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Proposed Fuel Pin Irradiation Facilities for the High Flux Isotope Reactor

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Abstract – *The Global Nuclear Energy Partnership (GNEP) is proposing to develop a sodium-cooled fast-spectrum reactor (SFR) to transmute and consume actinides from spent nuclear fuel. The proposed fuels include metal and oxide forms mixed actinides (U-Np-Pu-Am-Cm) as well as target concepts with perhaps both Am-Cm. The High Flux Isotope Reactor (HFIR) was built for the purpose of transmuting plutonium to various higher actinides including Am, Cm, and Cf. Since a fast-spectrum irradiation facility does not exist in the United States, HFIR can fulfill a first step in the GNEP— mission that being to establish a near-term domestic capability to irradiate materials in a fast neutron spectrum. Modifications to the HFIR central target region to accomplish this goal are described. A second ongoing project for HFIR is to design capsules and installation tools and procedures to irradiate short rods of innovative nuclear fuel types and cladding materials under prototypic light water reactor (LWR) operating conditions at an accelerated rate relative to expected reactor performance. This second proposal would be for a facility representative of thermal reactor conditions rather than the GNEP concept. In order to maintain power densities within the fuel at levels normally seen by LWR reactors, an entirely new experiment and test capsule design will be needed.*

I. INTRODUCTION

The Global Nuclear Energy Partnership (GNEP) is proposing to develop a sodium-cooled fast-spectrum reactor (SFR) to transmute and consume actinides from spent nuclear fuel. The proposed fuels include metal and oxide mixed actinides (U-Np-Pu-Am-Cm) as well as target concepts with perhaps only Am-Cm. These concepts require the development of new and advanced fuels and targets that meet the performance objectives and with fuel types and compositions that need further development. A significant part of the development process is the irradiation of the fuel and cladding system in a prototypic reactor environment to determine the performance of the fuels and cladding under irradiation. A fast-spectrum irradiation facility does not exist in the United States, and there is a strong desire to establish a near-term domestic capability to irradiate materials in a fast neutron spectrum. A complementary effort to utilize international facilities through partnering arrangements is also being pursued by DOE.

Less ambitious but still needed is a facility for the irradiation of advanced light water reactor (LWR) fuel pins. Such a facility allows for the testing of advanced pin designs before committing to an irradiation in a commercial power reactor. It is envisioned that the establishment of a closed fuel cycle could result in the introduction of new fuel pin designs and/or fuel management strategies in existing reactors while also providing the capability for independent testing of fuel designs for licensed-but-not-yet-built next-generation LWRs.

II. BRIEF DESCRIPTION OF THE HIGH FLUX ISOTOPE REACTOR (HFIR)

The HFIR (Figure 1) is a pressurized, light-water-cooled and -moderated, flux-trap-type reactor that currently uses U_3O_8-dispersed-in-aluminum, highly enriched uranium (HEU) fuel and operates at 85 MWth. The reactor core (Figure 2) consists of two annular fuel elements, each approximately 61 cm high (fueled height is 51 cm).[1] At the center of the core is a 12.70-cm-diameter, cylindrical hole, referred to as the "flux trap target" region, which contains 37 vertical, experimental target rod sites.

The HFIR fuel elements, surrounding the flux trap, consist of 1.27-mm-thick fuel plates having an involute-shape in the radial direction. The fuel elements are separated by a 1.27-mm water gap. The inner element

contains 171 involute-shape fuel plates, and the outer element contains 369 involute-shape fuel plates, as detailed in Figure 2. The fuel plates are a sandwich-type construction with a fuel-bearing cermet and aluminum filler bonded to a cladding of type-6061 aluminum. The HEU oxide is distributed (graded) along the arc of the involute aluminum plate. At the start of each fuel cycle, fresh inner and outer elements are loaded so there are no fuel management issues as in other reactors.

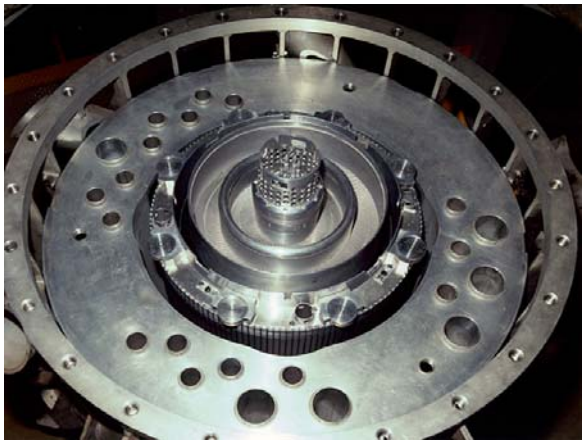

Figure 1. Configuration of HFIR core and reflector

Figure 2. The core of HFIR, showing the inner (IFE) and outer (OFE) fuel elements

Control plates, in the form of two thin (approximately 1.3 cm), europium/tantalum-bearing concentric cylinders, are located in an annular region between the outer fuel element and the beryllium (Be) reflector. These plates are driven in opposite directions and significantly impact the power density at the outside edge of the outer element.

The control plates and fuel elements are surrounded by a concentric ring of beryllium that serves as a reflector and is approximately 30 cm thick. This Be reflector is subdivided into three regions: the inner removable reflector, the middle semi-permanent reflector, and then the outer permanent reflector. The Be reflector is surrounded by light water and a steel pressure vessel. In the axial direction, the reactor is reflected by light water.

Nominally, there are eight fuel cycles in a calendar year (eight reloads, 26 day cycle length). Maintaining fresh fuel inventory requires the manufacturing of over 4000 fuel plates per year. The lifetime of the reactor is limited by fluence to the pressure vessel, but with the current vessel and at the current power level and availability factor, the reactor is expected to operate for another 30 years.

II.A HFIR Experimental Facilities

HFIR has a number of facilities designated for materials irradiation experiments and isotope production, as shown in Figure 3. All of these locations extend the full length of the reactor core.

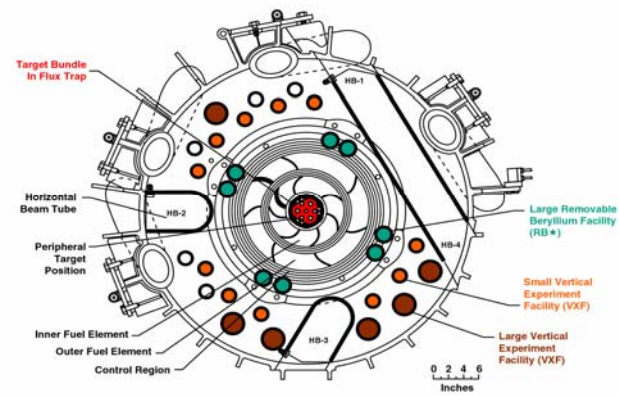

Figure 3. HFIR experimental locations

The central flux trap, or target basket, is filled with 28−30 target pins (depending on whether one or three hydraulic tubes are present in the reactor). Target capsule experiments typically have an outer diameter of about 1.27 cm. Most of these positions are not instrument capable and rely on passive temperature measurement. However, the three hydraulic tube positions can be alternately fitted with an experimental assembly with instrument capability and active gas flow. There is a nominal 241 kPa (35 psi) pressure drop providing coolant flow to target region experiments.

Outside the outer fuel element (OFE) in the semi-permanent reflector, there are eight positions designated RB*. These experimental locations have an outer diameter of 5.07 cm and are commonly used for fully instrumented and temperature-controlled experiments.

In the outer permanent reflector region, there are several experimental sites designated "vertical experiment facility" (VXF). There are six large VXF sites, each with a diameter of 7.20 cm, and 16 small VXF sites, with a diameter of 4.02 cm. The small VXF sites are further divided into inner and outer locations, depending on their radial distance from the reactor centerline. All of the VXF sites are capable of holding fully instrumented experiments with active temperature control. There is a 690 kPa (100 psi) pressure drop across the permanent reflector.

III. GNEP FAST−REACTOR IRRADIATON TARGET

HFIR has a distinct advantage for consideration as an irradiation facility because of the extremely high neutron fluxes that this reactor provides over the full thermal-to-fast neutron energy range. As described below, an assessment of the use of the available irradiation positions in HFIR was performed, and it was decided to use the central flux trap target region that is typically used for the irradiation of curium targets and other materials. The fast flux (>0.1 MeV) in this region exceeds 10^{15} n/cm^2·s. The combination of this high fast flux and the use of a highly absorbing europium oxide (Eu_2O_3) liner to eliminate thermal neutrons provides an irradiation environment that closely approximates that of a fast reactor. Primary benefits of this approach are that the shielding technology is already developed and additional fast-flux boosting fuel plates or pins are not required.

III.A. Thermal-neutron Shield

While the target region of HFIR has a fast flux in the realm of fast reactors (>10^{15} n/cm^2·s), the thermal flux is also a very large $2{\cdot}10^{15}$ n/cm^2·s. Over many years, the fusion materials program has sponsored the development of an Eu_2O_3 thermal-neutron shield at Oak Ridge National Laboratory. This shield has been successfully used several times in fusion materials experiments to control the rate of thermal-neutron-induced helium production in various materials and to minimize transmutation rates.

Current fabrication techniques call for the Eu_2O_3 to be thermally sprayed onto a stainless steel substrate. The process starts with a 100% stainless steel spray that transitions to 100% Eu_2O_3 over about 0.2 mm. Figure 4 shows a test piece fabricated with this method.

This shield technology has a dramatic effect on the neutron spectrum. Figure 5 shows a comparison between the normal neutron spectrum in the flux trap of HFIR and the spectrum inside a 3 mm thick Eu_2O_3 shield.

III.B. Fast-spectrum Design

Several design options were considered for the central flux trap region: a shielded single-pin design that fits into a flux trap target location, a somewhat larger single-pin design that provides for additional coolant flow, and a tri-pin design (shown in Figure 6 and the placement in the central target region in Figure 7) that occupies seven target locations (a “septa-foil” design) and provides an increased irradiation volume. The tri-pin assembly design (occupying seven target locations) provides flexibility, a fast-reactor irradiation environment, and supports multiple irradiation targets providing a sizable irradiation volume and is the current preferred design. Performance parameters were computed for all three design options, but only those of the tri-pin, europia-shielded flux trap target are included in this report. The parameters for the other configurations are similar.

Figure 4. Thermally sprayed Eu_2O_3 thermal neutron shield

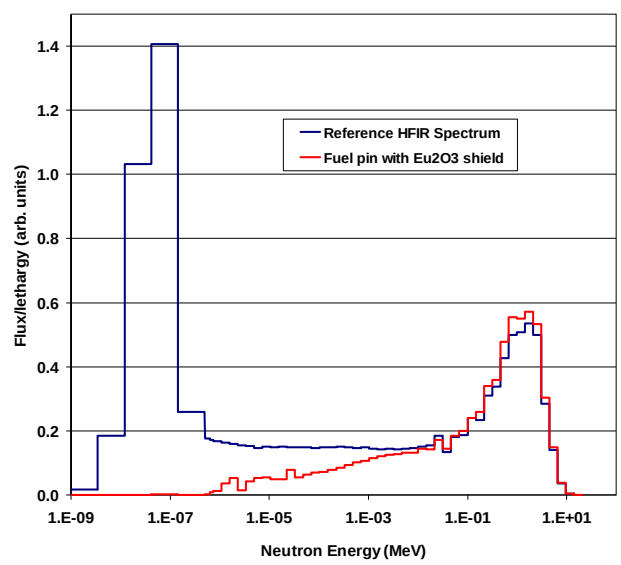

Figure 5. Neutron spectrum comparison with and without a thermal neutron shield in the flux trap of HFIR

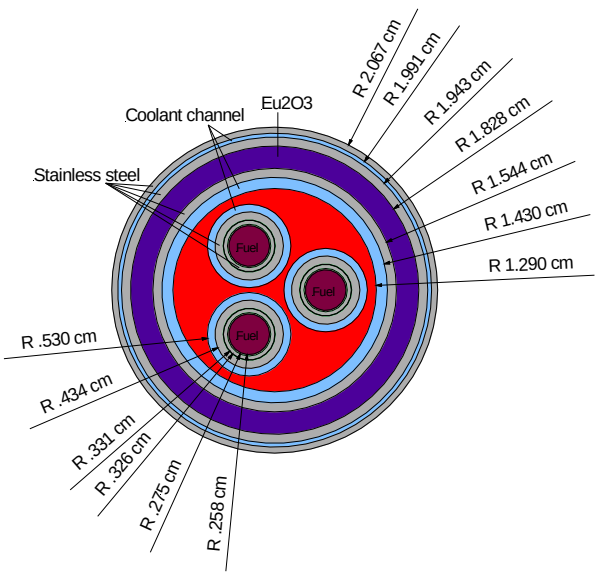

Figure 6. Septa-foil GNEP fast-reactor irradiation design

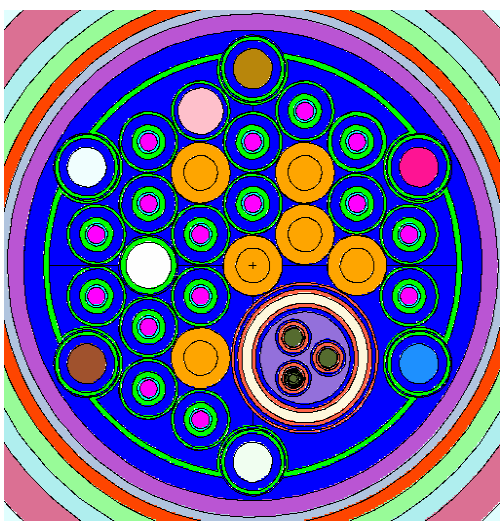

Figure 7. Placement of septa-foil capsule in HFIR central target

The key design features of this target design are that (1) it is sized to fit within the irradiation volume available when seven existing target sites are vacated, and (2) the thickness of the (Eu_2O_3) liner was chosen to match the desired performance characteristics (linear heat generation rate, fast/thermal ratio, etc.) as closely as possible.

Within the europia liner the amount of coolant was limited to preserve the low thermal-neutron-flux level that can be obtained with the strongly absorbing liner yet provide adequate coolant flow to maintain experiment temperatures. The liner has coolant channels both inside and out, and each fuel rod/capsule has its own annular coolant channel.

Performance characteristics of this target were calculated using the MCNP Monte Carlo Code[2] based on the ORNL reference HFIR model.[3] The calculations were performed to determine the key performance parameters that were requested, including linear heat generation rate, neutron flux, fast-to-thermal neutron flux ratio, displacements per atom (DPA), helium production, etc. The specific results along with the proposed requirements are provided in Table I. Note that annual fluence, burnup, DPA, etc., are conservatively based on seven cycles per year, rather than the nominal eight cycles. A GNEP-type fast reactor fuel with a stainless steel clad was assumed for all estimates.

TABLE I
HFIR irradiation parameters for proposed tri-pin concept.

Parameter	HFIR Value
Fast (> 0.1 MeV) neutron flux in irradiation volume	1.2×10^{15} n/cm^2·sec
Annual* fast (> 0.1 MeV) neutron fluence at peak irradiation position	1.6×10^{22} n/cm^2
Annual* fuel burnup	5.9% burnup
Annual* clad DPA	19.5 DPA
Fuel burnup–to–clad DPA ratio at peak irradiation position	0.3 atom % per DPA
Fast (>0.1 MeV) to thermal (<0.625 eV) flux ratio	400
helium–to–DPA ratio in iron at peak irradiation position	0.2 appm helium per DPA
Linear heat rate (variable depending upon design of Eu_2O_3 shield)	300 W/cm

**Annual estimates are conservatively based on seven cycles per year. HFIR plans on a nominal eight cycles per year.*

A thermal analysis was conducted, in part, using the ANSYS finite element code.[4] As shown in Figure 8, peak centerline fuel temperatures of <2000ºC are estimated using a helium fill gas in the fuel/clad and clad/capsule gaps. The coolant channels are sized to provide a ~20ºC temperature rise in the coolant through the entire experiment.

It is anticipated that temperature control will be possible by actively controlling a helium/neon mixture in the clad/capsule gap. Design work is currently under way

to assess the temperature control range through this necessarily small gap.

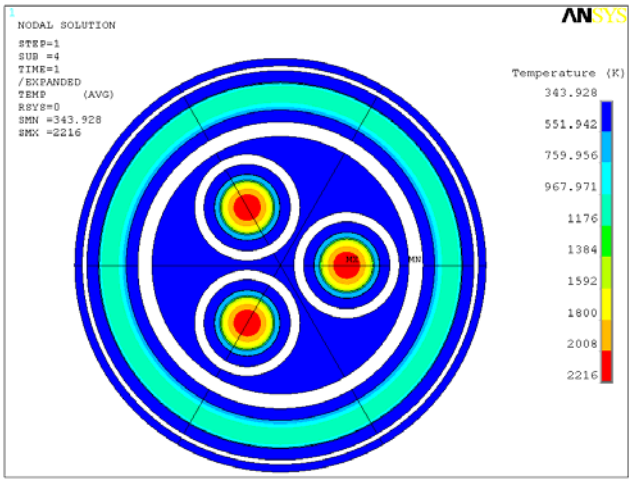

Figure 8. Temperature (K) plot of fast-spectrum fuel in the flux trap of HFIR

Limited analysis was performed to assess the impact on the reactor operation. One concern is the potential reduction in fuel cycle length owing to reactivity loads. Based on the MCNP calculations, the reactivity worth of the tri-pin design is comparable to the use of two Eu_2O_3 shielded experiments in the RB position. Therefore the impact on this key parameter is not outside of current experience. Additional analysis, per the standard irradiation experiment procedure, would need to be performed before actual insertion of the experiment in the reactor.

IV. RECENT HFIR IRRADIATION DESIGNS RELEVANT TO GNEP FACILITY

During 2004, ORNL staff designed a special irradiation capsule holder that occupied three of the target rod positions shown in Figure 7. These capsules, designated METS, require the use of a special trefoil holder because of size and coolant water requirements. The trefoil holder occupies three adjacent target rod positions and functions as an outer coolant shroud for directing reactor coolant flow past the METS capsule. The trefoil target holder is constructed from extruded aluminum stock that has been machined externally to provide the geometry needed to fit into three adjacent target locations and machined internally to provide the required space and coolant flow for the METS capsule. Special adapter plates that allow access to the three adjacent target positions while supporting the surrounding targets and a handling tool have been fabricated to allow installation/removal of the trefoil holder in the target basket. A hole has been drilled in the top of the adapter plate to provide a visual reference for locating the alignment pin that fits into the center alignment slot on the target bundle. The METS capsule is inserted and removed from the trefoil holder using the target rod picker tool. When properly seated, the top of the capsule is the same elevation as the top of all the other targets. The METS capsule trefoil holder is shown in Figures 9 and 10.

Figure 9. Trefoil holder (bottom)

Figure 10. Trefoil holder (top)

V. ADVANCED LWR IRRADIATION TARGET

This project is focused on advanced fuel/cladding experimental capabilities in HFIR and its capability to duplicate commercial LWR operating conditions. With a core power density approximately 30 times greater than commercial power reactors, HFIR has the ability to significantly shorten the test program irradiation period by controlling the level of thermal neutron flux at the experiment using various shielding designs over the lifetime of the experiment. The goal of this design is to maintain a relatively constant linear heat rate through many cycles. This requires "letting more neutrons in" as the fuel burns out – time-dependent neutron shielding.

Capsules containing fuel rods in the LWR facility will be arranged in a configuration shown in Figure 11. Each fuel rod, containing 11 fuel pellets, will be housed inside a stainless steel capsule, as shown in Figure 12. There will be three fuel channels in the basket, and each coolant channel will hold a stack of three capsules, for a total of nine capsules per HFIR experiment position.

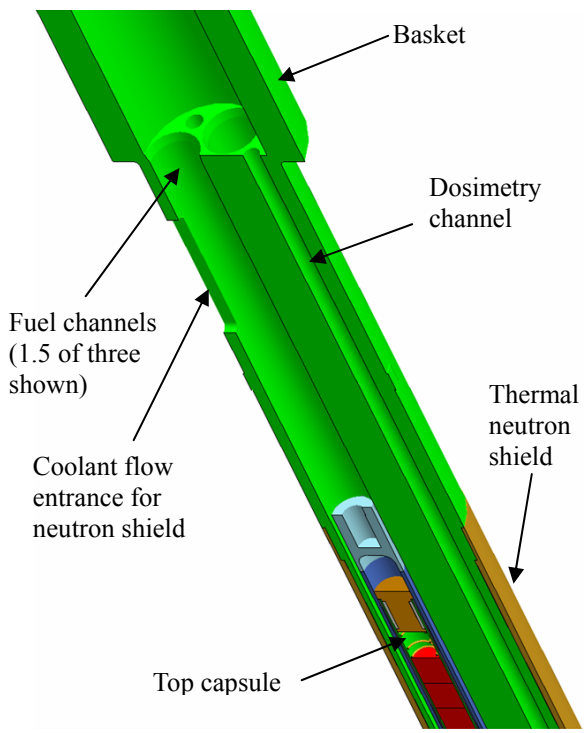

Figure 11. LWR fuel irradiation target schematic

The experiment will be located in the permanent Be reflector in one of the VXF positions (Figure 3). Initial irradiations will be in an outer small VXF, which allows for a step-increase in the neutron flux by migrating the capsule from an outer small VXF position to an inner small VXF. A step-increase can also be imposed by replacing the shield with one of a different material or thickness.

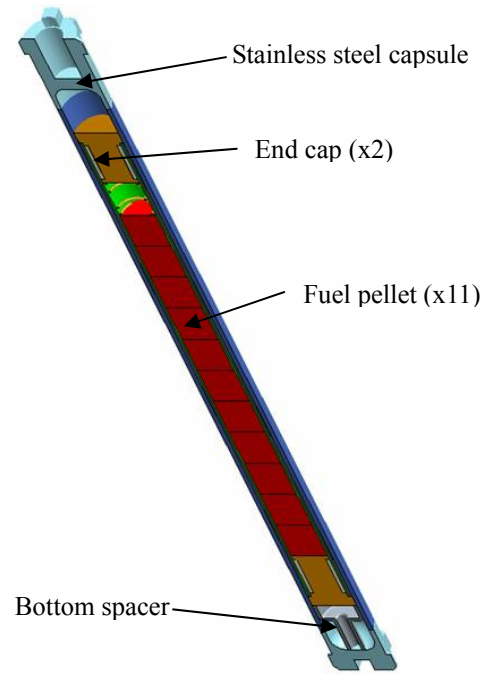

Figure 12. Portion of LWR-typical fuel rod to be loaded to capsule similar to Figure 6

However, design calculations indicate that a 1.61 mm thick hafnium shield degrades at a rate similar to the burnup of 3.8% enriched UO_2 fuel, so that the linear heat generation rate of the fuel stays relatively constant, at least over the first few cycles. With this configuration and shield thickness, linear power ratings average 22 kW/m for the upper and lower capsules and 32 kW/m in the middle capsule.

Although the VXF experiment locations are capable of fully instrumented and temperature-controlled experiments, the current design opts for simplicity. The experiment temperature will be set in the beginning by designing the thickness of the helium gap between the clad and the capsule. As shown in Figure 13, initial temperature calculations indicate that the peak centerline UO_2 temperature is less than 1500ºC.

All the coolant flow for the experiment enters through the top head of the experiment (Figure 11). The gap between the outer shield surface and the VXF permanent liner controls the volume of coolant flow that gets diverted to the outside of the shield. The remaining flow is split between the three fuel channels and the three dosimetry channels. The flow volume is controlled with an orifice that is located at the bottom exit of the experiment. In this way, nominal coolant flows of about 7.5 m/s are achieved

through all coolant channels. The coolant temperature increases about 10ºC through the experiment.

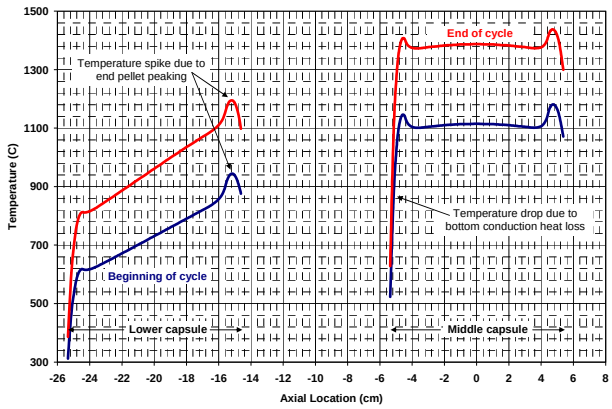

Figure 13. Temperature profile for the lower and middle capsules containing UO_2 fuel. Note that the upper capsule is symmetric with the lower capsule.

Two key advantages of this design are that (1) all capsules lock together in the basket using the tabs and slots shown in the capsule end caps in Figure 12, and (2) the central counterbore in the upper capsule end cap is threaded so that individual capsules can be removed, replaced, or shuffled between cycles. This gives the experimenter a high degree of control over the burnup rate of individual fuel rods.

Future work will be to qualify, install, and test the capability to irradiate short rods of innovative nuclear fuel types and cladding materials under prototypic LWR operating conditions. In order to maintain power densities within the fuel at levels normally seen by LWR reactors, an entirely new experiment and test capsule design will be needed than has been available in the past. This design will incorporate appropriate neutron attenuation shields around the experiment. These shields will allow the power density within the fuel to remain relatively constant over the experiment lifetime. Without this capability, the power density within the test modules would decline significantly over the life of the experiment.

VI. CONCLUSIONS

Two concepts have been developed to provide advanced fuel-clad testing capabilities in the HFIR reactor facility: (1) a thermal fuel testing facility located in the permanent reflector and (2) a fast-spectrum facility located in the flux trap to support fast-reactor fuel irradiations, specifically for the GNEP program. Both designs can provide a near-term capability with no reactor modifications required. The design of the thermal fuel testing facility is nearly complete, and fabrication is ongoing. The fast-spectrum facility is currently in the conceptual design phase.

VII. REFERENCES

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