# The High Flux Isotope Reactor
# Past, Present, and Future

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Following the conclusion of World War II and through the 1950s, nuclear science and engineering enjoyed an extraordinary period of growth and discovery in the United States. A key area of interest was in the heavy transuranium elements. Glenn Seaborg emerged as a leader in this field, winning the 1951 Nobel Prize in Chemistry for "discoveries in the chemistry of the transuranium elements." By 1957, Seaborg saw the need for a high flux reactor to further this field of study. Exerting his considerable influence, he expressed this need in a letter to Lewis Straus, Chairman of the U.S. Atomic Energy Commission (AEC). In this October 1957 letter, he suggested the construction of a “very high flux reactor” to produce weighable quantities of berkelium, californium, and einsteinium. The proposed program would require the irradiation of substantial quantities of $^{239}$Pu in the existing reactors at Savannah River to produce hundred gram amounts of $^{244}$Cm and higher curium isotopes that would be subsequently irradiated in the “very high flux reactor” to produce milligram quantities of berkelium, californium, and einsteinium.

In a meeting on January 17, 1958, the U.S. AEC decided to embark on a transuranium element production program that employed existing reactors. However, by late 1958, it became evident that the “very high flux reactor” suggested by Seaborg a year earlier would be necessary. Following a meeting on November 24, 1958, the U.S. AEC recommended that a high flux reactor be designed, built, and operated at Oak Ridge National Laboratory (ORNL), with construction to start in fiscal year 1961. As a result, ORNL submitted a proposal to build the High Flux Isotope Reactor (HFIR) in March 1959. Authorization to proceed with this project was granted in July 1959. This project included the new Transuranium Processing Plant (TRU) adjacent to HFIR for the processing, storage, and distribution of heavy actinide elements produced at HFIR in support of the U.S. AEC heavy element research program. TRU has since been renamed the Radiochemical Engineering Development Center (REDC).

The HFIR design is based on a “flux trap” concept in which an annular reactor core is arranged around an unfueled and over-moderated region where fast leakage neutrons from the fuel are moderated to produce a very high thermal neutron flux suitable for the production of heavy actinide isotopes. The “flux trap” design was chosen because of its relatively large ratio of peak thermal-neutron flux to reactor power. This characteristic allows production of the desired quantity of heavy isotopes at a reasonable reactor power of 100MW.

HFIR is light water cooled and moderated, and is beryllium reflected. The HFIR core is a cylinder approximately 17 inches in diameter and about 2 feet tall containing approximately 9.4Kg of 93% enriched $^{235}$U in two concentric annular elements. The inner element includes 2.8g of $^{10}$B to flatten the radial flux distribution and extend core life. The fuel elements surround a central 5 inch diameter cylinder that serves as the flux trap where the target isotopes of curium are loaded to produce the heavy actinide elements in an unperturbed thermal neutron flux of $5.5 \times 10^{15}$ neutrons/(cm$^2$·s). Fuel is contained in 0.050 inch thick plates curved in an involute shape to provide a constant coolant channel width. Fuel plates are a sandwich-type construction with a $U_3O_8$-Al cermet clad with 6061 aluminum.

Fuel is graded across each plate to minimize the radial peak-to-average power density ratio. The reactor is controlled by two cylinders that partition the beryllium reflector from the fuel region each containing $Eu_2O_3$ and Ta as neutron absorbers. The inner cylinder provides reactor control, while the outer cylinder serves the safety function. The outer cylinder is divided into four quadrant plates, each on an independent fast insertion mechanism tied to a 2-out-ot-3 coincidence safety system. Insertions of any one of the quadrant plates will effectively shutdown the reactor.

The REDC is designed to work in tandem with HFIR to produce the heavy actinide isotopes. Facilities are provided to remotely form actinide oxides, mostly curium, into pellets and load them into aluminum target rods. Fabrication and inspection of these target rods is performed remotely in a series of shielded cells. Once completed the rods are remotely loaded into a shielded cask for transfer to the HFIR. Following irradiation, the rods are received from HFIR in a similar transfer cask for processing. Processing begins with dissolution of the target followed by several steps to chemically separate, recover, and purify the heavy actinide elements plutonium through fermium. Portions of the plutonium, americium, and curium are recovered and processed for further irradiation in HFIR. The purified berkelium, californium, einsteinium, and fermium is used for in-house research; distributed to other researchers around the world; and distributed to medical and industrial users.

The heart of the REDC is a battery of nine heavily shielded process cells housed in a two-story building. Each cell, with its 54-inch thick wall of high-density concrete, has enough shielding to stop the neutrons and gamma radiation from 1 gram of $^{252}Cf$ and associated fission products. Four cells contain chemical processing equipment for dissolution, solvent extraction, ion exchange, and precipitation. Three contain equipment for the preparation and inspection of HFIR targets and two cells are used for analytical chemistry operations. In addition, there are eight laboratories used for process development, for part of the process-control analyses, and for product finishing operations.

HFIR construction was completed in early 1965 and REDC was completed in 1966. Final HFIR hydraulic and mechanical testing was performed until the first criticality test on August 25, 1965. A low-power testing program began with cycles operated at 20, 40, 75, and 90 MW until the first full power cycle (100MW) was begun in September 1966. All design projections were realized with one pleasant surprise; at 100MW, the fuel cycle was 23 days long or about 40% longer than predicted. Seaborg, having been appointed AEC chairman by President Kennedy, visited ORNL in November 1966 for the dedication of the HFIR/REDC complex. He declared that the exotic experiments made possible by the new High Flux Isotope Reactor would "deepen our comprehension of nature by increasing our understanding of atomic and nuclear structure."

During the first 15 years of HFIR operation, the heavy actinide isotope production mission was dominant. HFIR supported research and development of the heavy actinides, producing quantities of these isotopes for basic research and providing the target materials used in accelerator facilities to discover some of the super-heavy elements and isotopes and then create research quantities for investigating their nuclear and chemical properties. $^{252}Cf$, a neutron emitter, was produced and isolated in usable quantities for the first time at HFIR/REDC allowing the development of a number of practical applications including cancer therapy, neutron radiography, oil exploration, coal analysis, and quality control for civil-structural materials. Production of $^{252}Cf$ peaked in 1981 at 899mg. Though current

production rates are much less, HFIR/REDC remains the only source of this important isotope in the western hemisphere.

Heavy actinide production was not the only mission for HFIR. The HFIR designers having learned and gained insight from the design and operation of eleven predecessor reactors included thirty-eight vertical irradiation sites ranging in diameter from ½ inch to 3 inches and four slant engineering facilities in the beryllium reflector region providing a variety of neutron spectra for isotope production and materials irradiation studies. Also, at the insistence of ORNL Director, Alvin Weinberg, four horizontal neutron beam ports were included in the HFIR reflector to support neutron scattering science which was in its infancy at the time HFIR was designed. Over the first 15 years of HFIR operation while heavy actinide production dominated the flux trap, research and development of lighter industrial and medical isotopes flourished in these facilities. By 1970, one of the target positions in the flux trap had been replaced by a hydraulic rabbit facility that shuttles up to nine 2-inch long, ½-inch diameter capsules primarily for light isotope production and some materials irradiation studies. This facility allows capsules to be irradiated for periods less than a full operating cycle and allows for certain short half-life isotopes to remain in the flux until needed, providing the highest possible specific activity for the research or medical application.

Other, more specialized facilities also began to be added to the HFIR. A Neutron Activation Analysis (NAA) laboratory and associated pneumatic tube was installed in 1970. This pneumatic tube carries samples to vertical experiment facility VXF-7 in the permanent beryllium reflector about 7 inches from the edge of the core placing it in a 2.8 X $10^{14}$ neutrons/(cm²·s) flux with a thermal/epithermal ratio of 40. Later, in 1986 a second NAA pneumatic tube was added to carry samples to one of the slant Engineering Facilities on the periphery of the permanent reflector placing it in a 5.9 X $10^{13}$ neutrons/(cm²·s) flux with a thermal/epithermal ratio of 200. The difference in the flux of these facilities has proved to be complimentary in identifying some trace elements. This facility has recently been enhanced with the addition of a delayed neutron counter (DNC) for fissile nuclide analysis which is especially useful in nuclear forensics studies. The HFIR NAA laboratory has and continues to support a wide variety of sciences including geology, biology, forensics, nuclear forensics, and environmental studies.

As the production of the heavy actinides and other isotopes became routine in the early 1980s, the emphasis for HFIR shifted towards materials and nuclear fuels irradiation studies. Materials studies typically focus on candidate materials for fission and fusion reactors. Also, reactor fuel irradiation studies in HFIR advanced the development of high-temperature gas cooled reactor fuel designs. Since HFIR provides a wide spectrum of neutron energies close to the core, the spectrum for each capsule can be tailored to the desired spectrum by surrounding it with various neutron absorbers such as $Eu_2O_3$ and Hf. $Eu_2O_3$ shields can provide an environment with a fast to epithermal ratio of up to 375. This new emphasis prompted a reactor design change in the 1986 to more easily accommodate instrumented and gas-cooled irradiation capsules in the reflector and the flux trap. The four 1½ inch diameter irradiation facilities located in the reflector directly adjacent to the core were replaced with eight 2 inch diameter facilities. Core internal components and the pressure vessel hatch were modified to all these eight facilities and two target positions in the flux trap to directly accept instrumented and/or gas cooled irradiation capsules. A Materials Irradiation Facility (MIF) was constructed in the HFIR Experiment Room to monitor and control the gas cooling of these capsules. MIF also provided the capability to

automatically reduce reactor power if needed to protect the experiments based on the parameters monitored within the capsule. This feature is credited for experimental data protection only and is not used for reactor safety.

Just as the MIF facility and associated reactor modifications were completed, HFIR was shutdown to review vessel embrittlement concerns and to address reactor operations management concerns in light of the Three Mile Island and Chernobyl events. As a result of vessel embrittlement concerns, the reactor power was de-rated to the current power level of 85MW because of a required reduction in the operating pressure from 750psig to 468psig. The reactor resumed routine operations in May 1989.

By the 1990s, neutron scattering had matured and gained prominence in materials science research through contributions from the HFIR neutrons scattering facilities and other such facilities around the world. Plans to build a second generation HFIR began in response and culminated in the Advanced Neutron Source (ANS) project. By the mid-1990s, ANS had fallen out of favor because of accelerating costs and was canceled by the U. S. Department of Energy. At that time, it became evident that the potential of these HFIR facilities could be greatly enhanced by improving the design of the beam tubes, installing state of the art neutron scattering instruments, and the addition of a cold neutron source in one of the beam tubes. This was made possible by an extensive probabilistic facture mechanics study of the HFIR vessel that concluded that the reactor vessel can support continued HFIR operation through approximately the year 2040. Again, major reactor internal components including the Permanent Reflector and its support structure were redesigned and fabricated along with new beam tubes and vessel flanges. Complimenting these changes were upgrades to the neutron scattering instruments used by the scientists to perform their experiments. The majority of these changes were incorporated during a routine Permanent Reflector replacement outage in 2001. Following the outage, the thermal neutron scattering instruments were found to have a 300% gain in flux-on-target placing them among the world's best. Additionally, the upgrades had provided larger beams that support more neutron scattering instruments. The cold neutron source became available in 2007 and was measured to be the brightest in the world. The cold neutron source supports four super-mirror neutron guides. Currently, two Small Angle Neutron Scattering (SANS) instruments are operating while new instruments are being built out on the other two guides. The HFIR steady-state neutron scattering instruments are provided in tandem with the complimentary pulsed neutron scattering instruments at the new Spallation Neutron Source (SNS) located at ORNL in a robust and growing user program serving a wide variety of scientific inquiry.

HFIR is now positioned as one of the most versatile research reactors in the world providing unique heavy actinide other isotope production capabilities, instrumented and non-instrumented materials irradiation facilities, and world-class neutron scattering facilities. Although the plant infrastructure is 43 years old, routine maintenance and equipment replacement has positioned the facility so that it can operate reliably through at least 2040. However, no facility can be expected to operate indefinitely. In many cases, the capabilities of HFIR are unique and cannot be duplicated elsewhere. The science community should begin to look forward and plan the next generation of reactors that can supplement or replace the capabilities provided by HFIR. So what's next? Long-range planning of the next generation of research reactors should be taking place now so they will be ready to begin operating as

the current reactors near the end of their life. This process will involve years of planning and construction in order to accomplish a smooth transition.

HFIR has certainly realized Glenn Seaborg's vision and has done much more to advance a breadth of scientific inquiry. Fifty years later, it remains as one of the best and most versatile research reactor facilities in the world; the culmination of the ORNL reactor development efforts in the 1950s and 1960s. However, its contribution in the understanding and use of heavy actinide isotopes and other lighter isotopes is its crowning achievement. Perhaps Alvin Weinberg characterized it best as he reflected on his time directing ORNL: "If at some time a heavenly angel should ask what the laboratory in 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 the very first place."

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