INL/MIS-19-56867-Revision-0

Changing the World's Energy Future

The Advanced Test Reactor

June 2021

D. Sean O'Kelly

Idaho National Laboratory

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

DISCLAIMER

This information was prepared as an account of work sponsored by an agency of the U.S. Government. Neither the U.S. Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness, of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. References herein to any specific commercial product, process, or service by trade name, trade mark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. Government or any agency thereof.

INL/MIS-19-56867-Revision-0

The Advanced Test Reactor

D. Sean O'Kelly

June 2021

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

The Advanced Test Reactor

D. Sean O'Kelly
Associate Laboratory Director
Idaho National Laboratory
Sean.OKelly@inl.gov

Keywords: ATR, Test Reactor, uranium, experiments, nuclear reactor, nuclear fuel, MTR, ETR

Abstract

The Advanced Test Reactor (ATR) is currently the highest-powered research reactor in the world with a maximum thermal power of 250 MW. The ATR began operation in 1967 to support fuels and materials irradiation testing programs in the United States and current plans (2019) are to operate the ATR for two more decades. Since 2007, the ATR has been designated a National Scientific User Facility (NSUF) to provide more access for non-government researchers to use the ATR for academic irradiation research. This article is a brief description of the ATR history, construction, and experiment configurations.

Introduction

The Advanced Test Reactor (ATR) is an evolutionary research reactor that was conceived just over 16 years from the first criticality of Chicago Pile-1 (CP-1) and began operation less than ten years later. The history and the evolution of ATR begins with the design, construction, and operation of the two high-flux test reactors that preceded it, the Materials Testing Reactor (MTR) and the Engineering Test Reactor (ETR). Lessons learned from the operation of those two earlier facilities were applied to the design of the ATR. All three test reactors were built and operated in one area, now called the ATR Complex, within what is now the Idaho National Laboratory (INL) site near Arco, Idaho. This INL area was originally a World War II naval ordnance proving ground and aerial bombing practice range. The U.S. Atomic Energy Commission expanded the site and created the National Reactor Testing Station (NRTS) in 1949. The MTR planning began in 1947 but it was not clear where the reactor was to be constructed until the NRTS was created in Idaho and the AEC chose that location (due, in part to its remoteness) to build the MTR. Groundbreaking for the 30 MW MTR was in 1950 and the reactor went critical in March 1952. To achieve such a rapid construction schedule required the reactor facility to be designed almost at the same time as it was being built. The MTR was a highly-enriched-uranium fueled, beryllium-reflected and light-water cooled reactor. It was designed as a multipurpose reactor with over one hundred irradiation positions, including neutron beam tubes but was primarily focused on accelerated materials irradiation testing.

For years, MTR was the highest neutron flux research reactor in the world, but scientists and engineers desired higher fluxes for testing and MTR power was raised to 40 MW in September 1955. However, it was already clear that even higher fluxes were required for some testing programs than MTR could provide so an improved test reactor design effort began in 1955. The Engineering Test Reactor would use fuel similar to the MTR, but the power level was raised to 175 MW which would increase the neutron flux above the MTR maximum by a factor of four or more. There were many design improvements in the ETR, but two significant changes allowed experimental loops in the reactor interior and moved the location of the control rod drive motors below the reactor. The MTR only permitted relatively small experiments to be irradiated and only on the periphery of the reactor core lattice. By 1955, larger samples, up to ten inches in length, containing more fissionable materials required higher cooling and larger experimental volumes than MTR could provide. The ETR effective core height was 0.9 meters versus the 0.6 meters of the MTR core and the core lattice allowed approximately 7.6 cm by 7.6 cm locations for experiment insertion. Moving the control rod drives below the reactor allowed more access from above the reactor but still caused perturbations of the neutron flux as control rods were moved during operation.

Phillips Petroleum Company was the first contractor company for the operation of the MTR and ETR and was asked in late 1959 to design an advanced engineering test reactor that would have a neutron flux in test positions greater than 1E15 neutrons/cm^2-sec. The original conceptual design was referred to as ETR-II but the name eventually was changed to the Advanced Test Reactor.

The ATR is a unique purpose-specific reactor design and, with a maximum power of 250 MW, one of the highest power research reactors ever operated in the world. The building exterior of the ATR is shown below in Figure 1. The ATR typically operates at lower powers, in the range of 115MW, for normal experiments but does operate at higher power for specific experimenter needs. To achieve the high neutron flux, the fuel operates at high power densities of approximately 1 MW/L. The ATR was designed to provide variable neutron flux in different experiment locations and achieves this by operating in a radially unbalanced power condition. The unbalance ratio may be as high as four to one across the core for specific experiment needs; however, this large of a power split is rarely used. As with many high power, high performance research reactors, the ATR core may contain all fresh fuel or a mixture of fresh and recycled fuel elements to achieve experiment and cycle length demands. A typical experimental cycle for ATR is from two to eight weeks but cycles as long as nine weeks have occurred.

Figure 1. External view of ATR building.

Originally conceived by Deslonde deBoisblanc, a senior Phillips Petroleum reactor physicist, the ATR is a very unusual design for a nuclear research reactor. Computer modelling of nuclear reactors was not advanced in the 1950's and the ATR physics parameters were initially calculated using two-group diffusion theory and with a two-dimensional computer code. Following the standard practice for the MTR and ETR facilities, a low power but physically identical version of the ATR core was constructed to validate these computational models and measure core physics characteristics prior to ATR's initial startup. This reactor was named the ATR Critical Facility (ATRC) and started up in 1964. The ATRC typically operates at 600 watts or less and is still used to benchmark computational models and measure reactivity effects of experiments prior to insertion into ATR. As an aside, the ATR design was first mocked-up using the ETR Critical Facility (it had a rectangular grid array) to validate the conceptual five-lobe design and the computational approximations for a cylindrical flux trap.

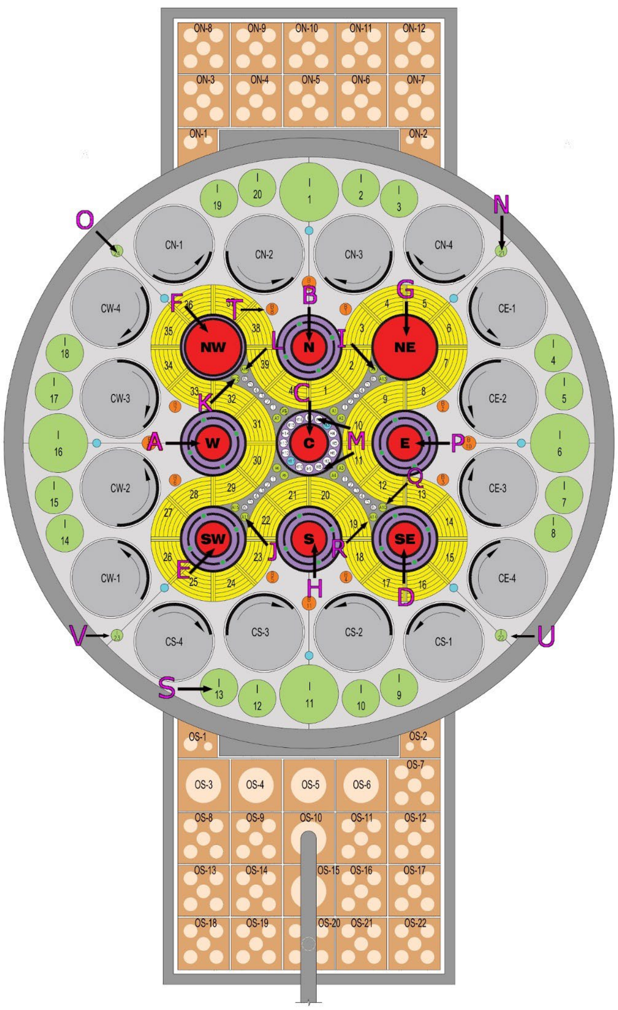
Reactor Internals

The ATR internals consist of a series of tanks or support structures internal to the reactor vessel. These tanks support the reactor fuel and reflector and direct primary coolant flow through the reactor core quadrants. The ATR operates with a pressurized primary cooling system (approximately 2.56 mPa) and uses demineralized light water for cooling. A significant portion of the cooling flow is directed downward through the fuel elements with the remainder providing cooling for the non-fuel reactor internals and experiments. At full flow the ATR primary coolant flow rate is 190,000 Lpm when three pumps are operating with approximately 113,000 Lpm flowing through the fuel.

Reactor fuel

The ATR reactor core contains forty fuel elements arranged in a clover leaf or serpentine pattern that creates four lobe areas as shown in Figure 2 below. This geometry maximizes the neutron flux for cylindrical experiments located in the formed flux traps. ATR was originally designed to have nine experiment loops utilizing the flux traps but was reconfigured in 1994 to allow some flux trap locations to have experiments cooled by the reactor primary coolant. The ATR has been reconfigured several times to accommodate different experiments in the flux traps.

Figure 2. ATR Radial Cross-Section



Each fuel element forms a 45-degree sector of a right circular cylinder and contains nineteen fuel plates roll-swaged into the side plates. The side plates have machined vents that provide interconnection of flow channels from fuel element to fuel element and reduces pressure differentials. Each fuel plate contains an active fuel length of 1.22 meters and is loaded with highly enriched uranium matrix (UAl_x) clad with 6061 aluminum alloy. Aluminum was selected due to its high thermal conductivity and low neutron cross section. The fuel elements are subjected to preconditioning at the manufacturer to establish a boehmite corrosion layer prior to use in the reactor for repeatable heat transfer. Small amounts of boron in the form of B_4C powder is added to some fuel plates as a burnable poison which allows longer cycle lengths and minimizes power peaking.

Reactivity Control Elements

The ATR reactivity control is unique in that it was designed to maintain a near cosine-shaped axial neutron flux profile throughout the operation cycle. The ATR has four independent reactivity control systems, and each has a separate function. These systems are the safety rod system, the neck shim rod system, the regulating rod system, and the outer shim control cylinder (OSCC) system. The safety rod system consists of aluminum tubes with hafnium inserts and provides for the automatic or manual rapid shutdown capability. The safety rods are located in six of the nine flux traps areas and are nearly fully withdrawn (7.62 cm remain) above the core region prior to starting up the reactor. There are twenty-four neck shim and regulating rods with six located in each of the four arms of the neck shim housing. Two of the neck shim rods are used as regulating rods to maintain power automatically via a servo system. All neck shim rods are fully inserted at the beginning of a cycle and gradually pulled out throughout the cycle to compensate for local fuel burnup. The OSCC system consists of sixteen beryllium cylinders and each cylinder is 1.19 meters in length to be nearly the same height as the active fuel region. The cylinders each have a 120-degree hafnium insert and are operated in pairs to establish lobe power splits and compensate for fuel burnup. Lobe power splits refer to the ability of the ATR to adjust local lobe power for experiment specific power levels. Each lobe consists of the eight fuel elements surrounding a flux trap. ATR is currently potentially able to operate with up to a four to one ratio split across the core for certain experimental programs but generally operates with a one to ten-megawatt difference across the reactor.

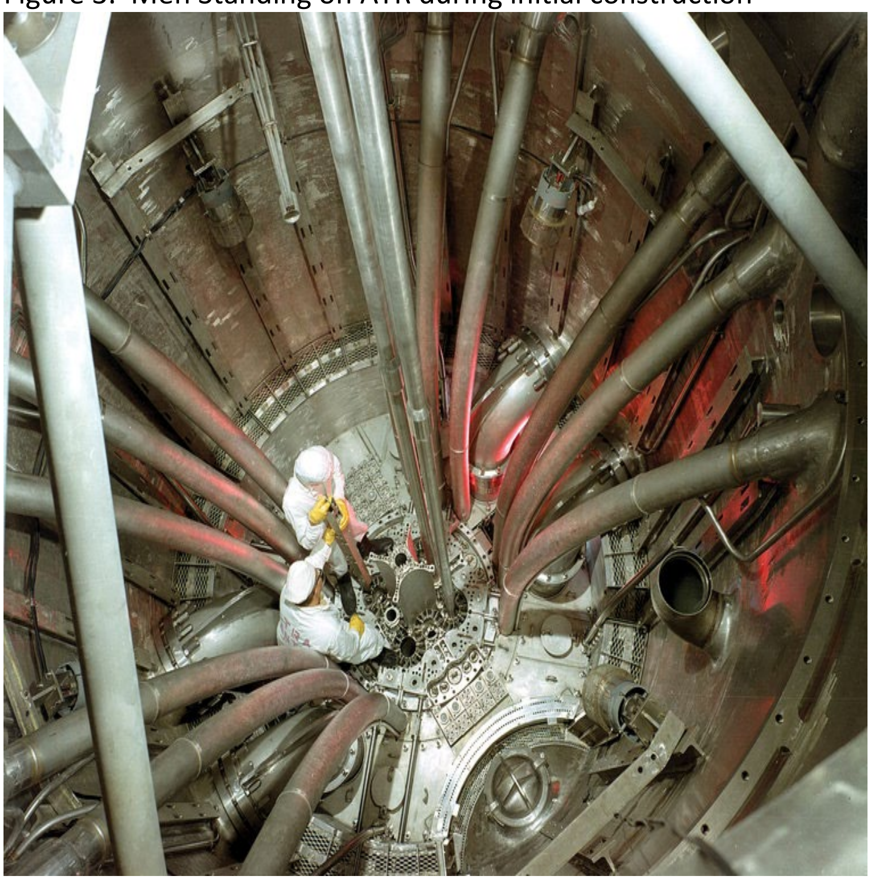
Beryllium Reflector

The ATR reflector is formed from eight high-grade beryllium manufactured pieces that fill the space between the fuel and the internal diameter wall of the core reflector tank. Space is provided between beryllium segments and four holes are drilled through the beryllium sections for cooling water flow. Beryllium in a nuclear reactor will suffer irradiation damage that causes swelling and cracking. Horizontal saw cuts in the ATR beryllium reduce the tensile stresses and increases the reflector life by reducing crack lengths. Evaluation of reflector end of life is performed after stressed-induced cracking is first observed during routine examinations and consists of finite element stress analysis, more frequent inspections, and comparison to neutron fluence of previous reflectors. Approximately every ten to twenty years, as determined by the swelling and cracking amount, the ATR beryllium is entirely replaced with new material. During this time, the majority of the other in-core components are also replaced in an evolution called a core internals change-out or CIC.

Instrumentation monitoring

ATR neutron power is monitored as with conventional research and power reactors by monitoring leakage neutrons which are proportional to total reactor power. These neutrons are detected by fission and neutron sensitive ion chambers in detector wells between the reactor reflector and the vessel wall. The ion and fission chambers are contained in 5-inch stainless steel instrument thimbles which are shown clearly in Figure 3 below. Radiation streaming is minimized by installed shield plugs at the tube exit. Because the ATR typically operates in a power unbalanced condition, additional local power monitoring is required to monitor and control lobe power. Many local neutron detector designs such as self-powered neutron detectors would quickly fail in the extreme neutron fluxes within the ATR. The ATR uses nitrogen-16 (N-16) and water power calculators to determine local lobe powers. The N-16 power monitoring system consists of ten channels which use reentrant flow tubes in various core lobe regions to sample water flowing through these areas. Fast neutron flux, which is directly proportional to fission power, converts some oxygen in the water to N-16 with a 7.2 second half-life. The decay of the N-16 is detected using beta sensitive detectors and that signal is used to determine relative lobe power. Output from water power calculators and the N-16 power monitoring system are reduced by the reactor data acquisition system to yield the lobe powers.

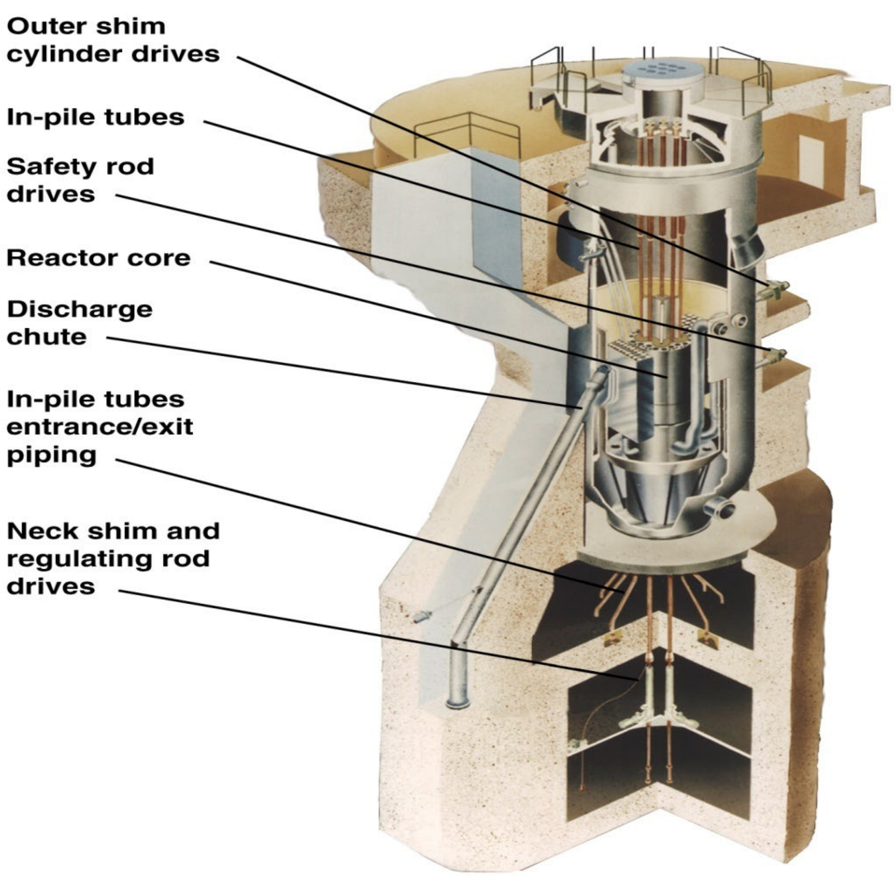
Figure 3. Men Standing on ATR during initial construction



Reactor Vessel

Another unique feature of the ATR is that the reactor pressure vessel is entirely manufactured from 304 stainless steel. The vessel is 3.66 meters in diameter, 10.7 meters tall, and 50.8 mm thick at the core mid-plane. Stainless steel was selected, rather than clad carbon steel, for corrosion resistance and a lower probability of brittle fracture after long radiation exposures. It is well known that the interaction of fast neutrons from the reactor with the stainless-steel increases tensile strength and reduces the ductility of the material. However, the fast neutron fluence on the ATR vessel is relatively low due to the intervening beryllium and reactor coolant. Calculated total fluence through the year 2060 only results in weldment fracture toughness reduced to 15% below the unirradiated materials; therefore, neutron embrittlement of the reactor vessel is not an issue in the foreseeable future for ATR.

Figure 4. ATR Vessel Cut-Away



Fresh fuel and new experiments may be loaded into the reactor vessel through penetrations in the reactor vessel head. Used fuel and experiments that are not in experiment loops are discharged to the working canal through the drop or discharge tube assembly. The penetration into the reactor vessel is closed during pressurized reactor operation using a double O-ring cover.

Reactor coolant enters the vessel through two 0.61-meter pipes welded to the bottom vessel hemispherical head and then flows up through the area between the reactor core tanks and the vessel wall, including cooling the thermal shields. The reactor coolant then flows down through the core and into a flow-distribution tank which divides the flow into quadrants which then flow into four 0.41-meter outlet pipes which transport the coolant above the reactor core and out the four outlet nozzles. The coolant flow path then transitions to 0.46-meter pipes which combine into two 0.61 m return lines and finally into a single 0.91-meter line that distributes flow to the five primary to secondary coolant heat exchangers.

ATR primary cooling system pressure is maintained by a feed and bleed pressure control system. An automatic pressure control valve bleeds coolant through a degassing tank that removes dissolved gases from the coolant. A pressurizing pump draws coolant from the degassing tank and discharges through a flow control valve back to the primary cooling system. Rapid pressure changes are dampened by a surge tank which has a pressurized air and water volume to provide pressure control.

Table 1. ATR General Characteristics.

Reactor	
Thermal Power	250 MW_{th}
Power Density	1.0 MW/L
Maximum Thermal Neutron Flux	1.0×10^{15} n-cm^{-2}-sec
Maximum Fast Neutron Flux	5.0×10^{14} n-cm^{-2}-sec
Number of Flux Traps	9
Number of Experiment Locations	77
Core	
Number of Fuel Assemblies	40
Active Fuel Length	1.2 m
Number of Fuel Plates per Assembly	19
Uranium-235 Content in Fresh Assembly	1,075 kg
Coolant	
Design Pressure	2.7 MPa
Design Temperature	115°C
Light Water Maximum Flow (3 Pumps)	3.36 m^3-sec^{-1}
Coolant Temperatures	< 52°C (inlet), 71°C (outlet)

Experiments locations

As seen in Figure 2 above, the prime experimental locations in ATR are in the higher flux regions inside the serpentine fuel area, especially the nine-flux trap locations. There are 77 ATR experiment locations with B- and I-positions located outside the core periphery in the beryllium reflector. The position diameters vary from 1.59 to 12.7 cm, but all locations have a 1.22 m available height providing large experiment irradiation volumes. Table 2 summarizes the neutron flux levels in several ATR experiment locations. The peak flux values are given at 110 MW because the ATR rarely operates at full design power for an experiment cycle.

Table 2. Approximate Peak Flux Values at 110 MW (22 MW in each lobe).

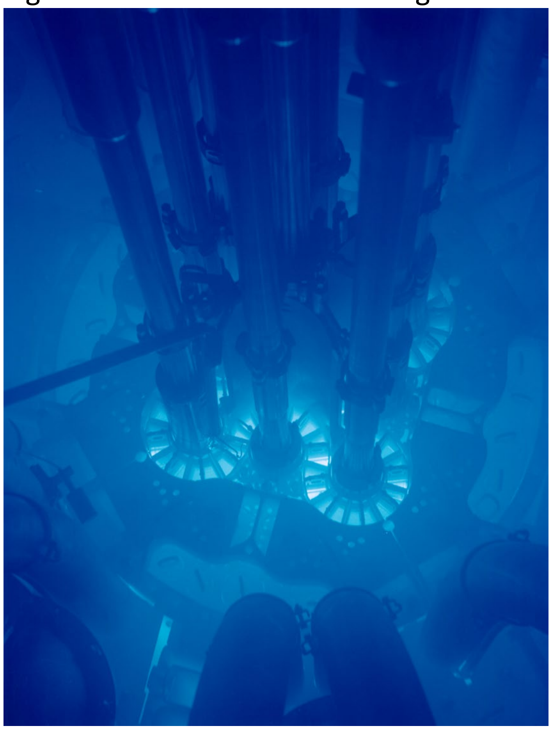
Core Position	Diameter (cm)	Thermal Flux (n-cm^{-2}-sec)	Fast Flux (E>1 MeV) (n-cm^{-2}-sec)
Northwest and Northeast Flux Traps	~12.7	$4.4x10^{14}$	$2.2x10^{14}$
Other Flux Traps	~7.6	$4.4x10^{14}$	$9.7x10^{13}$
A-Positions (16)	1.6	$2.0x10^{14}$	1.7 to $2.3x10^{14}$
B-Positions	2.2 to 3.8	1.1 to $2.5x10^{14}$	1.6 to $8.1x10^{13}$
H-Positions	1.6	$2.0x10^{14}$	$1.7x10^{14}$
I-Positions			
Large (4)	12.7	$1.7x10^{13}$	$1.3x10^{12}$
Medium (16)	7.6	$3.4x10^{13}$	$1.3x10^{12}$
Small (4)	3.8	$8.4x10^{13}$	$3.2x10^{12}$

The ATR utilizes three basic in-core experiment configurations; static capsule, instrumented lead experiments, and pressurized water loops. Static or drop-in capsules are a more familiar type of irradiation experiment to users of other research reactors. A static capsule may contain small samples stacked within the welded volume or for large diameter locations (i.e. a flux trap or I-positions) there may be engineering scale components or materials within the capsule. Static capsules are cooled by the primary coolant system and temperature is controlled by a gas gap that is adjusted with pressures and gas mixtures to have a known thermal conductance. Further temperature control would be by selection of the core location to account for local power or gamma heating. No direct temperature monitoring is available for capsule experiments. Melt-wires may provide peak temperature indication and flux wires provide integrated neutron flux measurements when the sample capsule is opened.

Instrumented lead experiments allow control of some experiment parameters and real-time monitoring of the experiment conditions. These experiment capsules are not completely sealed and have small tubes leading in and out of the reactor vessel that carry instrument wires and control or monitoring gases. These experiments are more complicated than simple static capsules and require some type of monitoring and control station to automatically adjust parameters as needed. Temperatures of these experiments may be adjusted by varying the ratio of helium to neon gases in the gas gap to change the thermal conductivity of the gap or by adjusting local reactor powers if agreed to by other experimenters.

The final and most complicated experiment type used by the ATR is the pressurized water loop. These loops are designed to simulate the conditions (pressure, temperature, chemistry, etc.) of a pressurized water nuclear power reactor (PWR) within the low pressure, low temperature environment of the ATR. To achieve the PWR conditions, each loop experiment has a dedicated system that cools or heats the experiment and maintains high pressure conditions utilizing a scaled down pressurizer system. A low-pressure helium gas gap surrounds the pressure boundary in the reactor vessel to insulate the loop cooling system from the lower temperature ATR primary coolant. These experiments have significant real-time monitoring capability but are quite long (approximately 7.5 meters) and must be removed from the reactor by withdrawing the experiment into a shielded cask on the reactor top for discharge to the canal or packaged for shipment.

Figure 5: Shutdown ATR showing IPTs



Future of ATR

In 2016, the U.S. Department of Energy began an investment program to replace or refurbish equipment at ATR that was operating beyond design lifetimes. This plant health program established long-term goals and plans to improve ATR operational reliability and provide a firm foundation to operate ATR for another two decades. The unique irradiation testing capabilities of the ATR are unlikely to be replaced in the near-term so this national and international asset will be maintained and upgraded as required to serve its diverse user community and provide essential long-term irradiation test program support well into the future.

References

FY 2009 Advanced Test Reactor National Scientific User Facility User's Guide, Idaho National Laboratory, INL/EXT-08-14709, (2008).

Gilbert, H.K and Stacy, S.M, Historical American Engineering Record Idaho National Engineering Laboratory Test Reactor Area: Materials Testing and Engineering Test Reactors, HAER No. ID-33-G, Idaho National Laboratory, INL/EXT-06-01185, (2006).

deBoisblanc, D.R. et al., Proposal for an Advanced Engineering Test Reactor-ETR-II, Phillips Petroleum Co., Atomic Energy Division, IDO-16666 (1960).

Stacy, S.M., Proving the Principle: a history of the Idaho National Engineering and Environmental Laboratory, 1949-1999, Idaho National Laboratory, DOE/ID-10799 (2000).