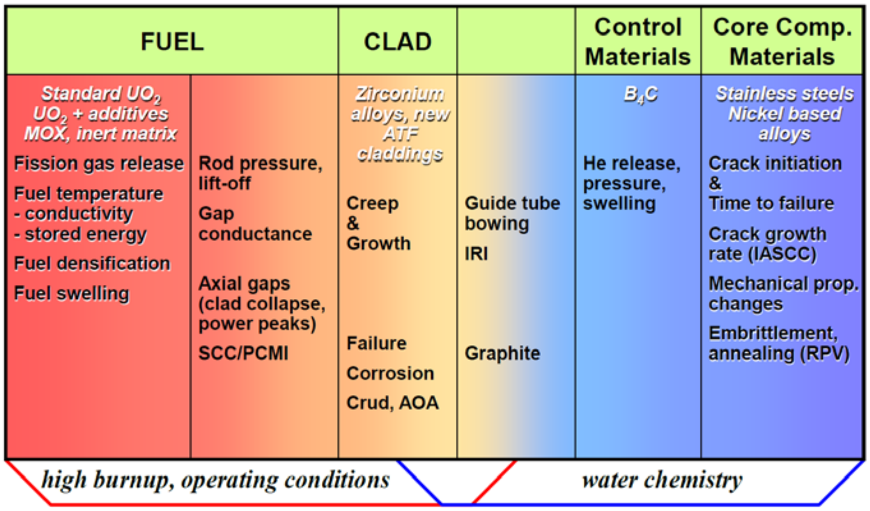

Figure 1. Spectrum of HRP fuels and materials investigations. (Illustration from presentation by M. McGrath, "Halden Reactor Project," GAIN Fuel Safety Research Workshop, May 1-4, 2017.)

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. The success of the HRP online instrumentation is closely linked to HRP capability to re-manufacture, instrument, 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 Boiling Water Reactor (BWR) and Pressurized Water Reactor (PWR) (and VVER and CANDU) 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 vital component of loop experimentation. The HRP has 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, and cladding corrosion and creep behaviors. Also, fuel safety margin studies such as rod overpressure "lift-off", secondary degradation, dry-out cooling transients, and power transients for PCMI, Fission Gas Release (FGR), and Pellet Cladding Interaction-Stress Corrosion Cracking (PCI-SCC). A special LOCA device is used to study fuel fragmentation, relocation, and dispersal (FFRD) behaviors, currently the only remaining in-pile LOCA device in the world. 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 test fuel in test devices to manipulate the local power level experienced by a fuel rod through pressure control of the gas. With this capability, power transients for experiments can be performed and support 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, though few facilities have carried out such experiments in recent times. Therefore it represents a key capability to address for 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. 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 is the key to their great success.

The primary instrumentation utilized in the HBWR includes thermocouples for temperatures (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 re-calibrate 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 nearly fuel rods from nearly any source into a form amenable to placing into irradiation test rigs. The “re”-instrumentation capability allows measurements to be made on fuel at nearly 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 on the current state of the fuel may be taken.

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 PIE, including electron microscopy. Fuel shipments between Halden, Studsvik, and Kjeller are routine.

Please 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 on-going at several DOE reactor/hot cell facilities, and LTR/LTA tests in commercial power reactors are now beginning.

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.

An important consideration not fully captured in this report but part of active discussion is that of specimen quantity requirements for ATF. 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 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 LTR/LTA fuel rods and associated materials, not only to provide operational data, but also to serve as a source of irradiated fuel rods available for potential follow-on experiments such as power ramping and design basis accident experiments. Further evaluation is needed concerning allowable positions for LTRs/LTAs in commercial facilities in regards to limiting positions in the reactor and potential approaches to access them through the regulatory process. With the reduction in volume of irradiated fuel specimens caused by the loss of Halden, the utilization of LTR/LTA materials for subsequent testing must be a fundamental component of developing a detailed strategy for fuel qualification going forward.

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 and describes 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 to corresponding testing categories to meet experimental needs. The categories on the right side of the table includes capabilities that are not specific to the HBWR. These are included because they represent key capabilities that can aid in meeting ATF objectives and represent classifications of capabilities available at various research reactors.

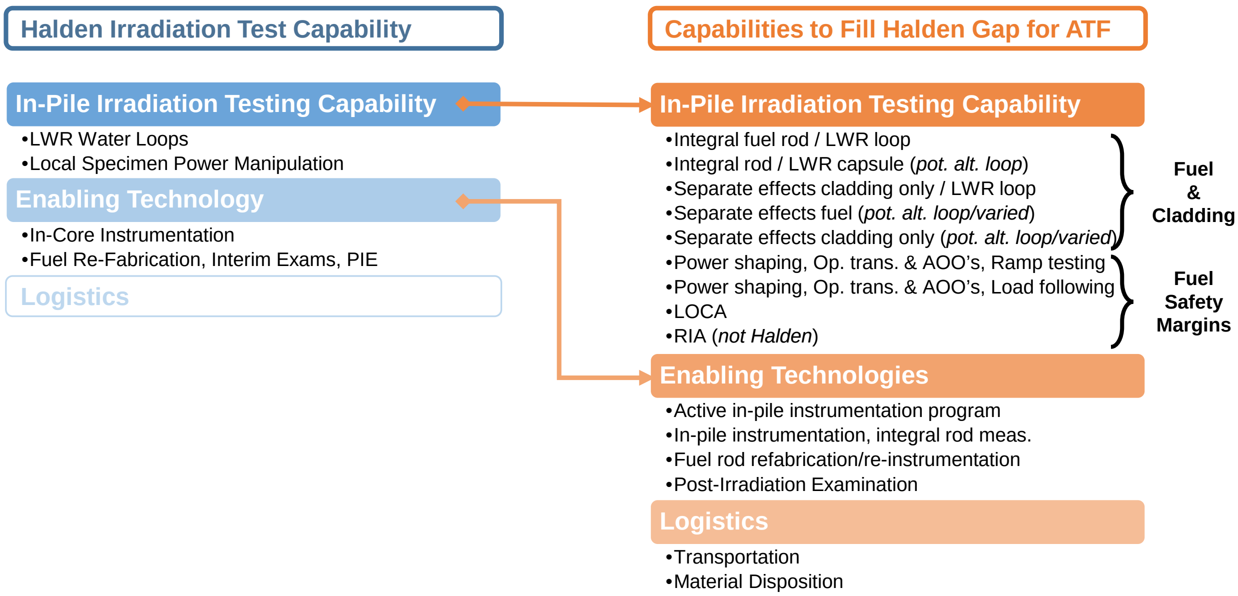

Figure 2. Mapping irradiation capability at Halden to categories for evaluating material test reactors.

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 capability 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. The objective in area was to capture specific nuances related to the individual test facilities. In reality, the logistics required for the ATF program is a complex issue. A later report may include more information about the logistics associated with the ATF program and will address in detail the primary concerns related to the ATF program.

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 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 B2 focuses on steady-state material test reactor specifications while Table B3 provides a brief overview of crucial supporting technologies, transportation, and waste considerations. Table B4 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 described description of HBWR capabilities, ATF testing needs, and international material test reactor 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, used in evaluating each facility's capability for a given mission. The table key is divided into 5 categories to distinguish if 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. 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. To be more comprehensive, the future test facilities JHR and PALLAS 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. After completing the table using the metrics described, credible capability options 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.

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 capabilities in the area of integral fuel rod testing, an important area for the ATF program. Capacity limitations in these facilities (not fully addressed here) 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 LWR pressurized capsules have inherent physical limitations that best provide thermal-hydraulic conditions of BWRs
- 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. 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 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 those capabilities generally correspond to the type of irradiation capability available at a given facility.

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. Important points 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 detailed review of shipping cask availability and characteristics for each facility will be included in the final report. Shipping materials within

the U.S. is not expected to be an issue, except possible cask or receiving limitations of a given facility (can a facility receive four meter long rods?).

- 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 American based platform with ATR and TREAT as the foundation and the JHR and CABRI facilities forming the European base) is an important recommendation moving 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 capability. At the recent workshop at INL, one ATF fuel vendor specifically recommended this approach and the OECD NEA also shared similar ideas about addressing post-HBWR testing needs internationally.

5. Recommendations

A primary finding of this study is that the closure of the HBWR does not represent a significant threat to the goals of the DOE ATF program. Experimental gaps of varying levels and importance have been identified and credible pathways to fill those gaps are available to meet the fuel qualification needs of ATF. Still, the experimental timeline drives some urgency with the goal of core batch reloads of high TRL ATF designs in commercial plants by 2025 followed by extension of existing fuel margins a few years later and/or qualification of lower TRL ATF concepts. Based on the preliminary conclusions of this work to date, the following recommendations are made in order to support continued development of ATF materials.

1) **Partner with HRP to Transfer Expertise and Technology for Experiments and Instrumentation in each of the areas that follow** *(with exception of #5)*

At the core of the unique capability and remarkable fuels and materials irradiation testing program are the HRP personnel, which have decades of testing experience and experimental knowledge. The detailed designs of experiments and associated hardware and instrumentation are openly available to all HRP participants. A very efficient approach to capturing and redirecting the key components of their testing program is to work directly with HRP personnel to adapt and develop the key testing technologies and experimental strategies. With recognized expertise by fuel modelers and regulatory agencies worldwide, the close involvement of HRP staff could provide accelerated validation of test results based on these systems. Collaborative partnership should focus specifically on water loop technology, in-pile LOCA device at TREAT (see #6 below), fuel rod refabrication capability at INL, and in-pile instrumentation for integral fuel rods as well as materials testing (see #8 below).

2) **Expand Testing Capability in Prototypic Loops for Increased Experimental Capacity**

The loop testing capacity lost with the closure of HBWR is clearly difficult gap to fill for broad LWR R&D needs. With ATR having the only pressurized water loop currently available for doing integral fuel rod experiments, it presents a capacity concern for ATF. For this reason, careful deployment of LTR/LTA fuels and materials in commercial reactors is imperative to produce sufficient quantities of irradiated fuels and materials for subsequent testing. Still, several options listed below should be considered to alleviate the loss of HBWR and provide significant capability to ATF. In all cases, the co-development of in-pile instrumentation and associated logistics should be a fundamental component of evaluations and designs.

a) **Utilize ATF-2 (Loop-2A) in ATR More Effectively**

Investigate enhancing specimen volume capacity (and current loop power limitations) in the ATF-2 experiment in Loop-2A at ATR. Current limitations could potentially be extended significantly to allow for added testing capacity. The instrumentation already designed for ATF-2 should be pushed to deployment to qualify online data collection for potential testing needs on non-UO_2 fuel materials. The partnership with HRP staff in Recommendation 1 would be key to realizing this in the near term.

b) **Explore Feasibility of Loops in ATR "I"-Positions**

Perform conceptual design studies to investigate the possibility of using underutilized I-positions in ATR for installation of additional pressurized water loops, including development of cost and schedule for deployment. Scoping studies have already been initiated at INL. On the core periphery, the I-positions generally have relatively low flux levels, though data indicates flux levels (heat generation rates) are comparable to HBWR and commercial power plants. These loops could be designed to provide filtering and clean up systems to allow for fuel failures and even secondary degradation studies. Design studies should also consider options for performing local power maneuvering to allow ramp testing and load following experiments. This design including fuel failure and power transients can leverage or even adapt the well-refined water loop capability developed by the HRP. HRP is already designing and building a water loop for the JHR based on HRP system.

c) **Investigate Pressurized Water Capsule Device at ATR and/or HFIR (thermosiphon)**
These devices represent a well-established technology used in many facilities around the world. They provide a smaller facility footprint and avoid issues related to potential contamination leaving the primary containment of the test reactor as is possible in loops with ex-vessel systems. (It is important to note that the HRP is very comfortable failing fuel in loops and has had not issues over many years.) A design evaluation for ATR should be carried out that could provide a nearer term solution and additional testing capacity in ATR. The device designed and tested out-of-pile at HFIR (ORNL) should be evaluated against ATF data objectives and cost and schedule for full implementation into HFIR.

Rough Order of Magnitude (ROM) additional cost in FY19 is $10M.

3) **Investigate Capability for Flexible Power Operations at BR-2 and Potential in ATR** *(this capability is recognized as an international capability gap with significant importance to the ATF program)*

Ramp testing is recognized as a near-term gap in HBWR capability that has importance for ATF materials. BR-2 is the only facility (other than HBWR) that has had this capability in the recent past, though it is inoperable at present. The recommended path forward includes obtaining cost and schedule for deployment of the BR-2 pressurized water capsule featuring their He-3 neutron filter for ramp testing. For ATR, a preliminary study has recently begun to investigate options for doing such testing at ATR. This study should continue to evaluate options including building a Powered Axial Located Mechanism (PALM) device for Loop-2A. PALM devices are used routinely at ATR by the U.S. Navy in other flux trap locations in ATR.

Rough Order of Magnitude (ROM) additional cost in FY19 is $5M.

4) **Establish Fuel Rod Refabrication and Reinstrumentation Capability at INL** (*a recognized vital capability gap already under development*)

Fuel rod refabrication system(s) are crucial to support testing of LTR/LTA materials and introduce measurements on pre-irradiated fuel specimens from test reactors. At INL, a fuel rod refabrication and reinstrumentation system has already been planned for implementation in support of transient testing at TREAT. ORNL has recently stood up capability to refabricate rods in order to perform LOCA tests in their hot cell. INL is already working closely with HRP to develop a system design to be located at the Materials & Fuels Complex (MFC) at INL. The effort is targeting system operation by 2021. The ATF need further emphasizes rapid deployment of this capability to enable use of LTR/LTA materials and access instrumentation opportunities on fuels.

Rough Order of Magnitude (ROM) additional cost in FY19 is $5M.

5) **Transportation and Waste – Expedite Resolution of State of Idaho Moratorium on Research Quantities of Commercial Spent Fuel**

The current moratorium on shipping commercial spent fuel into Idaho is the most important near-term issue in this category that must be resolved for the success of the ATF program. The current situation implies possible resolution within the next year as the DOE waste treatment facility in question is expected to come online, hopefully resolving the issue of bringing research quantities of commercial spent fuel into Idaho. LTR/LTA materials must be shipped to Idaho for PIE and follow-on testing in ATR and TREAT.

Further evaluation is needed of the cost and logistics of shipping irradiated fuels. Special consideration should be made for shipping between Oak Ridge National Laboratory, from commercial facilities to domestic R&D facilities, and intercontinentally.

6) LOCA – Utilize Hot Cell LOCA device at ORNL and Continue Development of TREAT LOCA Capability

The loss of the HBWR represents the loss of the only in-pile LOCA testing capability remaining in the world. An experimental capability for the TREAT reactor facility has been under design for some time and is rapidly maturing. Hot cell LOCA testing is already available at ORNL (recently demonstrated) with the Severe Accident Test Station (SATS). The ATF testing strategy should incorporate hot-cell testing where possible and appropriate, but should also include more integral in-pile experiments to ensure key behavioral mechanisms are captured in the in-pile experiments while validating the out-of-pile approach. The in-pile experiments will also provide key integral validation of modeling tools and the conclusions of separate effects and semi-integral hot cell experiments. Development of TREAT capability will be enhanced through greater cooperation with Halden staff (#1 above).

7) Adequate Materials Testing Capability appears to be available in Existing Facilities

Several options exist for performing material testing (i.e. creep and corrosion testing) to support ATF. Along with Loop-2A at ATR, the MITR provides capability for testing materials under prototypic thermal-hydraulic, chemical, and neutronic conditions. Testing of ATF materials has already been underway for some time. The HFIR reactor could also provide a prototypic environment (except flow) with the thermosiphon device. Several separate effects irradiations are already underway in these facilities. Instrumentation technology supporting this mission requires further evaluation but will be overviewed in the later report (see #8 below).

8) Develop Overall Instrumentation Strategy for In-Pile Testing while Continuing Qualification of Halden Sensor Technology for Use at the TREAT Reactor and ATR

Under close collaboration with HRP, the HRP LVDT technologies are already undergoing extensive testing and planning for qualification at the TREAT facility (# 1 above). ATF-2 is near qualification of LVDT devices at ATR. The loss of HRP should increase the urgency of maturing INL expertise with these technologies, including at ATR and TREAT. At the same time, the in-pile instrumentation needs of ATF as well as the broader fuels testing needs of DOE should be evaluated comprehensively. More detailed descriptions of in-pile instrumentation capabilities will follow in a later report this year.

Out-of-pile facilities are needed at INL or other partner institution(s) for instrumentation characterization and qualification to support in-pile testing at the TREAT reactor and ATR. Testing instrumentation performance including feedthroughs and connectors is crucial to in-pile deployment success. Prior to reactor deployment, in-pile instrumentation should be validated extensively in as near to reactor conditions as possible to characterize, validate, and qualify overall instrument configuration performance. Beyond neutron flux and fluence effects, the in-reactor thermal-hydraulic boundary conditions are challenging due to temperature, pressure, and flow rate. Static water autoclaves at INL are used extensively to simulate static water environment effects. A flowing water autoclave is needed to support instrument R&D for loop deployment.

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 US 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.

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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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**

Halden Capability Gap Assessment Workshop
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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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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 B2. 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 B3. 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 B4. Transient Material Test Reactor Overview – Reactor Data, Enabling Technology, Logistics

Reactor	Operating Facilities				Not Yet Operational
	TREAT	CABRI	NSRR	IGR	JHR (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

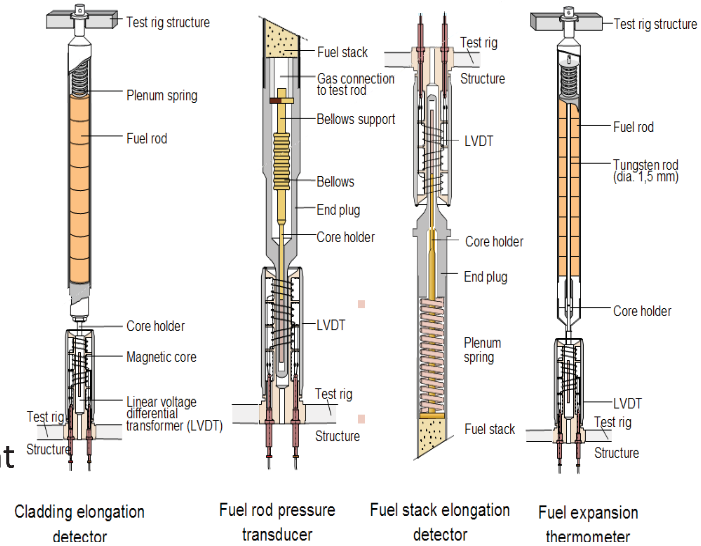
Contents of the presentation

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

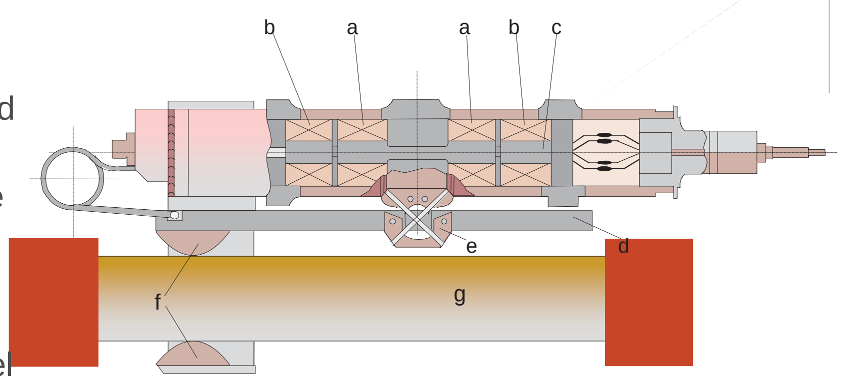
- All test assemblies are equipped with in-pile instruments to monitor fuel behavior:
  - ✓ Pressure in fuel rods
  - ✓ Fuel temperature
  - ✓ Elongation of fuel and clad
  - ✓ Change of cladding diameter
- Test assemblies create a controlled testing environment within the Halden Reactor



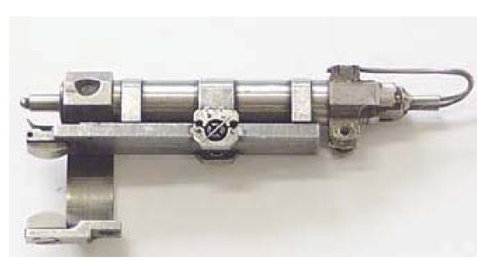
'On-line' measurements are the speciality of Halden's experimental work: reliable instrumentation provides direct insight into phenomena while they develop

Diameter gauges and hydraulic systems

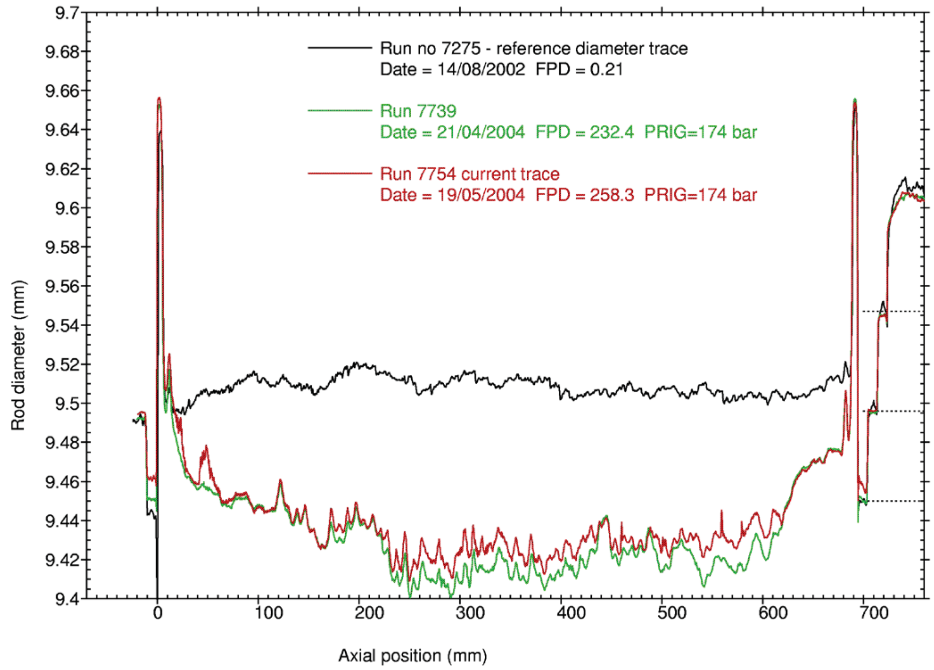
- Provides data on fuel rod diameter profile.
- Instrument based on the LVDT principle.
- Differential transformer with two feelers on opposite sides of the fuel rod.
- DG moved by hydraulic system while a position sensor senses the axial position along the rod.
- Operating conditions: 165 bar, 325°C



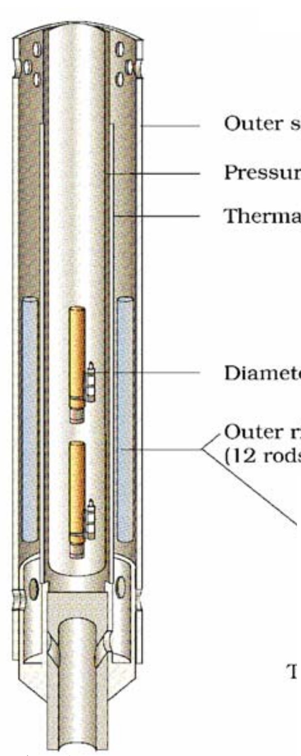
a: Primary coil
b: Secondary coil
c: Ferritic bobbin
d: Ferritic armature
e: Cross spring suspension
f: Feelers
g: Fuel rod



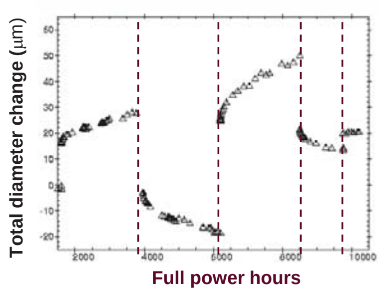
On-line evidence for crud loading by use of DG measurement



Cladding Creep Testing

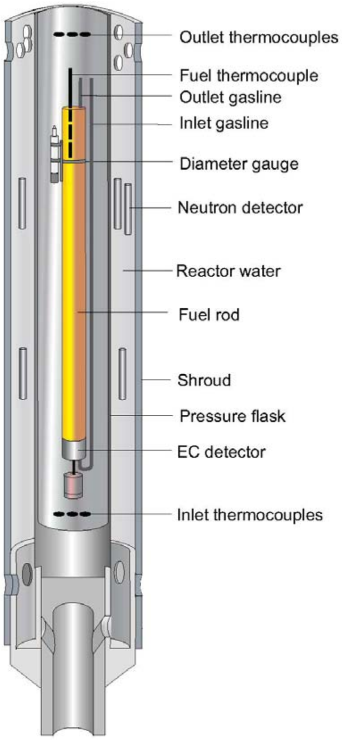


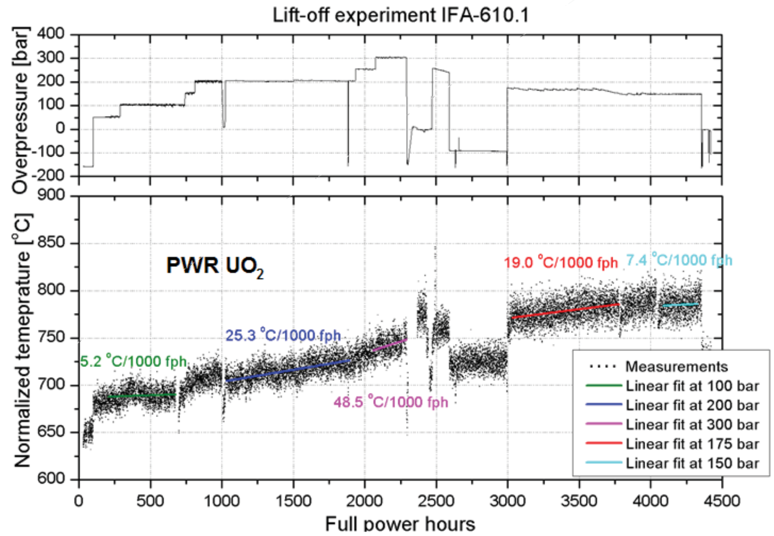
- Cladding OD change monitored on-line with diameter gauge
- Fuel rods with large gap to avoid PCMI connected to gas system for internal pressure change (hoop stress control)
- Hoop stresses of up to ~130 MPa (tension and compression)
- Booster rods to increase local fast flux to ~3-4 n/cm2/s



- 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)

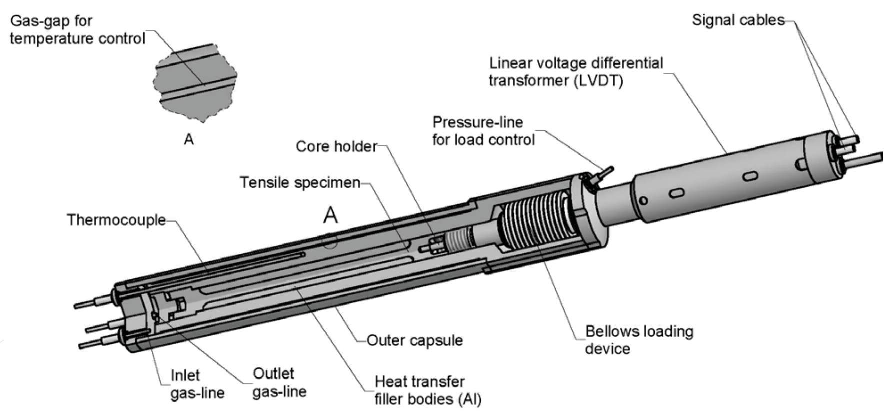
reference electrode
(mechanical seal)

reference electrode
(brazed seal)

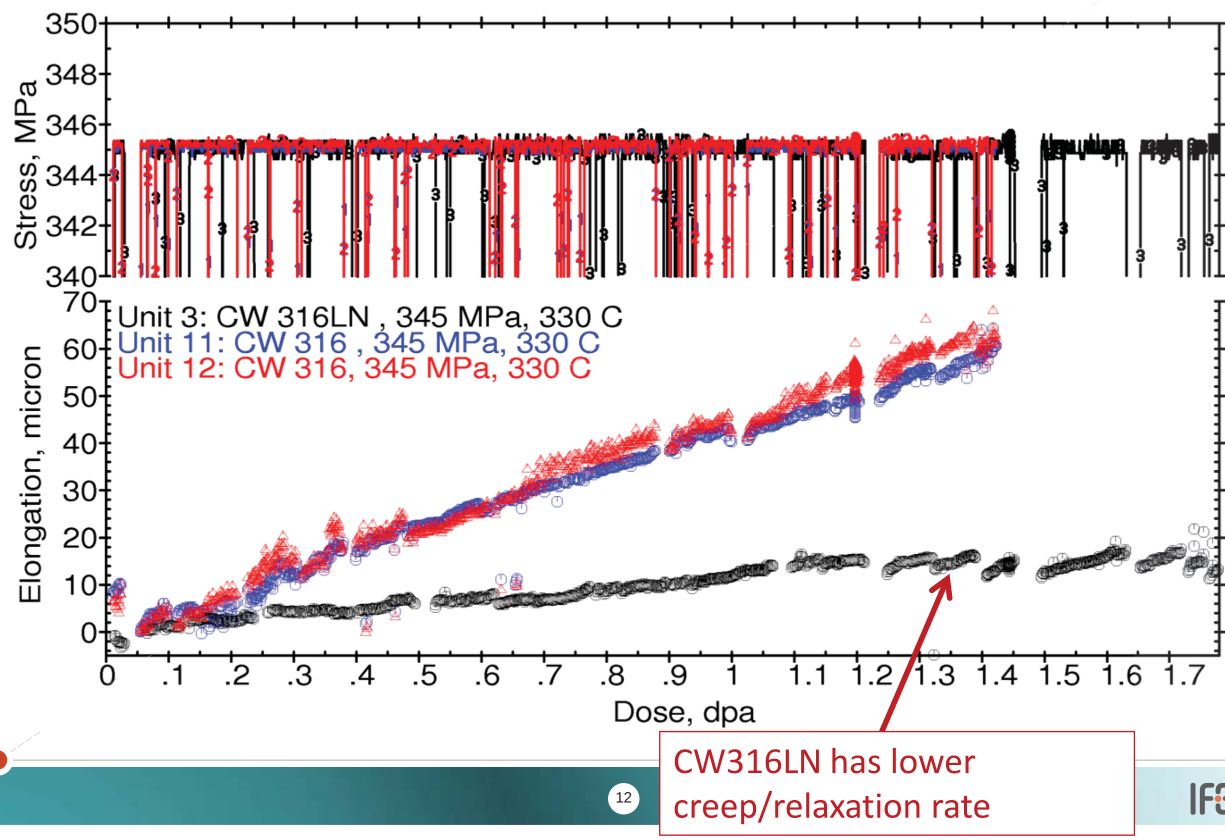
Tested successfully
at VTT under SCW conditions

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

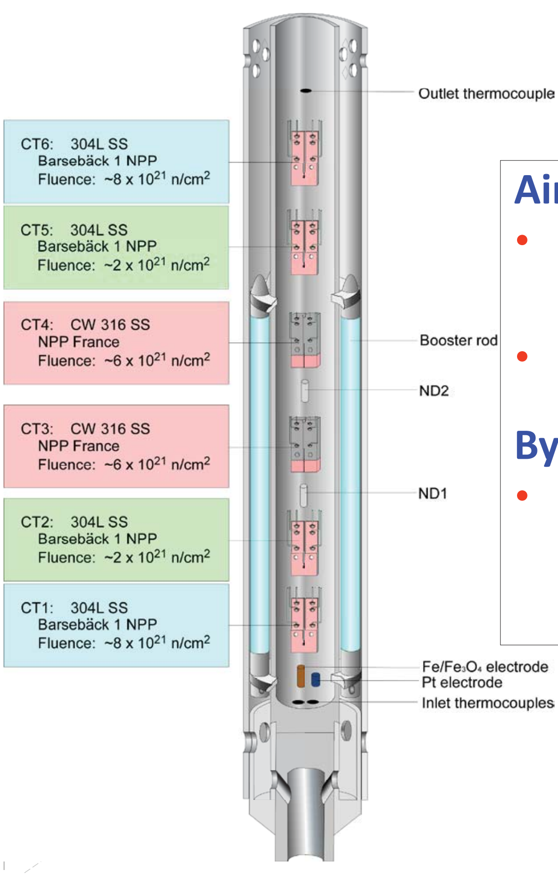


Comparitive testing to aid better-for-purpose materials selection: irradiation creep of CW 316 SS and CW 316LN



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.



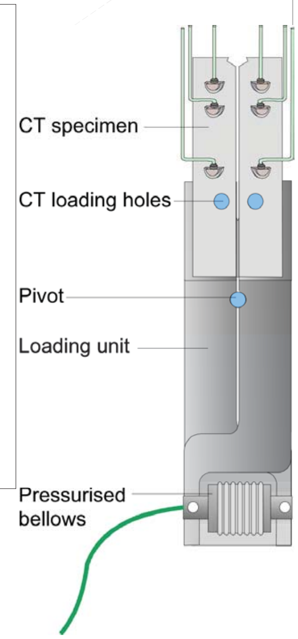
IASCC Studies

Aimed at:

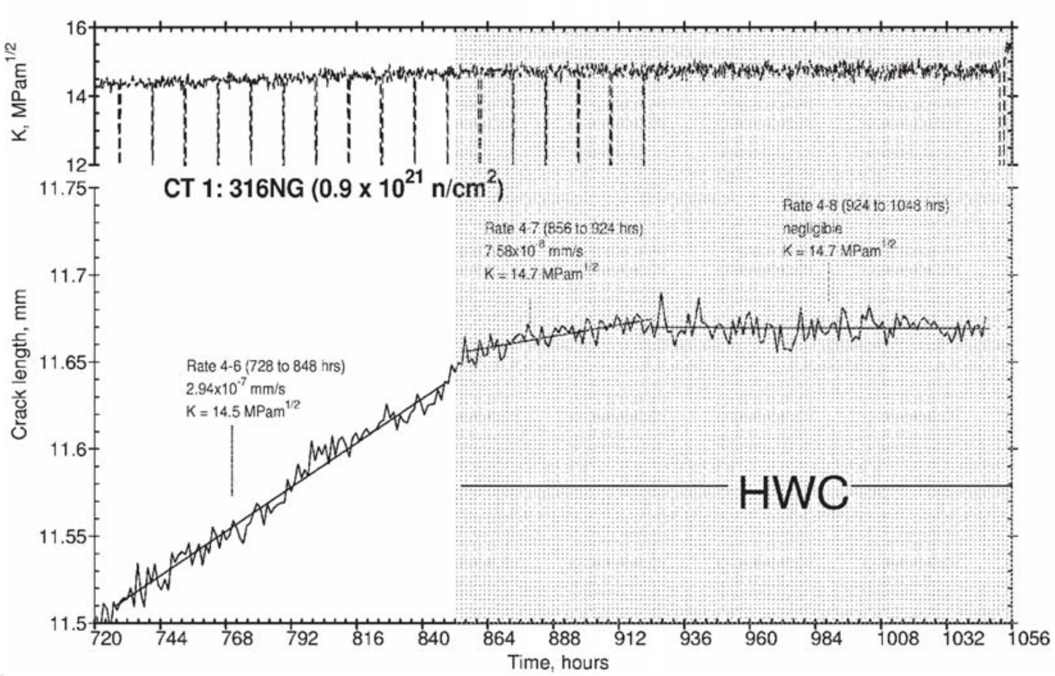
- develop understanding of key parameters affecting material cracking behaviour
- assess benefits of countermeasures

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)

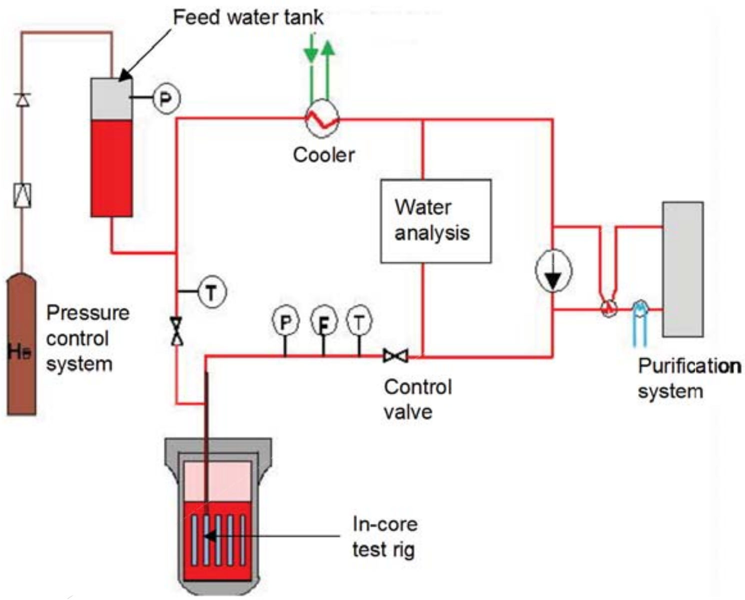
- Some loop systems are designed for long-term irradiation tests while other loop systems are designed for shorter-term transient tests
- All loop systems can be operated with fuel failures but the loop systems used for transient testing (e.g. for PCI / power ramps or LOCA) have «oversized» clean-up 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

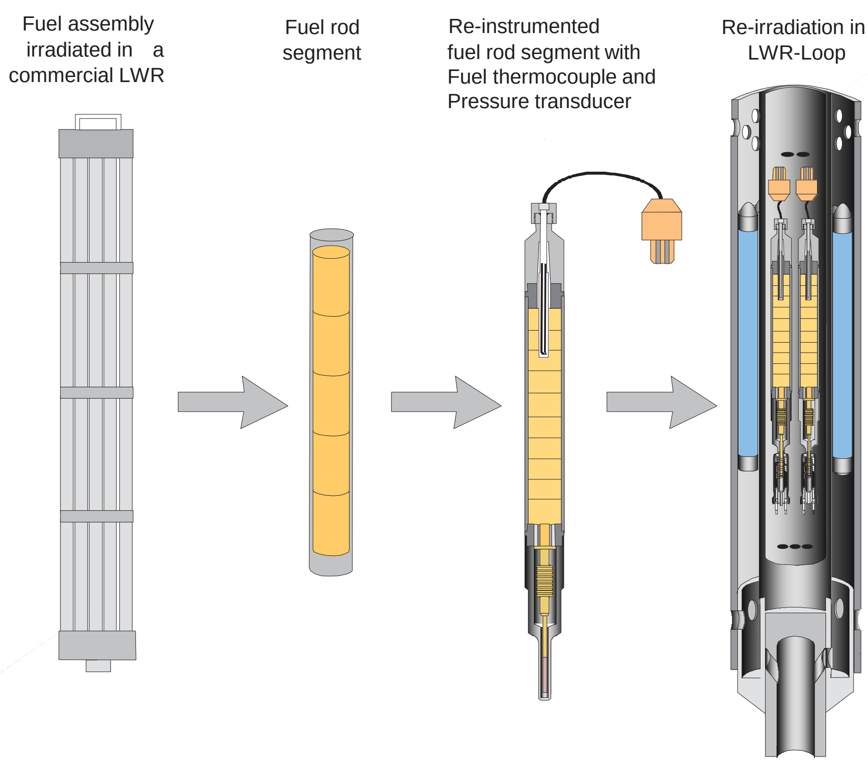
On-line measurements

- **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

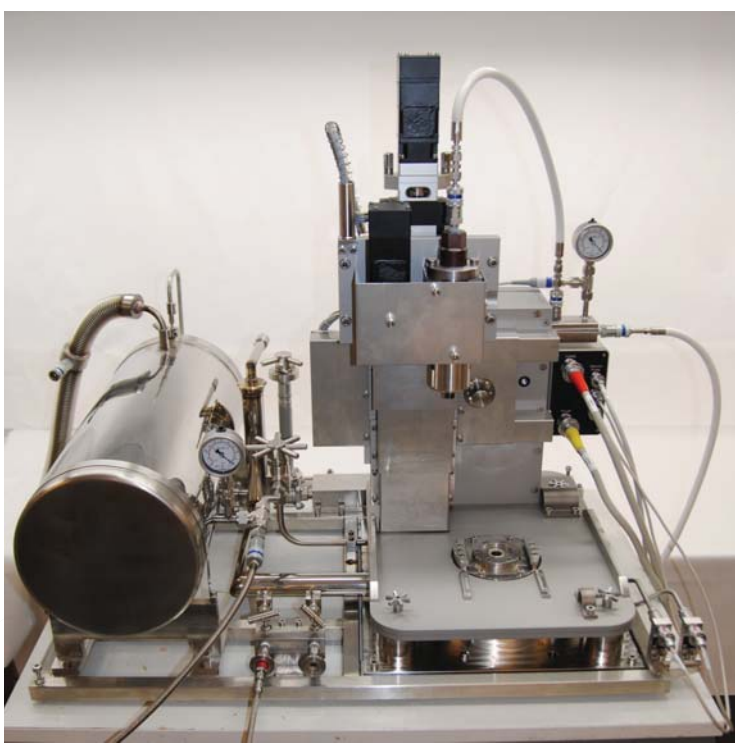
- The re-instrumentation equipment is designed and manufactured by IFE / HRP (based on principles demonstrated by RISØ in Denmark)
- Re-instrumentation equipment revised and updated several times since 1991
- Complete packages of re-instrumentation equipment have been delivered to SCK / CEN in Mol Belgium 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

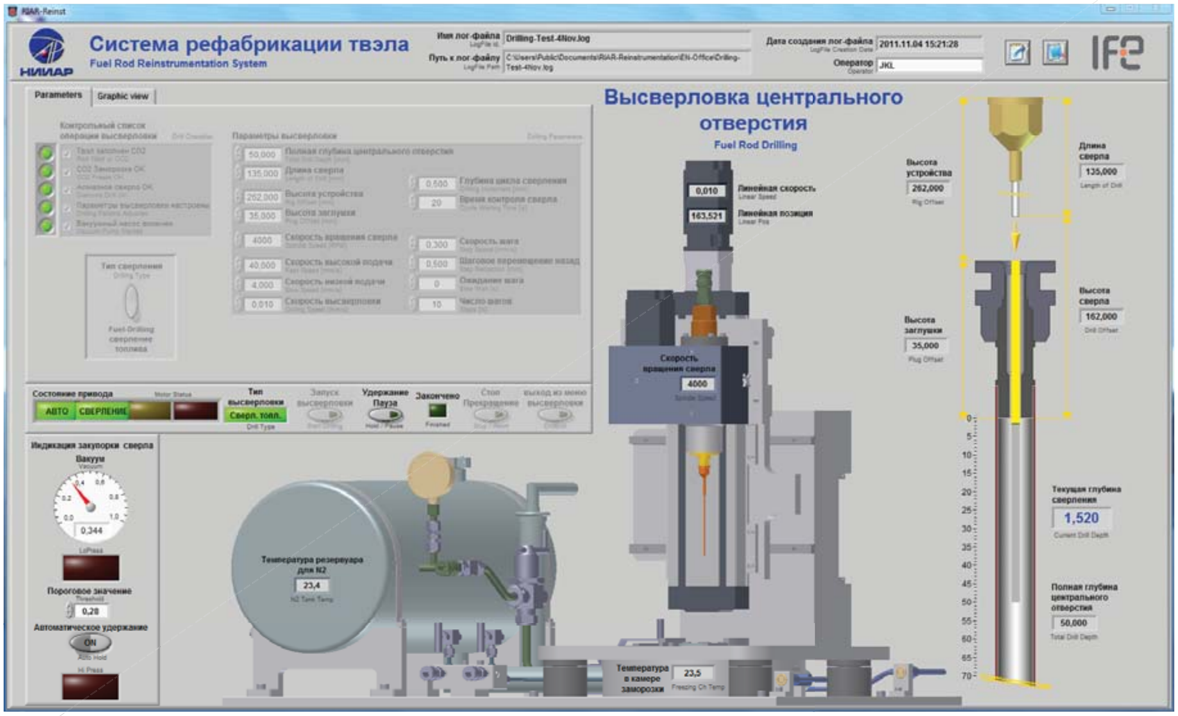


Re-instrumentation equipment - frame

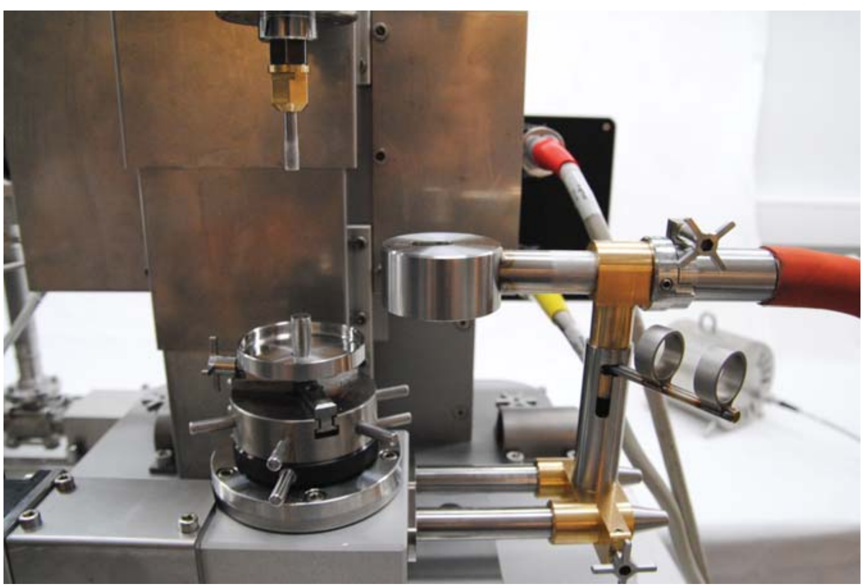
Re-instrumentation equipment – drilling unit



Re-instrumentation equipment - screen



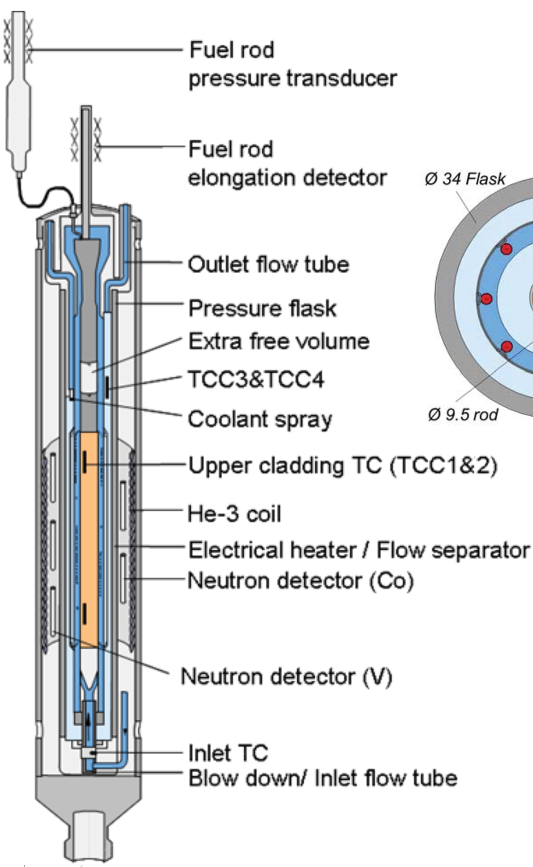
Re-instrumentation equipment - defuelling

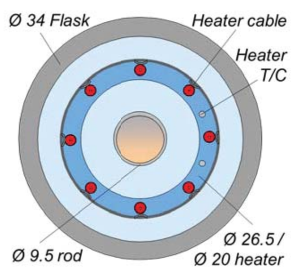


Re-fabrication and re-instrumentation for LOCA

- 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)

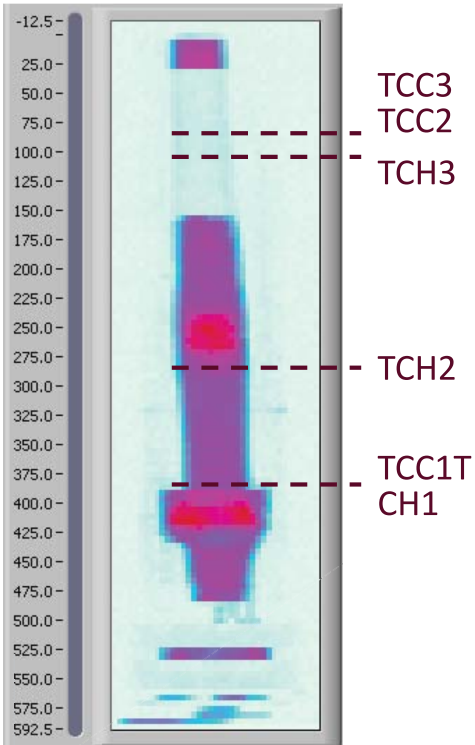


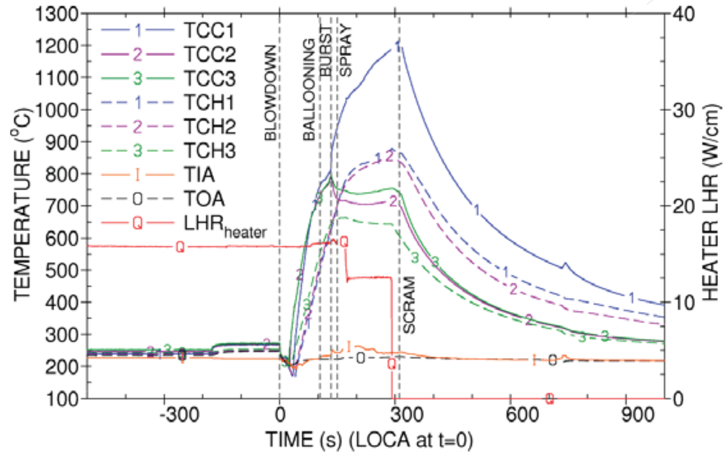


Irradiation Rig

- 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

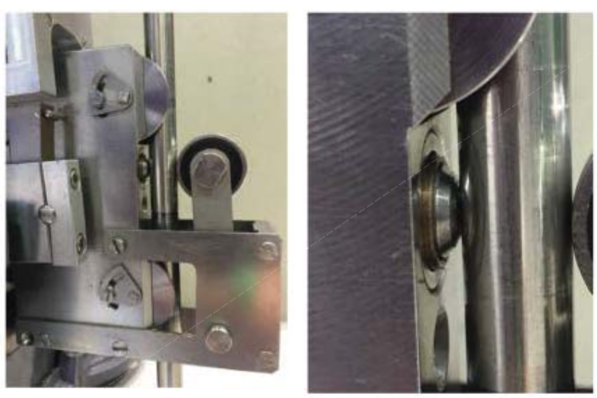
Interim inspection systems (I)

- 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