# NUCLEAR FUEL AND MATERIALS RESEARCH, EXPERIMENTAL CAPABILITIES, AND CONTINUATION OF THE HALDEN REACTOR PROJECT AFTER THE PERMANENT SHUTDOWN OF THE HALDEN REACTOR

S. HOLCOMBE, K-M HAUGEN, J. KVALEM, V. ANDERSSON, J.-H. HANSEN, H.-J. KLEEMANN, O. REISTAD

*Institute for Energy Technology – OECD Halden Reactor Project*
*P.O. Box 173, 1751 Halden, Norway*

## ABSTRACT

On June 27, 2018, the board of directors of the Institute for Energy Technology (IFE) announced the permanent shutdown of the Halden reactor (HBWR). Irradiations for bilateral projects and within the Halden Reactor Project (HRP) are thus no longer possible in the Halden reactor; however, out-of-pile experiments may continue as planned. Additionally, other HRP members' research reactors may be used to perform irradiations within the existing framework of the HRP. Research within the Man Technology Organization area of the HRP will continue as planned.

This paper gives an overview of the future nuclear fuel and materials research at IFE based on a combination of IFE's expertise in experiment design and execution, and facilities such as the JEEP II research reactor, fabrication workshops, experimental loop systems, and hot cells. The paper also gives an overview of the ongoing processes for establishing a revised Fuel and Materials (F&M) programme within the HRP.

## 1. Introduction

The Halden Reactor started operation in 1959 as a demonstration plant and research platform for a coming Norwegian nuclear power industry, which never materialized. The Halden reactor, however, continued to operate and was used as a research reactor for the world-wide nuclear power industry, through the OECD-Halden Reactor Project, and through bilateral experiments for customers across the global nuclear industry. The experiments performed in the Halden reactor included testing of nuclear fuel and cladding and nuclear reactor structural materials to generate empirical data for determining and verifying operation and safety margins. Experiments to determine failure thresholds and performance in off-normal conditions were also performed. [1]

During recent years, the Halden research reactor has faced increasing challenges, including; financial challenges in the market for nuclear fuel and materials testing, operational challenges, e.g. an offsite iodine release in 2016, and a failed safety valve detected in early 2018 during a routine maintenance outage, challenges associated with disposal of historic nuclear waste, and regulatory challenges which restricted the ability to perform certain fuels and materials experiments. Based on a strategic assessment of the challenges, the IFE board of directors decided to permanently shut down the Halden reactor and not restart it from the maintenance outage which began in early 2018. The announcement about the permanent shutdown was made on 27 June 2018. [2]

The Halden research reactor has been the centerpiece of the OECD-Halden Reactor Project for the past 60 years. The Halden reactor is, however, not the only infrastructure operated by IFE for fuel and materials research. IFE operates other facilities, including the JEEP II research reactor, out-of-pile loop systems, and hot-cell LOCA equipment which can continue to be used for nuclear fuel and materials testing. Due to previous experiments and experiments ongoing at the time of the announcement of the shutdown, IFE has an inventory of materials that are available for testing and examination. The HRP itself is also a valuable, and successful, international framework for conducting a fruitful Fuel and Materials (F&M) research programme, and research in the area of Man Technology Organization (MTO), which is not directly affected by the shutdown of the HBWR.

## 2. Experimental Facilities at IFE aside from the Halden Reactor

### 2.1. JEEP II Reactor

IFE operates the JEEP II research reactor at the Kjeller site, near Oslo, Norway, and utilizes it for a variety of research and industrial purposes [3]. Fig 1. shows a photo of the JEEP II reactor facility at the Kjeller site.

Fig 1. Photo of the JEEP II reactor facility.

The JEEP II reactor is heavy-water moderated and cooled with a thermal power of 2 MW. It operates at coolant temperatures in the range of 50-56°C, and a pressure of 1 bar. The core has a hexagonal layout with 19 fuel assemblies. Each fuel assembly consists of 11 fuel rods with 90 cm active length. The fuel rods are $UO_2$ pellets with aluminum cladding and the fuel is enriched to 3.5 wt.% $^{235}U$. The flux in the JEEP II is $3 \cdot 10^{13}$ $n \cdot cm^{-2} \cdot s^{-1}$. Fig 2. shows a schematic overview of the JEEP II reactor and an enlarged view showing the reactor tank and core configuration.

The JEEP II reactor is currently used for a variety of purposes, including; concrete irradiations [4], silicon doping for the photovoltaic industry, production of small quantities of medical isotopes (for research purposes), neutron radiography, and operation to support research conducted using the neutron beamlines.

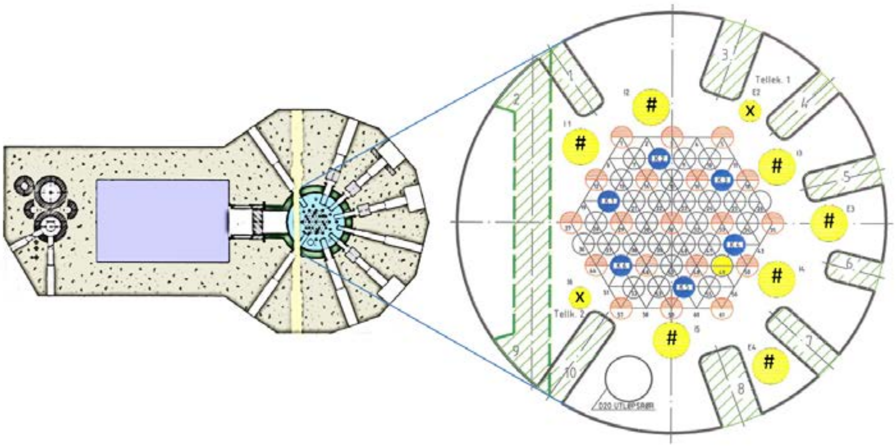

Fig 2. Left: Top cutaway view of the JEEP II reactor, showing the rectangular fuel pool, and several beamlines extending out from the reactor tank / core. Right: enlarged view of the reactor tank showing the hexagonal core layout, beamlines, and wet (#) and dry (x) irradiation positions outside the core.

JEEP II is licensed, in general, for performing experiments, and may be used for irradiation of fuel or material samples in wet or dry irradiation channels or core positions. Ongoing irradiations of concrete experiments in the core have demonstrated the use of instrumented experimental rigs in JEEP II. Pending approval by IFE's internal safety committee and by the Norwegian Radiation Protection Authority, instrumented and/or encapsulated fuel tests may be performed in the JEEP II.

## 2.2. Loop systems

Fuels and materials testing in the Halden reactor has relied extensively on the many loop systems, which are still available after the shutdown of the HBWR. Fig 3. shows a schematic overview of a typical Halden loop system.

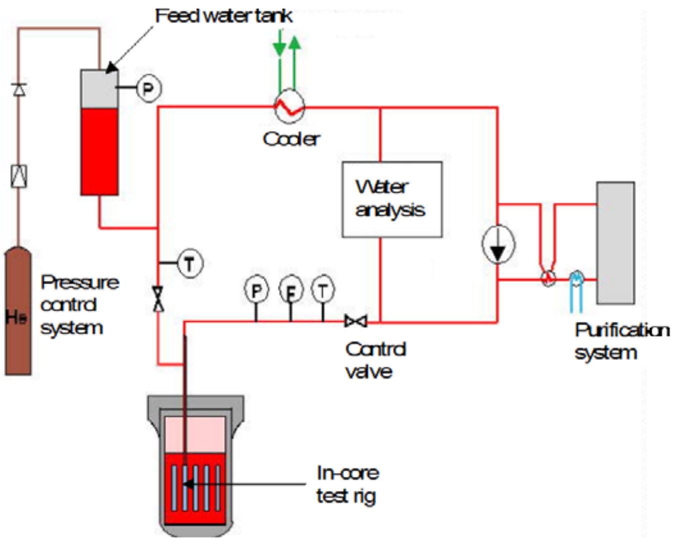


Fig 3. Schematic overview of a typical loop system at the Halden reactor.

There are two out-of-pile loop systems, and 11 loop systems which were connected to pressure flasks containing experimental fuel/material test rigs in the core. All of the loop systems can operate at temperature, thermal-hydraulic, and water chemistry conditions representative of BWR, PWR, CANDU, and VVER reactors. Of the two out-of-pile loop systems, one has been used for temperature, pressure, and flow testing of rigs as a final check before loading into the reactor, and one has been used for out-of-pile materials testing (e.g. corrosion fatigue testing of irradiated samples).

Despite the shutdown of the HBWR, the loop systems are still available for connection to out-of-pile instrumented experiments with representative temperature, thermal-hydraulic, and water chemistry conditions for BWR, PWR, CANDU, and VVER reactors. The loops may contain unirradiated or irradiated materials.

## 2.3. Hot-cell LOCA Facilities

IFE has developed hot-cell LOCA testing equipment at the Kjeller hot-cell facilities and conducted tests for bilateral customers. The system consists of an electrically heated furnace installed in a hot-cell where tests can be performed at up to 1050°C. Re-fabricated, instrumented fuel rodlets are installed in an Inconel 600 capsule which serves as a confinement vessel for fission gas and/or dispersed fuel. On-line measurements of cladding temperature and fuel rod pressure, as well as temperature and pressure measurements of the Inconel capsule are performed, and a microphone is used to record acoustic signals from fuel fragmentation. Fig 4. shows the type of furnace used in the hot-cell LOCA tests. The hot-cell LOCA equipment could also be modified to perform tests with steam. A previously-used setup similar to the current hot-cell LOCA equipment is described in [5].

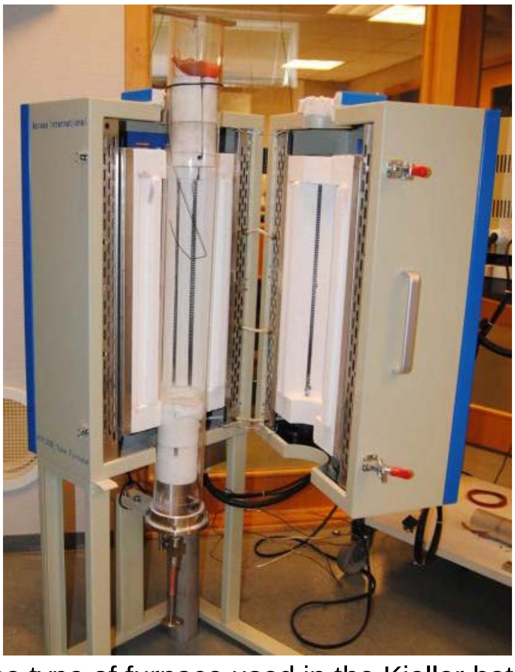

Fig 4. Photo of the type of furnace used in the Kjeller hot-cell LOCA tests.

## 2.4. Dry Storage Test Facilities

Equipment for testing fuel rods in dry storage conditions are under construction at the Halden site in a shielded location in the metallurgical laboratory adjacent to the reactor building. The current dry storage test consists of a test assembly with positions for 8 fuel rods that are equipped with thermocouples to monitor temperature, and pressure sensors to monitor the rod internal pressure. Electric heaters are used to control the temperature in test rig. Fuel rod diameters will be measured during interim inspections. Fig 5.  shows schematic views of a test rig installed in the dry storage test equipment.

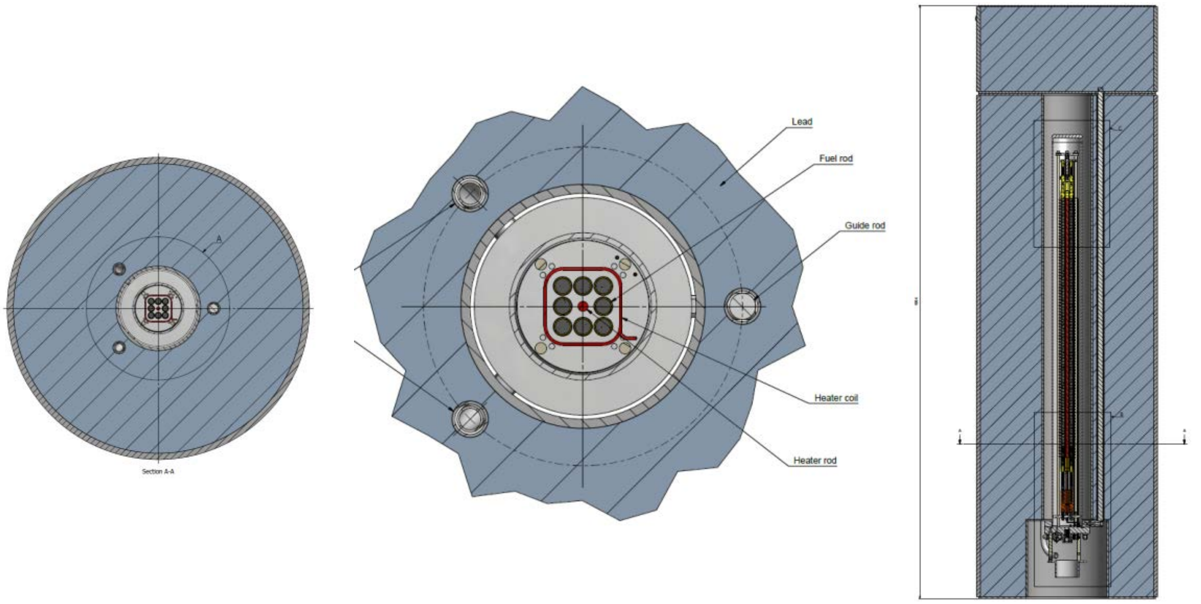


Fig 5. Schematic view of the dry-storage test facitlity. Left: top view showing experimental rig in the center of the shielded enclosure. Middle: close-up view of the experimental rig installed in the shielded enclosure, showing the eight fuel rod positions surrounded by an electrical heater for temperature control. Right: side view showing the experimental rig installed in the shielded enclosure.

The current project is in the design and fabrication phase. Mock-up tests have been performed, and re-fabrication of the fuel rods for the qualification test has started. Fabrication of the test assembly is expected to be complete in autumn 2018, and startup of the qualification test is expected by the end of 2018.

## 3. Post Irradiation Examination

IFE operates hot-cell facilities at the Kjeller site and several shielded compartments at the HBWR, which are used for performing several types of Post Irradiation Examination (PIE). Fig 6 shows a photo of the hot-cell facility at Kjeller and a photo of one of the shielded compartments at the HBWR.

Fig 6. Left: The Kjeller hot-cell facility. Right: A shielded compartment at the HBWR.

## 3.1. Non-destructive Examinations

Non-destructive examinations on fuel and materials which can be performed at Kjeller and/or the HBWR include:

- Visual inspection
- High-resolution macro photography
- Profilometry and dimensional measurements
- Eddy current
- Gamma Scanning
- Gamma tomography [6], [7]
- Neutron radiography (using the JEEP II reactor) [8]

Examples of neutron radiography on a fuel rod, and gamma tomography/gamma scanning on a LOCA test rod are shown in Fig 7.

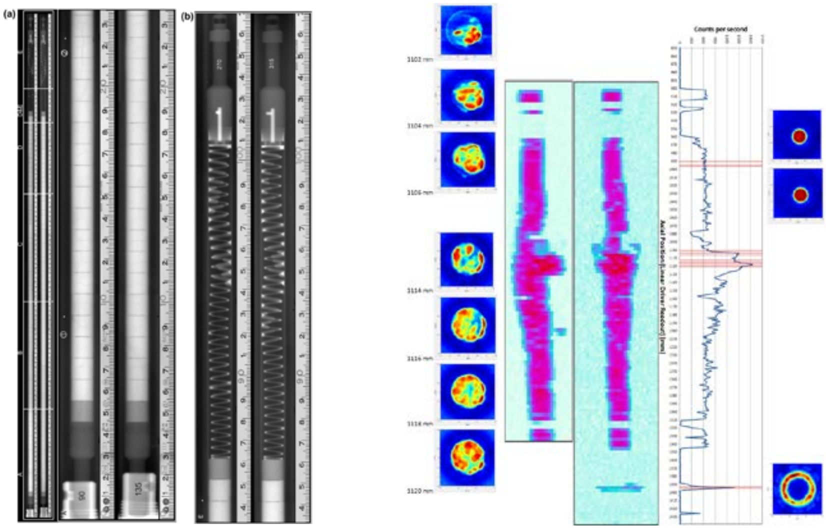

Fig 7. Left: example of neutron radiography on a fuel rod using the JEEP II reactor. Right: example of gamma tomography / gamma scanning on a LOCA test rod.

## 3.2. Destructive Examinations

Destructive examinations on fuel and materials which can be performed at Kjeller include:

- Rod puncturing and fission gas analysis (mass spectrometry: He, Kr, Xe)
- Metallographic preparation
- Light Optical Microscopy
- Scanning Electron Microscope (SEM) / Energy Dispersive Spectroscopy (EDS)
- Thermogravimetric analysis
- Hydrogen/oxygen measurements
- Mechanical testing (tensile, compressive strength, microhardness)
- Thin-slice LOM
- x-ray diffraction
- Density measurement of fuel pellets

Examples of LOM macro on a fuel rod cross section and on fuel rod cladding showing the hydride orientation are shown in Fig 8.

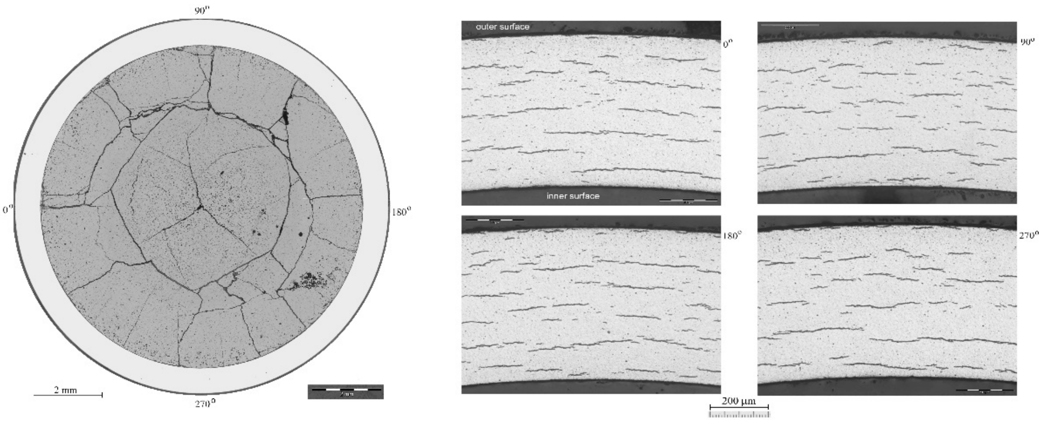


Fig 8. Left: LOM macrograph of fuel cross section. Right: LOM showing hydride distribution in fuel rod cladding.

## 4. Design & Fabrication Facilities

The design and engineering staff at IFE have extensive experience in design and fabrication of experimental fuel/materials test rigs, and in-core instrumentation, and experimental systems (e.g. light water test loops). The hot cells in Kjeller are used for instrumenting and fabricating test rigs using pre-irradiated fuel and materials. In addition to fabricating experimental fuel assemblies, instrumentation, and experimental systems, IFE manufactures its own driver fuel to power the HBWR and JEEP II reactors.

### 4.1. Experimental Assemblies, Instrumentation, and Systems

Experimental assemblies irradiated in the HBWR and JEEP II, are designed in-house and fabricated in IFEs advanced workshops. Instruments produced at IFE include e.g. Linear Variable Differential Transformers (LVDT), diameter gauges, and flow turbines which are used to monitor critical experimental parameters during irradiation [9]. Fig 9 shows examples of instruments and an experimental assembly designed and fabricated in-house at IFE.

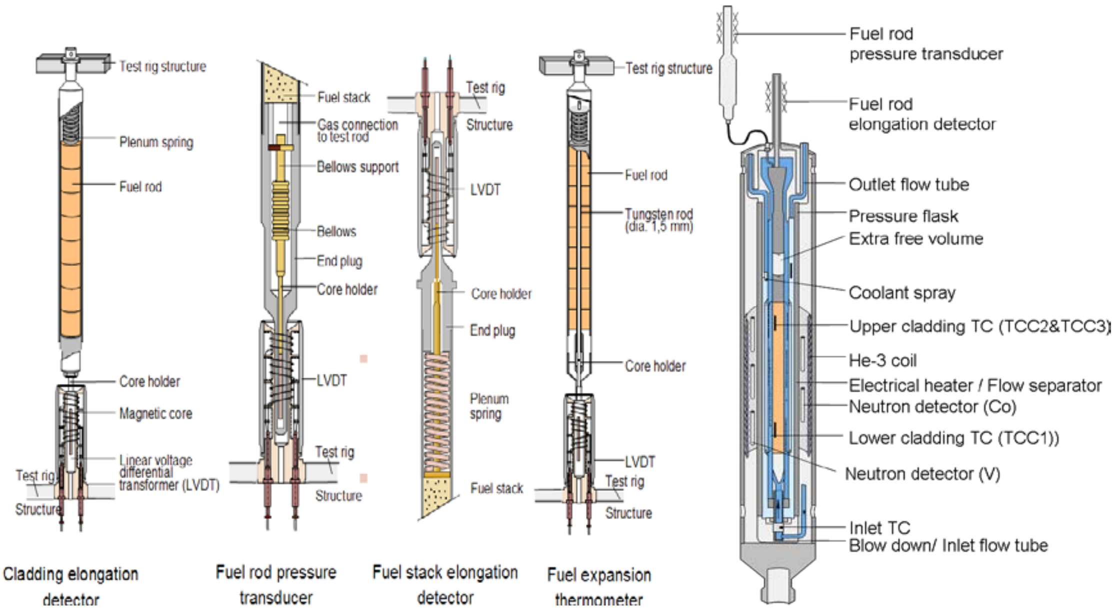


Fig 9. Left to right: LVDT for cladding elongation, LVDT for fuel rod internal pressure, LVDT for fuel stack elongation, LVDT for fuel expansion thermometer, experimental assembly including several instruments.

Re-fabrication equipment at the Kjeller hot cells is used for experiments which require the use of pre-irradiated materials. This equipment is specially constructed for safe modification of pre-irradiated fuel rods and materials for machining, welding, drilling, etc. required to add e.g. thermocouples or LVDT-based instrumentation. The equipment has been used to re-fabricate pre-irradiated $UO_2$ and MOX fuels.

Experimental systems such as light-water loops are also designed and fabricated at IFE. The 11 in-pile loops, and two out-of pile loops at the HBWR were all designed and fabricated in-house. The outer systems on experimental assemblies have also been designed and fabricated in-house at IFE. Such systems include e.g. high-pressure gas lines for controlling/monitoring gas composition, pressure in instrumented fuel rods, $^{3}He$ systems used in ramp experiments, temperature, and hydraulic drive systems for operation of in-core on-line diameter gauges. In addition to designing and fabricating the loop systems used at the HBWR, IFE has also designed the MADISON [10] loop system for the Jules Horowitz Reactor.

## 4.2. Fuel Fabrication

In addition to designing and fabricating experimental assemblies and systems, IFE manufactures the driver fuel which powers the HBWR and JEEP II reactors, and in many cases the experimental fuel for the experiments. The fuel production facilities are located at IFE's Kjeller site. The driver fuel for the HBWR and JEEP II reactors consists of $UO_2$ pellets with zircaloy and aluminum cladding, respectively. The fuel fabrication facilities consist of the $UO_2$ production line, and another production line in glove boxes for producing MOX or thorium-containing fuel [11]. Enrichments up to <20 wt.% $^{235}U$ are approved. Fig 10 shows the $UO_2$ pellet press and the MOX/thorium fuel production line.

Fig 10. Left: $UO_2$ pellet press. Right: MOX and thorium fuel production line in glove boxes.

## 5. The Halden Reactor Project

The HRP started in 1958, is hosted by the Norwegian IFE institute, and is operated under the auspices of the OECD-NEA. HRP is organized in 3-year research programme cycles, and consist of two main research areas: Fuel and Materials (F&M) and Man Technology Organization (MTO). In the 2018-2020 period there are 20 member countries, which together represent over 100 member organizations (such as national regulators, utilities, research institutions, fuel vendors, and regulatory bodies.).

On June 27, 2018, the IFE Board of Directors announced the permanent shutdown of the HBWR. Since the main part of the F&M research area was based on irradiation experiments in the HBWR, the planned F&M research programme for the 2018-2020 period needs to be revised.

## 5.1. Revision of the 2018-2020 HRP Fuels & Materials Programme

As a result of the decision to permanently shut-down the HBWR, the Halden Board of Management (HBM) asked IFE to initiate a revision of the approved 2018-2020 Fuels & Materials (F&M) programme to account for the lack of an operating reactor. To support to revision of the F&M programme, the HBM established a working group with participants from a selection of member organizations including participation from the OECD-NEA, where the working group has the objective to supervise a revision of the programme on behalf of the HBM.

The first draft revised F&M programme was prepared and made available to the HBM, the working group and the Halden Programme Group (HPG) early July 2018. The main objective of this first draft version was mainly to address all on-going projects with an alternative way forward, and to propose possible new research based on other infrastructure and capabilities at IFE as described in preceding sections.

During the Fall of 2018 there are scheduled a series of meetings of the HBM working group, the HPG, and HBM to determine on the technical content of the revised F&M programme. Ultimately, the overall objective is to present a revised F&M programme to the HBM with the purpose of obtaining the HBM's approval for the revised programme at the HBM meeting in the OECD-NEA Headquarters in Paris on December 7$^{th}$, 2018.

Once the technical content of the revised F&M programme is approved by the HBM, the remaining time in the 2018-2020 programme period will be executed in the same way as previous programme periods (i.e. with regard to HPG/HBM meetings, reporting, etc.). As has been done in previous periods, technical discussions will be also initiated on the possible research topics for the programme period 2021-2023 for both the F&M and MTO programmes.

# 6. Conclusion

The permanent shutdown of the HBWR necessitates a revision of the 2018-2020 HRP F&M programme, while the MTO portion of the HRP research programme is not directly affected by the reactor shutdown. Despite the shutdown of the HBWR, IFE maintains other valuable experimental infrastructure and expertise as described above. The infrastructure includes experimental facilities (such as the JEEP II research reactor), fabrication facilities (for experimental assemblies, instruments, and systems), and PIE facilities (including destructive and non-destructive methods).

In addition to these facilities, IFE has the necessary scientific competence and the substantial experience in hosting and executing the MTO and F&M research programmes within the HRP. The framework of the HRP, is itself a valuable asset, which brings together parties from all parts of the nuclear industry. The content and strategic direction of a future F&M HRP programme will be developed within this framework, in close collaboration with the NA, HBM and HPG.

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