INL/EXT-14-31700

# Strategy for Fuel Rod Receipt, Characterization, Sample Allocation for the Demonstration Sister Rods

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Idaho National Laboratory

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**Revision 0**
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**Peer Review:**

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# SUMMARY

This report fulfills the M2 milestone, M2FT-14IN0802013 Strategy for Fuel Rod Receipt, Characterization, Sample Allocation for the Demonstration Sister Rods, under Work Package Number FT-14IN080202.

The U.S. Department of Energy Office of Nuclear Energy (DOE-NE), Office of Fuel Cycle Technology, has established the Used Fuel Disposition Campaign (UFDC) to conduct the research and development activities related to storage, transportation, and disposal of used nuclear fuel and high-level radioactive waste. The mission of the UFDC is to identify alternatives and conduct scientific research and technology development to enable storage, transportation and disposal of used nuclear fuel (UNF) and wastes generated by existing and future nuclear fuel cycles. The UFDC Storage and Transportation staffs are responsible for addressing issues regarding the extended or long-term storage of UNF and its subsequent transportation. The near-term objectives of the Storage and Transportation task are to use a science-based approach to develop the technical bases to support the continued safe and secure storage of UNF for extended periods, subsequent retrieval, and transportation.

While low burnup fuel [that characterized as having a burnup of less than 45 gigawatt days per metric tonne uranium (GWD/MTU)] has been stored for nearly three decades, the storage of high burnup (HBU) used fuels[a] is more recent. The DOE has funded a demonstration project to confirm the behavior of used high burnup fuel under prototypic conditions. The Electric Power Research Institute (EPRI) is leading a project team[b] to develop and implement the Test Plan to collect this data from a UNF dry storage system containing high burnup fuel. The Test Plan for the demonstration outlines the data to be collected; the high burnup fuel to be included; and the storage system design, procedures, and licensing necessary to implement the Test Plan. To provide data that is most relevant to high burnup fuel in dry storage, the design of the test storage system must closely mimic real conditions high burnup UNF experiences during all stages of dry storage: loading, cask drying, inert gas backfilling, and transfer to an Independent Spent Fuel Storage Installation (ISFSI) for multi-year storage.

To document the initial condition of the used fuel prior to emplacement in a storage system, "sister"[c] fuel rods will be harvested and sent to a national laboratory for characterization and archival purposes. This report supports the demonstration by describing how sister rods will be shipped and received at a national laboratory, and recommending basic nondestructive and destructive analyses to assure the fuel rods are adequately characterized for UFDC work. For this report, a hub-and-spoke model is proposed, with one location serving as the hub for fuel rod receipt and characterization. In this model, fuel and/or clad would be sent to other locations when capabilities at the hub were inadequate or nonexistent. This model has been proposed to reduce DOE-NE's obligation for waste cleanup, decontamination of equipment and/or facilities.

[a] "High burnup" fuel has a burnup level at or above approximately 45 gigawatt-days per metric ton of uranium (GWD/MTU).

[b] The EPRI team includes AREVA Federal Services, AREVA-TN, Dominion Virginia Power, AREVA Fuels, and Westinghouse Fuels.

[c] A "Sister" fuel rod is one that has characteristics representative of another fuel rod that will be included in, and examined following completion, of the demonstration.

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# ACRONYMS

| | |
|---|---|
| AL | Analytical Laboratory |
| ANL | Argonne National Laboratory |
| BWR | Boiling water reactor |
| EBSD | Electron backscatter diffraction |
| EDS | Energy dispersive spectrometry |
| EPMA | Electron probe micro-analyzer |
| EPRI | Electric Power Research Institute |
| HBU | High Burnup |
| HFEF | Hot Fuels Examination Facility |
| INL | Idaho National Laboratory |
| ISFSI | Independent Spent Fuel Storage Installation |
| MFC | Materials and Fuels Complex |
| NAC-LWT | NAC International, Inc. Legal Weight Truck (shipping cask) |
| NRC | Nuclear Regulatory Commission |
| ORNL | Oak Ridge National Laboratory |
| PNNL | Pacific Northwest National Laboratory |
| PWR | pressurized water reactor |
| SET | separate effects test |
| SSC | Structures, Systems, and Components |
| SST | small-scale test |
| TN | (old) TransNuclear, Inc. (now AREVA-TN) |
| TN-FSV | TransNuclear, Inc. Fort St. Vrain shipping cask |
| UFDC | used fuel disposition campaign |
| UNF | used nuclear fuel |
| VEM/EC | visual examination machine/eddy current |
| WDS | Wavelength dispersive spectroscopy |

# REGISTRATIONS AND TRADEMARKS

| | |
|---|---|
| M5® | A trademark of AREVA NP registered in the USA and in other countries. |
| Ectane™ | A registered trademark of Eddyfi, Inc. in the USA and other countries. |
| Inconel™ | A registered trademark of Special Metals Corporation |
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| Zirlo™ | A registered trademark of Westinghouse Electric Company LLC in the USA and other countries. |

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# 1. INTRODUCTION

Low burnup fuel [that characterized as having a burnup of less than 45 gigawatt days per metric tonne uranium (GWD/MTU)] has been stored in dry storage systems for nearly three decades. High burnup (HBU) used fuels[4] have only begun to be placed in dry storage in the past decade or so. As of December 2012, approximately 200 dry storage casks have been loaded with at least some HBU used nuclear fuel (UNF). Furthermore, almost all UNF being loaded in the U.S. is now high burnup. Since HBU UNF has different mechanical properties than lower burnup UNF, industry needs additional data on HBU UNF under typical conditions. The DOE has funded a demonstration project to confirm the behavior of HBU UNF under prototypic conditions.[1] The Electric Power Research Institute (EPRI) is leading a project team[5] to develop and implement the Test Plan to collect this data from a UNF dry storage system containing HBU fuel. The Test Plan for the demonstration outlines the data to be collected; the HBU UNF to be included, and the storage system design, procedures, and licensing necessary to implement the Test Plan.

## 1.1 Fuel for the Demonstration

To provide data that is most relevant to high burnup fuel in dry storage, the design of the test storage system must closely mimic real conditions HBU UNF experiences during all stages of dry storage: loading, cask drying, inert gas backfilling, and transfer to an Independent Spent Fuel Storage Installation (ISFSI) for multi-year storage.

A TN-32B bolted lid cask will be loaded with intact, HBU UNF assemblies with four different kinds of cladding at Dominion Virginia Power's North Anna Power Station (North Anna). Those fuels are listed in Table 1.1.1

| Cladding Material | Burnup Range (GWD/MTU) | Number of Assemblies Available | Year of Last Irradiation | Fuel Manufacturer | Assembly Type |
|---|---|---|---|---|---|
| Standard and Low-Tin Zircaloy-4 | 53-58 | 3 | 1989 | Westinghouse | Lo-Par |
| Zirlo™ | 51-55 | 20 | 2004-2007 | Westinghouse | V5H |
| M5® | 52-67 | 11 | 2001-2010 | AREVA | AMBW |
| Low-Tin Zircaloy-4 | 49-50 | 3 | 1994 | Westinghouse | V5H |

Table 1.1.1 Fuel types available for the high burnup demonstration. All these fuels are presently stored in the North Anna Spent Fuel Pool.

The selection of which assemblies go into the TN-32B cask is not resolved. Based on the fact that some of the fuel assemblies have been recently discharged, there is the possibility that some low burnup fuel may be needed to ensure the cask thermal limit is not exceeded. It is known the EPRI team desires to place two "standard" Zircaloy-4 clad assemblies with burnup of

4 "High burnup" fuel has a burnup level at or above approximately 45 gigawatt-days per metric ton of uranium (GWD/MTU).

5 The EPRI team includes AREVA Federal Services, AREVA-TN, Dominion Virginia Power, AREVA Fuels, and Westinghouse Fuels.

approximately 58 GWD/MTU in the storage cask. Similarly, the team desires to include at least one additional "low-tin" Zircaloy-4 clad assembly in the storage cask.

Of the remaining fuel assemblies, not all will be used for the demonstration. Design analyses (i.e. thermal modeling) will be performed to include most of the assemblies. Criticality and shielding analyses also need to be performed to find the optimal loading pattern. The final design, including fuel selection and placement, is not part of the EPRI Test Plan.

## 1.2 Sister Rods

The main purpose of the high burnup demonstration is to evaluate the effect of long-term storage on the mechanical properties of HBU UNF. This requires knowing the properties of the fuel as it would be placed in a storage cask/canister and comparing those properties to fuel that has been dried and then stored in a cask/canister for a long period of time.[1] Fuel characterization involves destructive examination of the fuel (e.g. gas analysis, microscopy, analytical chemistry, mechanical testing). These destructive examinations impose the requirement for similar fuel rods for these pre- and post-test examinations. These "sister rods" must have similar characteristics (i.e. same fuel design and clad, similar in-core operating histories, same cooling times, etc.) as rods to be placed in the TN-32B Research Project Cask that will be used in the demonstration. It should be noted that sister rods need not come from the same assembly, a fuel rod with similar characteristics (e.g., irradiation history, enrichment, clad type, etc.) from a different assembly may be determined to be an appropriate "sister" for another fuel rod. It is expected that some sister rods will, by necessity, come from fuel assemblies that will not be used in the demonstration.

Due to limitations in the fuel design for the "standard" Zircaloy-4 clad assemblies (no removable top nozzle which prevents rod removal), sister rods will come from the Low-Tin Zircaloy-4 clad assemblies, the M5® clad assemblies, and the Zirlo™ clad assemblies, including from those assemblies that might not go in the TN-32B cask.[1]

Because the decision regarding which specific assemblies will be used in the demonstration has not been made, the actual sister rods cannot be selected. This is planned to be resolved prior to the end of FY 2014. There are some important factors that can be discussed. The EPRI team intends to select and ship the sister rods to a laboratory for examination between one and two years ahead of the TN-32B loading. In general, spent fuel pool water chemistry is tightly controlled, but if there is an upset in chemistry during the time following the shipment of the sister rods, there is a chance the rods remaining in the pool could have different surface characteristics than the sister rods. Also, to ship the sister rods, the rods must be loaded into a transportation cask and vacuum dried. The drying process for a transportation cask and a large storage cask are different, and the thermal profile of the TN-32B will only be known once the cask is loaded and dried (up to two years after the sister rods are shipped). To reduce the chance for alteration of the sister rod fuel clad during drying and transportation, thermal calculations are being performed to determine if a transport cask can be dried at low temperature. The desire is to preserve the sister rods mechanical condition in the "as-stored" condition while in the spent fuel pool. Any thermal treatments of the clad to investigate property changes due to drying (i.e. clad hydride reorientation) can be performed "in the laboratory" under controlled conditions.

As discussed earlier, there are two potential fuel assembly sources for sister rods

- Assemblies that are going to be placed in the TN-32B, or
- Assemblies having similar operating histories (symmetric partners) to those assemblies that are selected for placement in the TN-32B

Sister rods can be removed from an actual fuel assembly planned for storage. The void in the assembly where the removed rod existed can be filled with a solid, non-fuel rod. Sister rods from the same fuel assembly planned for storage are ideal in that they truly share the same power and operating history. The sister rods will be removed prior to loading the TN-32B Research Project Cask. The minor amount of decay heat removed with the sister rods should have a negligible effect on the overall decay heat of the individual assemblies.[1] This must be confirmed by thermal modeling, but it is expected the behavior of the rods in the TN-32B cask would not be altered.

Symmetric partner assemblies have burnup characteristics that are nearly the same (i.e., there may be minor differences in relative power between the symmetric partners) and operating histories would be similar. Typically, symmetric partner assemblies come from the same reload batch of fuel assemblies fabricated for use in the reactor. Therefore, rods from an assembly that is a symmetric partner to a fuel assembly planned for storage in the TN-32B cask should provide good references for the fuel rods in the stored assembly.

In some instances no sister rod donor assembly exists. It is likely that some of the highest burnup fuel assembly storage candidates were used as center assemblies. Center assemblies are those assemblies located in the single center location in the reactor core, and have no symmetric partner donor assemblies to provide sister rods. Some of the high burnup assemblies were lead-test assemblies and may have been used in the center location of the core to drive the burnup to very high levels (i.e., beyond their normal design limit) for subsequent post-irradiation examinations.

The number of sister rods to be shipped to a lab will be influenced by several factors. For a complete characterization campaign, at least one fuel rod is needed per cladding type, preferably two or three if for any reason one or more characteristics need some level of statistical basis behind the results. If there are operational and handling variations within a cladding subset, then additional fuel rods should be obtained to bracket those variables.[1] Additional fuel may be desired to facilitate additional testing by the Used Fuel Disposition Campaign (UFDC). The upper limit on the number of fuel rods that can be shipped is 25. This is the limit for the fuel rod canister in the NAC International, Inc. Legal Weight Truck (NAC-LWT) transport cask (the only transport cask available at this time). For the purposes of this report, it will be assumed the fuel rods are to be transported to Idaho National Laboratory (INL) where the quantity and mass of heavy metal represented by 25 fuel rods can be accommodated within the current agreement between the DOE and the State of Idaho.

# 2. FUEL SHIPMENT TO INL

## 2.1 NAC-LWT

The EPRI team will utilize the NAC International, Inc. (NAC) Legal Weight Truck (LWT) transport cask for shipping sister fuel rods from Dominion's North Anna Power Station to the INL for post-irradiation examination and testing. The NAC-LWT is a steel-encased, lead-shielded Legal Weight Truck transportation cask. The cask is authorized for transporting several types of UNF, including one pressurized waste reactor (PWR) or two boiling water reactor (BWR) assemblies. Full assemblies of UNF are not presently allowed for shipping in this cask due to the potential for a high heat load involving short cooled fuel (e.g. fuel that has been recently discharged with little cooling such that the heat load would be >2.3 kW). However, up to 25 rods of PWR or BWR HBU UNF can be shipped with a burnup up to 80 GWD/MTU and cooling times as short as 150 days (keeping under the 2.3 kW for PWR or 2.1 kW for BWR fuels). A special 25-rod canister is used for this purpose. This canister will accommodate fuel rods up to 165 inches (419 cm) in length.[2] For the purposes of this report, it will be assumed the fuel rods are to be transported to INL.

The selected fuel rods will be placed in a 25-rod canister provided by NAC. The canister will be sent to Dominion's North Anna Power Station for use in their spent fuel pool prior to any fuel movements. Once in the spent fuel pool, the fuel vendors can load their designated sister fuel rods into locations in the 25-rod canister. Records will be kept by Dominion to ensure the location of each fuel rod is known.

Once the 25-rod canister is loaded, and once the fuel shipment window is reached, NAC will send a LWT cask to North Anna for loading, drying, and transport. The cask will be placed inside the spent fuel pool, and the canister containing the fuel rods will be loaded into the cask. The inner lid will be placed in the cask while underwater. The cask will then be removed from the water and set next to the spent fuel pool where the bolts can be placed in the lid and tightened followed by water removal. The cask is then backfilled with helium and vacuum-dried. Passage of the pressure rebound test indicates the outer lid can be placed on the cask and the cask prepared for transport (i.e. leak check, decontamination, loading into the ISO-container, loaded onto a trailer for transport). It is not anticipated the fuel will heat substantially in the cask and it is expected the temperature will remain low enough to preclude altering of the fuel in any way.

The NAC-LWT will be shipped under the conditions of the cask Certificate of Compliance, using truck transport (see Figure 2.1.1). It is expected the transport from North Anna to INL will take no more than three days. Once at INL, a receiving inspection will be performed at the Materials and Fuels Complex (MFC) to ensure the cask seal has been maintained over the course of transport and no other tampering or damage has occurred.

Once cleared, the truck is escorted to the Hot Fuels Examination Facility (HFEF) where the trailer is brought inside the HFEF truck lock for unloading. Figure 2.1.2 shows the unloading of a NAC-LWT in the HFEF. The NAC-LWT cask has been handled in the HFEF eight times since 2007, and the 25-rod canister has also been handled at the facility. The HFEF has operating procedures for loading and unloading the cask's payload into the main hot cell. The main hot cell utilizes an argon atmosphere. The NAC-LWT must be vented to the radioactive ventilation system to install a “shutter shield” assembly that is used to mate the cask with the hot cell. The cask remains under air atmosphere for about one day during the unloading operations. Once the cask is mated to the main hot cell, the cask contents are again under inert atmosphere from the hotcell.

Following receipt of the tractor-trailer in the truck lock, the ISO-container can be opened and the cask lifted free of the cask cradle. The cask is next lowered through a hatch-covered opening down into the cask transfer tunnel. The cask will be secured to the cask transfer cart for all further operations and until the cask is lifted out of the cask transfer tunnel for reloading into the ISO-container. Appendix B contains a series of diagrams that illustrate the loading/unloading sequence for the NAC-LWT in HFEF.

Figure 2.1.1. NAC-LWT loaded in an ISO-container on a transport trailer demonstrating the transport configuration. The lid is not installed in this image, nor is the end-wall of the ISO-container.

Figure 2.1.2. A NAC-LWT cask being unloaded in HFEF. The cask is lifted out of the ISO-container and lowered into the cask transfer tunnel and onto the cask transfer cart.

Once positioned, the cask will be accessed and the 25-rod canister lifted and secured through the Window 1M cask access hatch of the HFEF main cell using the HFEF 1M1 Universal Support Fixture. The 25-rod canister is shown in Figure 2.1.3. Each of the 25 fuel rods will be lifted one at a time with the Window 1M manipulators and have a Type D end fitting secured to it using the end fitting station. Type D end fittings (Figure 2.1.4) have an adjustable collet, allowing them to be used on fuel rods up to 0.375 in. (9.525 mm) in diameter (Westinghouse 17x17 fuel rods are 0.374 in [9.5 mm] in diameter). If needed, new end fittings can be made to accommodate large fuel rod diameters (such as those from BWR reactors or 15x15 PWR assemblies).

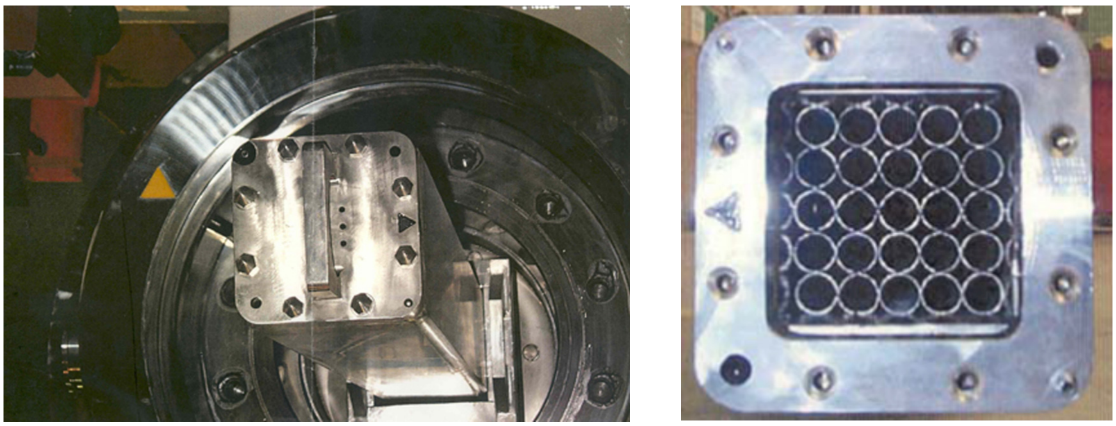


Figure 2.1.3. The 25-rod canister in closed (left) and open (right) configuration.

Figure 2.1.4. Type D end fittings that are attached to the end of each fuel rod for handling.

Once the end fittings are attached, the fuel rods will be secured in a storage can for protection and preservation. It is proposed that a storage can used previously for storing Lead Test Assembly (LTA) rods be used for this purpose. The storage can is known as the LTA-1 container and is sized to fit full-length PWR fuel rods. This container is constructed of 8-in. (203 mm) schedule 10 aluminum pipe and has a capacity of 8 fuel rods. Four of these containers would be needed for 25 fuel rods. An additional one or two containers may be needed depending on how many sub-sectioned fuel rods will need to be stored individually in the hot cell.

For transfer of fuel to LTA-1 canisters, the most efficient handling method is to unload the NAC-LWT 25-rod canister immediately upon cask receipt. After fittings are installed onto the ends of fuel rods, fuel can be transferred from the NAC-LWT canister to LTA-1 containers via a below-the-hook lifting attachment with gripper adapter attachment (see Appendix B, step 14). The LTA-1 container is capable of storing fuel rods with installed end fittings in a closed configuration. The container closure is a top hat-shaped lid that installs to a flange partway down the main container body, allowing fuel rods up to 12 ft. 9 in. (3886 mm) in length to be stored with the end fittings installed (more than sufficient for the Westinghouse-type 17x17 fuel rods to be received from North Anna). A schematic of the LTA-1 container is shown in Figure 2.1.5.

The location of each fuel rod must be carefully tracked. Initially, the LTA-1 canisters will be stored near the middle of the HFEF main cell in storage wells. As fuel rods are examined, there will come a time when some of the rods are sectioned for destructive examination. Small rod segments will be taken from the fuel rods leaving shorter sections that must be permanently marked/identified with their orientation and location within the fuel rod. These segments will be capped with end cap fittings, and then placed in pipe nipples for protection and preservation. The details of this marking will be included in the test plan that will guide the examination of each fuel rod.

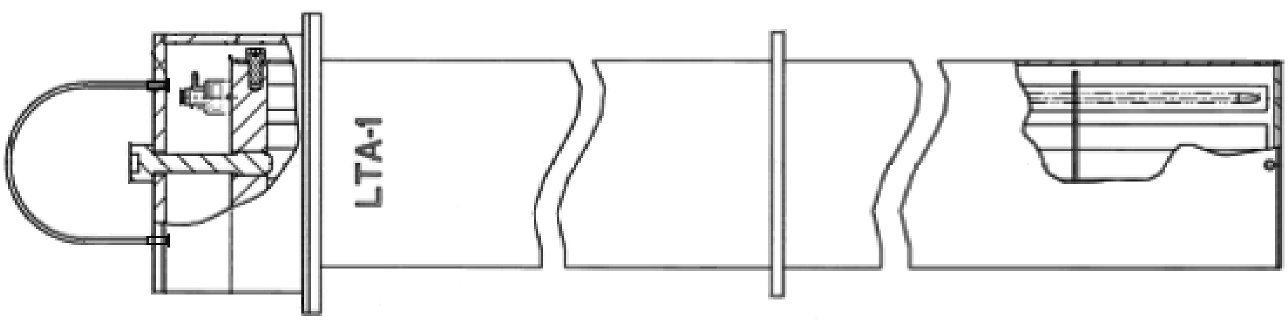



Figure 2.1.5. Schematic view of the LTA-1 container.

# 3. FUEL CHARACTERIZATION

## 3.1 Gap Analysis

The UFDC has issued *Gap Analysis to Support Extended Storage of Used Nuclear Fuel*[3] that documents the initial gap analysis performed to identify data and modeling needs to develop the desired technical bases to enable the extended storage of UNF. For most Structures, Systems, and Components SSCs important to safety, additional data are required, often because there are limited data on the new materials used in more modern fuels or dry storage cask systems or because the effects of high burnup and extended storage are not fully known. Once identified, the program began to establish the methodologies to close those gaps. For several of these "gap closure strategies," a test material must be acquired for use in the strategy's R&D efforts.

The analysis identified several gaps that require data from UNF samples can provide useful information. These gaps are:

- Subcriticality (burnup credit and moderator exclusion) – radionuclide inventory in fuel rods
- Stress profiles – mechanical strength of the fuel rod
- Fuel Transfer Options – ensure fuel is handled in a prototypic manner
- Cladding – annealing of radiation damage
- Cladding – $H_2$ effects, reorientation and embrittlement
- Cladding – $H_2$ effects, delayed hydride cracking
- Cladding – oxidation
- Cladding – creep
- Fuel Assembly Hardware – stress corrosion cracking (SCC) of lifting hardware and spacer grids

The data needed to close these gaps will help guide what types of fuel should be acquired by the program.

The report, *Gap Prioritization and Closure Plan*[4] provides recommendations for the types of testing that may close the gaps. A summary of these data types is below:

- Subcriticality (burnup credit and moderator exclusion). Radiochemical assays of fuel rods are recommended along with reactor operational history data. HBU fuel can be analyzed by any of the national laboratory's radiochemical labs. The challenge is to get the reactor operational history. Utilities consider this data part of their competitive advantage, and are reluctant to release that information. Efforts to revive the requirement for utilities to fill out the Nuclear Fuels Data Survey, Form RW-859, met strong resistance to providing this additional data and the request was withdrawn. However, efforts by Oak Ridge National Laboratory (ORNL) to gather this data have been more fruitful in FY 2013. This information request becomes an item for consideration when selecting a utility from which to acquire fuel.
- Stress Profiles. The testing recommended for this cross-cutting data gap include vibration testing of fuel assemblies and potentially individual fuel rods. If a full fuel assembly is acquired, it may be useful to instrument the shipping cask and truck trailer. Applying instruments (i.e. strain gages) to the fuel is difficult and likely could not be done in the fuel pool prior to loading (attempting to perform a complex operation in a highly regulated work space).
- Cladding. The most important cladding information to be obtained is the mechanical properties at different times. These mechanical properties will vary based on cladding type, burnup, oxide and crud layer thicknesses, hydride quantity and orientation, radiation damage and annealing, and temperature. Mechanical properties data will be obtained from ring compression tests, expanded plug tests, burst tests, 3- and 4-point bend tests, and creep tests, in addition to traditional hardness, impact, and tensile strength tests. Testing will involve both Separate Effects Tests (SETs) and potentially a Small-Scale Test (SST). Characteristics to be evaluated include annealing of radiation damage,

hydride reorientation and embrittlement, delayed hydride cracking, clad oxidation, and cladding creep.

Characterizing these effects will require the largest sample set. It may not be sufficient to simply request fuel that has a certain cladding and fuel burnup. While the burnup has become a generalized expression that is used to infer that a fuel with a high burnup has experienced more operational stress than a low burnup fuel. However, there is another metric, "fuel duty," that captures estimates of fuel clad corrosion, hydrogen pickup, temperature history and is more descriptive of the clad condition as opposed to the fuel pellet burnup.[5] It will be important to gather information on proposed fuels to be acquired so the fuel duty can be calculated. This can be done by a utility or by the UFDC (EPRI methods that are used are described in [5]). The higher the fuel duty, the higher the clad corrosion and fission gas release. It would be useful to acquire fuel rods with a range of fuel duty values, however, if that is not possible, then acquiring fuel rods with high fuel duty values may be desirable to bound the worst case conditions of the fuel.

- Fuel Assembly Hardware. In general, irradiated fuel assembly hardware will not be available to the UFDC. However, if a full assembly of fuel is acquired for testing and placed in a SST, then grid spacers and end plates can be subjected to testing. Even then, the testing will be limited to a single alloy. Different fuel vendors use different materials for hardware (Zircaloy, Inconel™, stainless steel).

## 3.2 Post-Irradiation Examination

The following sections provide detail on how fuel rods can be characterized in a manner that will support gathering the data needed for the high burnup dry storage demonstration and for technical gap closure. In their test plan, the EPRI team provided a section detailing the fuel rod characterization important to their demonstration. This section is reproduced in Appendix A. These needs are either identical to or complementary to those examinations needed for other technical gap closure.

A fuel characterization campaign is segregated into non-destructive and destructive examinations. It is always advisable to conduct and complete as many non-destructive examinations as possible to have the needed data to inform where destructive examinations should be conducted.

A test plan will be developed for each fuel rod to be examined. These test plans will detail the specific examinations to be conducted on that rod. Not every rod will be examined, and not every rod will be subjected to the full suite of examinations. The UFDC Storage and Transportation team will make those decisions, with concurrence of the EPRI team on exams specifically related to the demonstration.

### 3.2.1 Non-Destructive Post-Irradiation Examination

A series of post-irradiation examinations (PIE) will be conducted on select fuel rods. A minimum of one fuel rod per clad type will be fully characterized to establish the condition of fuel rods prior to use in the demonstration.

#### 3.2.1.1 Receipt Visual Inspection

**Purpose:**

It is anticipated that 25 HBU fuel rods will be received at the INL HFEF in a NAC-LWT cask. The fuel rods will be held in a 25-rod canister. A visual inspection of each fuel rod will be completed as the rods are removed individually from that canister in the argon atmosphere main hot cell. This visual exam will check for:

- Confirmation of the fuel rod location in the basket, and identifying marks (a fuel handling collet will be placed on each fuel rod and those collets will also have identifying marks to ensure fuel rod identification is preserved)
- Unexpected gross failures of a fuel rod during transport
- Macroscopic failures that might occur after loading and transport
- Visible signs of surface scratching or other damage that might occur during loading
- Qualitative impression for fuel rod bowing (i.e. “large,” “moderate,” “slight,” “straight”)
- Any other visual anomalies on the fuel rod surface that can be observed with the human eye through the hot cell window.

**Method:**

The hot cell operators and cognizant engineer who will be present during the fuel rod unloading will conduct the receipt visual inspection. Their observations will be kept in a log book at the hot cell window. All of the fuel rods received will be inspected. These observations will be used in planning for further PIE operations, and to inform operators of any potential characteristics that might require preservation or indicate additional care during handling. These initial examinations will be conducted near the cask loading port at Window 1M at HFEF. The pages will be scanned and converted to digital file format (e.g. Adobe Acrobat) for storage in the project records.

#### 3.2.1.2 Visual Examination

**Purpose:**

Select fuel rods will be subjected to a complete suite of PIE. These rods will receive a detailed surface visual examination. This is done to provide a physical record of the fuel rods as-received condition that is complemented by the receipt inspection.

**Method:**

This examination is conducted by utilizing the visual examination machine/eddy current (VEM/EC) stage at Window 7M of HFEF. A high resolution Keyence camera system will be used to capture high-resolution, real-color images of the fuel rod surface.

The imaging process works by taking four images that cover slightly more than 90-degrees of the fuel rod surface with a ~15 mm field of view. After the entire circumference is captured (four images), the fuel rod is moved ~15 mm up. Then, another four images are taken. This continues until the entire fuel rod length is documented. Thus, a 12.5-feet long fuel rod (3810 mm) can be imaged along the length (roughly 254 movements). Thus, to document the entire circumference and length of a fuel rod, approximately 1016 images will be taken. These images are recorded in a database. Next, the images can be recovered and "stitched" together via a computerized stitching system to produce a 2-D image of the entire diameter and length of the fuel rod. The resolution of the image can be captured between 1 and 3X at about 1 megapixels/mm data capture. Thus, very detailed images of the fuel rod surface are possible.

#### 3.2.1.3 Eddy Current Examination

**Purpose:**

Eddy current examination is a technique that uses electromagnetic induction to conduct surface analysis on materials. Applied to zirconium-based nuclear fuel cladding, the technique can be used for the detection of surface defects (e.g. scratches, pits, cracks, holes) and to measure the thickness of surface oxide layers.

**Method:**

At INL, a new eddy current detection station has been developed. This system utilizes the Eddyfi NDT, Inc., Ectane™ analyzer (Figure 3.2.1.3.1) coupled with a specialized multi-coil scanning array that was developed through collaboration between Eddyfi, EPRI, and INL.


Figure 3.2.1.3.1. The Eddyfi Ectane™ has an internal multi-channel analyzer (256 channels of data) that is programmable to support any coil topology that may be deemed more efficient for a given inspection. The Ectane™ allows users to take advantage of any absolute, differential, or transmit-receive eddy current coil technology.

A cross-section of the hot cell "scanning head" is shown in Figure 3.2.1.3.2. The head has poly-ether-ether-ketone (PEEK) fingers that locate and "follow" the fuel rod. Twenty-one coils that stand off from the surface of the fuel rod are used to detect surface defects. Eight additional coils are held in close proximity to the fuel rod surface to evaluate surface oxide/crud thickness. Thus, both surface layer thickness and defects are determined in a single pass of the fuel rod. Additional detail for the scanning head is shown in Figure 3.2.1.3.3.

This system is mounted to the VEM/EC stage located at Window 7M. Figure 3.2.1.3.4 shows the mock-up that was performed prior to hot cell installation. This figure is useful to illustrate the size of the equipment; the system was built to examine fuel rods greater than 14-feet in length.

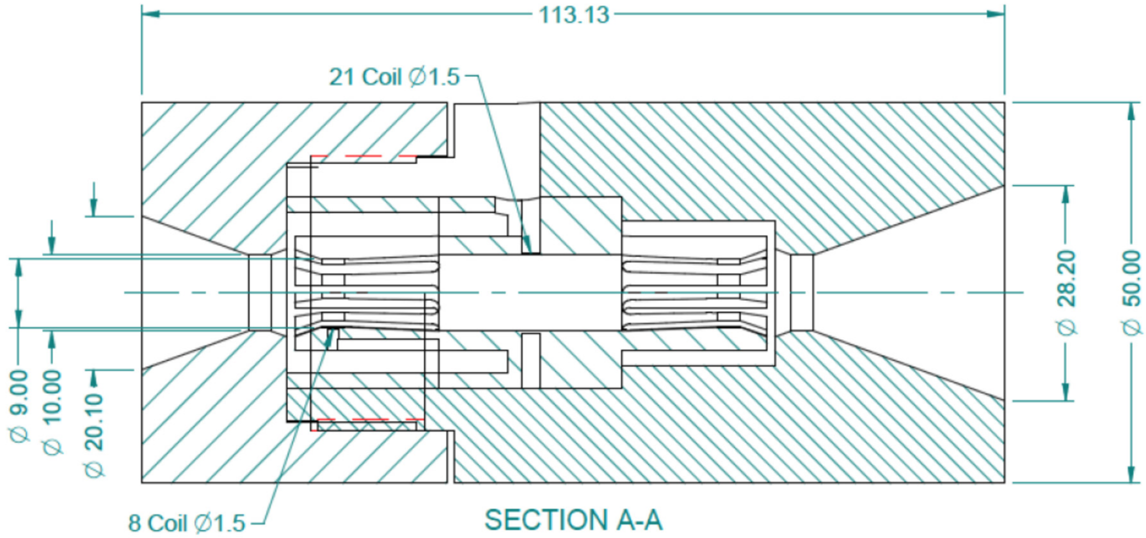



Figure 3.2.1.3.2. Cross-sectional view of the eddy current scanning head used for UNF rods.

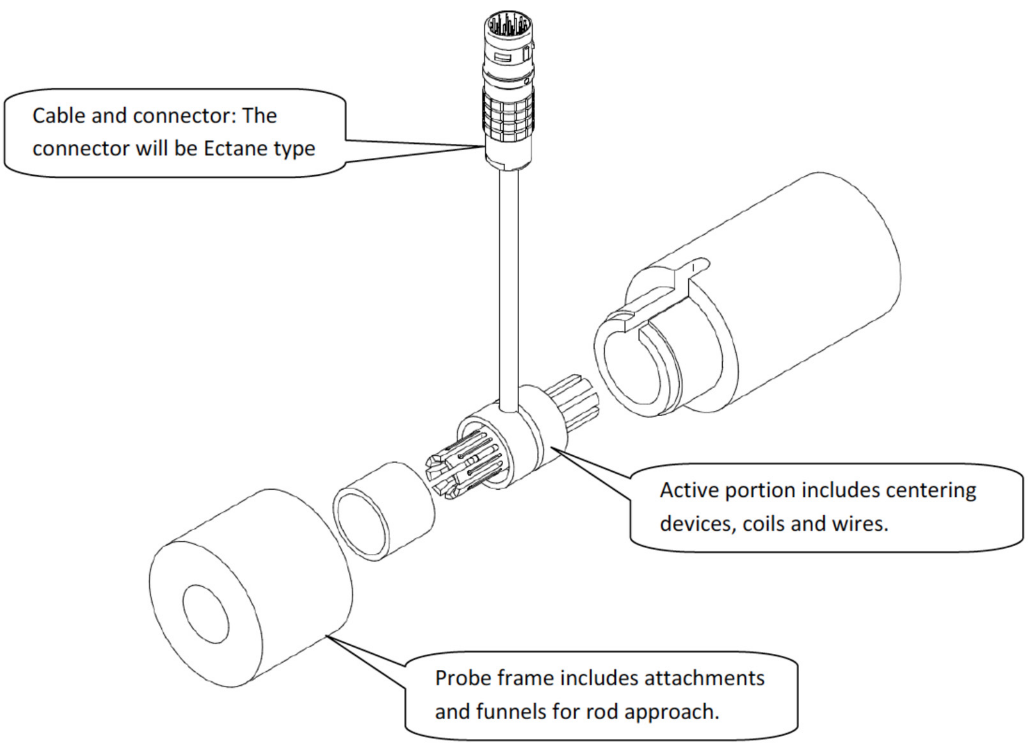



Figure 3.2.1.3.3. Additional detail of the scanning head used for eddy current analysis.

The Ectane™ utilizes EddyFi's Magnifi® software for data acquisition and analysis. This software will be used to interpret the data and visually present it. The surface defect data from a fuel rod can be "unwrapped" (the circumference opened up as a flat surface) to allow a 2-D representation of the surface by the length of the fuel rod) similar to the visual examination data. An example of this is shown in Figure 3.2.1.3.5.


Figure 3.2.1.3.4. VEM/EC stage mock up in the Fuel Conditioning Facility Mock-Up Shop at INL.

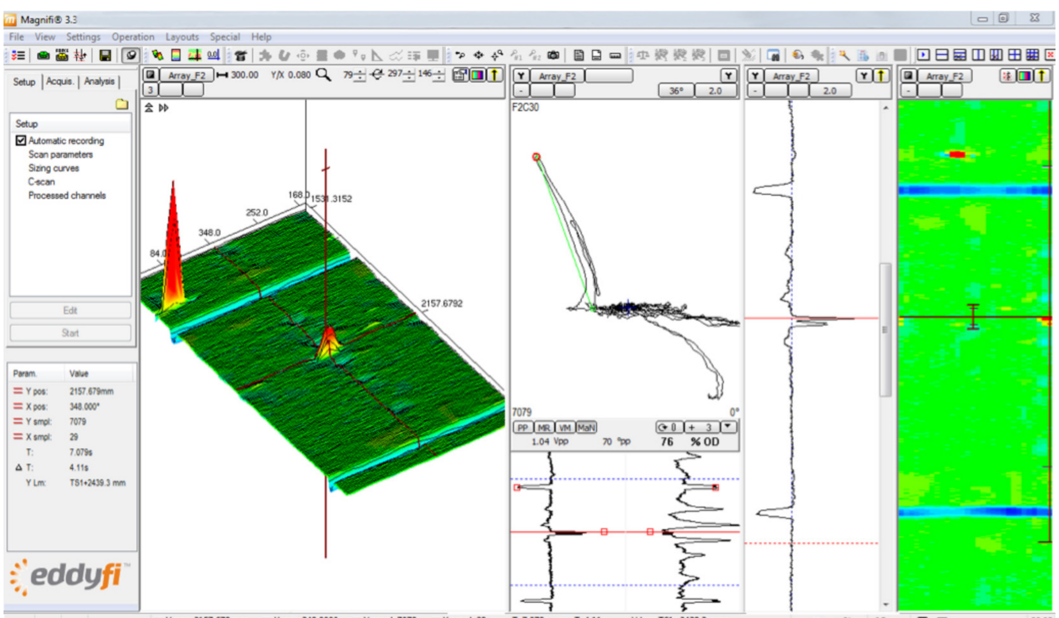



Figure 3.2.1.3.5. Example of data representation using Eddyfi Magnifi® software. Defects can be represented in color in a pseudo-3D representation with other information displayed on the same screen.

#### 3.2.1.4 Gamma Scanning

**Purpose:**

Gamma scanning is used to determine the irradiated fuel location, relative isotopic concentrations, relative axial fuel-burnup profiles, isotopic migrations, fuel dimensions, fission-gas generation, and other data to aid in evaluating the performance of irradiated fuels.

**Method:**

The HFEF Precision Gamma Scanner (PGS) records, analyzes, and stores gamma spectra from fuel rods for use in characterization of their properties. Gamma rays from an irradiated fuel rod are passed through a narrow variable slit and collimator so rays from only a small and identifiable part of the element are counted over a particular time interval. The gamma rays strike a gamma detector, which emits a pulse of electric charge proportional to the energy of each individual ray. The pulses, after shaping and amplification, are counted. The data is analyzed for information with regard to isotope identification of the material. Of interest for UNF, these measurements are most useful for:

- Relative fuel burnup and power profiles of a fuel rod
- Relative distribution of various isotopes in the fuel rod
- Identification of any fuel material relocation inside the cladding

The gamma scanner can be used for scanning large components such as test loops, as well as reactor components and fuel elements. Two types of gamma scans are generally performed:

- Gross gamma scans to determine the distribution of activity over the fuel rod's length
- Isotopic gamma scans to determine the isotopic distribution of activity over a fuel rod's length.

Gross gamma scans are performed by traversing the fuel rod in front of the collimator and the total gamma count rate is measured without regard to the energy of the gamma rays. The data is presented as a plot of the count rate versus the component's position.

In the isotopic gamma scan, the component is also traversed in front of the collimator and the count rate measured as in the gross scan; but the data in the isotopic scan is broken down into individual energies and the corresponding isotopes are identified. These data are presented as a plot of the isotopic activity versus the fuel rod's position. The isotopic gamma scan is used to determine the isotopic distribution of activity over a fuel rod's length.

The PGS has the ability to step lengthwise along a fuel rod in 0.001 inch (0.0254 mm) steps and is repeatable to +/- 0.005 inch (+/- 0.127 mm). Angular position resolution is better than +/- 0.1 degree and repeatable to +/- 0.5 degrees. The PGS is equipped with Compton suppression to aid in the analysis of isotopes with lower energy peaks.

Performance of a gamma scan on a full length LWR fuel rod requires the rod to be scanned in two halves and the data assembled in a computer. This method has proven reliable in the past. An example of gamma scan data is shown in Figure 3.2.1.4.1.

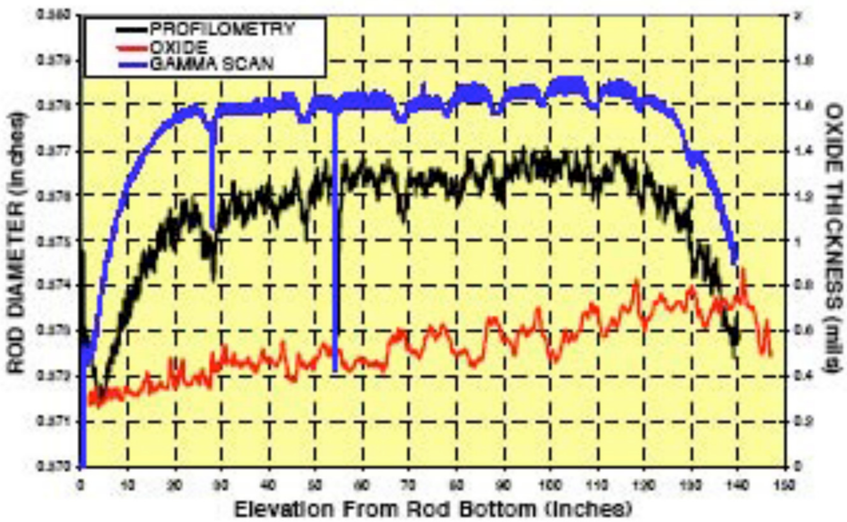



Figure 3.2.1.4.1. Example gamma scan data for a fuel rodlet.

### 3.2.1.5 Metrology

**Purpose:**

Metrology documents the physical measurements of a fuel rod. This includes the diameter and length of the fuel rod. This provides an indication of potential creep or growth of the fuel rod during irradiation and storage.

**Method:**

Two systems are located on a single stage at Window 5M of the HFEF; the element bow and length machine which is used to measure the distortion (bow) and actual length of fuel rods, and the Element Contact Profilometer which is used to measure the diameter of a fuel rod.

The bow and length machine can be used to determine the fuel rod's length and bow as well as the direction of the plane of the bow. The machine is a standard element handling stage equipped with a set of perpendicular bars (shown in Figure 3.2.1.5.1). Lead screws drive the bars and the element or core component's bow is measured by the position of the bars with respect to the axis of rotation. In order to prevent the bars from disturbing the element during the measurement, they are equipped with light sensors. When the element or component breaks a beam of light, the drive on the bars is stopped. Encoders on the bar's lead screws convert the position of the bar into an X-Y coordinate pair. The X-axis of the Cartesian coordinate system runs parallel to the cell wall. The Y-axis of the system runs perpendicular to the wall. The Z-axis is vertical. Measurements are made at various positions along the length of the component by incrementally moving the component past the bars.

At each measurement position, the X, Y and Z positions are recorded. The element or component's bow is determined by calculating a tip-to-tip centerline, then calculating a perpendicular distance from this centerline to the element's actual centerline. The direction of bow is calculated from the information used to calculate the magnitude of the bow. These calculations are performed at each location measured along the axis of the element or component.

To determine the element or component's length and the tip-to-tip centerline, the axial position of the bottom tip of the element is measured by lowering the element or component until the bottom tip contacts a pad on the X-position bar. From the indications provided by the machine, and from data obtained from a length standard, the axial position of the top end of the element or component is calculated. The X and Y coordinates of the ends of the element or component are determined by extrapolating the top and bottom two measured points and the calculated end points. The element's free hanging length is determined by summing the chord lengths. Bow measurements of elements or components that have spacer wires are taken in a plane away from the wire. This prevents the wire from breaking the light beam and causing a false reading.

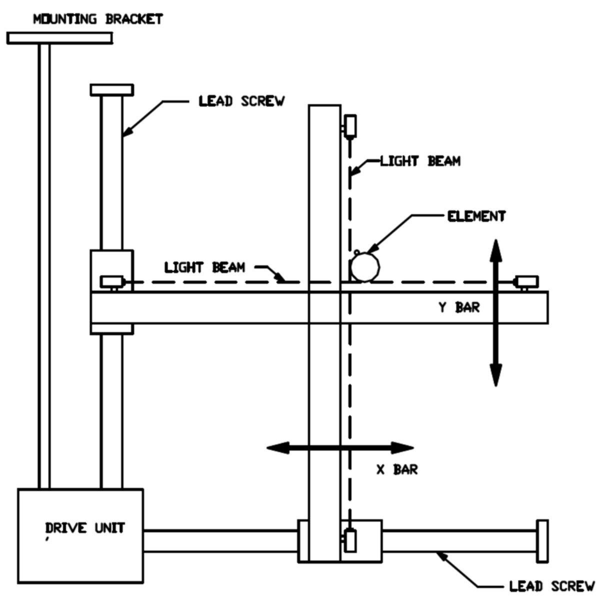



Figure 3.2.1.5.1. A schematic view of the bow and length machine at HFEF.

The Element Contact Profilometer (ECP) is a continuous-contact profilometry gauge for measuring axial and spiral diameter profiles of fuel rods. Horizontally opposed linear transducers contact the fuel rod as it is pulled vertically through sapphire-tipped probes. Guide rollers positioned above and below the transducers maintain the element vertical with respect to the transducers.

The measurement range is designed for fuel diameters between 0.174 in. and 0.840 in. (4.4 to 21.3 mm), having a maximum diametral swelling of 0.02 in. (0.5 mm). The swelling range is limited by the linearity of the probes for the fuel rod size being handled. Data output of the fuel rod profile is in the form of a spreadsheet file. A schematic representation of the ECP is shown in Figure 3.2.1.5.2.

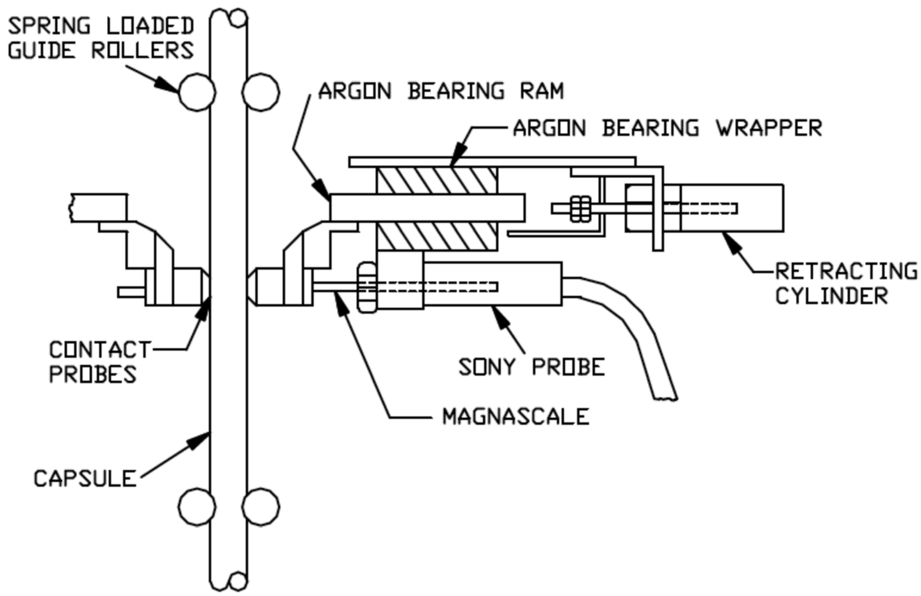



Figure 3.2.1.5.2. Schematic of the Element Contact Profilometer at HFEF.

### 3.2.1.6 Neutron Radiography

**Purpose:**

Neutron radiography is a nondestructive technique that can be used to examine the internal contents of a fuel rod. The cross-section of a fuel rod can reveal important information about the presence of cracks in fuel pellets, fuel pellet rim restructuring as burnup increases, information about the fuel pellet-clad interface and potential bonding, pellet-pellet interface, potential relocation of fuel within the clad, evidence of water in-leakage, condition of the springs and spacers, and size of the gas plenum.

**Method:**

The Neutron Radiography Reactor (NRAD) is a 250kW Training Research Isotope General Atomics (TRIGA) reactor located below the main floor on the north side of HFEF. Shown schematically in Figure 3.2.1.6.1, two beam lines are provided, east and north. The east radiography station is used for examining individual fuel rods (the north station was used for examining the contents of transient tests of sodium cooled experiments that were much larger in size).

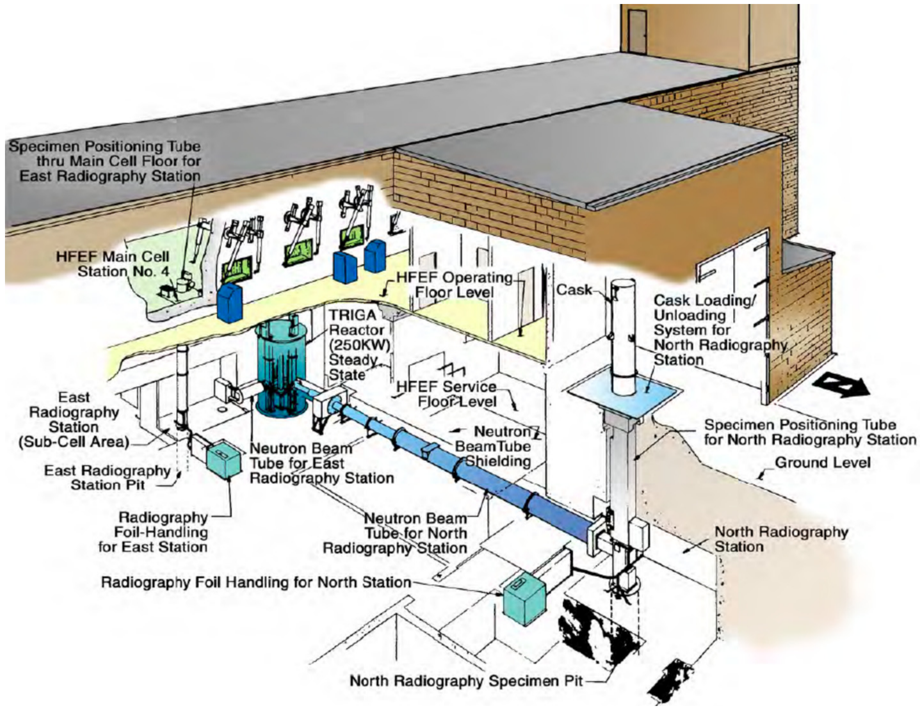



Figure 3.2.1.6.1, Schematic view of the NRAD at HFEF. The east radiography station is used for examining individual fuel rods.

The east radiography station is accessed at Window 4M of HFEF. At the workstation the fuel rod is attached to a holder that allows the fuel rod to be lowered into the neutron beam in a subcell below the main cell floor. The radiograph holders are designed to position the specimen in the optimum position for radiography without excessive scattering of the neutrons. Because the intense gamma activity of most irradiated specimens will immediately darken X-ray film, HFEF uses an indirect radiography process. In this process gamma-insensitive neutron detector foils are activated in the neutron beam. Both indium and dysprosium are used as neutron detector foils. These foils are irradiated in the neutron beam then transferred to a film cassette and allowed to decay for three to four half-lives against ordinary X-ray film to form the image. The dysprosium foils are used for thermal neutron radiographs of low enriched fuels and thin structural materials. The thermal neutron radiographs show excellent detail of the specimen. Examples of radiographs from fuel rods and fuel experiments are shown in Figure 3.2.1.6.2.

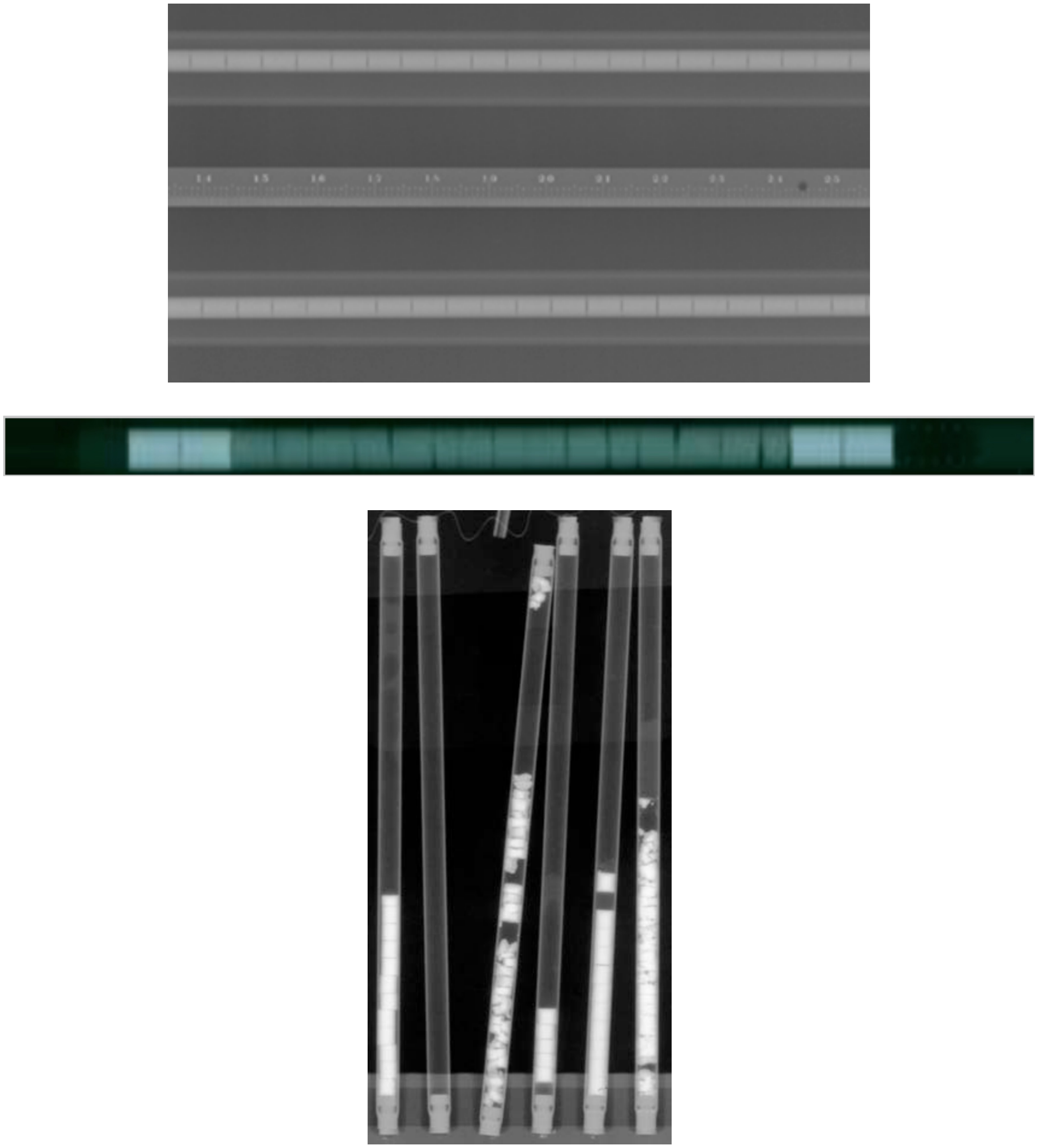


Figure 3.2.1.6.2. Examples of neutron radiography of fuel segments and rodlets from NRAD.

### 3.2.1.7 Summary of Non-Destructive Post-Irradiation Examination

Non-destructive PIE can provide a great deal of information about a fuel rod while keeping the rod intact. The general condition of the fuel clad can be assessed; any defects/pinholes/cracks and surface degradation/oxide layers can be determined. The in-core performance of the fuel can be assessed. The condition of the fuel inside the clad can also be assessed. This information can be used to make decisions about the need for additional PIE and also in guiding what fuel rods may be useful for characterization testing needed to close data gaps identified by UFDC.

### 3.2.2 Destructive Post-Irradiation Examination

Destructive examination of fuel rods should only be performed once all needed non-destructive PIE is complete. Destructive examinations change the characteristics of the fuel rod; for example, gas pressure is lost with the chance for inleakage of unwanted gases into the fuel, fuel particles can fall out of cut segments of fuel resulting in unwanted contamination or loss of material, surface oxides/layers can be disturbed or destroyed during handling.

#### 3.2.2.1 Gas Pressure, Fission Gas Sampling, Free Volume Determination

**Purpose:**

Commercial fuel rods are backfilled with helium gas in the range of 2 atm pressure. The generation and release of fission gases during in-core performance raises that pressure slightly. The overall fuel rod internal pressure is important because during the transition from wet storage in a spent fuel pool to dry storage in a used fuel cask/canister, it is this pressure that helps determine the resultant microstructure of the fuel clad and the orientation of zirconium hydrides. As a fuel rod heats up during fuel drying in the storage cask/canister (due to gamma heating), the hydrogen solubility increases in the clad and some of the zirconium hydrides formed during in-core irradiation dissociate and the hydrogen dissolves in the clad. Once the drying is complete and the cask/canister is filled with helium, the fuel cools and reaches equilibrium in a fews days to weeks. During this cooling process, the hydrogen solubility in the clad decreases and excess hydrogen "precipitates' from the clad in the form of new zirconium hydrides. The driving force for the orientation of these new hydrides is the fuel rod internal pressure, and the hoop stress generated in the fuel rod causes some of the hydrides to be oriented in a radial direction across the thickness of the clad. This orientation is important to the overall strength of the fuel rods, thus the internal pressure's importance to understanding the overall properties of fuel rods.

Fisson gas analysis provides a measure of isotopic composition of the gases found within a fuel rod. Combined with the free volume within a fuel rod, the number of moles of fission gas and helium can be calculated. This can also be used in verifying the percent of fission gas released from the fuel into the free volume of the clad.

**Method:**

The Gas Assay Sample and Recharge System (GASR) located between Windows 3M and 4M at HFEF provides the ability to puncture fuel rods in their plenum regions to measure the free volume and pressure and to gather a sample for gas composition and isotopic analyses. The system provides volume and pressure data to within ± 5% on capsules in the pressure – volume range of 0.03 to 60 liter-atmosphere. The system is comprised of a 150 W pulsed laser, shielded optical and gas cell-wall feed-through, a mechanical pump, calibrated volumes, gages and controls. Operational sequences are fully interlocked to prevent improper valve or laser operations. Fuel rods are positioned on the laser by a clamp onto a neoprene gasket. The gasket provides a seal between the element and laser seal head. Once the gas sample(s) is taken, it can be transferred to an analytical laboratory for analysis using a magnetic sector gas mass spectrometer. A schematic of the GASR is shown in Figure 3.2.2.1.1.

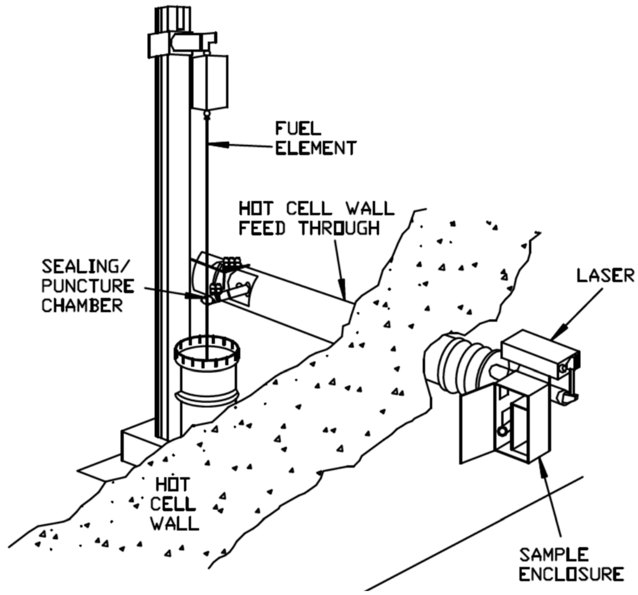



Figure 3.2.2.1.1. Schematic view of the GASR at HFEF.

### 3.2.2.2 Fuel Microstructure

#### 3.2.2.2.1 Optical Microscopy

**Purpose:**

Optical examinations are performed to examine the microstructure of the fuel and clad. These examinations can reveal information about the clad performance (e.g. hydrogen pickup, hydride formation and orientation, outer surface oxide/crud layer, inner fuel-clad interactions, swelling, and bambooing. The fuel meat can be examined for evidence of fracturing, swelling, fuel/clad bond delamination, and rim restructuring.

**Method:**

Optical metallography and ceramography begin by examination of the non-destructive data to select regions of interest for more detailed examination. Once a location on a fuel rod is selected, that region is cut out of the fuel rod at Window 12M cutoff saw. It is at this point that careful identification and labeling of fuel segments must be made. The orientation and location of each segment within the fuel rod must be maintained. It is also important to cap each cut end to prevent fuel fragments from spilling out of the clad due to handling.

Once a segment is properly marked, it is transferred to the Window 2M Containment Box. It is in the Containment Box that all segment cutting/sizing, mounting, planar grinding, polishing, and etching can occur. The cognizant scientist works directly with the hot cell operators to ensure the sample is properly sectioned and mounted. Slow speed diamond saws with sample-specific mounts are used to cut the fuel rod segment into a size that can be mounted in standard 1.25” (32 mm) ring mounts in a manner that will reveal the feature of interest (e.g. pinhole in clad, cross-section of clad, longitudinal section of clad). Low viscosity, radiation resistant epoxy resins are used in the mounting process. Once mounted, the samples are planar ground using a combination of diamond and silicon carbide abrasive disks. An in-cell camera is used to inspect the surface of the sample as the grinding is carried out. Once the sample is ground flat, polishing begins. Polishing is done using a combination of abrasive disks and liquid or paste abrasive suspensions on polishing clothes. Once polished, the surface is inspected to assure the features of interest are present. The samples can be examined in an as-polished condition; however, it is often advantageous to etch the polished surface to reveal features that would otherwise not be visible. Grain boundaries and hydrides in zirconium metals require an acid etch to reveal those features.

Following polishing or polishing/etching, the sample mount is transferred to the Metallography Hot Cell via a pneumatic transfer ("rabbit") system. The "met box" is located in a room to the north of the main hot cell in HFEF, and, like the main hot cell, has an inert argon atmosphere. A remote Leitz MM5 RT metallograph is located in the hot cell and will be used for optical microscopy. Photo documentation of images will be recorded using an integrated digital camera with 6-megapixel resolution in black and white or color format. Sample touchup and additional etching require the sample to be returned to the Window 2M containment box. While this can be tedious, it does prevent acid etching fumes from ever reaching the optical microscope.

### 3.2.2.2.2 Microhardness Testing (optional)

**Purpose:**

Microhardness measurements can provide an indication of variations in the mechanical properties of the clad as a function of location.

**Method:**

A LECO AMH43 microindentation hardness-testing instrument is located in the "met box." This system is a microhardness tester equipped with optical microscopy capability. Like the metallograph, the microindenter system is equipped with an integrated digital camera with 6-megapixel resolution in black and white or color format for photo documentation. The specimens prepared for optical examination can also be used for microhardness testing.

Microhardness measurements can be taken radially across the fuel clad to provide an indication of variations in the mechanical properties of the clad as a function of location. The measurement locations on the specimen can be performed to interrogate the clad and the pellet/clad interface region. Figure 3.2.2.2.2.1 shows an example of microhardness testing of irradiated metallic alloy transmutation fuel[6]. The length dimensions indicated on the image are calibrated using a traceable reference optical stage micrometer.

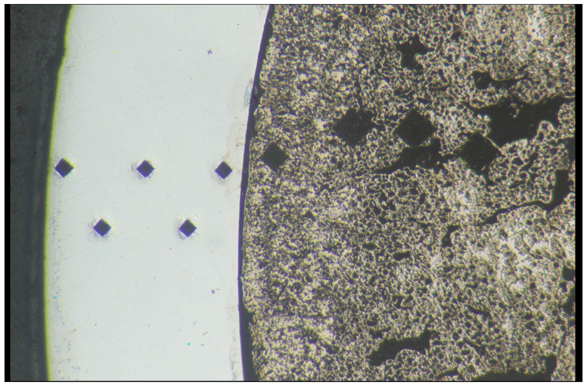


Figure 3.2.2.2.2.1. Microhardness testing of metallic alloy transmutation fuel at 6 at.% burnup.[6]

#### 3.2.2.2.3 Electro-Optical Examinations (optional)

**Purpose:**

Electro-optical examinations can be used to more carefully examine the fuel and clad. The achievable magnification and resolution are much higher allowing examination of features that might not be resolved using light microscopy.

**Method:**

Scanning electron microscopy can be used to examine fuel and clad at magnifications well above 1000X. INL has a JEOL 7000F field emission gun scanning electron microscope (FEG-SEM) equipped with energy dispersive spectrometry (EDS), wavelength dispersive spectroscopy (WDS), and electron backscatter diffraction (EBSD) detectors (shown in Figure 3.2.2.2.3.1).

Samples to be examined are first sized at the HFEF and transferred to the Electron Microscopy Laboratory (EML). Sample mounting and preparation are conducted in the EML. If needed, the samples can be prepared using a Focused Ion Beam (FIB) to ensure the samples are small which reduces the radiation dose rate to the worker and instruments.

One particular use for the SEM is the resolution and qualitative determination of the amount of radial and circumferential hydrides in a section of clad. Optical microscopy can be used, but is subject to error due to the etchant needed to resolve the hydrides. Often, the hydrides continue to darken over time giving the impression that more hydride is present as the sample ages. Samples examined on a SEM can be performed under vacuum and the hydrides resolved without etching, thereby giving a more accurate result.

Figure 3.2.2.2.3.1. JEOL 7000F FEG-SEM with EBSD, EDS and WDS detectors.

**Method:**

Transmission electron microscopy can be used to determine the crystallography of very small features/phases by electron diffraction, determine the microcracks or fine surface/oxide layers on phases, nucleation of species at grain boundaries (e.g. 5-metal particles), and examination of hydrides in clad.

INL has a JEOL 2010F scanning transmission electron microscope (TEM) in the EML that can be used for these purposes if required. Sample preparation would be performed using the FIB. The JEOL 2010F is shown in Figure 3.2.2.2.3.2.

Figure 3.2.2.2.3.2. JEOL 2010F scanning transmission electron microscope

#### 3.2.2.3 Radio-Analytical Chemistry

**Purpose:**

Radio-analytical chemistry methods are used to determine the isotopic assay of the fuel, the quantity of fission products that diffuse into the clad, the amount of hydrogen in the clad, the composition of fission gases inside a fuel rod, the burnup of fuel, linear heat generation rate, and more.

**Method:**

While many chemical analyses can be performed, this section focuses upon those analyses that should be performed to address data gaps important to UFDC.

Fission gas collected from the GASR will be analyzed using a magnetic sector gas mass spectrometer. INL currently sends these samples to Pacific Northwest National Laboratory (PNNL) for analysis. Gas collected in stainless steel sample "bombs" are packaged and sent for analysis. PNNL has a Finnigan MAT-271 quantitative gas mass spectrometer that is capable of rapid sample turn-around, with typical detection limits for most permanent gases and low mass organic at concentration level of 10 part per million. This sensitivity is sufficient to determine the isotopic concentrations of the fission gases present in the sample "bombs."

Burn-up determinations are typically done utilizing stable fission products. Currently, the INL Analytical Laboratory (AL) measures stable isotopes between $Rb^{85}$-$Sm^{154}$ via Quadrupole Inductively Coupled Plasma Mass Spectrometry (Q-ICP-MS). This approach gives experimenters information from both fission product curves. Best results have been obtained with $La^{139}$, $Pr^{141}$ and other isotopes with no isobaric (same mass) interferences. Each isotope of interest is calibrated directly utilizing NIST traceable standards or equivalent. Typical uncertainties for the fission products are on the order of 3-5% 2 sigma.

The fuel isotopic mix of uranium, plutonium, curium, americium, and other elements is important to confirmation of models and other calculations (e.g., thermal analysis). Small segments of clad can be defueled, the fuel dissolved, and the elements and isotopes quantitatively analyzed. The determination of U and its isotopic composition is typically done in a two-step process. First, U and Pu are measured via Q-ICP-MS. This gives concentrations and isotopic composition for the sample. The totals have errors similar to the fission products of ± 3% 2 sigma. Isotopic composition uncertainties will be on the order of 0.1% for the major components to 1% for the minor components. Second, the samples will be analyzed via either Multi-Collector ICP-MS (MC-ICP-MS) or Thermal Ionization Mass Spectrometry (see Figure 3.2.2.3.1). The samples will utilize the isotope dilution for quantitation. The analytical figures of merit will increase greatly vs. Q-ICP-MS. Total U will be less than 0.5% 2 sigma and isotopic composition better than 0.1 % for all isotopes.

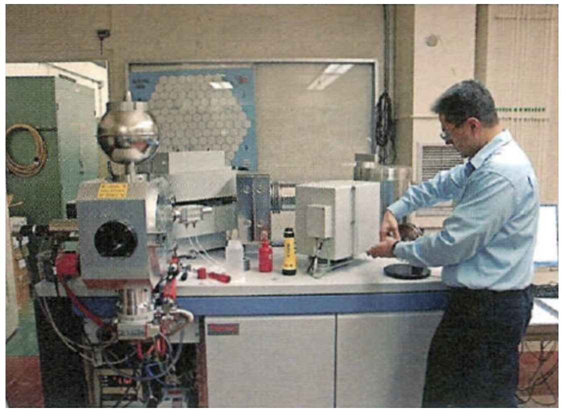


Figure 3.2.2.3.1. Finnigan MAT 262 Thermal Ionization Mass Spectrometer

Total hydrogen in the fuel clad is important to understanding the resultant mechanical properties of the clad. The INL AL is installing an ELTRA 2000 Hydrogen instrument in a radiological glove box. The instrument is a total combustion type instrument, as compared to a diffusivity type instrument. The instrument is calibrated utilizing manufacturer provided standards (hydride titanium rods). The error associated with the standards is ± 5% 2 sigma. The total assay of cladding samples is expected to be ± 10 % 2 sigma. Quantitation limits for the determination of Hydrogen should be 5 ppm in the solid (99% confidence level).

#### 3.2.2.4 Microchemistry

**Purpose:**

There may be phases or features in the fuel and clad that investigators will want to examine more closely. There are semi-quantitative analytical tools that can be deployed for these purposes.

**Method (SEM with Wavelength Dispersive Spectroscopy):**

As described earlier, The JEOL 700F FEG-SEM is equipped with EDS and WDS. The WDS uses the characteristic X-rays generated by individual elements to enable quantitative analyses to be measured for features as small as a few micrometers. The method is often useful for features as small as a few microns. WDS can also be used to create element X-ray compositional maps over a broader area when the beam is scanned over the surface of a sample. These capabilities provide fundamental quantitative compositional information for features within a material. One must be careful when using these techniques as the electron beam can excite X-rays from beneath the surface one is examining, so compositions determined by WDS can have some error.

**Method (Electron Probe Micro Analyzer)**

The electron probe micro-analyzer (EPMA) is a micro-beam instrument used primarily for the non-destructive chemical analysis of very small solid samples. Though very similar to a SEM, the EPMA has multiple WDS instruments to provide increased accuracy of the analysis being conducted. Where a SEM with a single WDS can analyze spots of "several microns" in size, an EPMA can routinely quantitatively analyze spot sizes between 1 and 2 microns.

INL has a CAMECA SX100R shielded EPMA. The instrument was constructed specifically for analyzing radioactive samples. It has four WDS detectors and has a sensitivity of 20-100 ppm from atomic number 4 through the actinides. The instrument is shown in Figure 3.2.2.4.1.

The EPMA could be useful for characterizing features such as the pellet-clad interface, high-burnup pellet rim restructuring, and cladding degradation.

Figure 3.2.2.4.1. CAMECA SX100-R shielded electron probe micro analyzer.

# 4. FUEL SAMPLE ALLOCATION

INL would serve as the "hub in a "Hub-and-Spoke" concept for used fuel PIE and testing. While there are testing capabilities at INL, not every capability needed to support the needs of UFDC exist there. Fuel and clad samples would be sent to other laboratories (spokes) when it is not practical to perform the work at, or capabilities do not exist at the "hub."

As proposed, INL would receive the sister fuel rods from North Anna and conduct the non-destructive and destructive PIE on the fuel. The testing required (beyond PIE) for the fuel has not be formalized at this time. However, for the purposes of this report, it is important to identify what types of samples might be shipped from INL to other laboratories. These are, de-fueled clad and used fuel segments. While the INL cannot serve as a waste disposal site for any of the "spokes" (due to the conditions of the 1995 Settlement Agreement between the State of Idaho and DOE and subsequent addendums), most labs can still dispose of small quantities of fuel and clad on a limited basis.

Argonne National Laboratory (ANL) performs ring compression tests and ductile-brittle transition temperature (DBTT) tests on fuel clad segments. ANL only needs clad samples and does not perform testing on the fuel meat. Clad samples can be defueled and decontaminated sufficiently to allow shipment of these to ANL as a standard Type A radiological shipment[6]. Fuel segments about 3-inch (76mm) in length would be cut and the fuel meat carefully removed. This often requires drilling a small hole down the center of the fuel meat so it can be removed as

[6] The reader is referred to 10CFR CFR Part 173, Subpart I - Class 7 (Radioactive) Materials, and to the following document for information regarding the requirements of Type A and Type B radioactive material shipments: https://www.orau.org/PTP/PTP%20Library/library/DOT/miscelaneous/ramreview.pdf

fuel fragments. The samples would be barrel brushed and acid cleaned to remove additional oxide fuel meat. Once cleaned the remaining clad samples would be packaged for shipment. ANL would not receive the fuel meat that could later incur large waste cleanup costs. After testing, ANL can dispose of fuel clad as low-level waste.

When complete fuel segments (fuel and clad) are needed for testing, the shipping must be conducted using a Type B shipping container due to the quantity of fissile isotopes in the fuel meat. For example, Oak Ridge National Laboratory (ORNL) is performing pure bending tests on fuel segments for the Nuclear Regulatory Commission (NRC) and UFDC. Each test requires about 6-in (152 mm) of fuel. For their purposes, it has been proposed to cut 8-inch (203 mm) segments of fuel that have end caps attached to seal the fuel in the clad. The extra one-inch on each end (25.4 mm) is provided to allow ORNL to cut off the ends that will be slightly damaged by the end caps.

Other tests may be identified in the future that will need used fuel. The pros and cons of where those tests are performed will be evaluated once those tests and the amount of material needed is identified. However, the materials that will be shipped will be shipped under the requirements for Type A or Type B shipments

## 4.1 Sample Shipping

### 4.1.1 Shipping Defueled Cladding

**Type A Shipping**

With sufficient cleaning, defueled cladding segments can be shipped under Type A shipment requirements. There are several packages that can be used for this purpose, and this type of shipment and receipt at all the national laboratories is routine. There is no need to identify a specific container at this time as they are plentiful and routinely used by the laboratories already.

### 4.1.2 Shipping Used Fuel Samples

**Type B Shipping**

Unfortunately, there is no simple way to ship used nuclear fuel. The NAC-LWT transport cask is the only option, at present, that has a valid Certificate of Compliance for shipping fuel samples. While the NAC-LWT has been handled by several laboratories, the cost to use this cask for small quantities of material is prohibitive.

Another cask available within the DOE-Complex is the TransNuclear, Inc. Fort St. Vrain shipping cask (TN-FSV) cask. The DOE owns two of these casks, their hardware, and transport trailers. These are located at INL. This cask is presently certified for graphite fuel blocks and full-length PWR fuel rods. The cask would require an amendment to the Certificate of Compliance for carrying smaller fuel rod segments.

Another potential option is to amend a Certificate of Compliance for a shipping drum. Presently, there are no shipping drums certified for mixed fission products or used nuclear fuel. The ES-3100 shipping package is the closest package that might be modified for shipping used fuel. A group from PNNL is examining the potential for using this drum in the future.

The pros and cons of each option (drum or shipping cask) need to be evaluated. Each will have costs that must be considered. For example, a drum reconfigured with for used fuel may present challenges for handling and unloading a highly radioactive inner package. Alternatively, no drop test would be required for the TN-FSV, but a receiving site might need to fabricate new handling fixtures to mate the cask to their hot cell.

Because used fuel samples will not require shipping for several years, there is time to resolve the type of package that can be used to ship fuel and clad samples between laboratories. However, if no other option is forthcoming, the NAC-LWT can be used for this purpose. This cask has been handled by ORNL, PNNL, and INL; these labs have procedures and equipment to utilize this transport package.

# 5. CONCLUSIONS

Up to 25 HBU fuel rods will be removed from assemblies to be placed in the Research Project Cask or sister assemblies that remain in the North Anna spent fuel pool and sent to INL for PIE. These sister fuel rods will be examined by non-destructive and destructive methods to document the condition of high burnup fuel as received. Ultimately, samples will be cut from select fuel rods and utilized in testing activities. The test results will be used by the EPRI team in support of their HBU fuel dry storage demonstration. The results will also be used by the UFDC to guide tests designed to address closure of identified technical data gaps.

Capabilities exist within the DOE laboratory complex to gather the data needed to address the EPRI recommendations for the sister rods. The PIE to be performed is expected to be sufficient to characterize the fuel and clad for any tests needed by the UFDC.

Shipping used fuel samples between laboratories is an issue that will need to be resolved. While de-fueled cladding does not present a problem, there are no Type B shipping packages certified for samples of used nuclear fuel. A commercial truck cask is available, however, for shipping small samples, it is not cost effective.

# 6. REFERENCES

1. “High Burnup Dry Storage Cask Research and Development Project: Final Test Plan.” Contract No.: DE-NE-0000593 Electric Power Research Institute, Palo Alto, California., February 27, 2014
2. U.S. Nuclear Regulatory Commission Certificate of Compliance, certificate number 9225, NAC International Inc. NAC-LWT package. Available from: http://rampac.energy.gov/certinfo/certificates/nrc/default.aspx
3. “Used Fuel Disposition Campaign – Gap Analysis to Support Extended Storage of Used Nuclear Fuel,” Revision 0, FCRD-USED-2011-000136 (PNNL-20509), Pacific Northwest National Laboratory, January 31, 2012
4. Used Fuel Disposition Campaign – Gap Prioritization and Closure Plan,” Draft, FCRD-USED-2012-000109, Pacific Northwest National Laboratory, April 30, 2012
5. “Used Nuclear Fuel Characteristics at End of Life,” Revision 0, FCRD-UFD-2013-000130, March, 2013
6. “Microhardness Testing of AFC-1B and AFC-1F,” INL/EXT-09-15626, Idaho National Laboratory, March 2008.

# APPENDIX A

## Section 3.6 Work to be Performed at the National Laboratories: Sister Rod Characterization

Section 3.6 of the EPRI *High Burnup Dry Storage Cask Research and Development Project: Final Test Plan* is reproduced here for clarity. Then entire test plan is available at this website: http://www.energy.gov/ne/downloads/high-burnup-dry-storage-cask-research-and-development-project-final-test-plan

## 3.6 Work to be Performed at the National Laboratories: Sister Rod Characterization

The characterization activities proposed in this section are intended to be performed at the national laboratories. Though these activities are necessary for the completion of the long-term cask demonstration project, they are not required for EPRI's performance of the scope of work under contract DE-NE-0000593. This work will be funded directly by DOE through their work control processes and procedures. All activities proposed are subject to DOE's discretion and the availability of appropriated funds.

The fuel rod cladding property testing described in this section provides the initial conditions of the fuel that will be used as a basis for the comparison when the Research Project Cask is opened for fuel investigation. A combination of non-destructive and destructive exams is to be performed.

Non-destructive examination (NDE) of the cladding will start at the national laboratory with detailed visual examination of each rod for signs of crud or oxide layer spallation, local wear, or other indications of degradation. NDE also includes cladding profilometry to determine the cladding outer diameter (OD) prior to destructive exams. The amount of creep during storage can be determined by comparing the OD of rods removed after the storage period with the OD of the rods removed before HDRP initiation. To capture OD variability of each rod, profilometry measurements should be taken at various axial positions as well as at two circumferential positions at each axial position.

After the NDE is completed, a series of destructive exams are performed to obtain detailed data on the fuel and cladding. The following is the list of destructive exams to be conducted:

- *Rod internal gas pressure and content.* The rods will be punctured to determine internal rod pressure, internal rod free volume, and gas composition (FP gases, helium) to determine the amount of fission gas released into the rod inside the cladding. The majority of the fission gas during reactor operation remains trapped inside the ceramic fuel pellets inside the fuel rods. The portion of the fission gas that escapes the fuel pellets is termed the 'fission gas release fraction,' and contributes to the overall pressure inside the rod. Rod internal pressures, in combination with local cladding temperatures, provide the driving force for microstructural changes in the cladding.

Rod segmentation after puncture tests will be carried out for subsequent destructive testing. The following tests at the national laboratories should be performed after segmentation with the fuel pellets still inside the rod segments:

- *Hydride content and orientation.* Hydrides contribute to cladding embrittlement. During reactor operation, a fraction of the hydrogen generated by the zirconium-water reaction is picked up by the cladding and diffuses into the cladding. Typically, most hydrides are oriented circumferentially, as shown in Figure 3-9. Under higher cladding tensile stresses and temperatures, which may occur during the cask-drying operation, some of the hydrides may reorient into a radial direction, as shown in Figure 3-10. Hydrides in the radial direction may substantially reduce cladding ductility. Hydride concentration and orientation data taken from rods that have experienced typical drying and long-term storage conditions will provide valuable additional information on the behavior of high burnup SNF during storage and subsequent transportation under normal and hypothetical accident conditions.

  Similar testing on rods extracted at the end of the prolonged HDRP period will provide information on the degree of hydride reorientation into the radial direction that actually occurs during normal cask-drying and storage conditions. This is because the primary conditions of interest for hydride reorientation are the initial rod internal gas pressure and the true temperature distribution throughout the cask during the drying and long-term storage period. At present, bounding assumptions are usually made, such as assuming 100 percent of the rods have internal gas pressures at the upper end of the known rod gas pressure distribution, and 100 percent of the length of every rod in every assembly increases in temperature to the 400°C temperature limit. Best estimate thermal models show rod temperatures are less than 400°C. Hence, it is anticipated that less hydride reorientation will occur—in the Research Project Cask and all other casks/canisters in current use—than is usually assumed.

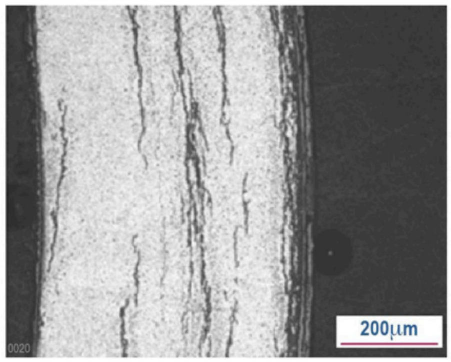



**Figure 3-9: Cross-section of a Fuel Rod (Zirconium hydrides in this rod are primarily in the circumferential direction).**

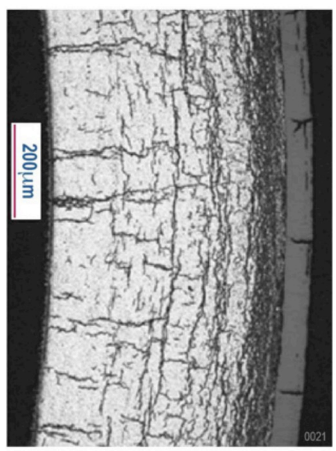



**Figure 3-10: Cross-section of a Fuel Rod with Significant Radial Hydride Orientation.**

- *Cladding mechanical testing.* After the above testing is completed, the cladding mechanical properties will be examined via ductility testing. Specific ductility tests will include ring compression and tensile testing with and without fuel inside the cladding segments. These ductility tests can be correlated to the hydride concentration and orientation data to provide an evaluation of fuel behavior under dynamic mechanical conditions. Ductility testing will be performed at various temperatures to determine DBTT ranges. Along with cladding temperature measurements and models, the DBTT data can be used to evaluate when the cladding in storage enters the DBTT region.

The number of tests that should be conducted will be a function of the following issues:

- Number of rods that can be shipped in a single transportation cask. This will provide approximately two dozen rods sampled from all three high burnup fuel types and a range of burnups above 45 GWD/MTU.
- The variability of properties and cladding types of interest previously described. For example, hydride concentration and orientation is expected to vary as a function of fuel design, burnup, and axial and circumferential position.
- Laboratory capabilities. This also includes the capacity to store rods in the hot cell(s).

It is anticipated that all rods received will have the NDE performed, such as profilometry to determine the OD of the rods. Even if some of the rods will be stored for later possible examination, it is important to measure their as-received cladding diameter to ensure accurate initial diameter information for comparison to post-storage profilometry data. While it is unlikely that storage of initially untested rods in a hot cell will affect the rod diameter, performing profilometry examinations at the time of receipt will eliminate this potential variable.

Rod puncture tests will be performed for all rods that will be subsequently sectioned for additional testing.[31] This would provide up to approximately two dozen data points. It would be preferable to have such tests performed on two or more rods with the same properties (e.g., fuel type, burnup, reactor operating history) to capture the variability in the properties.

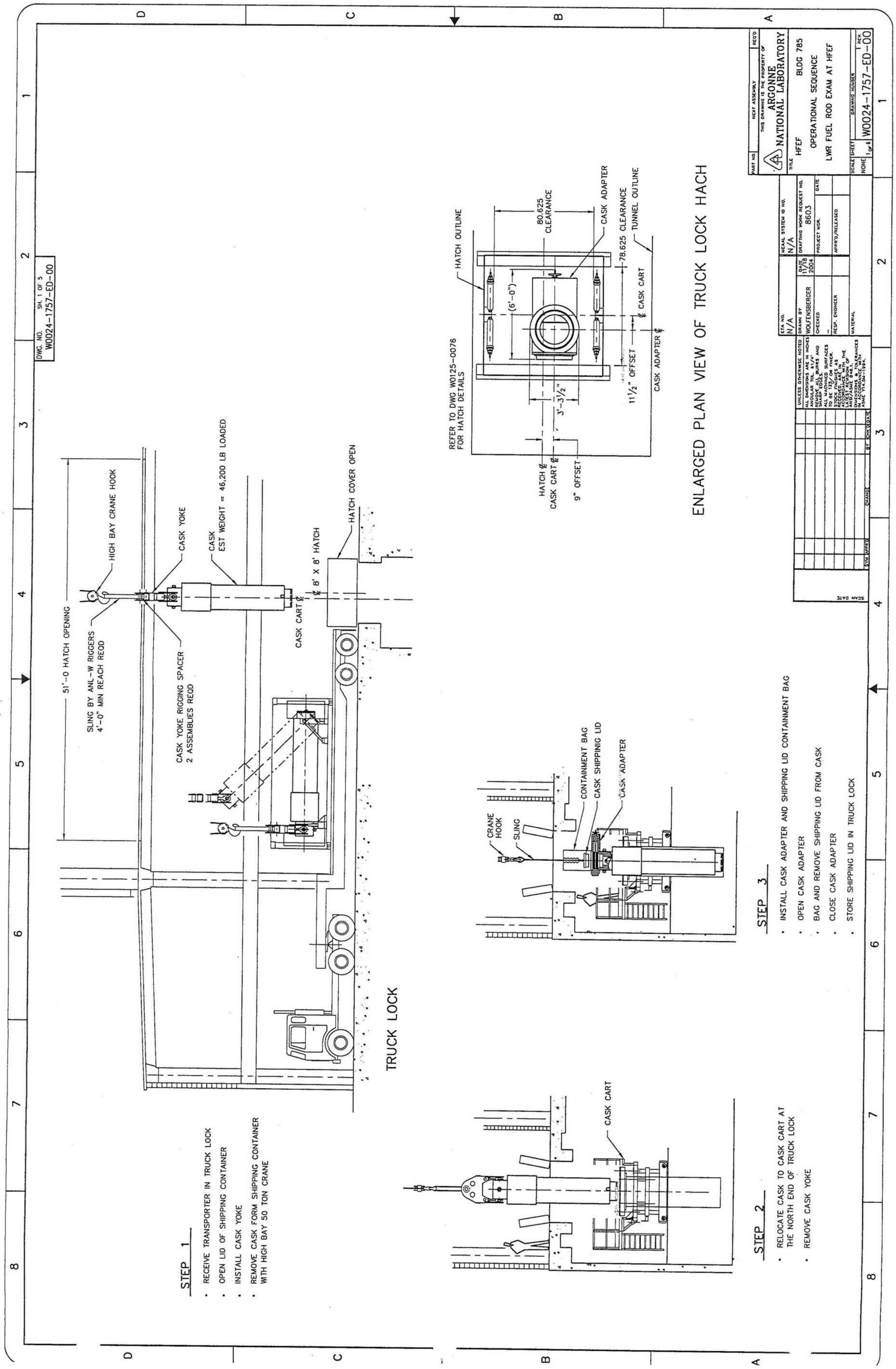
Oxide thickness, hydride concentration and orientation, and ductility measurements should be conducted at several axial and circumferential positions for all rods for which puncture testing was performed. Of particular interest will be the length of the fuel rods that would experience the highest temperatures during drying and storage. Hence, two or more axial locations within the center two meters of the rods should be selected for examination.

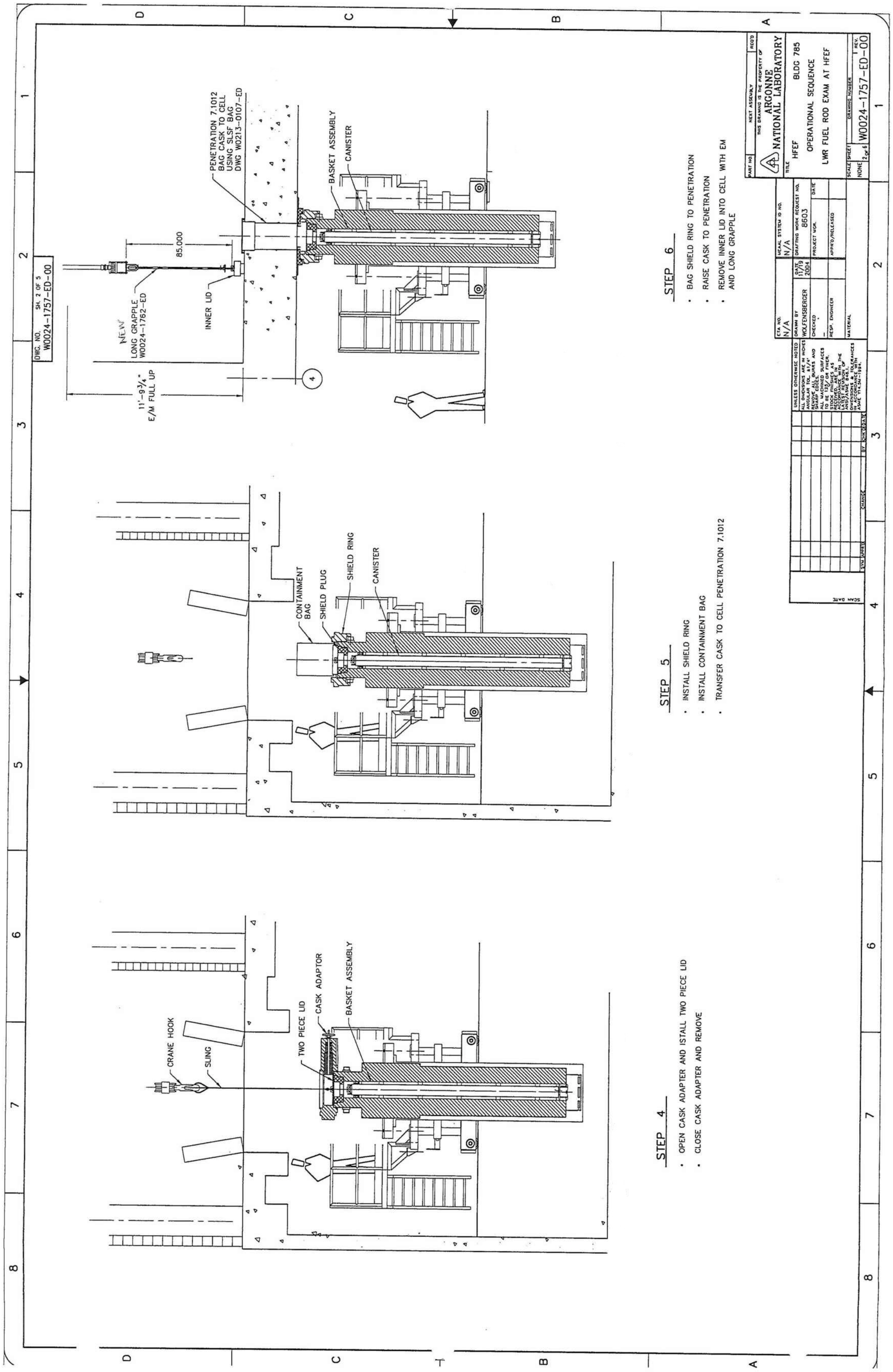
Cladding mechanical property testing should include replicates for combinations of fuel characteristics (e.g., fuel type, burnup, reactor operating history, axial location). Many existing tests have been conducted at more extreme conditions, using higher cladding temperatures and/or tensile stresses, than would be expected under actual operating conditions. Therefore, it is important that the mechanical property testing be performed under conditions characteristic of dry storage, which include, for example, the effect of pellet-cladding bonding and the mechanical load the fuel pellets can absorb so as to limit the amount of strain on the cladding.

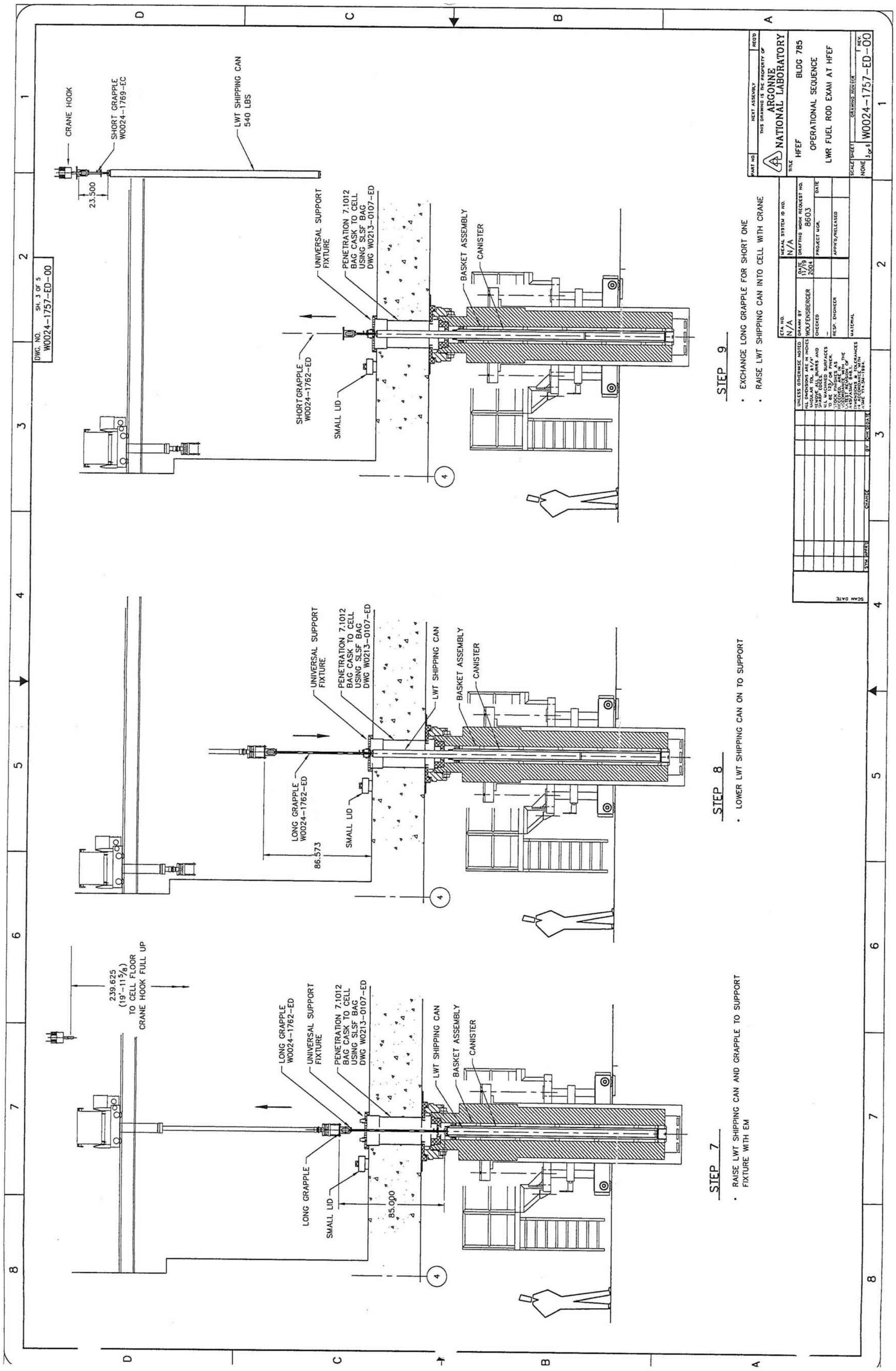
[31] Some rods shipped to the national laboratory(ies) may be set aside for future testing.

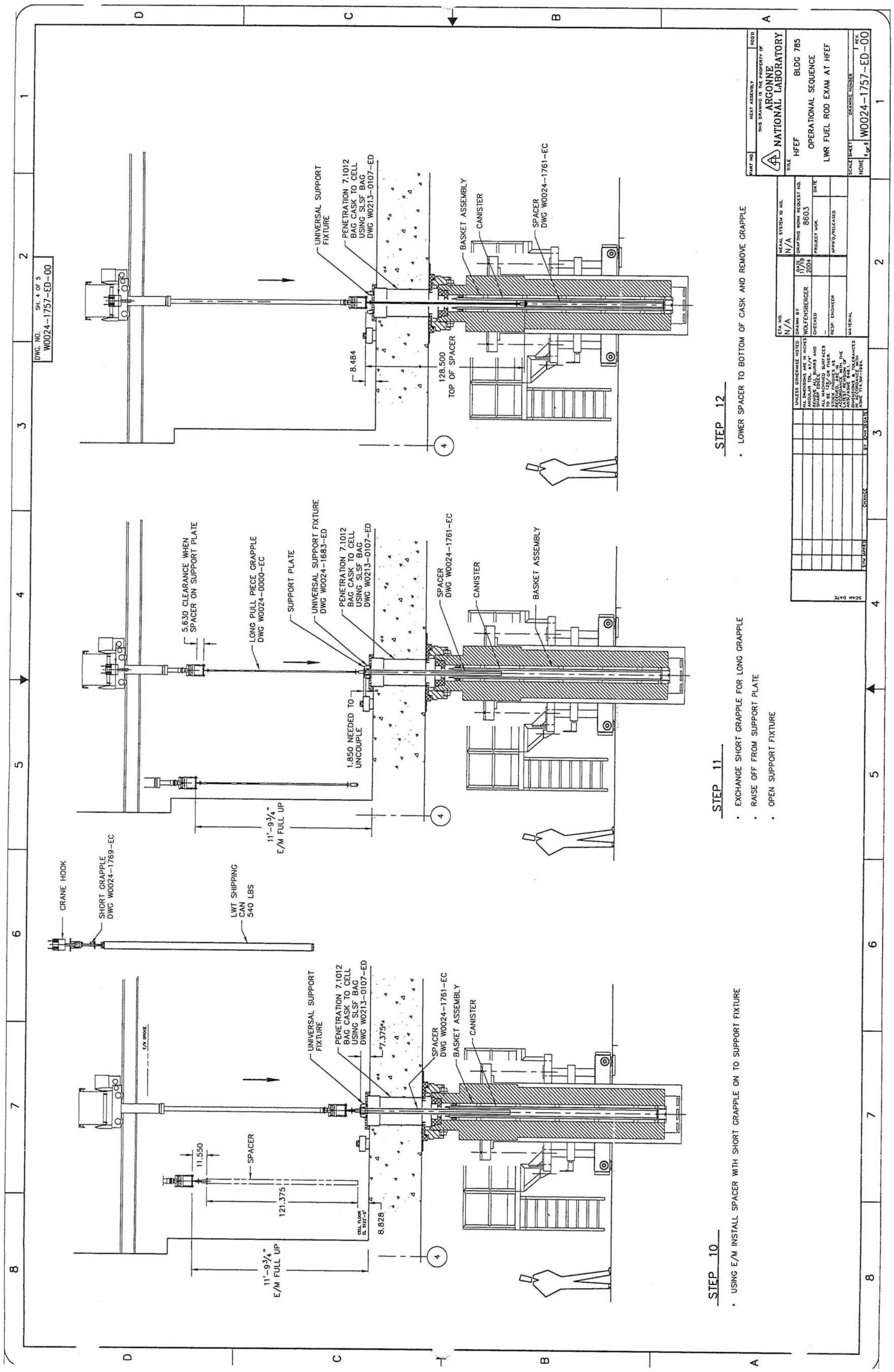
# APPENDIX B

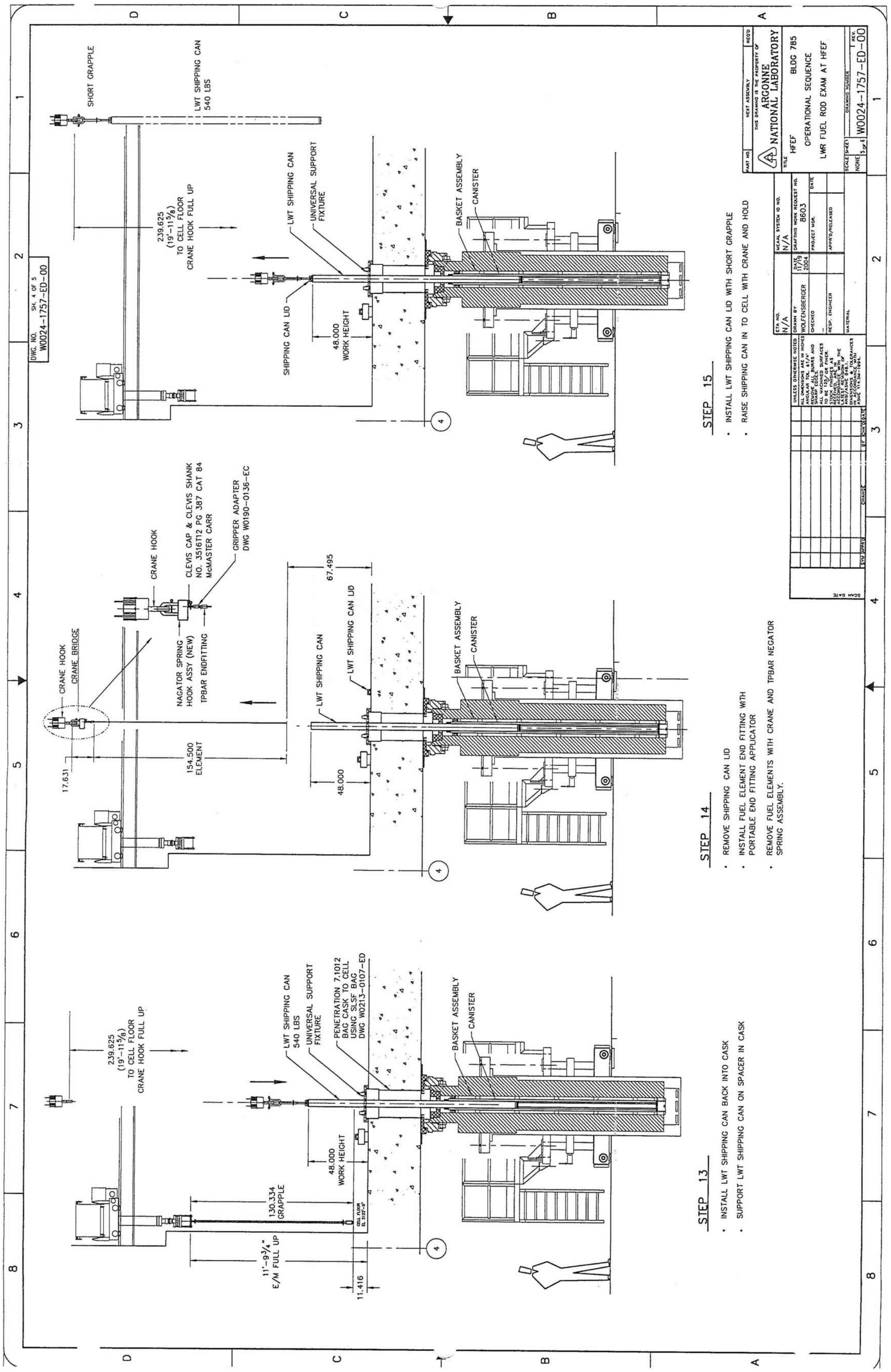
# HFEF NAC-LWT Loading/Unloading Sequence Diagrams

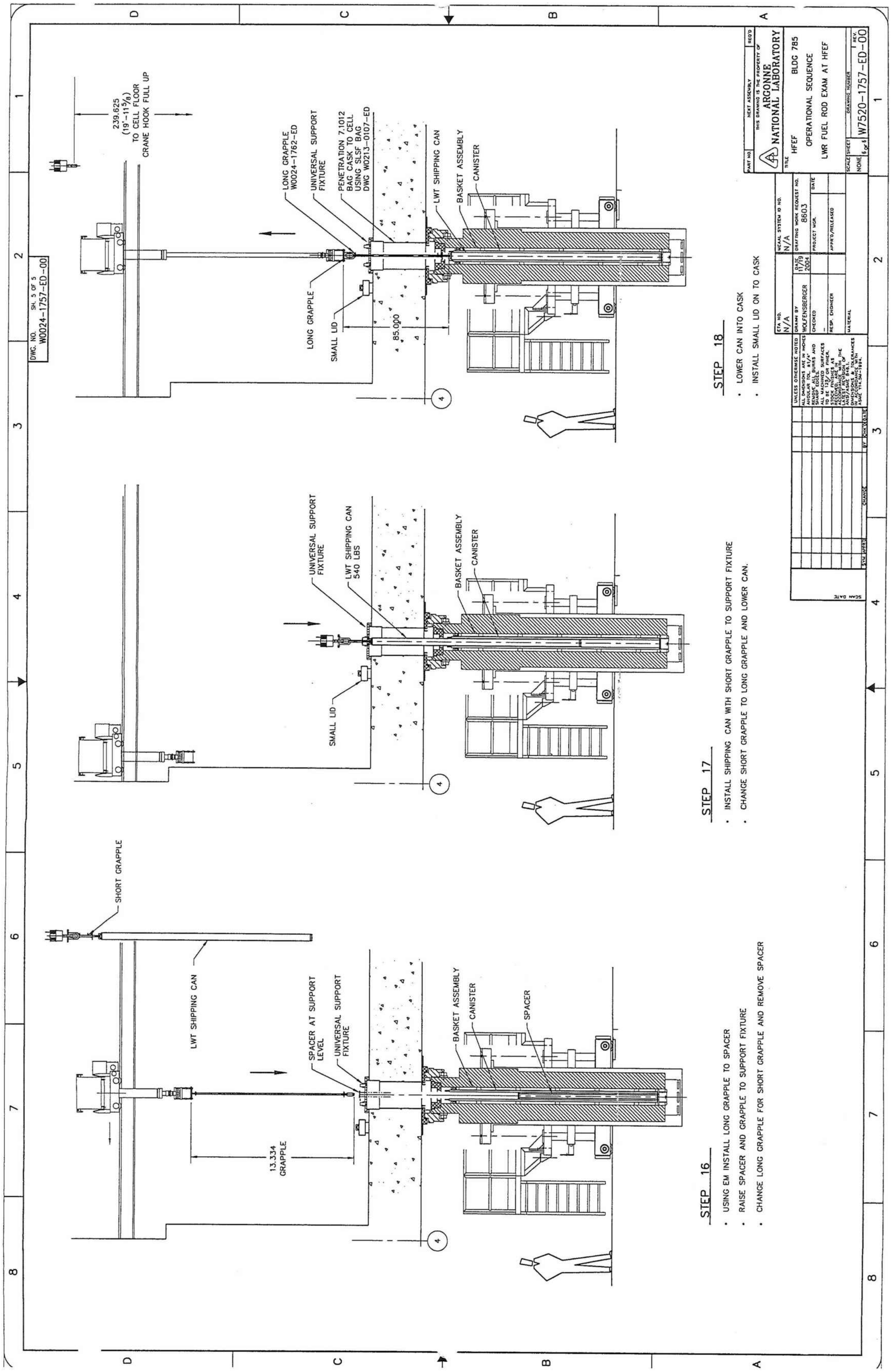

ENLARGED PLAN VIEW OF TRUCK LOCK HACH
REFER TO DWG W0125-0076 FOR HATCH DETAILS
HATCH OUTLINE
80.625 CLEARANCE
CASK ADAPTER
78.625 CLEARANCE
TUNNEL OUTLINE
CASK CART
CASK ADAPTER ℄
11½" OFFSET
3'-3½"
(6'-0")
HATCH ℄
CASK CART ℄
9" OFFSET
51'-0 HATCH OPENING
SLING BY ANL-W RIGGERS 4'-0" MIN REACH REQD
HIGH BAY CRANE HOOK
CASK YOKE
CASK YOKE RIGGING SPACER 2 ASSEMBLIES REQD
CASK EST WEIGHT = 46,200 LB LOADED
CASK CART ℄
℄ 8' X 8' HATCH
HATCH COVER OPEN
TRUCK LOCK
CRANE HOOK
SLING
CONTAINMENT BAG
CASK SHIPPING LID
CASK ADAPTER
CASK CART
STEP 1
RECEIVE TRANSPORTER IN TRUCK LOCK
OPEN LID OF SHIPPING CONTAINER
INSTALL CASK YOKE
REMOVE CASK FORM SHIPPING CONTAINER WITH HIGH BAY 50 TON CRANE
STEP 2
RELOCATE CASK TO CASK CART AT THE NORTH END OF TRUCK LOCK
REMOVE CASK YOKE
STEP 3
INSTALL CASK ADAPTER AND SHIPPING LID CONTAINMENT BAG
OPEN CASK ADAPTER
BAG AND REMOVE SHIPPING LID FROM CASK
CLOSE CASK ADAPTER
STORE SHIPPING LID IN TRUCK LOCK
DWG. NO. W0024-1757-ED-00 SH. 1 OF 5
ARGONNE NATIONAL LABORATORY
HFEF BLDG 785
OPERATIONAL SEQUENCE
LWR FUEL ROD EXAM AT HFEF
W0024-1757-ED-00
WOLFENSBERGER
8603


DWG. NO. W0024-1757-ED-00 SH. 2 OF 5
PENETRATION 7.1012 BAG CASK TO CELL USING SLSF BAG DWG W0213-0107-ED
BASKET ASSEMBLY
CANISTER
85.000
NEW
LONG GRAPPLE W0024-1762-ED
INNER LID
11'-9¾" E/M FULL UP
STEP 6
BAG SHIELD RING TO PENETRATION
RAISE CASK TO PENETRATION
REMOVE INNER LID INTO CELL WITH EM AND LONG GRAPPLE
CONTAINMENT BAG
SHIELD PLUG
SHIELD RING
CANISTER
STEP 5
INSTALL SHIELD RING
INSTALL CONTAINMENT BAG
TRANSFER CASK TO CELL PENETRATION 7.1012
CRANE HOOK
SLING
TWO PIECE LID
CASK ADAPTOR
BASKET ASSEMBLY
STEP 4
OPEN CASK ADAPTER AND ISTALL TWO PIECE LID
CLOSE CASK ADAPTER AND REMOVE
ARGONNE NATIONAL LABORATORY
HFEF BLDG 785
OPERATIONAL SEQUENCE
LWR FUEL ROD EXAM AT HFEF
W0024-1757-ED-00


STEP 7
• RAISE LWT SHIPPING CAN AND GRAPPLE TO SUPPORT FIXTURE WITH EM
STEP 8
• LOWER LWT SHIPPING CAN ON TO SUPPORT
STEP 9
• EXCHANGE LONG GRAPPLE FOR SHORT ONE
• RAISE LWT SHIPPING CAN INTO CELL WITH CRANE
CRANE HOOK
SHORT GRAPPLE W0024-1769-EC
LWT SHIPPING CAN 540 LBS
23.500
UNIVERSAL SUPPORT FIXTURE
PENETRATION 7,1012 BAG CASK TO CELL USING SLSF BAG DWG W0213-0107-ED
BASKET ASSEMBLY
CANISTER
SHORT GRAPPLE W0024-1762-ED
SMALL LID
LONG GRAPPLE W0024-1762-ED
LWT SHIPPING CAN
86.573
85.000
LONG GRAPPLE
239.625 (19'-11⅝) TO CELL FLOOR CRANE HOOK FULL UP
ARGONNE NATIONAL LABORATORY
HFEF
BLDG 785
OPERATIONAL SEQUENCE
LWR FUEL ROD EXAM AT HFEF
W0024-1757-ED-00


STEP 10
USING E/M INSTALL SPACER WITH SHORT GRAPPLE ON TO SUPPORT FIXTURE
STEP 11
EXCHANGE SHORT GRAPPLE FOR LONG GRAPPLE
RAISE OFF FROM SUPPORT PLATE
OPEN SUPPORT FIXTURE
STEP 12
LOWER SPACER TO BOTTOM OF CASK AND REMOVE GRAPPLE
CRANE HOOK
SHORT GRAPPLE DWG W0024-1769-EC
LWT SHIPPING CAN 540 LBS
UNIVERSAL SUPPORT FIXTURE
PENETRATION 7.1012 BAG CASK TO CELL USING SLSF BAG DWG W0213-0107-ED
SPACER DWG W0024-1761-EC
BASKET ASSEMBLY
CANISTER
SUPPORT PLATE
UNIVERSAL SUPPORT FIXTURE DWG W0024-1683-ED
LONG PULL PIECE GRAPPLE DWG W0024-0000-EC
5.630 CLEARANCE WHEN SPACER ON SUPPORT PLATE
1.850 NEEDED TO UNCOUPLE
11'-9¾" E/M FULL UP
121.375
11.550
SPACER
8.828
7.375
8.484
128.500 TOP OF SPACER
DWG. NO. W0024-1757-ED-00 SH. 4 OF 5
ARGONNE NATIONAL LABORATORY
HFEF BLDG 785
OPERATIONAL SEQUENCE
LWR FUEL ROD EXAM AT HFEF
W0024-1757-ED-00
WOLFENSBERGER
8603


STEP 13
INSTALL LWT SHIPPING CAN BACK INTO CASK
SUPPORT LWT SHIPPING CAN ON SPACER IN CASK
STEP 14
REMOVE SHIPPING CAN LID
INSTALL FUEL ELEMENT END FITTING WITH PORTABLE END FITTING APPLICATOR
REMOVE FUEL ELEMENTS WITH CRANE AND TPBAR NEGATOR SPRING ASSEMBLY.
STEP 15
INSTALL LWT SHIPPING CAN LID WITH SHORT GRAPPLE
RAISE SHIPPING CAN IN TO CELL WITH CRANE AND HOLD
ARGONNE NATIONAL LABORATORY
HFEF BLDG 785
OPERATIONAL SEQUENCE
LWR FUEL ROD EXAM AT HFEF
W0024-1757-ED-00


DWG. NO. W0024-1757-ED-00 SH. 5 OF 5
239.625 TO CELL FLOOR CRANE HOOK FULL UP
LONG GRAPPLE W0024-1762-ED
UNIVERSAL SUPPORT FIXTURE
PENETRATION 7.1012 BAG CASK TO CELL USING SLSF BAG DWG W0213-0107-ED
LWT SHIPPING CAN
BASKET ASSEMBLY
CANISTER
LONG GRAPPLE
SMALL LID
85.000
STEP 18
LOWER CAN INTO CASK
INSTALL SMALL LID ON TO CASK
UNIVERSAL SUPPORT FIXTURE
LWT SHIPPING CAN 540 LBS
BASKET ASSEMBLY
CANISTER
SMALL LID
STEP 17
INSTALL SHIPPING CAN WITH SHORT GRAPPLE TO SUPPORT FIXTURE
CHANGE SHORT GRAPPLE TO LONG GRAPPLE AND LOWER CAN.
SHORT GRAPPLE
LWT SHIPPING CAN
SPACER AT SUPPORT LEVEL
UNIVERSAL SUPPORT FIXTURE
BASKET ASSEMBLY
CANISTER
SPACER
13.334 GRAPPLE
STEP 16
USING EM INSTALL LONG GRAPPLE TO SPACER
RAISE SPACER AND GRAPPLE TO SUPPORT FIXTURE
CHANGE LONG GRAPPLE FOR SHORT GRAPPLE AND REMOVE SPACER
ARGONNE NATIONAL LABORATORY
HFEF
BLDG 785
OPERATIONAL SEQUENCE
LWR FUEL ROD EXAM AT HFEF
W7520-1757-ED-00