Neutron Production and Uses at the High Flux Isotope Reactor

Kevin Smith, RRD Deputy Director
June 16, 2016

ORNL is managed by UT-Battelle
for the US Department of Energy

OAK RIDGE National Laboratory | HIGH FLUX ISOTOPE REACTOR

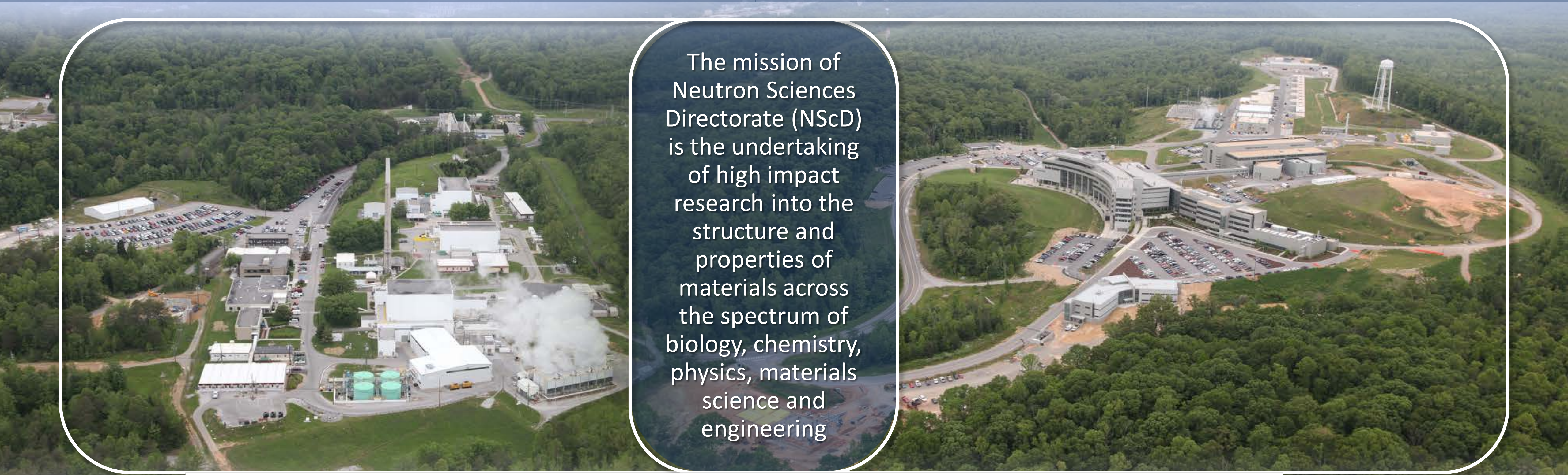
ORNL is DOE's largest science and energy laboratory

ORNL's nuclear infrastructure capabilities are unique and diverse

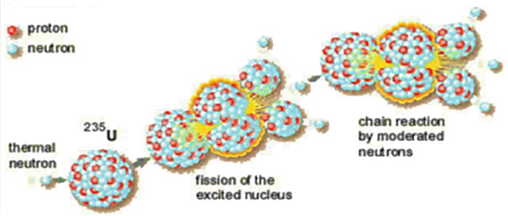
ORNL has significant capabilities to facilitate the science and technology for neutron scattering, isotope production and R&D, fuels processing and development, radiochemistry R&D, and materials testing

NScD operates two world-leading neutron scattering facilities that work together to meet community needs

High Flux Isotope Reactor	Spallation Neutron Source

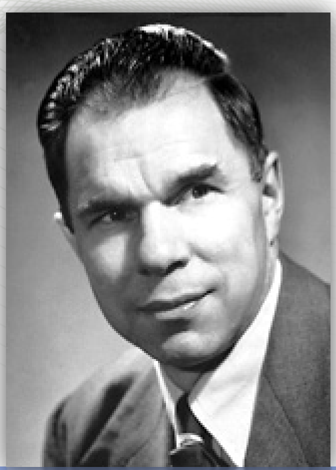


The mission of Neutron Sciences Directorate (NScD) is the undertaking of high impact research into the structure and properties of materials across the spectrum of biology, chemistry, physics, materials science and engineering



Fission	Spallation
• chain reaction • continuous flow • ~2.5 neutrons/fission	• No chain reaction • Pulsed operation • ~30 neutrons/proton

The need for HFIR was expressed by Glenn Seaborg in 1957



G. T. Seaborg
Berkeley, October 24, 1957
awarded the Nobel Prize in Chemistry 1951
"for discoveries in the chemistry of the transuranium elements"

"The field of new transuranium elements is entering an era where the participating scientists in this country cannot go much further without some unified national effort…. The future progress in this area depends on substantial weighable quantities (say milligrams) of berkelium, californium, and einsteinium…"

Dick Cheverton was the leader of the original HFIR Design Team

When Cheverton first presented the idea for HFIR to then-Lab Director Alvin Weinberg, Weinberg said:

"That's the most hare-brained idea I have ever heard"

According to Cheverton…

The Soviet announcement of an advanced reactor project to produce nuclear materials greatly worried Glenn Seaborg, the Nobel Prize winner who was then chairman of the Atomic Energy Commission.
We told Seaborg we knew exactly what to do, we had the plans for a *better* one.

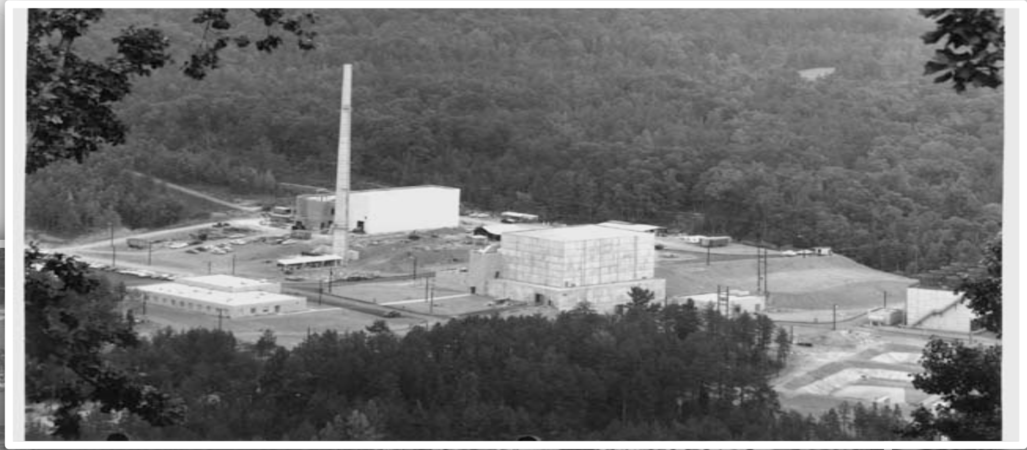
Dick Cheverton (left); Jess Irwin (right)

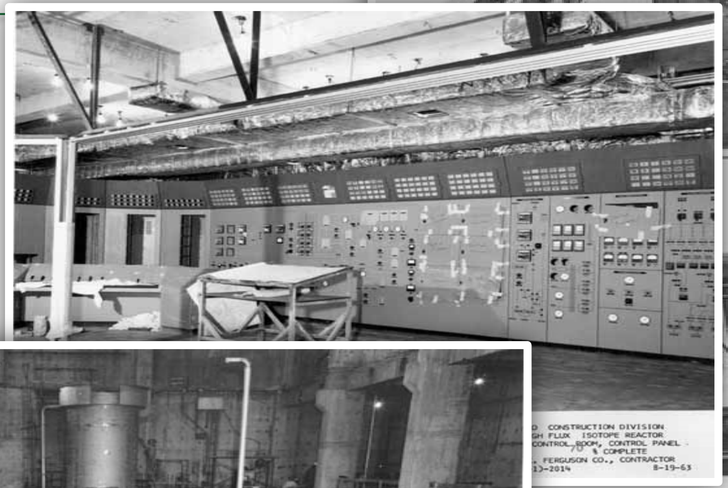
Richard D. Cheverton (Dick) led a small thesis group that pursued the conceptual nuclear design and optimization of a high performance flux-trap research reactor, which was the predecessor to the HFIR. During the period from 1958 to 1968 Dick was responsible for the nuclear design of the HFIR core. The net result of Dick's effort was, and still is, the highest thermal flux and average power density of any similar test/research reactor.

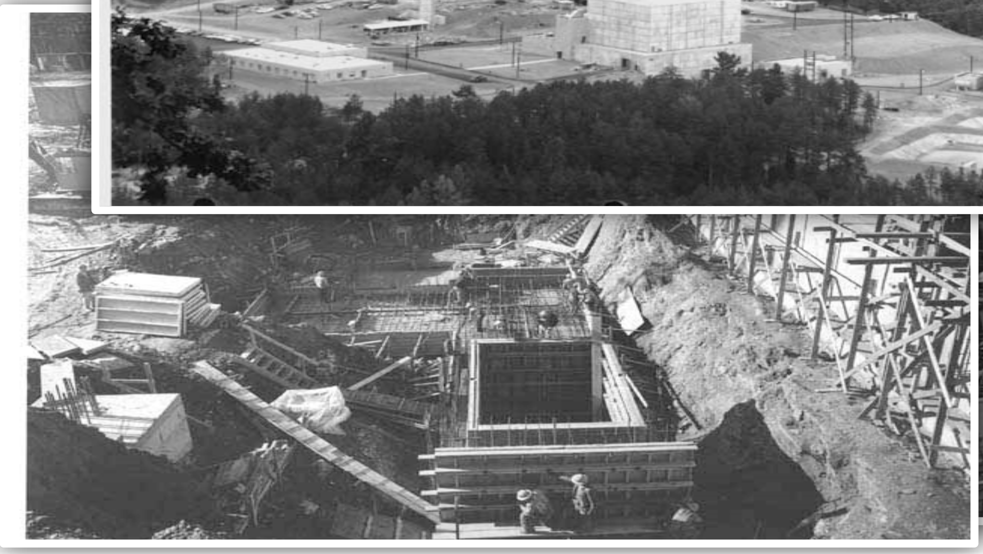
In 1958 the US Atomic Energy Commission recommended HFIR construction

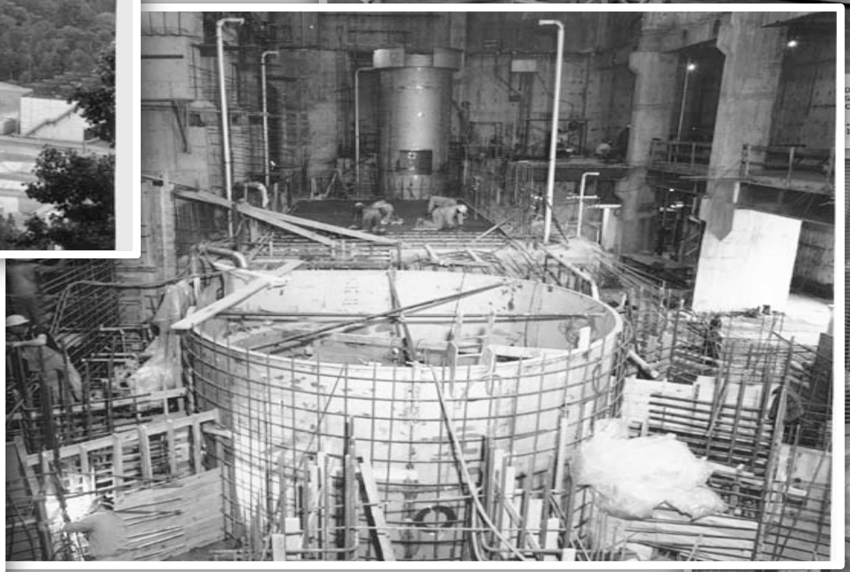
The HFIR design proposed by ORNL was accepted in 1959

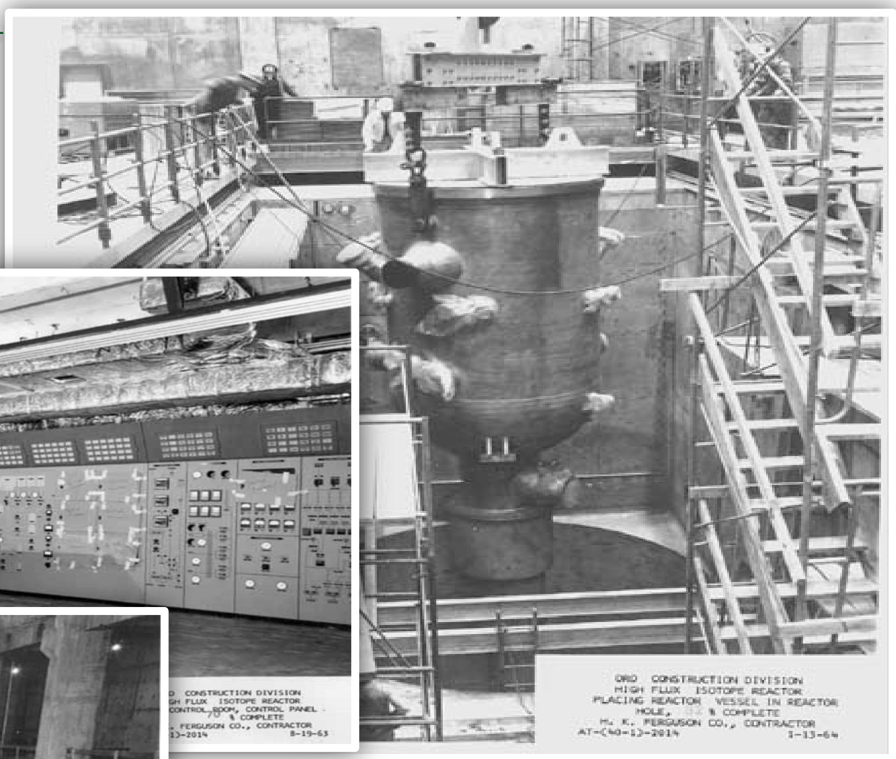
Construction began in 1961

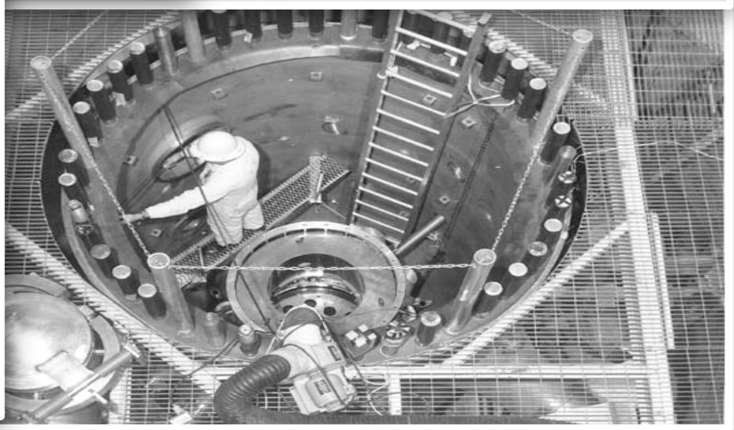




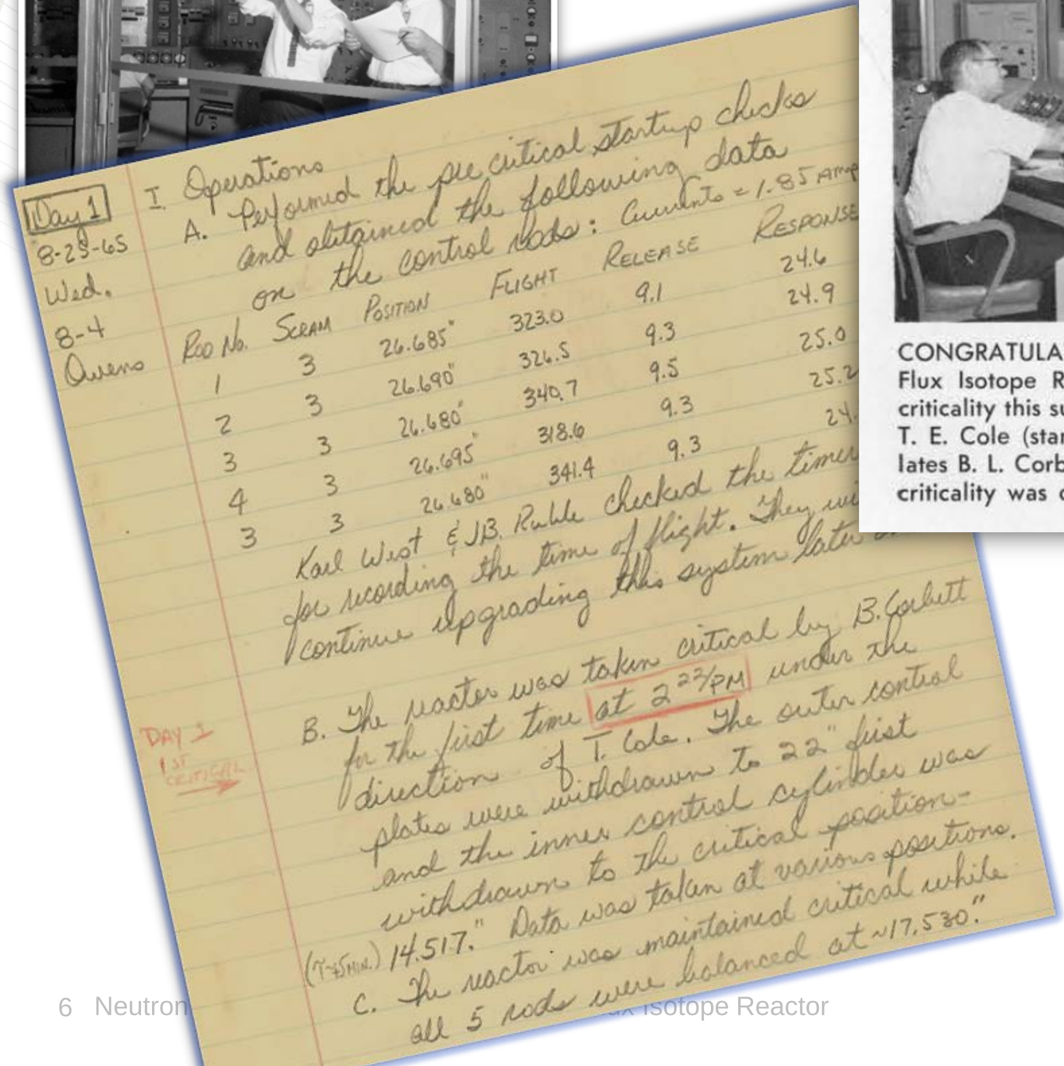








Initial criticality achieved…



Day 1
8-25-65
Wed.
8-4
Owens

I. Operations
A. Performed the pre critical startup checks and obtained the following data on the control rods: Currents = 1.85 Amp

Rod No.	Scram	Position	Flight	Release	Response
1	3	26.685"	323.0	9.1	24.6
2	3	26.690"	326.5	9.3	24.9
3	3	26.680"	340.7	9.5	25.0
4	3	26.695"	318.6	9.3	25.2
5	3	26.680"	341.4	9.3	24.

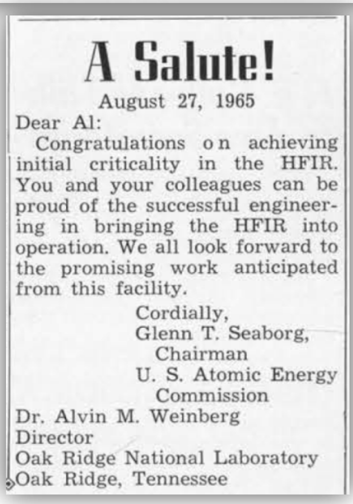
Karl West & J.B. Ruble checked the timer for recording the time of flight. They wi[ll] continue upgrading this system later

DAY 1 1ST CRITICAL

B. The reactor was taken critical by B. Corbett for the first time at 2 22/PM under the direction of T. Cole. The outer control plates were withdrawn to 22" first and the inner control cylinder was withdrawn to the critical position (T-45 Min.) 14.517". Data was taken at various positions.
C. The reactor was maintained critical while all 5 rods were balanced at ~17.530"

…At 2:22 PM Wednesday, August 25, 1965

CONGRATULATIONS AND SMILES were in order when ORNL's High Flux Isotope Reactor became the second major reactor to achieve criticality this summer. (MSRE went critical on June 4). In the left photo, T. E. Cole (standing), associate technical director for HFIR, congratulates B. L. Corbett (Operations Division) who was at the controls when criticality was officially recorded. In center photo, a HFIR model fuel assembly is backed up by ORNL personnel who have largely been responsible for the reactor's engineering design and development. At right, A. M. Weinberg extends a hearty handshake to A. L. Boch (left), director of the HFIR project. Looking on (L-R) are E. H. Taylor, director of Chemistry Division, and H. G. MacPherson, ORNL deputy director.



A Salute!

August 27, 1965

Dear Al:

Congratulations on achieving initial criticality in the HFIR. You and your colleagues can be proud of the successful engineering in bringing the HFIR into operation. We all look forward to the promising work anticipated from this facility.

Cordially,
Glenn T. Seaborg,
Chairman
U. S. Atomic Energy Commission

Dr. Alvin M. Weinberg
Director
Oak Ridge National Laboratory
Oak Ridge, Tennessee

HFIR overview

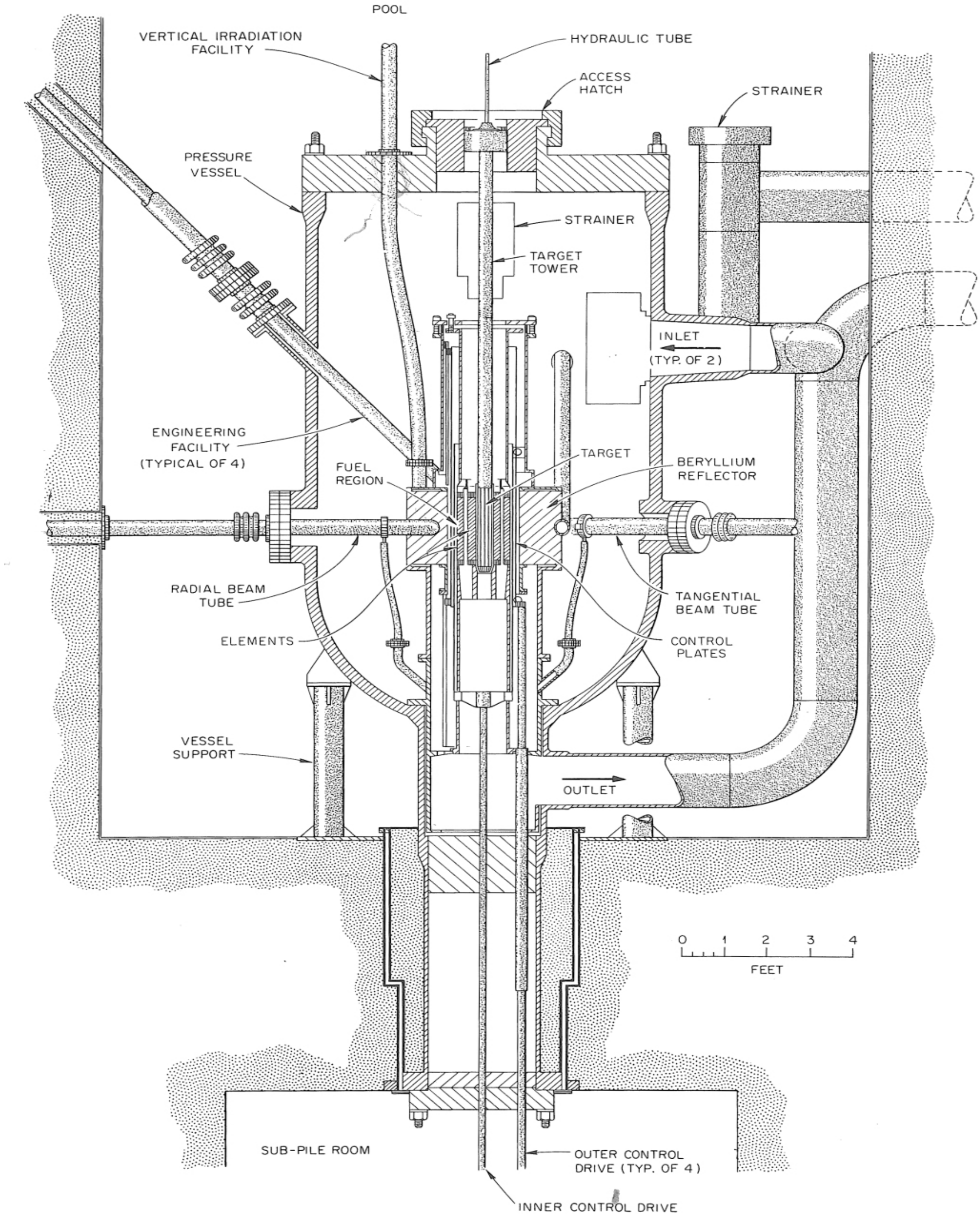
The reactor is used exclusively for research, it does not produce power

It has a peak thermal neutron flux of 2.5×10^{15} neutrons per square centimeter per second, which is the highest in the western world which is 50 to 100 times higher than cores of commercial nuclear power plants

The HFIR is a beryllium-reflected, light water-cooled and moderated flux-trap type reactor that uses highly enriched uranium-235 as the fuel

A fuel cycle normally consists of full-power operation for approximately 23-26 days at 85 MW

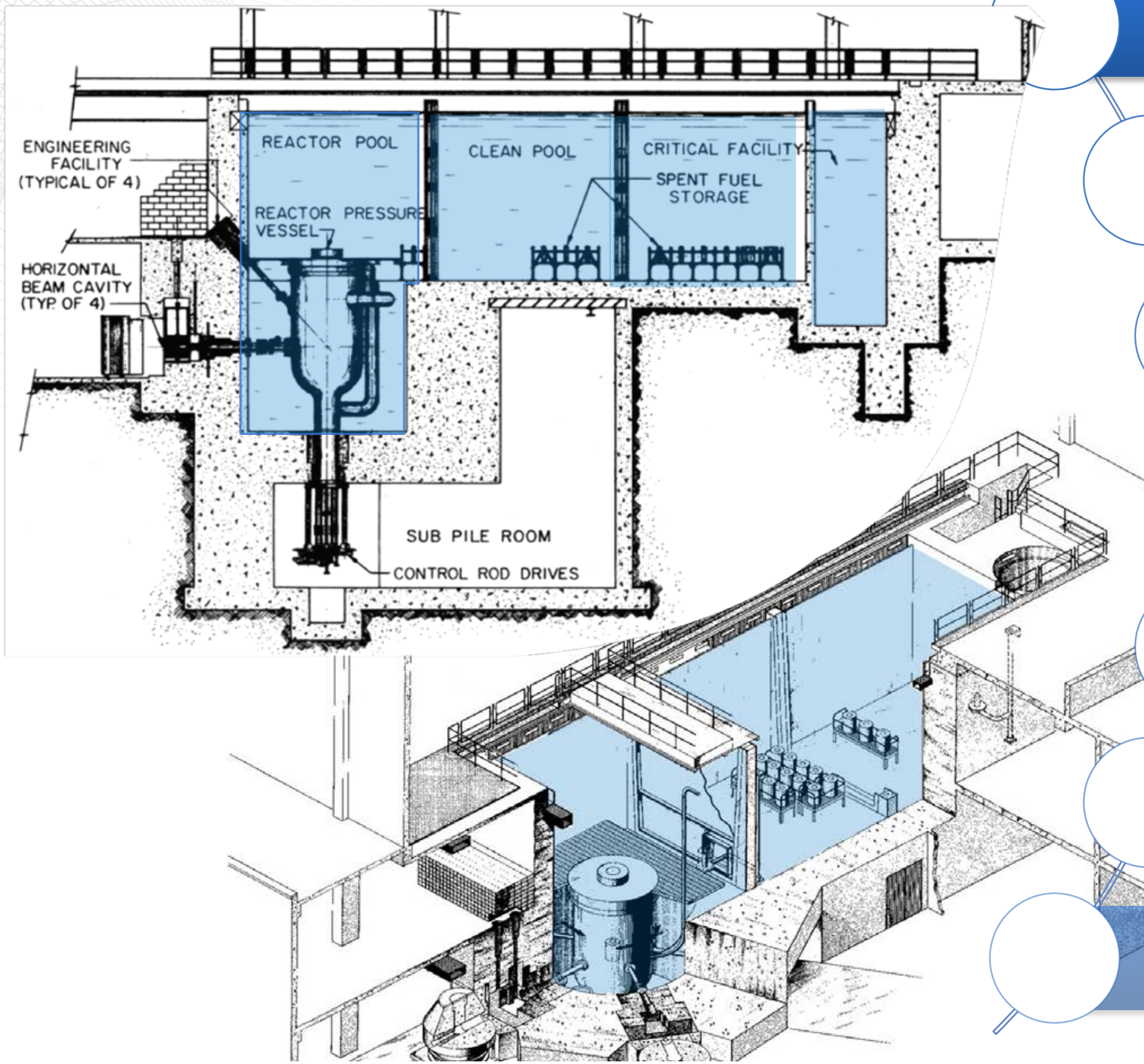
Coolant Flow	16,000 GPM	60,500 L/min
Inlet Pressure/Temperature	468 PSIG / 120°F	3.2 MPa/48.9°C
Outlet Pressure Temperature	358 PSIG / 156°F	2.5 MPa/68.9°C



Key differences between HFIR and a commercial BWR

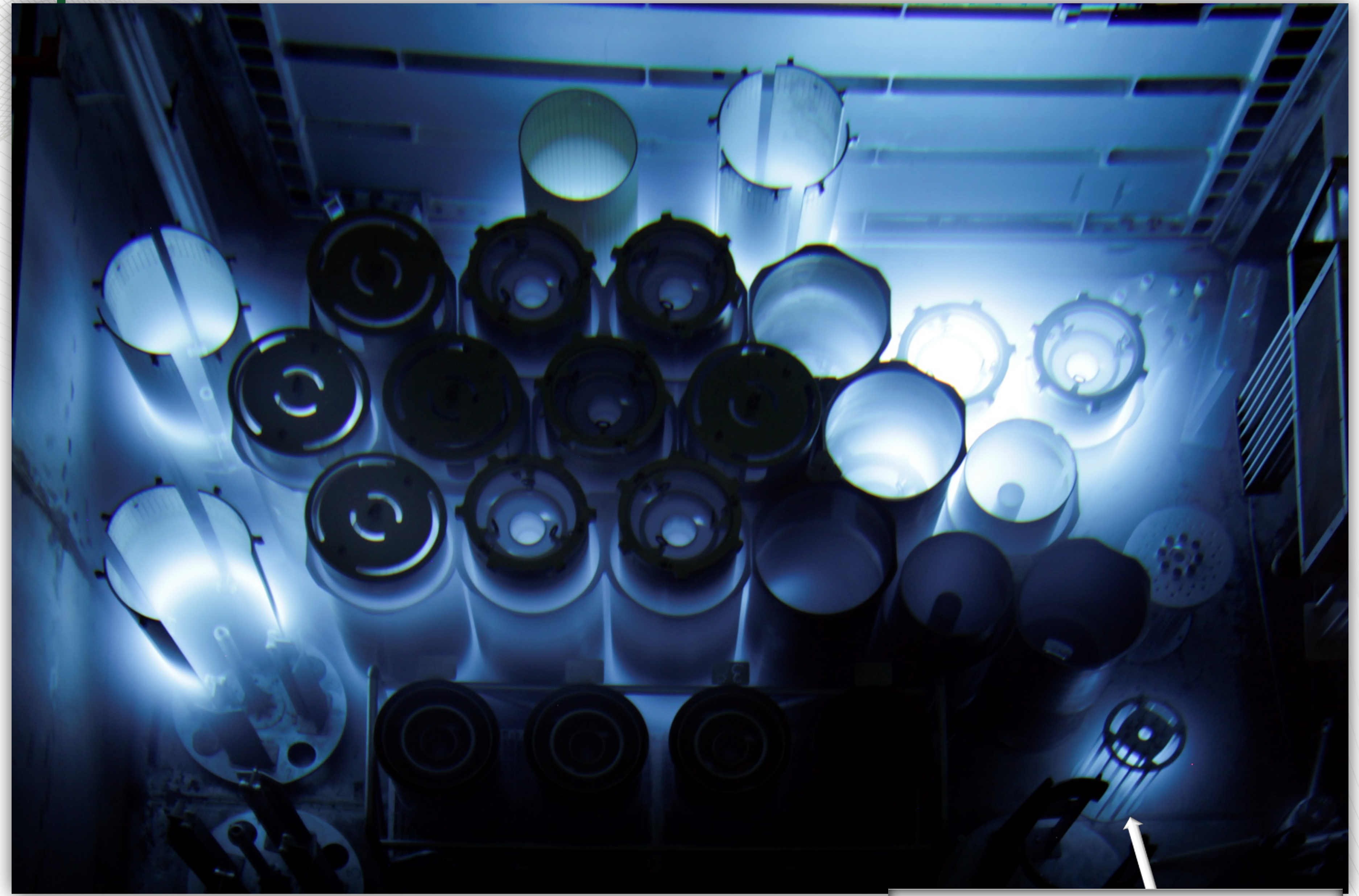
	BWR	HFIR
MASS OF CORE	On the order of 110,000 lb of uranium fuel and 50,000 lb of Zircaloy cladding	22 lb of uranium fuel and 200 lb of aluminum cladding
POST-SHUTDOWN HEAT REMOVAL	AC power or diesel generators needed to keep the reactor safe	Batteries provide all the cooling needed for 12 hours, and after that, no power for cooling is required at all
ULTIMATE HEAT SINK	Coolant must be pumped from a remote volume of water	The reactor is submerged in a pool capable of absorbing all the heat that the core will generate after shutdown
OPERATING TEMPERATURE	500 °F water must be cooled down to achieve a safe shutdown condition at low pressure	155 °F water is already at a temperature that will be safe at low pressure
GEOGRAPHY	Prone to severe earthquakes and location is susceptible to tsunami	Earthquake frequency/severity is less and no potential for tsunami; flooding from nearby rivers/dams does not threaten facility due to elevation

Reactor pools



- The vessel is submerged in an 80,000 gallon (303kl) , 36 foot (11m) deep reactor pool
- Above the vessel top the pool is rectangular, below cylindrical
- Reactor core centerline is 27 feet (8.2m) below water
- There are two rectangular 114,000 gallon (431kl), 20 foot (6m) deep clean pools used for spent fuel storage
- The pools provide for radiation shielding and heat removal
- The critical pool was intended to house a critical experiment facility and is a 10,000 gallon (38kl) , 25 foot (7.6m) deep cylindrical pool
- The pools are circulated, demineralized, filtered and cooled

Spent fuel



Control Rod Access Plug rack with colbalt-60 samples irradiated in the 1980’s

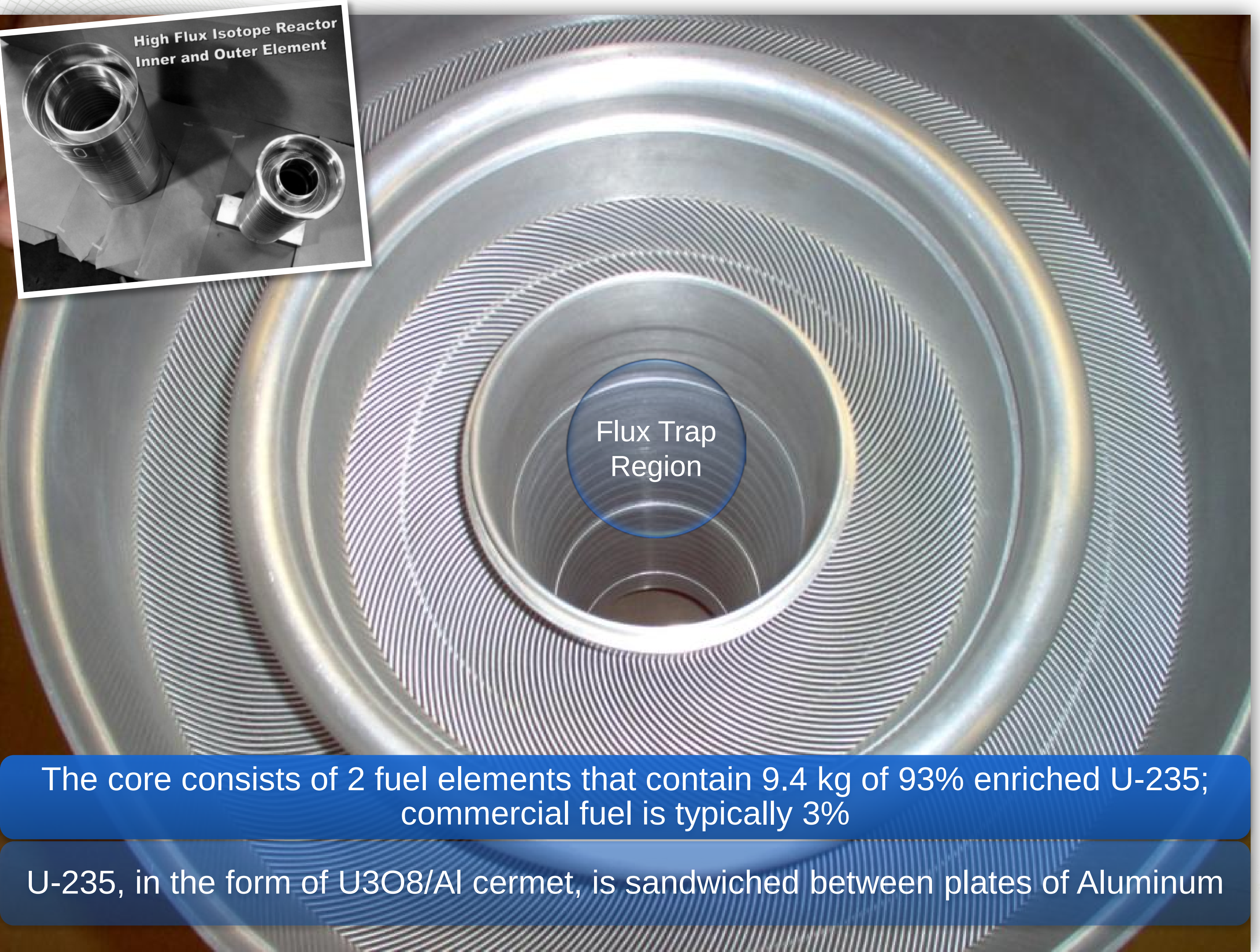
The most recently used fuel element is glowing most brightly

The blue glow is Cherenkov radiation which is caused by beta particles from decay of fission products in the spent fuel passing through the water faster than light would pass through

The beta particles excite the water, and as the water releases energy, a shockwave of high frequency photons (blue light) is released

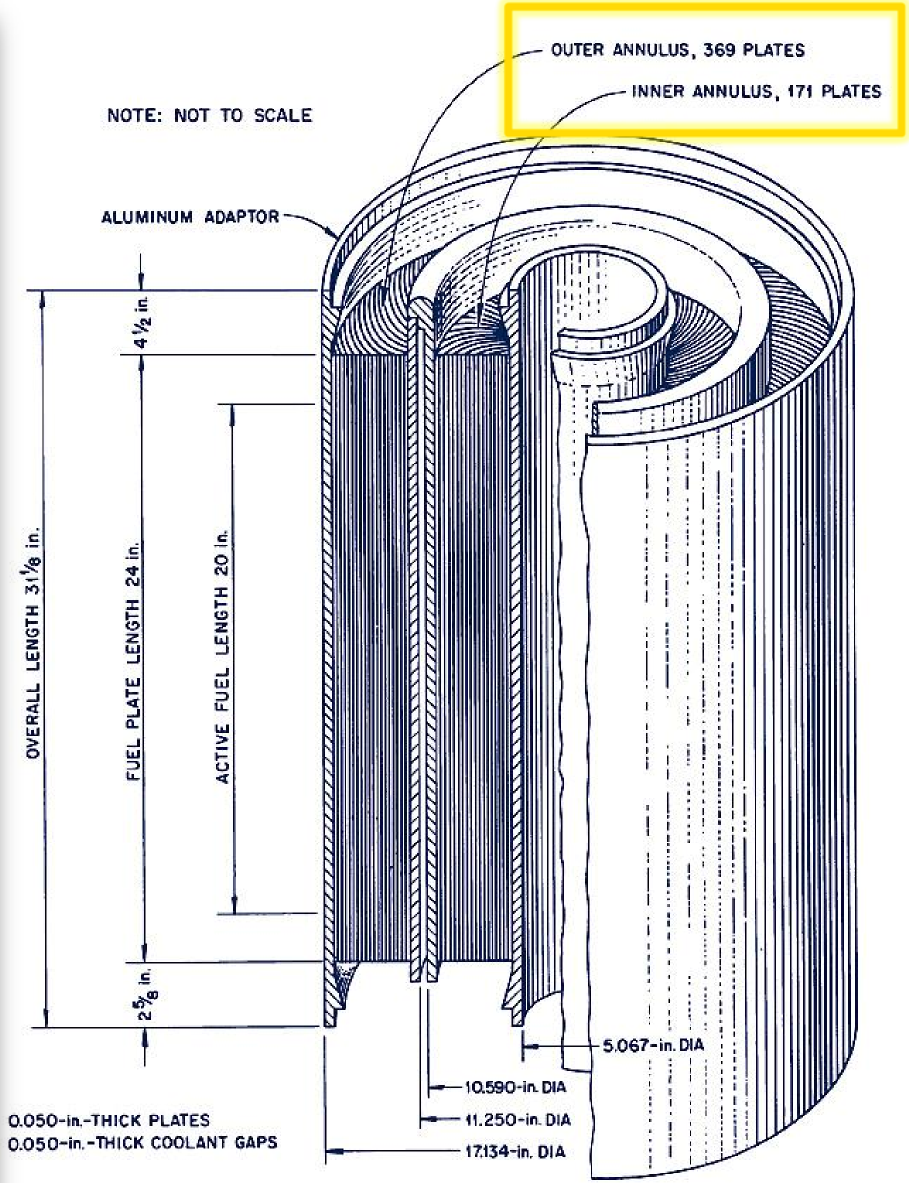
If the spent fuel was removed from the vessel the first day after shutdown and taken out of the water, it would measure millions of Rad/hr

Curved (involute) fuel plates offer constant width water gap, critical to fuel performance

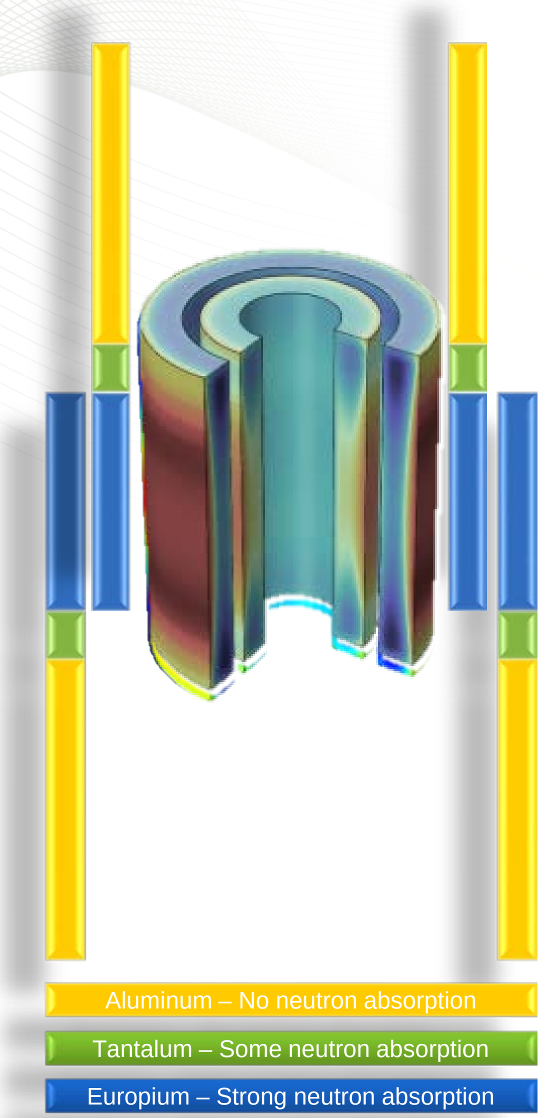


The core consists of 2 fuel elements that contain 9.4 kg of 93% enriched U-235; commercial fuel is typically 3%

U-235, in the form of U3O8/Al cermet, is sandwiched between plates of Aluminum



The position of the four control plates and the inner cylinder controls reactivity



We start with a fresh core and all rods fully inserted

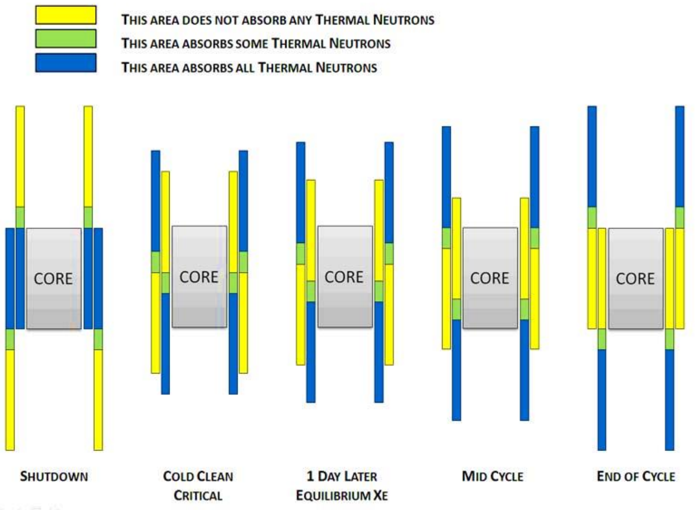
Rods are withdrawn to the critical position

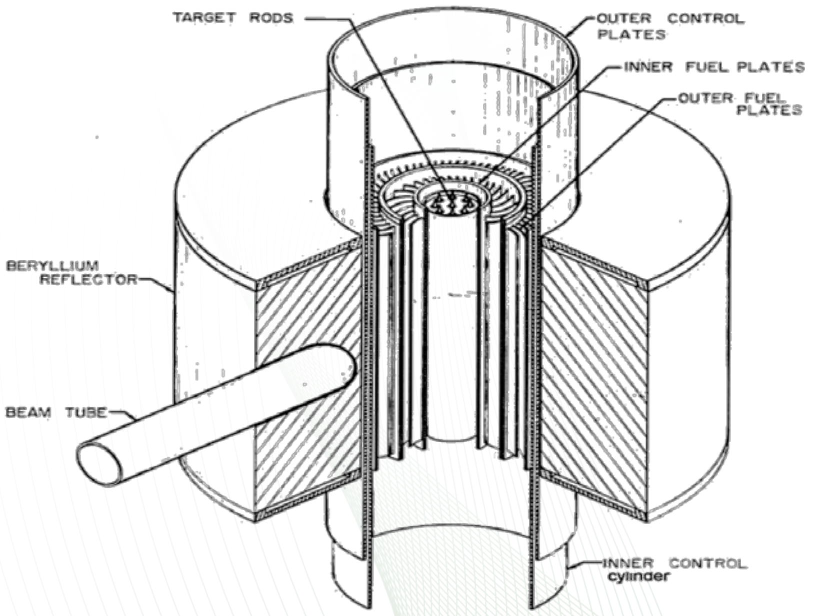
And the Reactor goes critical
(self-sustaining chain reaction)

We maintain full power and withdraw the rods as the fuel depletes over ~23-26 days

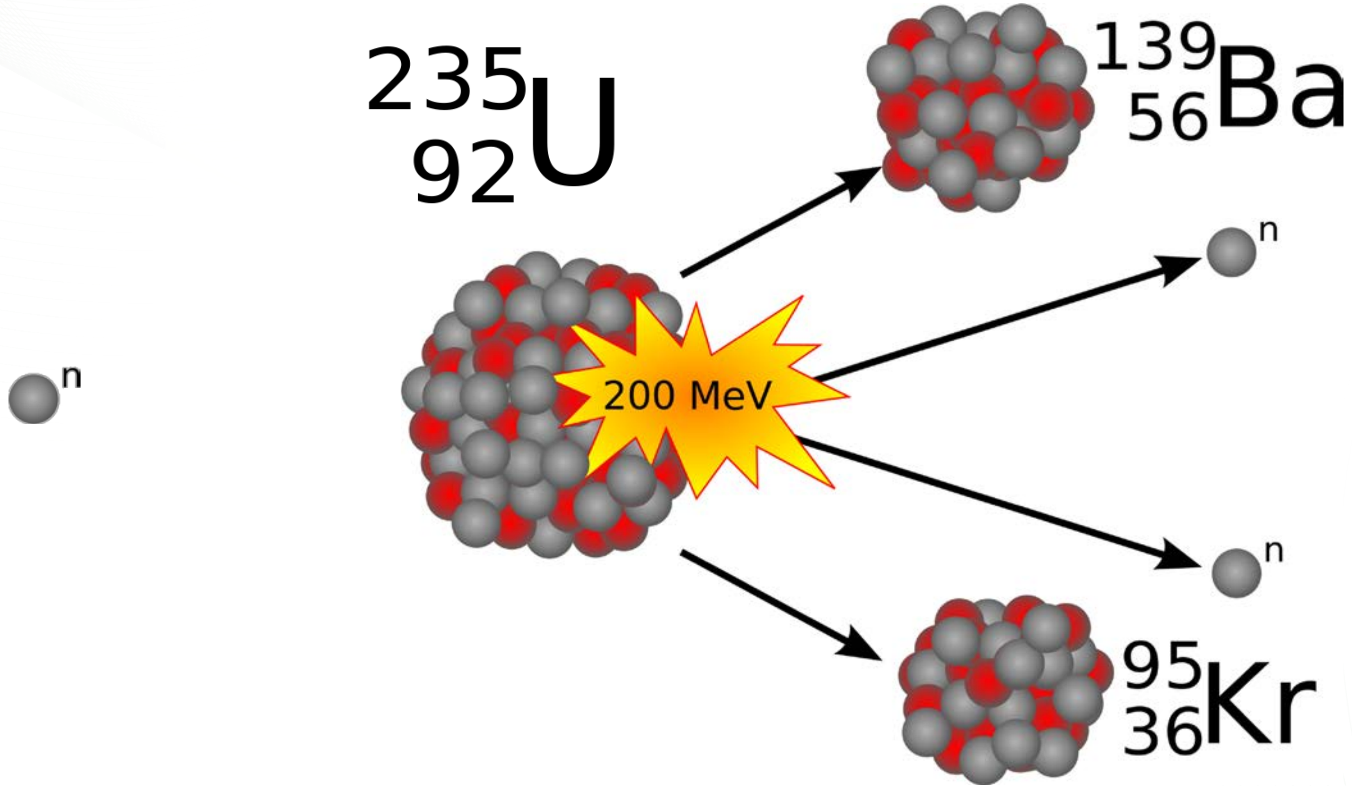
At the end of cycle, the outer plates are released *(scrammed)* to shut down reactor

The inner cylinder is then inserted to secure the reactor. *Note that the fuel still has decay heat*





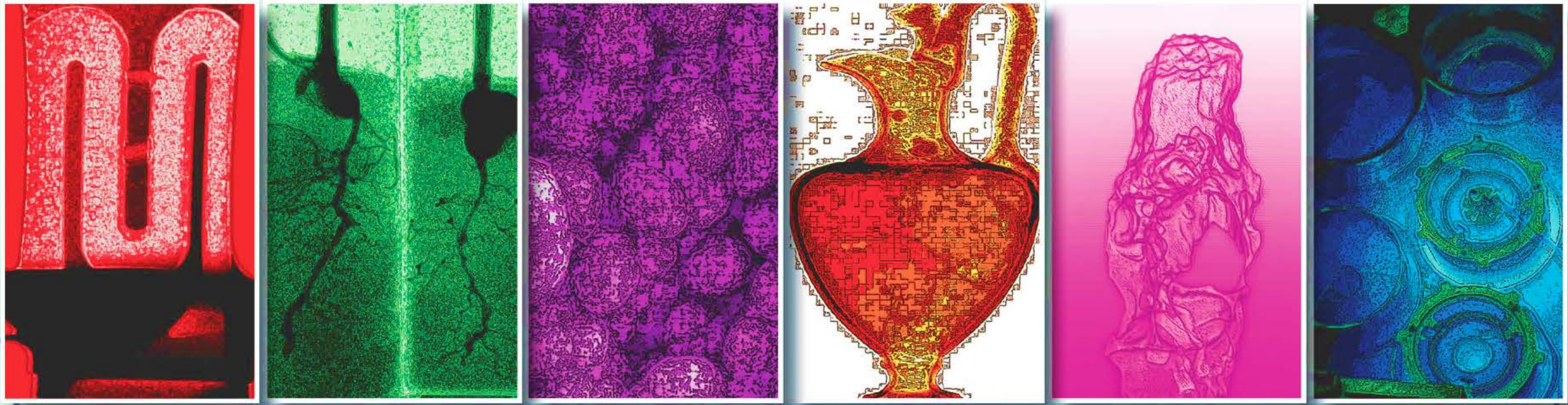
Animation of the fission process



HFIR has 4 primary missions

A brighter future

The neutron scattering research facilities at HFIR contain a world-class collection of instruments used for fundamental and applied research on the structure and dynamics of matter. HFIR is also used for medical, industrial, and research isotope production; research on neutron damage to materials; and neutron activation analysis to examine trace elements in the environment. Additionally, the building houses a gamma irradiation facility that uses spent fuel assemblies and is capable of providing high gamma doses for studies of the effects of radiation on materials.



Neutron Scattering

Neutron scattering can provide information about the structure and properties of materials that cannot be obtained from other techniques such as x-rays or electron microscopes. There are many neutron scattering techniques, but they all involve the detection of particles after a beam of neutrons collides with a sample material. HFIR uses nuclear fission to release neutrons, which are directed away from the reactor core and down four steady beams. Three of these beams use the neutrons as they are created (thermal neutrons), and one beam moderates (cools and slows) the neutrons with supercritical hydrogen, enabling the study of soft matter such as plastics and biological materials. The thermal and cold neutrons produced by HFIR are used for research in a wide array of fields of study, from fundamental physics to cancer research. The high neutron flux in HFIR produces the world's brightest neutron beams, which allow faster and higher-resolution detection.

Irradiation Materials Testing

HFIR provides a variety of **in-core irradiation facilities**, allowing for a wide range of materials experiments to study the effects of neutron-induced damage to materials. This research supports fusion energy and next-generation nuclear power programs, as well as extending the lifetime of the world's current nuclear power plants. HFIR has the unique ability to deliver the highest material damage in the US.

The HFIR **Gamma Irradiation Facility** is designed to expose material samples to gamma radiation using spent HFIR fuel elements. The facility offers high dose rates and custom sample environments for the most innovative research.

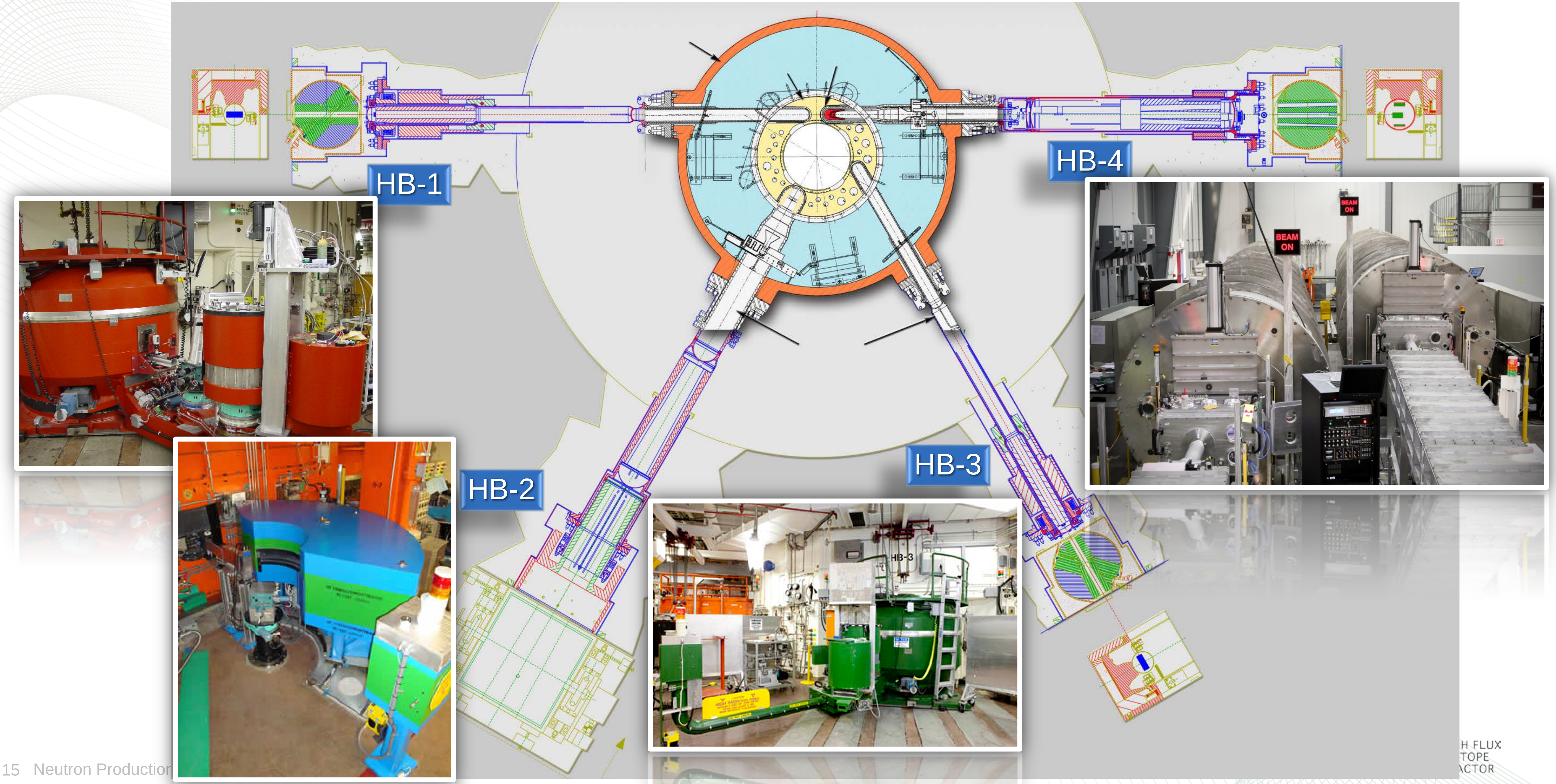
Isotope Production

Isotopes play an extremely important role in the fields of nuclear medicine, homeland security, energy, and defense, as well as in basic research. HFIR's high neutron flux enables the production of key isotopes that can not be made elsewhere, such as californium-252, selenium-75, and nickel-63, among others. Additionally, HFIR will produce plutonium-238, which is used to power NASA's deep space missions.

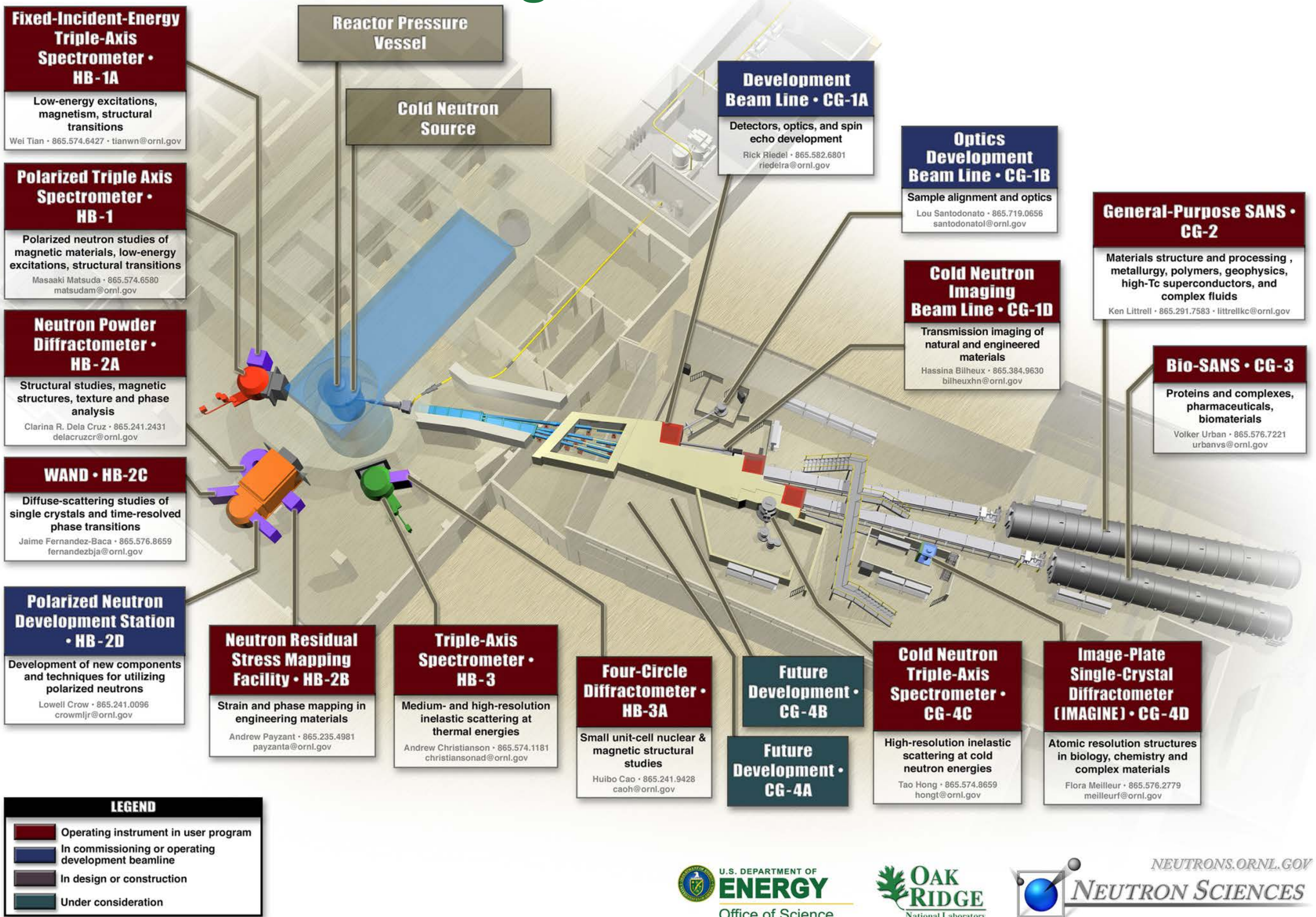
Neutron Activation Analysis

Neutron Activation Analysis (NAA) is an extremely sensitive technique used to determine the existence and quantities of major, minor, and trace elements in a material sample for applications including forensic science, environmental monitoring, nonproliferation, homeland security, and fundamental research.

Beam tubes



Neutron scattering instruments



U.S. DEPARTMENT OF ENERGY
Office of Science

OAK RIDGE
National Laboratory

NEUTRONS.ORNL.GOV
NEUTRON SCIENCES

OAK RIDGE National Laboratory
HIGH FLUX ISOTOPE REACTOR

Missions: Irradiation Materials Testing and Isotope Production

Irradiation Materials Testing

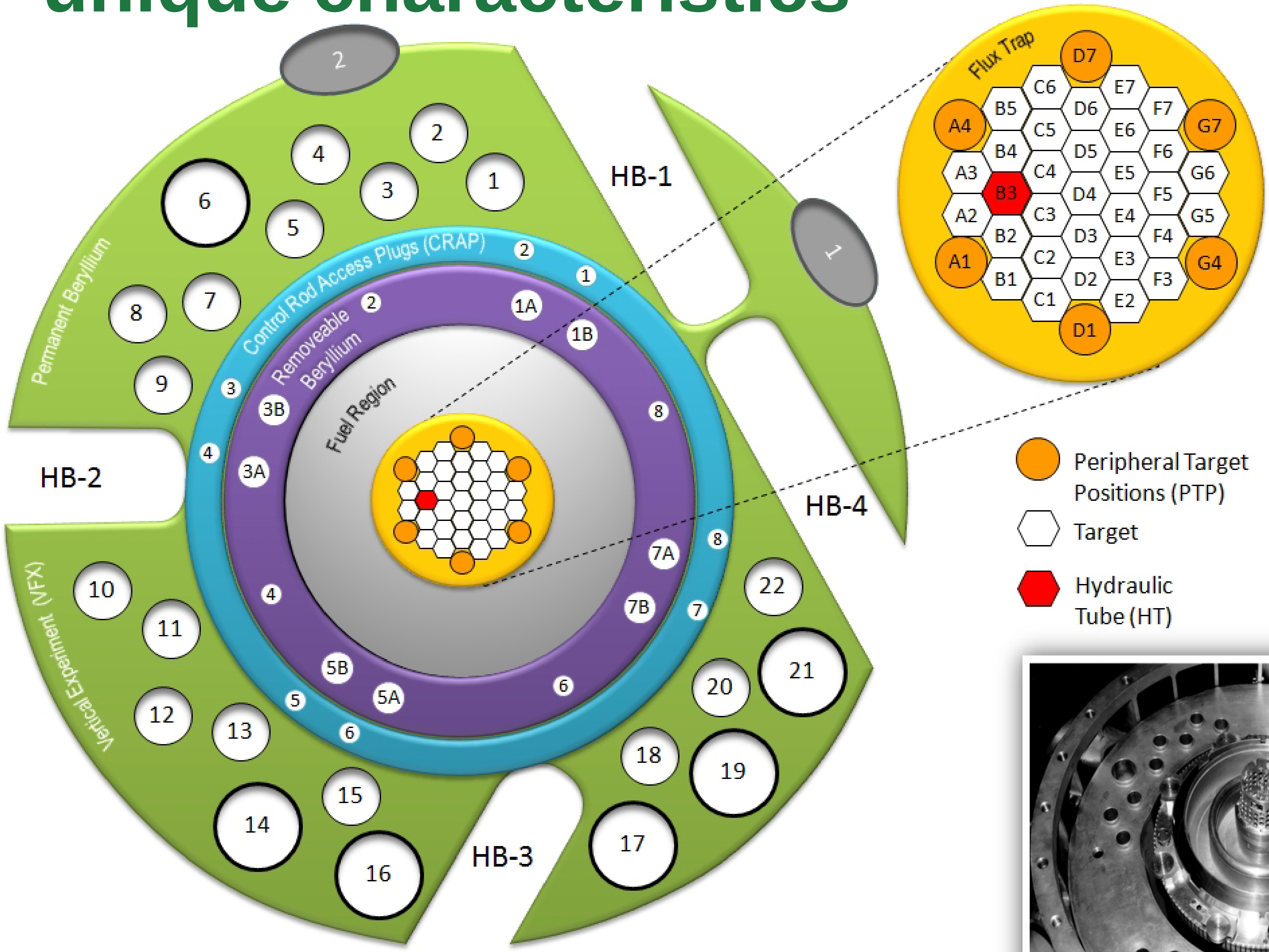
HFIR provides a variety of **in-core irradiation facilities**, allowing for a wide range of materials experiments to study the effects of neutron-induced damage to materials. This research supports fusion energy and next-generation nuclear power programs, as well as extending the lifetime of the world's current nuclear power plants. HFIR has the unique ability to deliver the highest material damage in the US.

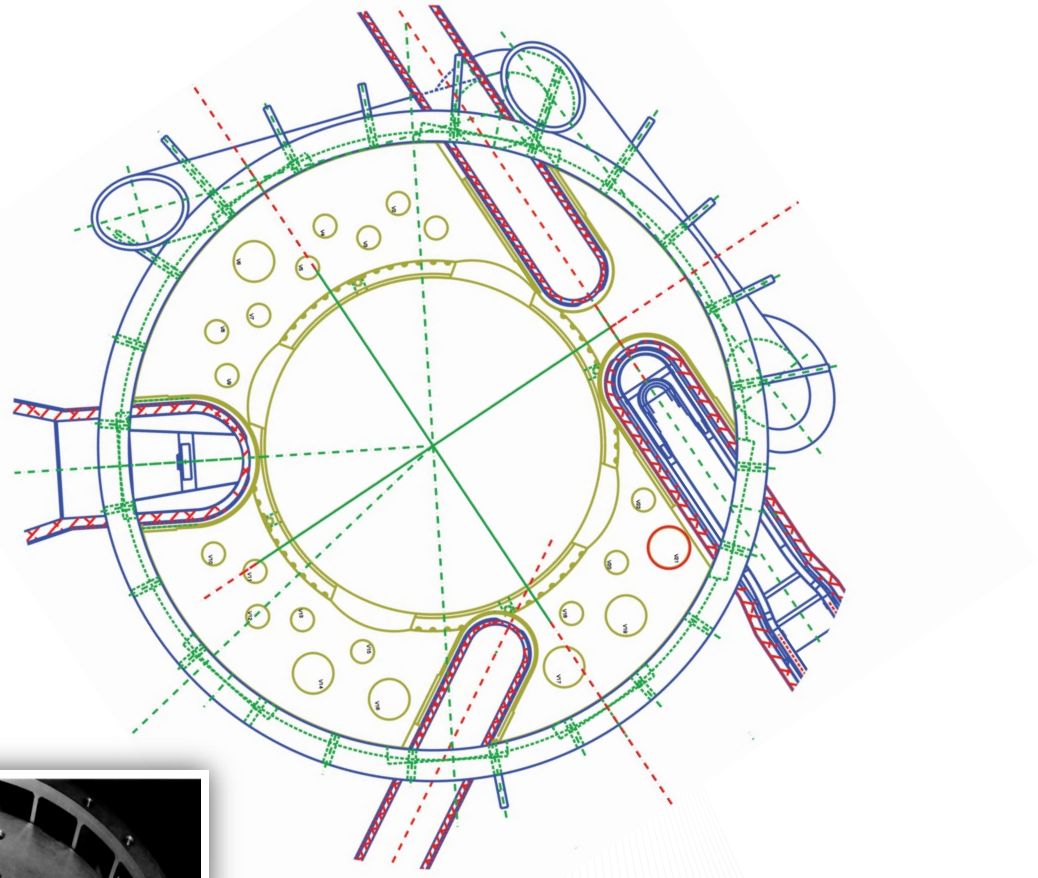
The HFIR **Gamma Irradiation Facility** is designed to expose material samples to gamma radiation using spent HFIR fuel elements. The facility offers high dose rates and custom sample environments for the most innovative research.

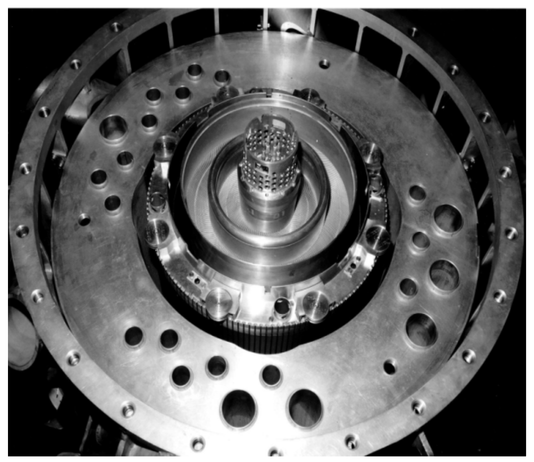
Isotope Production

Isotopes play an extremely important role in the fields of nuclear medicine, homeland security, energy, and defense, as well as in basic research. HFIR's high neutron flux enables the production of key isotopes that can not be made elsewhere, such as californium-252, selenium-75, and nickel-63, among others. Additionally, HFIR will produce plutonium-238, which is used to power NASA's deep space missions.

HFIR offers a wide variety of irradiation sites, each with unique characteristics







OAK RIDGE National Laboratory | HIGH FLUX ISOTOPE REACTOR

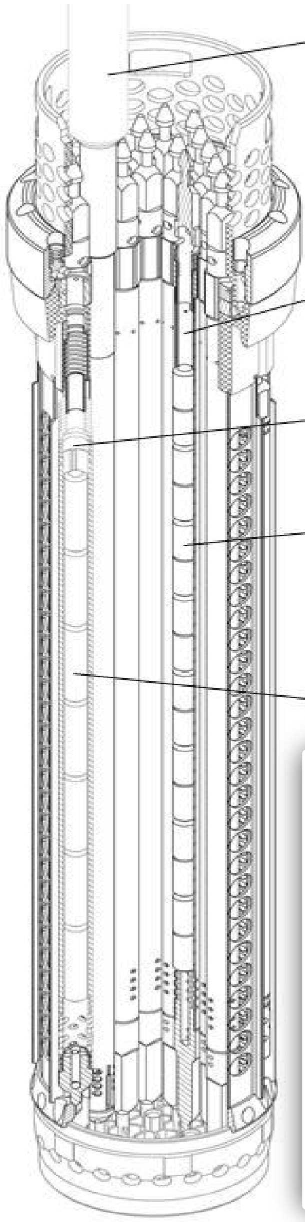
Flux trap allows for a flexible configuration of experiments/isotope capsules

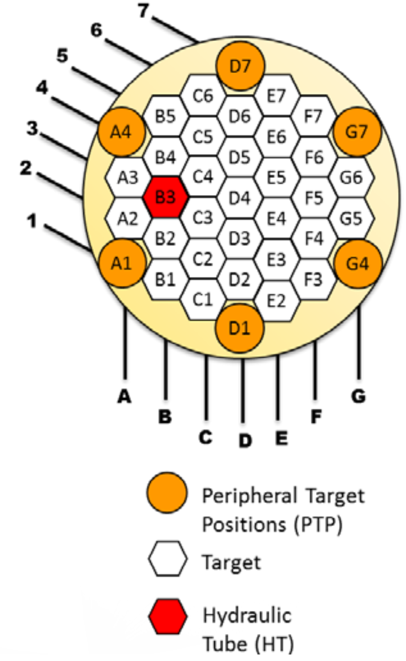
Primary Applications

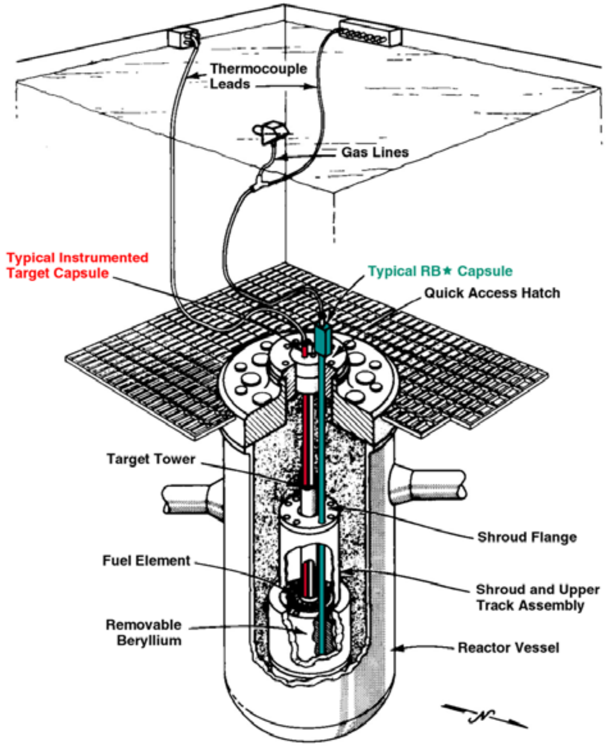
- Materials irradiations
- Transuranic element production
- Industrial and medical isotope production
- Fuels irradiation

Specifications

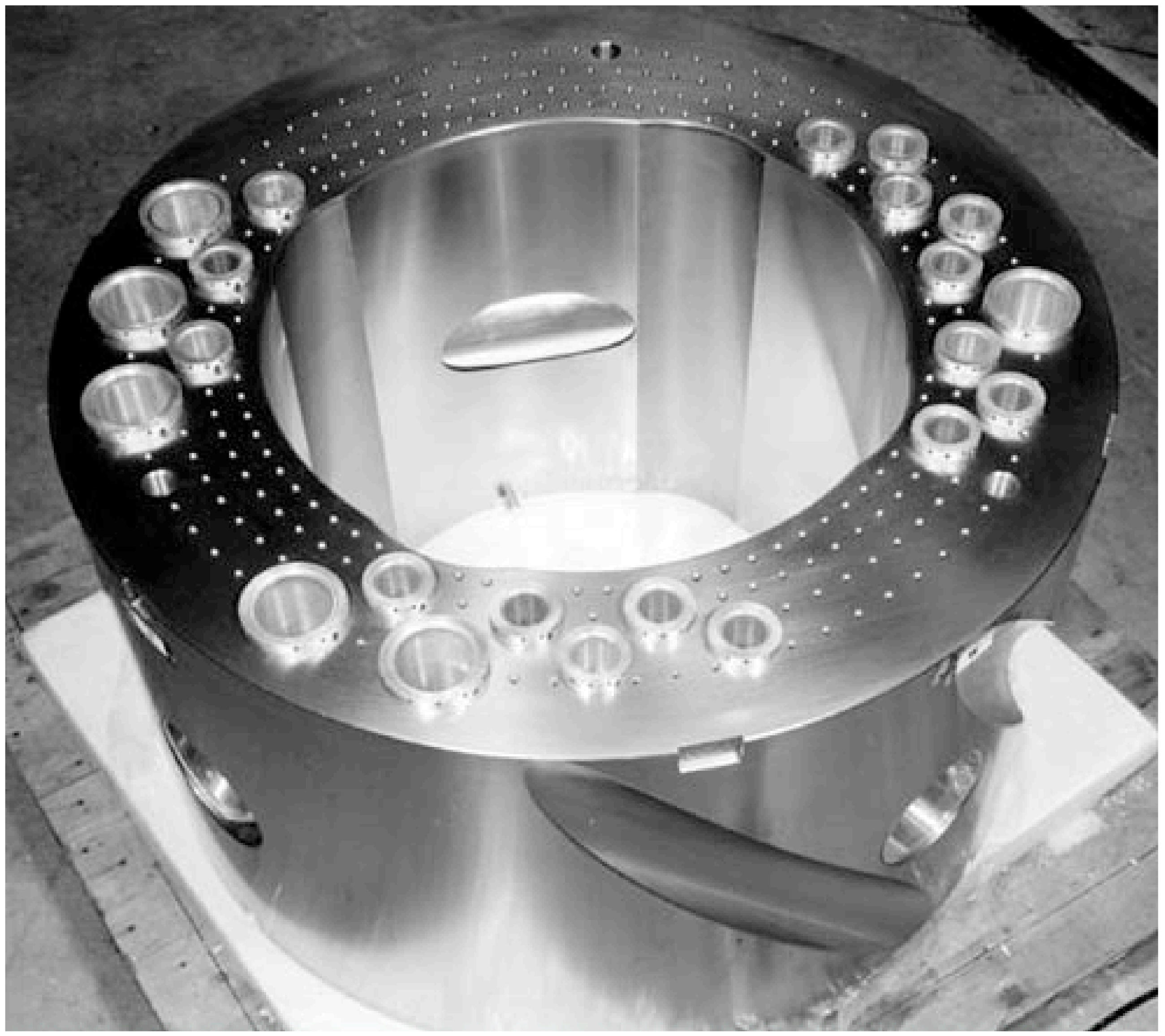
Diameter	6.50 mm
Length	508.0 mm
Thermal Flux (< 0.4eV)	2.5 x 10^{15} N/cm^2-s
Fast Flux (> 0.1MeV)	1.2 x 10^{15} N/cm^2-s
Instrumented experiments possible	2 sites







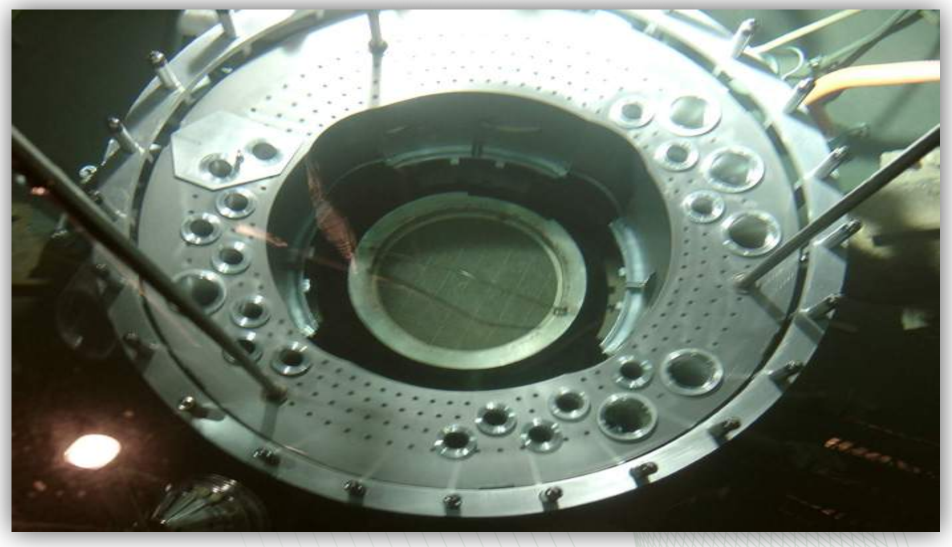
Beryllium Reflector offers larger volume for experiments/isotope production



Suitable for isotope production (C-14, Pu-238)

Lower flux and gamma rates well suited for fuels testing

Lower fast flux not ideal for radiation-induced damage (DPA), but still high

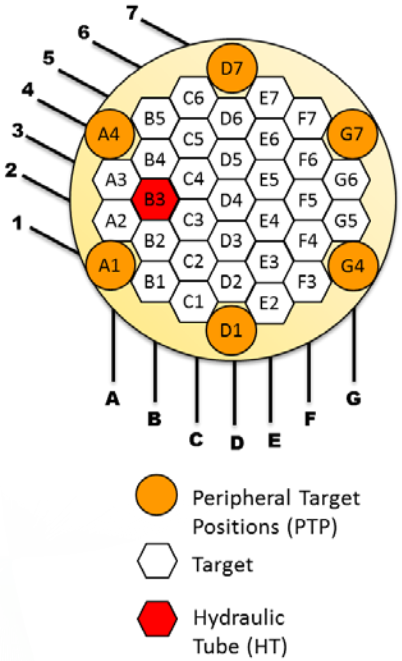


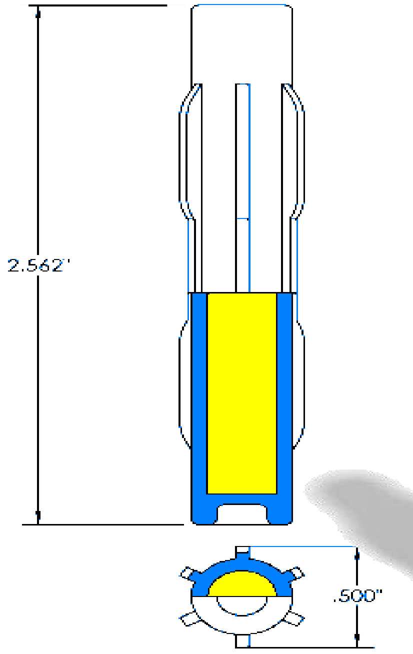
HFIR Hydraulic Tube facility allows online insertion and removal of experiments during operation

Production of short-lived isotopes for research (Mo-99, W-188)

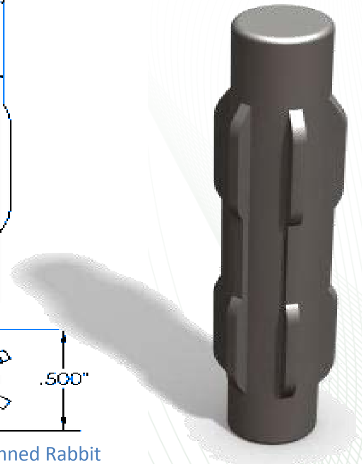
Short-term irradiation testing of fuels, cladding and other materials

Accommodates up to 9 capsule targets (rabbits)





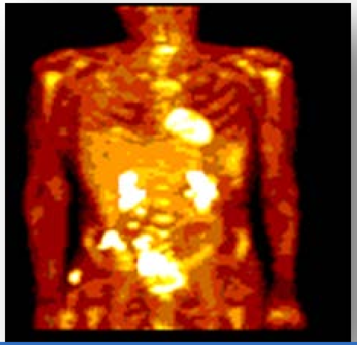
Overall Dimensions of a Finned Rabbit



OAK RIDGE National Laboratory | HIGH FLUX ISOTOPE REACTOR

In-core isotope production

HFIR produces a diverse set of isotopes for a variety of industries and applications



Energy

- Nuclear fuel quality control
- Reactor start-up sources
- Coal analyzers
- Oil exploration

Industrial

- Mineral analyzers
- Cement analyzers
- FHA measurements for corrosion (bridges, highway infrastructure)

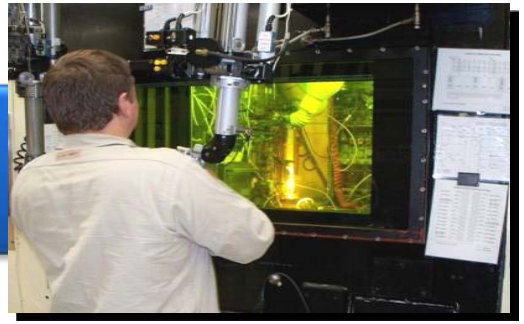
Security

- Handheld contraband detectors (CINDI)
- Standard for all neutron fission measurements
- Monitoring downblending of HEU
- Identifying unexploded chemical ordnance and detecting land mines

Medical

- Cancer Treatments

Californium-252 (Cf-252) is a radioactive neutron source with many important uses



ORNL supplies ~70% of ^{252}Cf worldwide

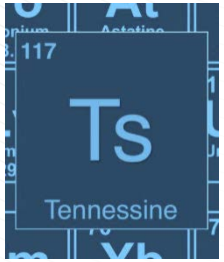
- The only other production facility is in Dimitrovgrad, Russia

Cf-252 is important to the U.S. economy, security, and healthcare

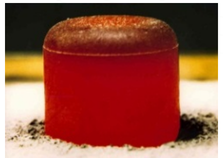
- Oil well logging
- On-line coal quality analysis
- Cancer treatment
- Nuclear reactor start-up sources
- Nuclear fuel rod examination
- Homeland Security
  - Neutron radiography
  - Check sources for portal detectors
  - Portable neutron activation
- More than 200 sources on loan to ~25 major universities and research institutions

HFIR is a reliable source of unique isotopes

- **Californium-252**
  - HFIR supplies 70% of the world's demand of Cf-252, which is used as a reactor startup source, for radiography, for the coal and oil industry as well as medical therapy applications. The remainder is supplied by Russia. *HFIR operation forms an irreplaceable cornerstone of this billion dollar industry.*



- **Berkelium-249**
  - In the pursuit of new elements on the periodic table, researchers from the US and around the world rely on HFIR irradiations to produce Bk-249 and other heavy element target material (Cf-251). Recent (2010) campaigns to produce Bk-249 have resulted in the discovery of element 117 and use of these heavy element target materials continues in the search for 119+. This effort exemplifies fundamental scientific collaboration on an international scale.



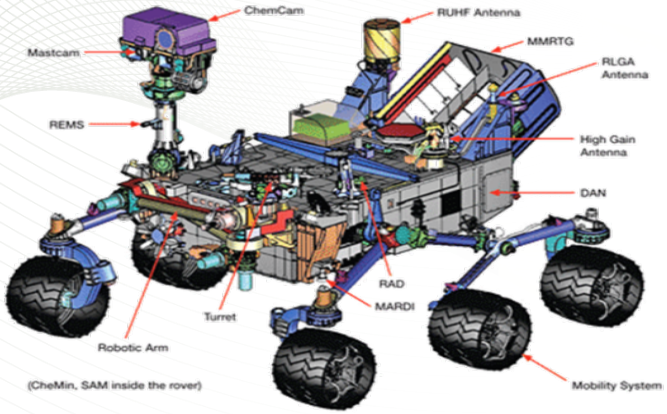
- **Plutonium-238**
  - The necessity for reliable power for deep space and planetary NASA missions drives the need for Pu-238. Used in Radio Thermoelectric Generators (RTG), Pu-238 provides the most efficient heat source for these electricity-generating units, and is the basis for the next generation Stirling engine generators which are in NASA's development pipeline.

- **Selenium-75**
  - Used in commercial/industrial gamma radiography, Se-75 is becoming the isotope of choice for many pipeline and other non-destructive testing (NDT) efforts. HFIR's production of Se-75 is increasing with this rising demand for this isotope. Additionally, the high specific activity only available from HFIR has become the industry standard.

- **Nickel-63**
  - Because of the low target cross-section, HFIR is the only source for high specific activity Ni-63 used for national security applications and detection of explosives and drugs at airports.

*Other isotopes produced at HFIR include **tungsten-188, lutetium-177, and actinium-225**.*

Examples of in-core irradiation



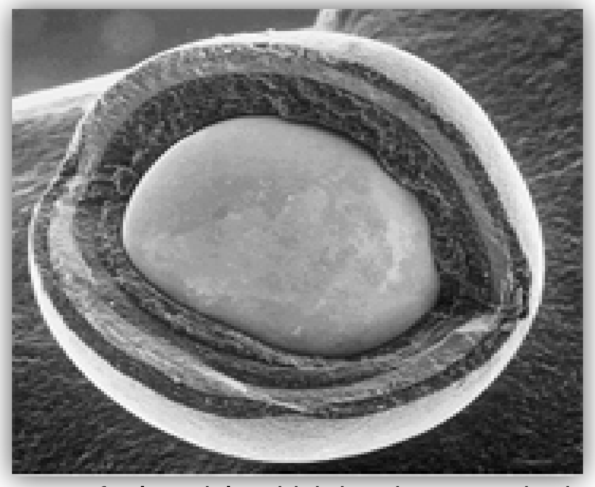
Mars Rover Curiosity uses an RTG containing 3.6kg ^{238}Pu to produce electricity. -NASA image

^{238}Pu for NASA space missions

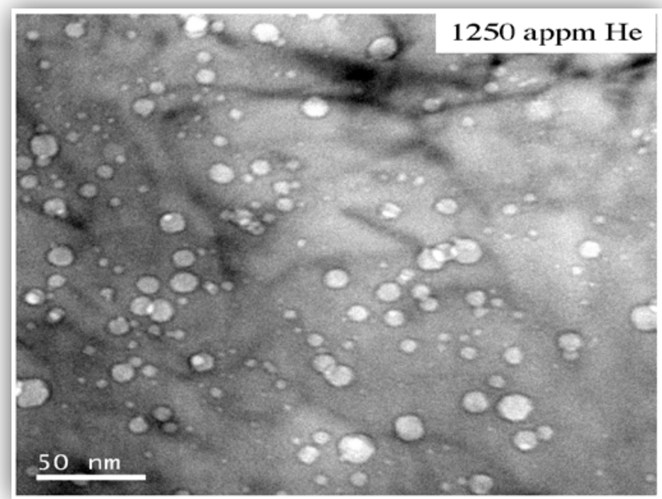
Accident tolerant nuclear power reactor fuel

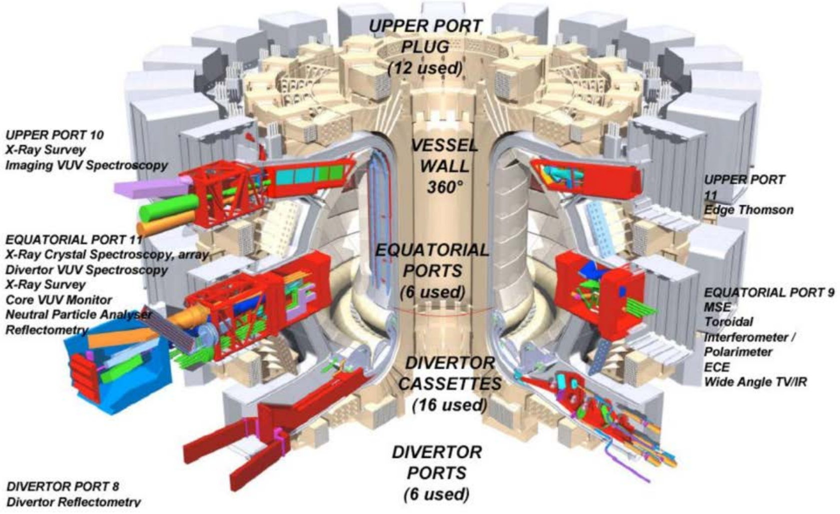
Helium bubbles in Steel

First wall material for fusion reactor (ITER)



TRISO fuel particle which has been cracked, showing the multiple coating layers





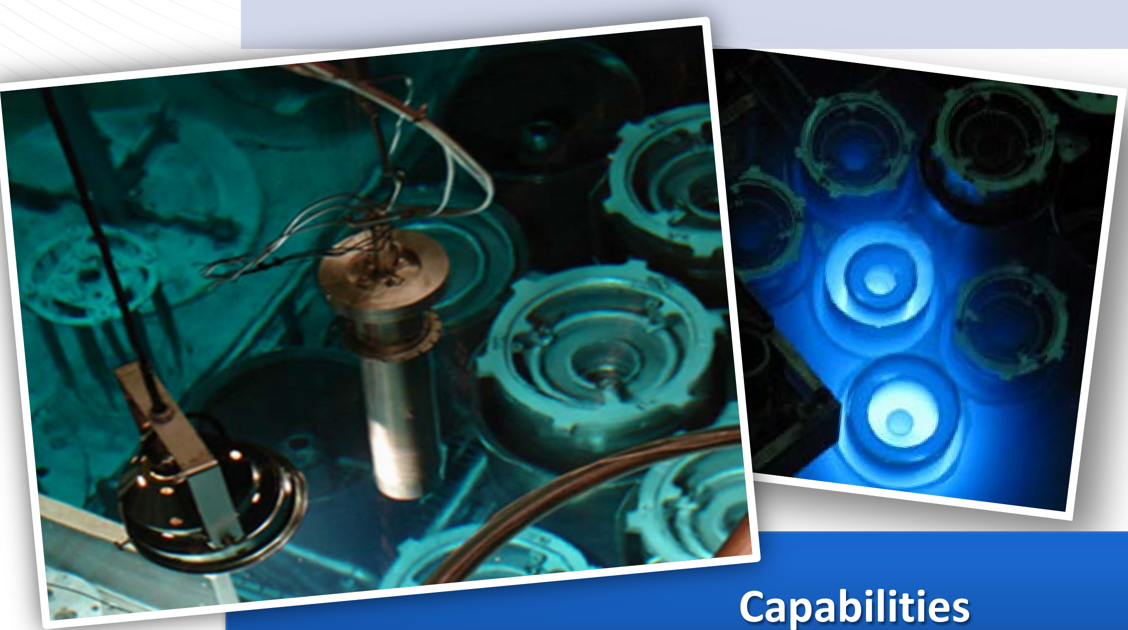
OAK RIDGE National Laboratory | HIGH FLUX ISOTOPE REACTOR

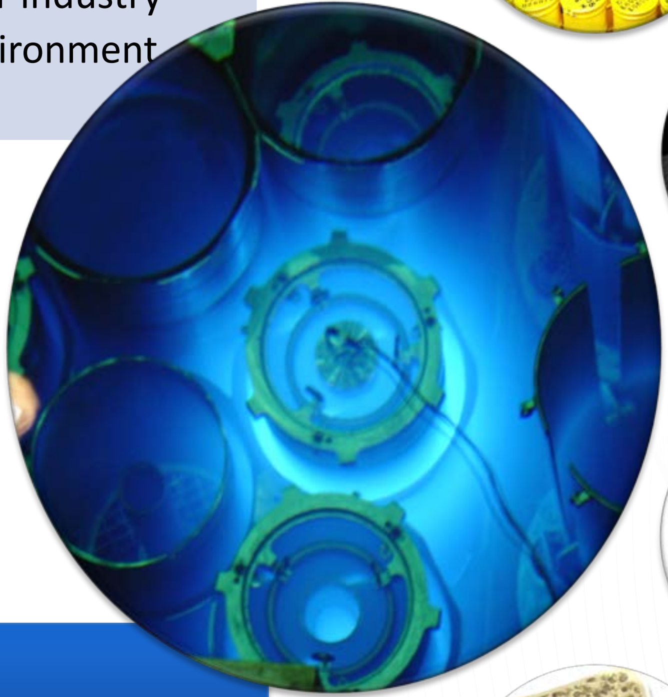
Select topic to view additional information

Gamma irradiation facility supports accelerated radiation damage studies

Primary Uses

- Qualify materials and components for the nuclear industry
- Understand material behaviors in a radiation environment

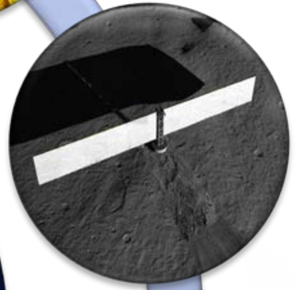




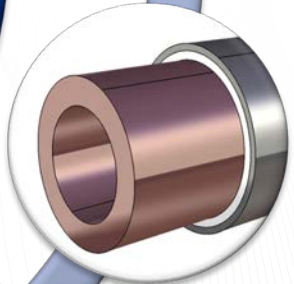
Capabilities

- Samples can be subjected to gamma fluxes up to 10^8Rad/h
- Samples are placed in a 3-in diameter X 25” long (7.62cm x 63.5cm) canister in the flux trap of a spent fuel element
- Sweep gasses provide cooling and inert environment
- Electrical connections allow data acquisition and power to the samples

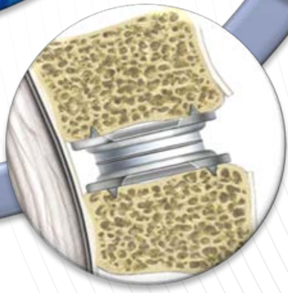
Ion exchange resin radiation tolerance studies (for removing Cs-137 from high level waste)



Investigating radiation resistance of materials for lunar reactor environments (NASA)



Understanding radiation induced conductivity changes in high voltage insulators



Characterizing the wear properties of artificial spinal discs (FDA)

Mission: Neutron Activation Analysis

Neutron Activation Analysis

Neutron Activation Analysis (NAA) is an extremely sensitive technique used to determine the existence and quantities of major, minor, and trace elements in a material sample for applications including forensic science, environmental monitoring, nonproliferation, homeland security, and fundamental research.

NAA technique is distinctive from other options

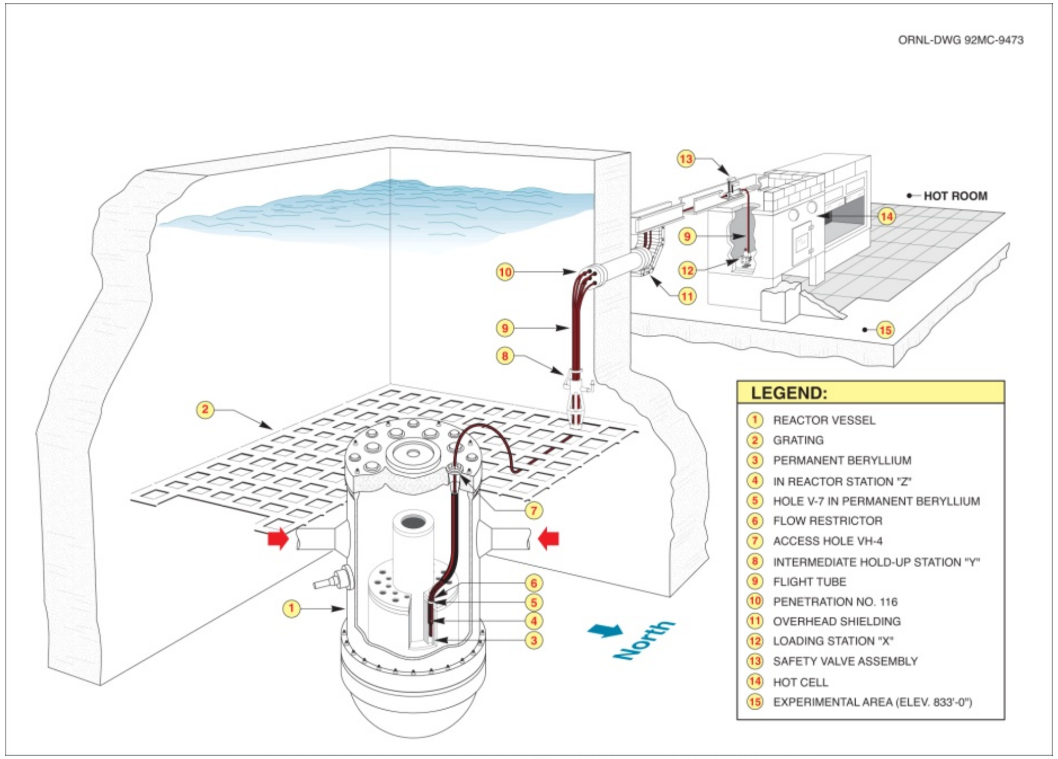
Two Pneumatic Tubes:

PT-1: Thermal Neutron Flux: 4×10^{14} n cm^{-2} s^{-1}

- Thermal-to-Resonance Ratio: 35
- Shielded sample loading station with remote manipulators
- Decay station in pool
- Rabbit travel time: 2.5 seconds

PT-2: Thermal Neutron Flux: 4×10^{13} n cm^{-2} s^{-1}

- Thermal-to-Resonance Ratio: 250
- Loading station in hood
- Automated delayed-neutron counting station that will measure 20 - 30 picograms of ^{235}U or other fissile material in 5 minutes
- Other characteristics of PT-1 apply



NAA Lab provides distinctive capabilities to various industries and institutions from applied forensics to basic scientific research

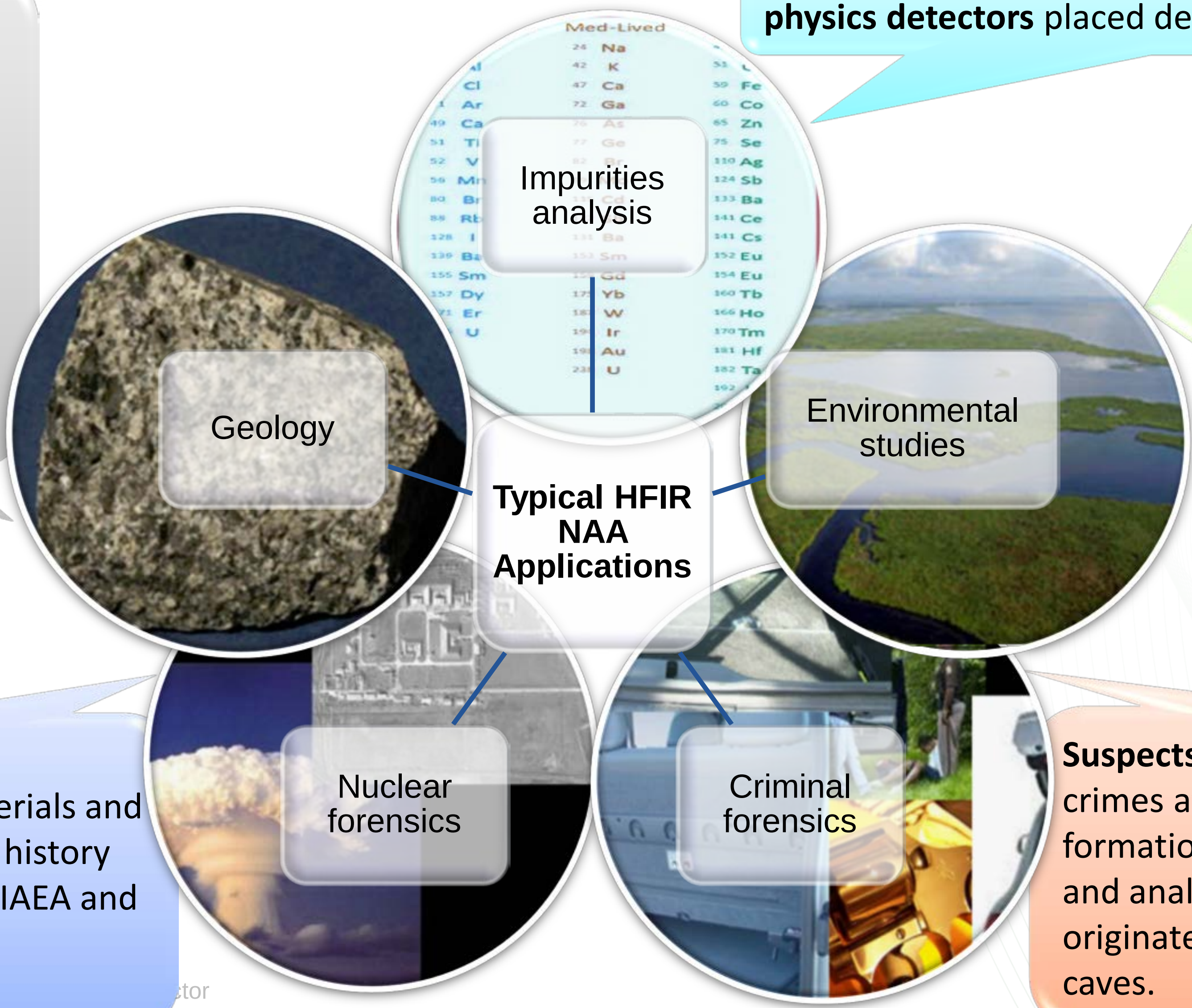
With extremely low detection limits, NAA is one of the best tools for non-proliferation testing, forensics and advanced materials research

Unlike mass-spectrometry and chromatography, NAA ignores chemical formulations and relies on interactions with the atomic nucleus

Pneumatic tube facility - HFIR NAA lab supports a wide variety of applications

Analysis of terrestrial and extraterrestrial geological matrices including **Apollo 11 lunar rocks**, **iron meteorites**, marine estuary sediments and biota, and the characterization of background trace element levels in geological strata

Analysis of high purity polyethylene used in **high-energy physics detectors** placed deep underground



Comprehensive trace element characterization of tree leaves from a population of genetically mapped trees in order to determine the **effects of climate change** on the composition, movement, and metabolism of salts and electrolytes.

Global efforts to stop the proliferation of nuclear materials and to determine the origin and history of banned materials for the IAEA and **domestic nuclear forensics** laboratories

Suspects were charged with federal crimes after samples of cave formations found in their possession, and analyzed, were determined to have originated in National Park system caves.

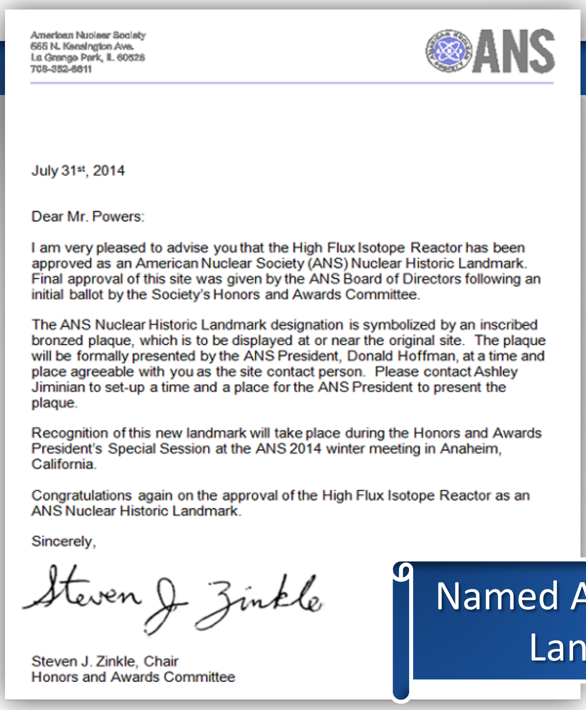
HFIR recognition by the American Nuclear Society

Featured in the Nuclear News September 2010

Meritorious Performance in Operations Award in FY13

1965 50 of outstanding scientific research YEARS 2015
OAK RIDGE National Laboratory | HIGH FLUX ISOTOPE REACTOR

HFIR Software Development Lifecycle featured in December 2011



American Nuclear Society
555 N. Kensington Ave.
La Grange Park, IL 60526
708-352-6611

ANS

July 31st, 2014

Dear Mr. Powers:

I am very pleased to advise you that the High Flux Isotope Reactor has been approved as an American Nuclear Society (ANS) Nuclear Historic Landmark. Final approval of this site was given by the ANS Board of Directors following an initial ballot by the Society's Honors and Awards Committee.

The ANS Nuclear Historic Landmark designation is symbolized by an inscribed bronzed plaque, which is to be displayed at or near the original site. The plaque will be formally presented by the ANS President, Donald Hoffman, at a time and place agreeable with you as the site contact person. Please contact Ashley Jiminian to set-up a time and a place for the ANS President to present the plaque.

Recognition of this new landmark will take place during the Honors and Awards President's Special Session at the ANS 2014 winter meeting in Anaheim, California.

Congratulations again on the approval of the High Flux Isotope Reactor as an ANS Nuclear Historic Landmark.

Sincerely,

Steven J. Zinkle

Steven J. Zinkle, Chair
Honors and Awards Committee

Named ANS Nuclear Historic Landmark in FY14

HFIR: 1965–present (and still going strong)

“If at some time a heavenly angel should ask what the Laboratory in the hills of East Tennessee did to enlarge man’s life and make it better, I daresay the production of radioisotopes for scientific research and medical treatment will surely rate as a candidate for first place.”

Alvin Weinberg, ORNL Director (1955–1973)