INL/MIS-21-64143-Revision-0

Capabilities of the Halden Reactor and ATR Modifications to Partially Support Haldens Former Capabilities

September 2021

Changing the World's Energy Future

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Idaho National Laboratory

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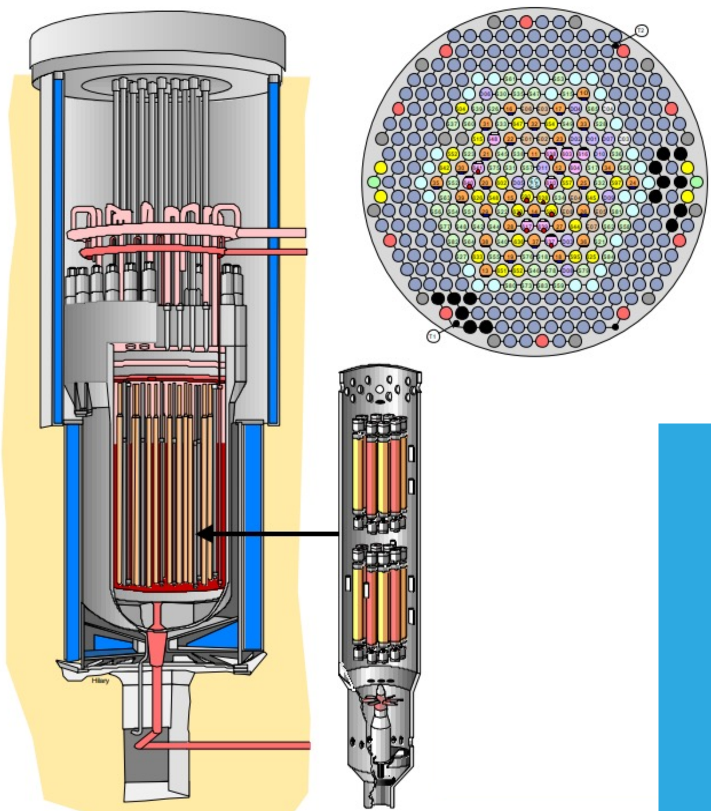

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I-Loop Information provided by:
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Capabilities of the Halden Reactor and ATR Modifications to Partially Support Halden's Former Capabilities

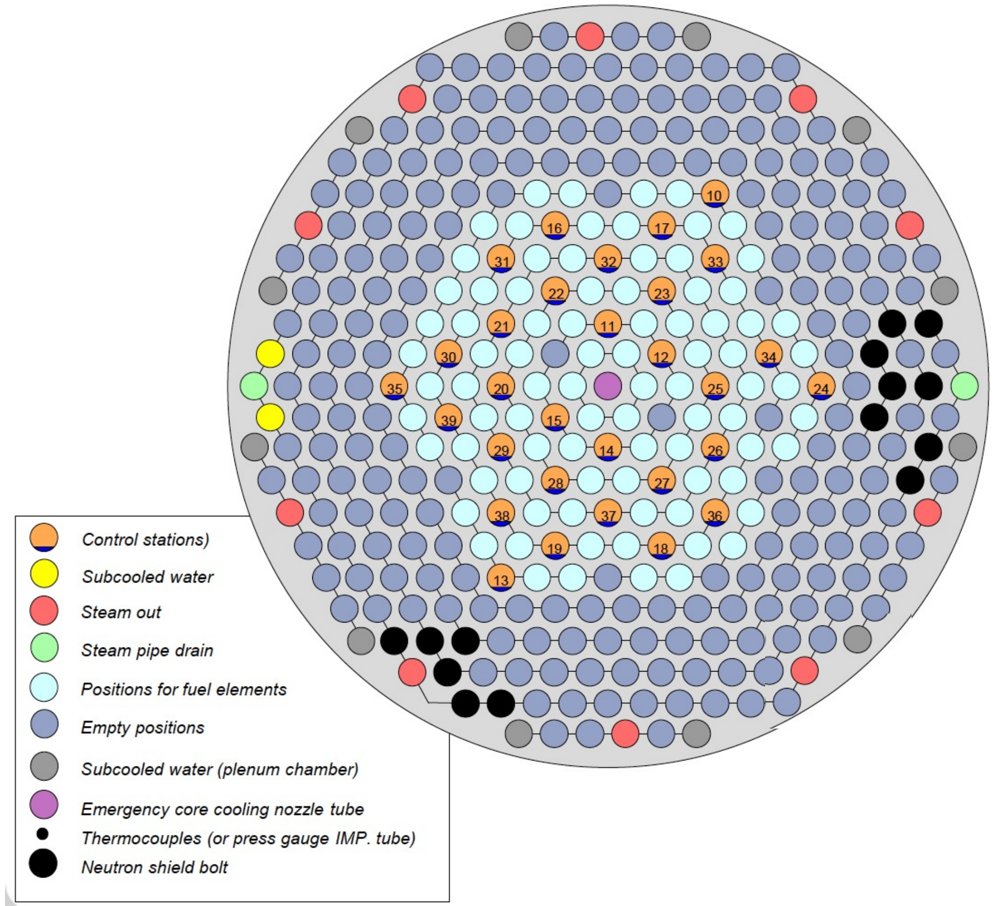
Idaho National Laboratory

Background

- The Halden Boiling Water Reactor (HBWR) began operation in 1958.
- Unlike a typical BWR design, Halden was moderated and cooled by heavy water with natural convection
- Initially operated with natural uranium, the second charge in 1962 used 1.5 w/o ^{235}U enrichment; at shutdown it was operated with 6% enrichment with natural U pellets on top and bottom
- It operated at a maximum power of 25MW with a peak temperature of 235°C at 3.4 MPa (~500 psia) for cycle lengths on the order of 120 full power days.
- Driver fuel assemblies were circular with UO2 pellets,1.049 cm pellet diameter in an ~80cm stack.
- Typical core loading was:
  - 65-75 driver fuel assemblies
  - 15-35 instrumented and fueled test rigs
  - Up to 110 total fuel elements in the core

Halden Core Configuration

- 110 usable positions – driver fuel and experiments (typically fueled) could be intermixed.
- Empty positions remained empty to reduce radiation damage to pressure vessel
- Managed and owned by the Institute for Energy Technology (IFE), Norway
- Research facility for the OECD NEA Halden Reactor Project since the beginning
- Also used for contract work for utilities, vendors, licensing authorities and R&D centers
- There have been more than 400 test assembly loadings with several thousand instrumented fuel rods and material specimens

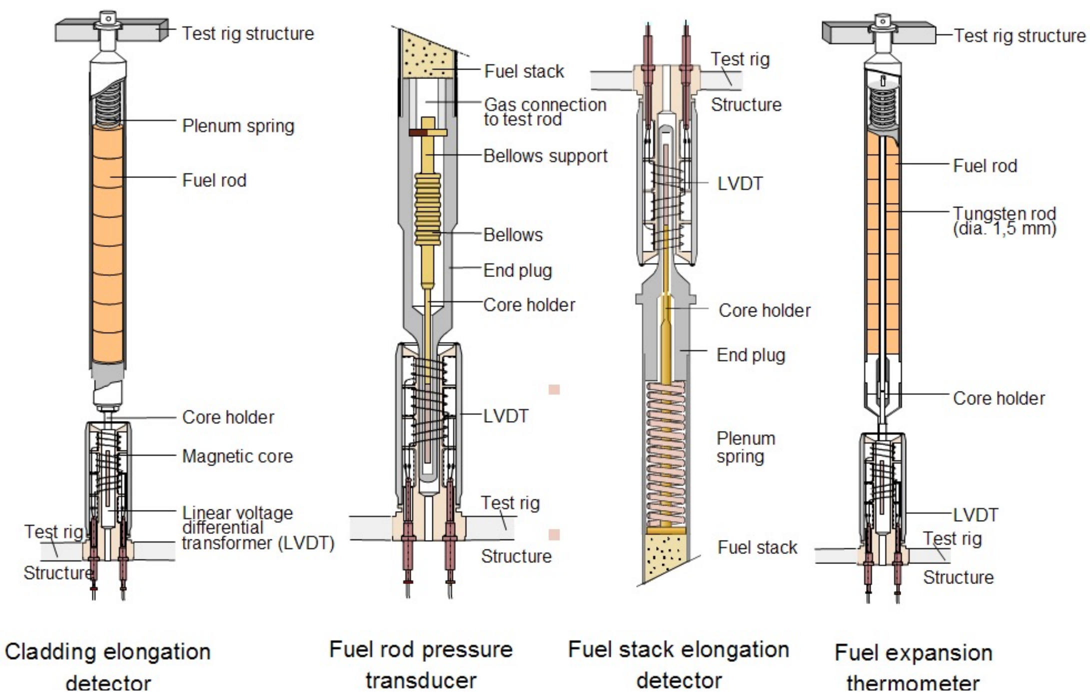


Halden Mission

- One of the most significant aspect of Halden reactor experimental work was in 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 could be operated with a controlled testing environment (not unlike ATR's pressure tube locations).
- The current loop design supports both BWR, PWR, VVER and PHWR (CANDU) reactor fuel designs for prototypic thermal-hydraulic and chemistry environments
- Typically 10-11 of the experiments in the core are within flow loops; remainder are generally instrumented configurations cooled by reactor coolant.

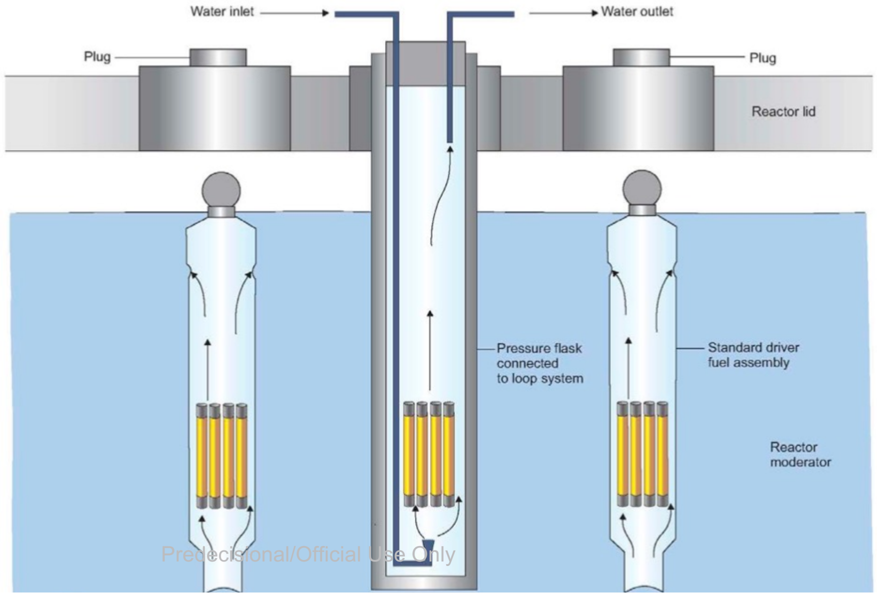
Experiments and Instrumentation

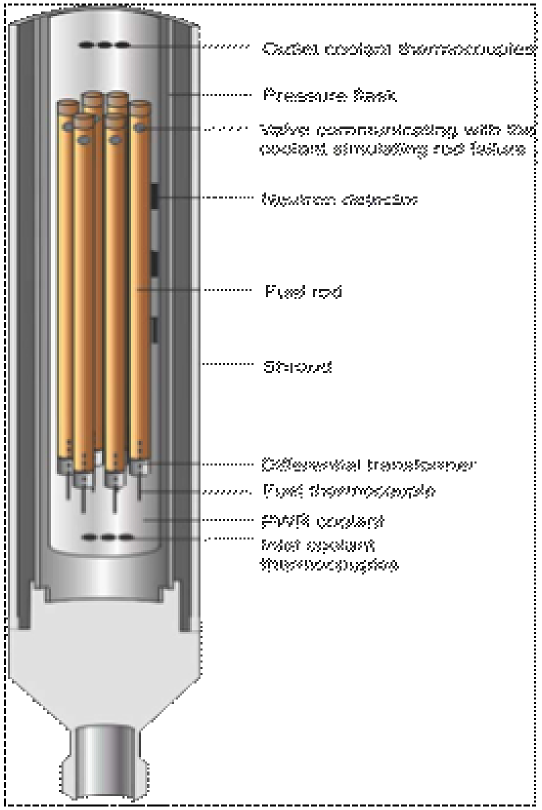
- Halden has excelled in development of in-core instrumentation for experiment monitoring.



In-Core Experiments

- Test rigs using reactor coolant have a 7.1 cm diameter channel
- Flow loops with pressure vessels have 3.3 to 5.7 cm diameter depending on vessel used.
- For reference, 4.5 cm ID inside SIPT pressure tube, 10.2 cm ID inside LIPT
- Multipin configurations commonly used.



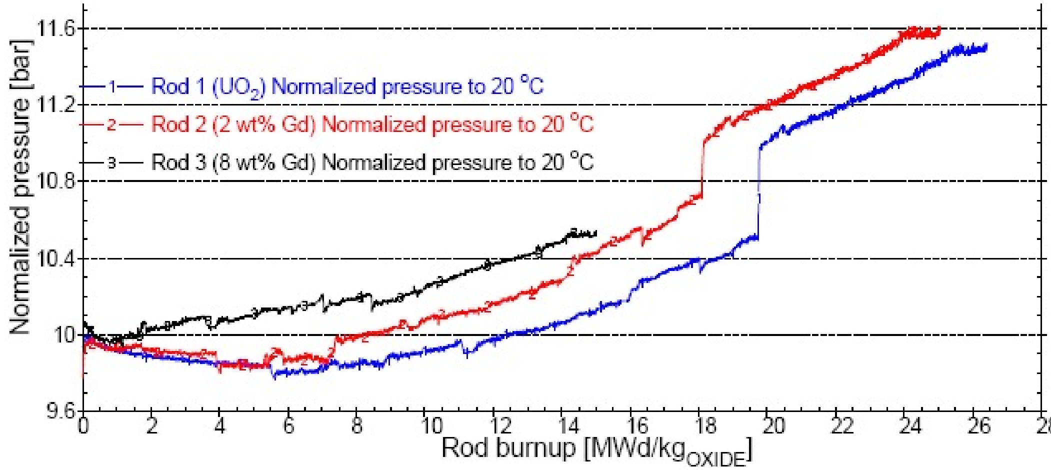


OECD Halden Reactor Project

- Two specific focus areas
  - Fuels and Materials
    - Nuclear fuel safety
    - Operational margins
    - Plant aging and degradation
  - Man-technology organization
    - Plant monitoring and control
    - Human factors
- 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
- HRP is international organization spanning 21 countries and more than 130 organizations.
- The HRP is formally part of the Institute for Energy Technology (IFE) in Norway with 35% of its funding coming from the Norwegian government.

Typical HRP Fuels Tests

- Fuel (pellet) performance
  - Fission gas release
  - Thermo-mechanical behavior
  - Comparing different fuel types
- Cladding performance
  - Clad creep, growth, corrosion, hydriding
  - Comparing different cladding types
- Safety margins and criteria
  - Power transients - PCMI and failure
  - T/H transients – dryout / DNB
  - Overpressure conditions (EOL rod internal pressures)
  - Fuel rod behavior under LOCA conditions
  - Code development and validation



Fission gas release measurements

Halden Spectrum of Fuels & Materials Studies

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

high burnup, operating conditions

water chemistry

Halden Accident

STOCKHOLM - Norwegian authorities say there has been a small leak of radioactive iodine at a nuclear reactor in Halden, in southern Norway.

Officials said Tuesday that the leak posed no risk to workers at the plant or the environment.

Plant officials said a technical failure during the handling of fuel led to the release of radioactive Iodine-131 and -132 to the reactor hall. They said staff were immediately evacuated and "no employees have received any radioactive doses of significance."

They said the situation is under control and that local authorities were informed.

The Norwegian Radiation Protection Authority said Tuesday that based on its information, the leak was small and "will not have any consequences for health or the environment outside the facility."

The Halden reactor is used for research purposes.

Accident Aftermath

- The accident occurred in Oct. 2016.
- In 2018 it was determined that the release was due to the failure of a safety valve.
- Norway's Institute for Energy Technology (IFE) carried out a strategic review of reactor operations, including a financial and operational risk assessment.
- In June 2018 IFE concluded that operation of the reactor beyond the current license period (through 2020) would not be viable.
- Over the previous seven years, IFE had lost more than €18 million on its nuclear operation and had in 2018 relied on “extraordinary funding” from the Norwegian government.
- As a self-owned foundation, IFE said it would not able to manage the financial risk of operating the reactor.

Post-Shutdown Actions

- Two workshops were held at INL in early July to respond to the void created by the permanent shutdown of the HBWR
- An "Irradiation Rig Development, Instrumentation, and Qualification Workshop" held on July 2, 3, and 5, 2018.
- July 9-10 the second workshop entitled "Halden Capability Gap Assessment" was held with diverse participation from
  - U.S. national laboratories
  - Halden
  - DOE
  - Fuel vendors participating in the ATF program,
  - NRC
  - NEI
  - EPRI
  - MIT
  - OECD/NEA
  - SCK-CEN (Belgium)
  - NRG (Netherlands)

Post-Shutdown Actions

- The HBWR had been performing (or was planning) testing to support some aspects of the DOE's ATF program.
- In July, after the first meeting, INL issued the report *Post-Halden Reactor Irradiation Testing for ATF: Preliminary Recommendations* (INL/EXT-18-46101)
- In Dec., INL issued the report *Post-Halden Reactor Irradiation Testing for ATF: Final Recommendations* (INL/EXT-18-46101)
- The purpose of the second report was to provide deeper evaluation and reinforced recommendations after the first report:
  - Evaluate potential testing gaps created by the loss of the HBWR for the ATF development program
  - Provide recommendations for filling irradiation testing capability gaps to support ATF program needs and objectives.
- These reports represent the INL perspective on behalf of the DOE Accident Tolerant Fuel (ATF) program for LWR fuels

Post-Halden Reactor Irradiation Testing for ATF: Final Recommendations

1. Knowledge transfer: Halden possessed unique technologies and knowledge for testing, refabrication, and instrumentation of nuclear fuels and materials. Transfer of Halden expertise to relevant facilities should be an immediate effort going forward through collaborative partnership with DOE irradiation testing facilities.
2. Expand LWR irradiation capacity in test reactors: DOE needs to increase its capacity for steady-state and operational transient testing capabilities for fuels within its complex.
   a. The priority to fill the hole left by Halden would be the design and installation of at least two I-Loops in ATR.
   b. The in-pile loss-of-coolant accident loop in TREAT will be unique in the western world and should continue as planned.
3. Advanced fuel rod re-fabrication and re-instrumentation should be established to support DOE test facilities to allow researchers to take full advantage of Lead Test materials irradiated in commercial plants to obtain irradiated material data in a timely manner.

Post-Halden Reactor Irradiation Testing for ATF: Final Recommendations (cont'd)

4. Reliable in-pile instrumentation to complement in-pile testing facilities: Qualify Halden instrumentation technology as baseline capabilities to support integral fuel rod measurements.
5. Consolidating irradiation testing activities to a limited number of "continental" facilities (Centers of Excellence) would:
   - reduce schedule and shipping costs and simplify data qualification efforts for fuel vendors
   - ensure no facility could become a single point of failure for needed capabilities.
   - A U.S. Center of Excellence would require transporting fuel from commercial reactors to INL for testing in TREAT and ATR.
   - The current moratorium by the State of Idaho on the receipt of research quantities of commercial spent fuel must be resolved to allow delivery of experiment sample irradiated in commercial reactors.

Mapping of HBWR to Capabilities Needing to be Filled

Halden Irradiation Test Capability

In-Pile Irradiation Testing Capability

- LWR Water Loops
- Local Specimen Power Manipulation

Enabling Technology

- In-Core Instrumentation
- Fuel Re-Fabrication, Interim Exams, PIE

Logistics

Capabilities to Fill Halden Gap for ATF

In-Pile Irradiation Testing Capability

Fuel & Cladding:

- Integral fuel rod / LWR loop
- Integral rod / LWR capsule (*pot. alt. loop*)
- Separate effects cladding only / LWR loop
- Separate effects fuel (*pot. alt. loop/varied*)
- Separate effects cladding only (*pot. alt. loop/varied*)

Fuel Safety Margins:

- Power shaping, Op. trans. & AOO's, Ramp testing
- Power shaping, Op. trans. & AOO's, Load following
- LOCA
- RIA (*not Halden*)

Enabling Technologies

- Active in-pile instrumentation program
- In-pile instrumentation, integral rod meas.
- Fuel rod refabrication/re-instrumentation
- Post-Irradiation Examination

Logistics

- Transportation
- Material Disposition

Credible capabilities for post-HBWR R&D needs for ATF

Table Key

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

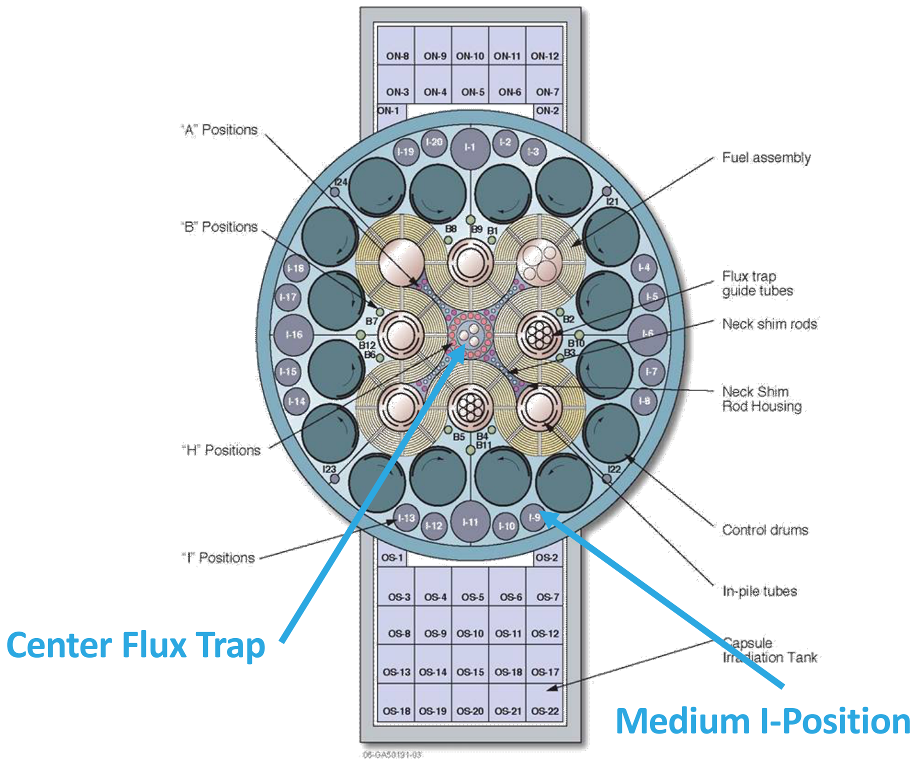
* Limited (capacity, size, etc.)
** Out-of-pile capability

In-Pile Irradiation Testing 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**
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

ATR's Current Capabilities

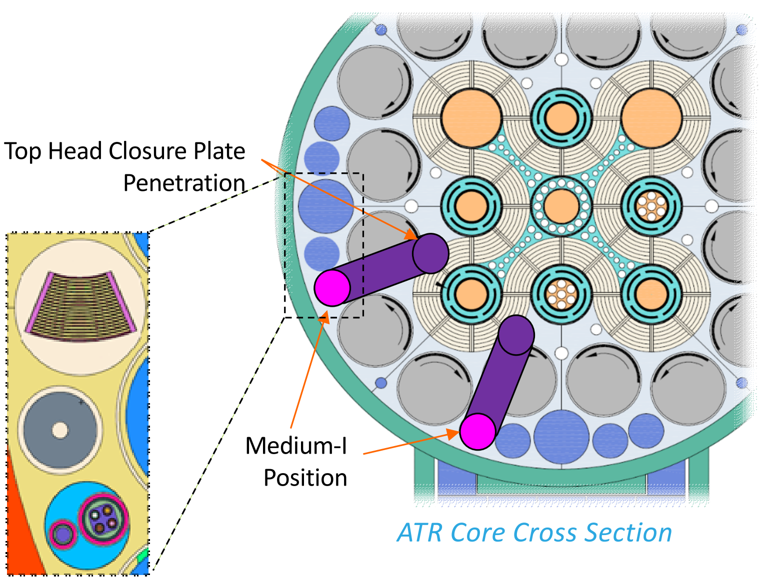
- Drop-in experiments in A-positions, B-positions, and I-positions
  - Easy to construct and handle
  - May contain fuel or materials sealed inside a capsule
  - Temperature is roughly controlled usually via a gas gap
- Instrumented Lead Experiments
  - Lead tubes attached for carrying instrument wires and gas lines outside the reactor vessel
  - Instrumented lead experiments are more complex than simple drop-in capsules, e.g., with relatively large number of thermocouples connected to individual capsules or even single specimens
  - The lead out tube provides a path to convey instrumentation and/or gas lines from the experiment through the reactor vessel
- Flowing Water Loop Experiments
  - In-pile tubes that pass through the reactor core with independent water coolant
  - Independent coolant water chemistry, pressure and temperature control

Advanced Test Reactor Core Cross-Section

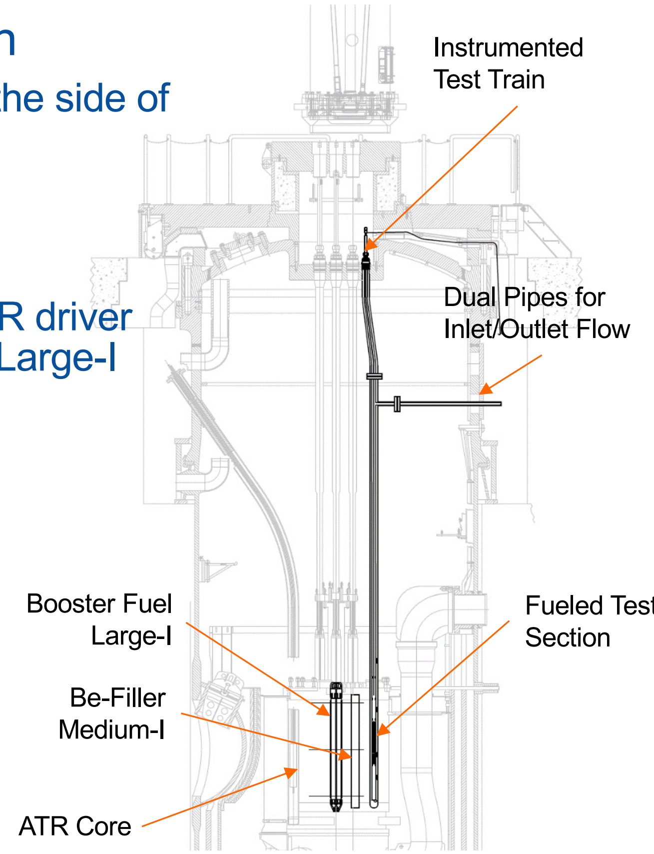


I-Loop Design

- Mechanical Design
  - Test section in Medium-I position(s)
  - Instrument connections in reactor top
  - Test insertion / removal through reactor top head
  - Test handling using an existing cask for pool side examinations
- Thermal Hydraulic Design
  - Inlet / Outlet flow through the side of reactor
  - Annular flow in-pile tube
- Nuclear Design
  - Reflector booster fuel - ATR driver fuel assembly in adjacent Large-I position

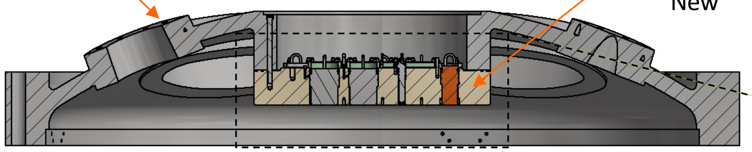


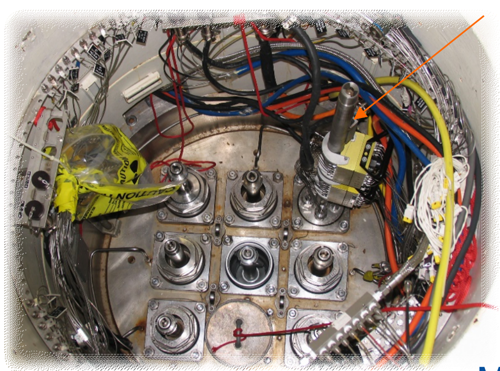
ATR Core Cross Section



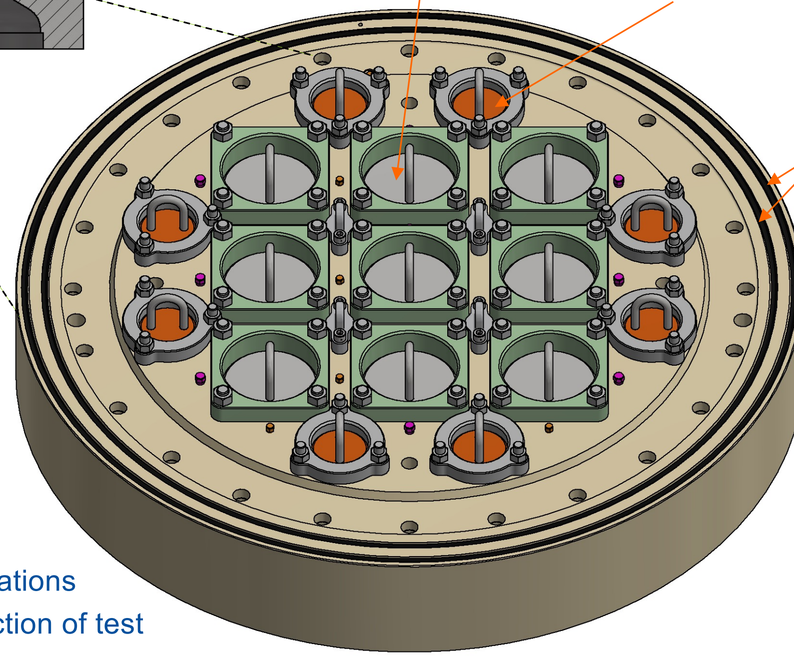
Advanced Test Reactor

New Top Head Closure Plate





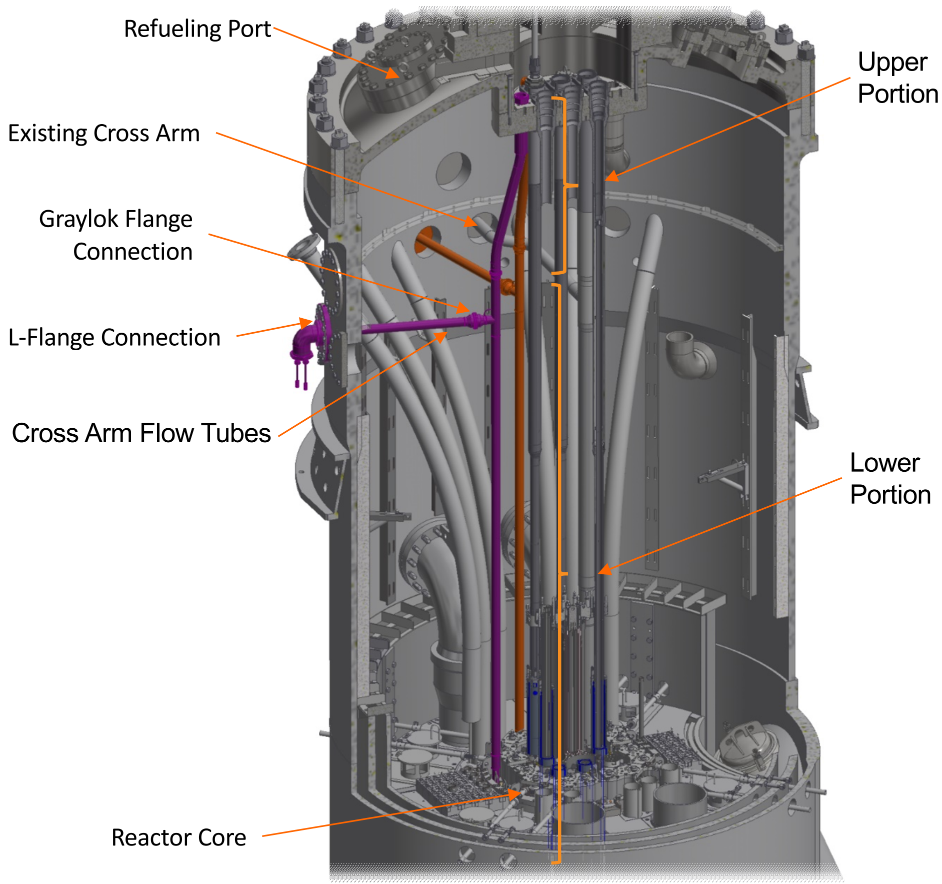
ATR Donut Area



Main Design Features

- Additional eight penetrations
- Allows for easy connection of test instrumentation
- Allows for easy test train insertion \ extraction

I-Loop In-Pile Tubes

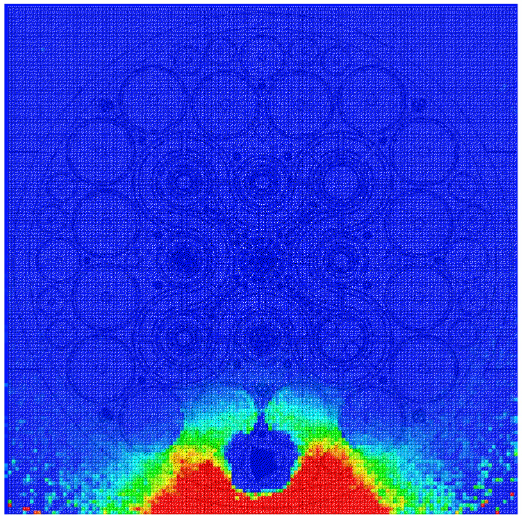


I-Loop In-pile Tubes in ATR

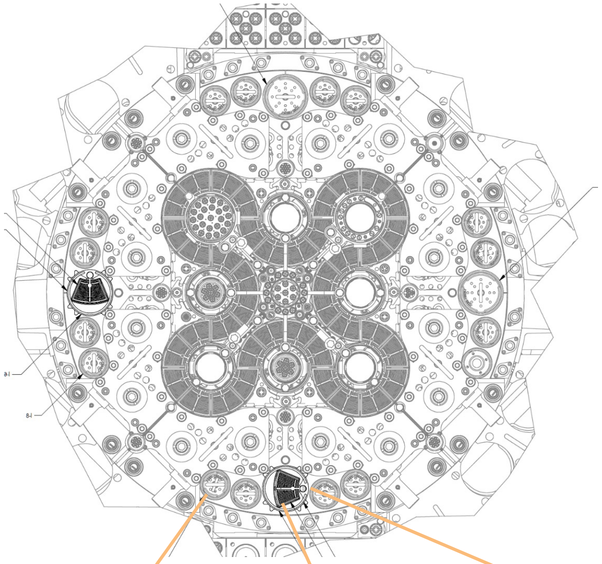
- Two in-pile tubes
  - I-14 and I-13
- Lower Portion
  - Material is Zr-2.5Nb (strongest available nuclear grade zirconium alloy) for neutron economy
  - Annular flow
  - Bolted hub connections
  - ~1.56" (40 mm) inside diameter test section
  - Installed in Medium-I position
- Upper Portion
  - Material is stainless steel
  - Offset tube
  - Allows for test train from the reactor top
- Cross Arm Flow Tubes
  - Inlet and outlet flow
  - Bolted hub connections
- Located in the Southwest quadrant 3
  - Minimizes impact to refueling/test handling

Booster Element

- Standard ATR driver element
- Located in a Large-I position
- Boosts neutron flux outside core control cylinders
- Monte Carlo analysis shows a 10% thermal neutron flux increase
- Elevates thermal neutron flux to same level available in HBWR at 5e13 n/cm2s



Monte Carlo Thermal Flux Difference Tally



Fuel Rod Reactor Heating Rate Comparison Table

Reactor	PWR	HBRW	ATR I-Loop
kW/m	~20	~15	~18
kW/ft	~6	~4.5	~5.5

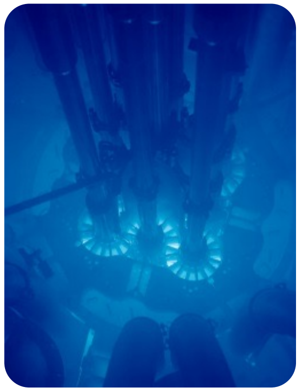
I-Loop Deployment Schedule in ATR

Completed

- Design and execute booster fuel irradiation in Large I position under ESA
- Design and establish engineering basis for I-loops in ATR
- Design and fabricate new reactor head closure plate

ATR CIC (Present)

- Install new reactor head closure plate

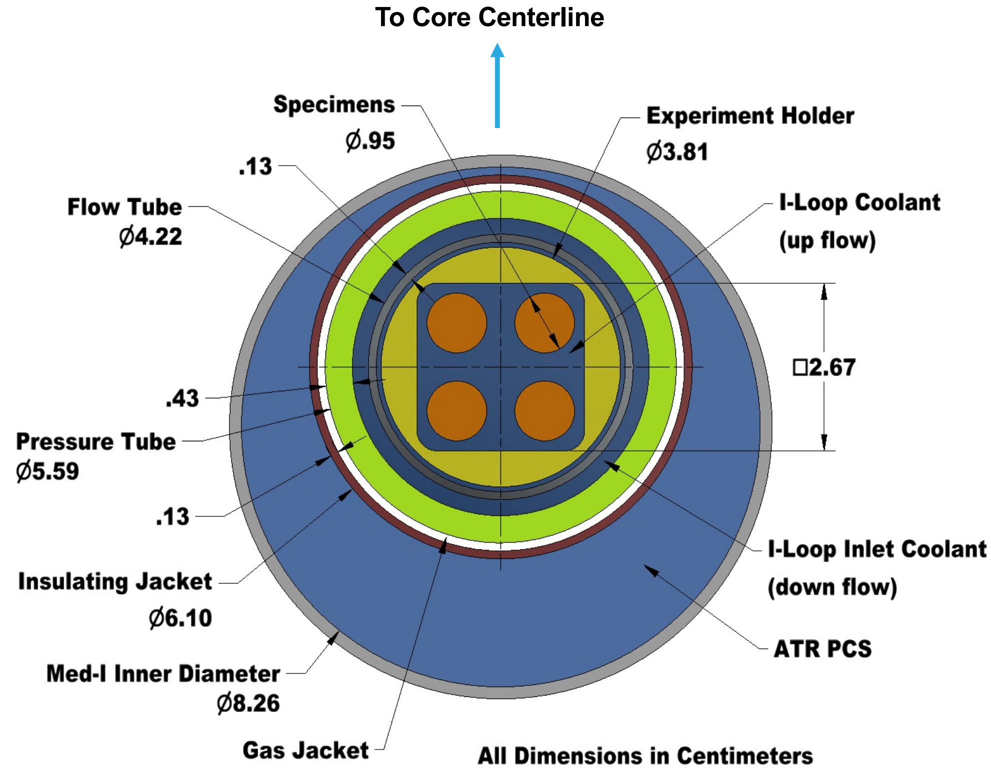


Post- CIC (~2023)

- Install loop support equipment
- Install I-Loop in-pile tube(s)
- Commission/characterize new med I-loop system with large-I booster fuel option in preparation for LWR tests

I-Loop Capabilities

- Coolant
  - Up-flow (PWR and BWR)
  - Flow ~1.5 liters/second
  - Temperatures up to 320° C (600° F)
  - Pressures up to 15.5 MPa (2300 psig)
  - Customizable water chemistry e.g., borated PWR coolant
- Test Section
  - Experiment holder 2.67 cm x 2.67 cm
  - Experiment section ~120 cm long
  - Can accommodate 2 x 2 array of tensile specimens or fuel rods
  - 5 x 10^{13} n/cm^2·s thermal flux
  - 1.3 x 10^{12} n/cm^2·s fast flux
- Testing Options
  - Instrumentation for temperature, pressure, elongation, swelling, and creep measurement
  - Ramp testing - designed with ^{3}He screen for flux manipulation independent of reactor



I-Loop Cross Section

Closing Comments

- ATF testing was perhaps hardest hit by shutdown of HBWR. ATR replacement won't be online in time to help the ATF program.
- With 10 water loops and up to 25 additional locations for instrumented experiment, ATR is not going to replace Halden.
- I-Loop upgrades will help to some extent for instrumented experiments.
- TREAT also would support many of the experiment needs.
- Outer positions generally have the flux needed for many experiments but are drop-in type positions.
- Multiple cores or special purpose core would would allow transient testing; increasing transient testing outside of PALM cycles is unlikely to fly in ATR.
- Halden mastered reliable in-pile instrumentation for in-pile testing facilities – this is something that the US, and certainly a replacement reactor, could benefit from.
- HBWR was primarily an LWR test facility. Will LWRs be as important/relevant after ~2040?

Discussion

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