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March 30, 2012

Mr. Ken Sorenson
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P.O. Box 5800
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Dear Ken:

Neutron Irradiation of Hydrided Materials in HFIR—Summary of Initial Activities – ORNL Fuel Cycle Research and Development (FCR&D) Milestone M2FT-12OR0805041 – Due 03/31/20112

The enclosed report, *Neutron Irradiation of Hydrided Materials in HFIR—Summary of Initial Activities,* documents ongoing work performed at Oak Ridge National Laboratory for the Department of Energy, Office of Fuel Cycle Technology Used Fuel Disposition Campaign (UFDC) and satisfies the deliverable for milestone M2FT-OR0805041, "Initiate Clad Testing at HFIR," due March 31, 2012.

Three capsules containing hydrogen-charged Zircaloy-4 cladding material have been placed in the High Flux Isotope Reactor (HFIR). Irradiation of the capsules began in HFIR Cycle 440B on March 26, 2012. Two of the capsules contain three 1-in. hydrided Zircaloy-4 samples, and one capsule contains a single 6-in. (15.24 cm) hydrided Zircaloy-4 sample. The 1-in. samples included in the initial HFIR insertion will be removed after one and two HFIR cycles of irradiation for post-irradiation examination (PIE) metallography to perform an early evaluation of the hydride morphology. The 6-in. cladding sample will be irradiated for approximately 11 HFIR cycles to accumulate a fast neutron fluence to match the end-state neutron fluence of the reference high-burnup cladding material discharged from the H. B. Robinson reactor. Additional capsules containing hydrided cladding material will be inserted in the HFIR at later dates.

If you have any questions, please contact me at (865) 241-5750.

Sincerely,

Robert L. Howard
Reactor and Nuclear Systems Division

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Neutron Irradiation of Hydrided Cladding Material in HFIR—Summary of Initial Activities

Fuel Cycle Research & Development

Prepared for:
U.S. Department of Energy
Used Fuel Disposition Campaign

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March 30, 2012

FCRD-UFD-2012-000080

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FIGURES

TABLES

1. Summary

This report documents ongoing work performed at Oak Ridge National Laboratory (ORNL) for the Department of Energy, Office of Fuel Cycle Technology Used Fuel Disposition Campaign (UFDC), and satisfies the deliverable for milestone M2FT-OR0805041, “Initiate Clad Testing at HFIR.”

Three capsules containing hydrogen-charged Zircaloy-4 cladding material have been placed in the High Flux Isotope Reactor (HFIR). Irradiation of the capsules began in HFIR Cycle 440B on March 26, 2012. Two of the capsules contain three 1-in. hydrided Zircaloy-4 samples and one capsule contains a single 6-in. (15.24 cm) hydrided Zircaloy-4 sample. The 1-in. samples included in the initial HFIR insertion will be removed after one and two HFIR cycles of irradiation for post-irradiation examination (PIE) metallography to perform an early evaluation of the hydride morphology. The 6-in. cladding sample will be irradiated for approximately 11 HFIR cycles to accumulate a fast neutron fluence to match the end-state neutron fluence of the reference high-burnup cladding material discharged from the H. B. Robinson reactor. Additional capsules containing hydrided cladding material will be inserted in the HFIR at later dates.

2. Introduction

When fuel is no longer capable of efficiently contributing to the fission chain reaction, it is removed from the reactor and is termed used nuclear fuel (UNF) or spent nuclear fuel (SNF). Because of the high heat load and radioactivity, UNF is initially stored in water-filled pools to provide both cooling and shielding. Reactors were not designed or built to store all of the UNF produced over their lifetime of operation. This is especially true for reactors applying for license extensions of up to 20 years, bringing their total operating lifetime to 60 years. Most reactors initially addressed this storage shortfall by reracking their pools to increase the in-pool storage capability by decreasing the spacing between assemblies. Typically, this also requires the use of additional fixed neutron poisons and burnup credit to meet the 10 CFR 50.68 criticality safety requirements. As the pools reach capacity, it is necessary to remove assemblies and place them into dry cask storage.

Until a disposition pathway (either recycling or geologic disposal) is chosen and implemented, the storage periods for UNF will likely be longer than were originally intended. The ability of the important-to-safety structures, systems, and components (SSCs) to continue to meet safety functions over extended times must be determined. In addition, it needs to be determined if these SSCs can also meet applicable safety functions when the UNF is transported to its final location. To facilitate all options for disposition and to maintain retrievability and normal back-end operations, the likelihood that the UNF remains undamaged after extended storage needs to be evaluated. This does not preclude consideration of other options, such as canning of all UNF, from a total systems perspective to determine overall benefit to nuclear waste management.

As noted in *Gap Analysis to Support Extended Storage of Used Nuclear Fuel* (DOE 2012),[1] a significant amount of data is needed to determine the effects of high-burnup and different clad alloys with regards to hydrogen embrittlement and reorientation and their subsequent effects on the ability of cladding to maintain structural integrity. Very little, if any, data is publicly available on the newer cladding alloys and on high-burnup cladding. Most current data that is available is on unirradiated cladding.

Experimental work must be performed to obtain this data and to obtain additional information to address the numerous challenges regarding justification of cladding behavior, such as whether low-temperature mechanisms (e.g., for delayed hydride cracking, annealing, and creep) are important over extended storage.

Irradiation is known to have a significant impact on the properties and performance of Zircaloy cladding and structural materials. High-energy neutrons (>1 MeV) are known to produce two different dislocation loops, the <a> and <c> loops. The size and density of the dislocation loops alter the mechanical properties, specifically the strength (e.g., hardness, tensile strength, burst strength) and ductility (e.g., uniform and total elongation strains). Irradiation increases the cladding strength and decreases the cladding ductility by changing the configuration (amorphization) of the second-phase precipitates (SPPs) such as $Zr(Nb,Fe)_2$. The processes that lead to dislocation formation or SSP amorphization depend on the material temperature; as a result, the irradiation temperature has an important effect on the cladding microstructure and consequently the mechanical properties. Higher irradiation temperatures result in larger <a> loop dislocations, whereas <c> loops do not form at 77°C (EPRI 2006).[2] Thermal annealing, such as can occur at the higher clad temperatures during drying or initial dry storage, can result in a dramatic decrease in hardness and corresponding increase in ductility.

Normal operation in reactors cannot only result in irradiation damage of cladding, but also introduce hydrogen into the metal due to formation of a waterside corrosion layer. During reactor operations, the high-temperature water reacts with the cladding surface producing a zirconium oxide layer. Hydrogen is released during this chemical reaction, and a fraction of this hydrogen is absorbed by the Zircaloy-4 (hydrogen pickup). The solubility of hydrogen in zirconium is highly temperature-dependent, with increased solubility at higher temperatures. When the concentration of hydrogen exceeds the solubility limit, zirconium hydride precipitates form. Depending on the size, distribution, and orientation, these hydrides can embrittle the cladding and reduce ductility. Furthermore, the presence of hydrides can facilitate cracking if the hydrides are aligned radially, perpendicular to the tensile stress field. Cladding hydrides are typically observed to be oriented in the circumferential direction but can reorient to the radial direction, depending on the stress level of the cladding when it is cooled from a higher temperature, such as will occur following the drying process. Hydrides have also been shown to diffuse to colder regions of the cladding under a relatively small temperature gradient. The reorientation and diffusion of hydrides can result in cracking of the cladding.

One of the primary needs identified in the *Gap Analysis to Support Extended Storage of Used Nuclear Fuel FCRD-USED-2011-000136*[1] is to establish the link between the behavior and performance of unirradiated cladding and actual irradiated cladding. The UFDC is planning to address this need through both testing and modeling and in collaboration with university partners under the NE Universities Program (NEUP). ORNL has begun to address part of the testing component of this linkage with an experimental concept to simulate high-burnup cladding by irradiating cladding material in the HFIR.

2.1 General Description of Approach

Fast neutron irradiation of pre-hydrided zirconium-alloy cladding in the HFIR at elevated temperatures will be carried out to simulate the effects of high burnup on used fuel cladding for use in understanding the material properties relevant to very long-term storage (VLTS) (e.g., >60 y). Irradiated pre-hydrided metallic materials will generate baseline data to benchmark hot-cell testing of high-burnup used fuel cladding at relatively low cost, and more importantly, samples free of alpha contamination that can be provided to researchers/students in universities that do not have hot cell facilities to handle highly contaminated high-burnup used fuel cladding to support their research projects for the UFDC.

This simulation approach should provide well-controlled neutron irradiation of pre-hydrided materials in the desired temperature range (200–350°C) similar to the service temperatures of the BWRs and PWRs that generate high-burnup fuel. The pre-hydrided specimens will be fabricated by using an existing hydrogen charging system at the ORNL, which was developed by an ongoing program for the Nuclear Regulatory Commission (NRC). The hydrogen content will be in the range of 100-800 weight parts per million (wppm), which are similar to what has been observed for high-burnup used fuel cladding. The hydrogen content will be analyzed, and the hydride morphology will be characterized and compared to the high burnup used fuel cladding to optimize experimental conditions. The pre-hydrided specimens will be irradiated up to a fast fluence of 1.3×10^{22} neutrons/cm^2 (>1 MeV), corresponding to a burnup level of 65 GWd/MTU.[3]

Table 2-1. Proposed Neutron Irradiation at the HFIR

Irradiation temperature	200–250°C	Service temperature of the cladding for BWR
	300–350°C	Service temperature of the cladding for PWR
Typical sample size	Cladding OD: 9.5–10 mm	Varies with cladding type
	Wall-thickness: 0.60–0.76 mm	Varies with cladding type
	Length: 25–75 mm	75 mm for as-received, 25 mm for hydrided samples
Neutron fluence (>1 MeV)	$\sim 6.0 \times 10^{21}$ n/cm^2	Corresponding to burnup level of 31.5 GWd/MT (5 HFIR cycles)
	9.5×10^{21} n/cm^2	Corresponding to burnup level of 50 GWd/MT (8 HFIR cycles)
	13.0×10^{21} n/cm^2	Corresponding to burnup level of 64.5 GWd/MT (11 HFIR cycles)
Materials	Zircaloy-2, Zircaloy-4, M5, and ZIRLO	M5 and ZIRLO: advanced zirconium alloy for PWR
	As-received and hydrided Zr alloys	Pre-hydrided materials will be fabricated at ORNL

3. Overview of Activities

3.1 Identification of Surrogate Material Size Constraints

There are several physical constraints on the length of material that can be produced in this experiment. First, the fuel height in the HFIR is about 20 in., so that will be the maximum usable length of material that could be produced for specimens that could be irradiated. The maximum usable furnace length of the current ORNL hydriding system is 12 in. The ends of the material placed in the furnace will not be as uniformly hydrided as the center length of material, thus further limiting the length of usable hydride material produced. Further, as can be seen from Figure 3-1, 3 in. (7.62 cm) on either side of the HFIR core midplane will see a relatively uniform neutron fluence; steeper fluence axial gradients will occur for samples over 6 in. long. These size constraints were communicated to national laboratory and university researchers participating in the UFDC Cladding Workshop held in Las Vegas, Nevada, November 15-17, 2011. The size constraints were communicated so that researchers could start to plan their future testing on surrogate material based on these size constraints.

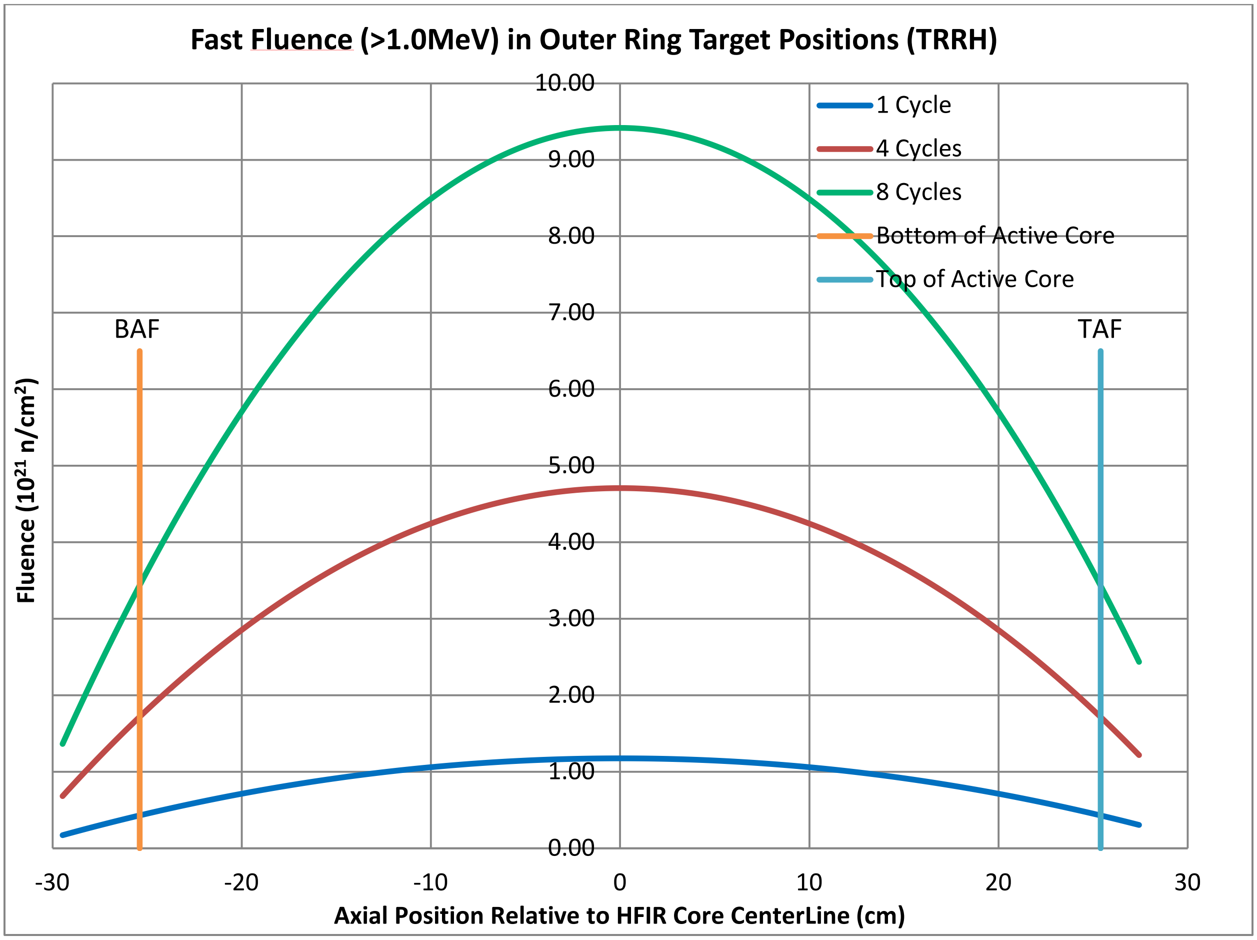


Figure 3-1. Fast Fluence in the Outer Ring Target Positions.

3.1.1 Selection and Receipt of Cladding Material from Sandia National Laboratory

ORNL and Sandia National Laboratory (SNL) collaborated to identify an initial source of cladding material for testing. SNL researchers were able to identify a small amount of Zircaloy-4 cladding that was made available from another project. SNL shipped three 24.5-in. pieces of Zircaloy-4 cladding designed for a 17×17 PWR assembly to ORNL in early November 2011.

3.1.2 Identification of Reference Material for Surrogate Development and Design Point for HFIR Target Setup

Benchmarking was discussed at the UFDC Cladding Workshop conducted in Las Vegas, November 15-17, 2011, to solicit input from a diverse group of national laboratory and university researchers. Specifically, input was requested on what material should be used as a reference target for comparitive purposes. Since the first batch of surrogate high burnup clad will be Zircaloy-4, workshop participants agreed one of the PWR Zircaloy-4 materials available (H. B. Robinson, Surry, TMI-1, or Calvert Cliffs highlighted in Table 3-1) should be selected as the reference material. The following points were taken into consideration in selecting the reference material:

- The Calvert Cliffs material should not be used as a benchmark material because the hydrogen content has not been adequately characterized.

- Trying to match the Surry material may be attractive because the lower burnup (36 GWd/MTU) would allow for fewer cycles in HFIR and would allow access to the surrogate material in a shorter time frame for comparison. An obvious downside of this selection would be that this does not meet the definition of high burnup (greater than 45 GWd/MTU).
- The TMI-1 material might be a useful benchmark to target given the burnup values and that the material appears to be well characterized.
- The H. B. Robinson Zircaloy-4 would offer the highest burnup material to benchmark against. It is well characterized and has the largest hydrogen pickup. ORNL, the Electric Power Research Institute (EPRI), NRC, and Argonne National Laboratory investigators are familiar with this material.

Table 3-1. Characteristics of Fuel Rod Segments ORNL for Possible Use as Reference Material (Burnup Values are Rod Averaged)

Reactor name	H. B. Robinson	Limerick	Surry	TMI-1	Calvert Cliffs	Cooper	North Anna	Catawba (MOX)
Reactor type	PWR	BWR	PWR	PWR	PWR	BWR	PWR	PWR
Enrichment, wt %	2.90	3.40-3.95	3.1%	4.00	2.45 to 3.04%	1.33-2.93	4.20	2.4 to 5%
Burnup, GWd/MTU	63-67	54-57	36	48-50	43	28	63-70	40-47
Discharge date	1995	1998	1981	1997	1982	1982	2004	2008
Cladding	Zircaloy-4	Zr-lined Zircaloy-2	Zircaloy-4	Low-Sn Zircaloy-4	Zircaloy-4	Zircaloy-2	M5	M5
Nominal OD, mm	10.76	11.18	10.72	10.92	11.18	14.3	9.50	9.50
Initial wall thickness, mm	0.76	0.71	0.62	0.69	0.66	0.94	0.57	0.57
OD oxide, µm	≤100	≈10	<40	≤50	Not provided	Not provided	<20	<10**
Hydrogen pickup, wppm	≤800	70	<300	≤300	Not provided	Not provided	<120	<55
Fueled	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

** Estimated.

Based on the discussions held at the workshop, the H. B. Robinson fuel has been selected as the reference material to target for the first batch of surrogate high-burnup clad material. As such, the following parameters were identified for the experiment setup:

- Hydrogen content: charging between 500-800 wppm (this is the range of hydrogen obtained from post-irradiation examination characterization of H. B. Robinson fuel)
- Maximum Neutron Fluence: will be in the range 11 to 13 × 10^{21} n/cm^2 based on data provided in EPRI Technical Report 1001558, *Design, Operation, and Performance Data for High Burnup*

PWR Fuel from the H.B. Robinson Plant for Use in the NRC Experimental Program at Argonne National Laboratory[3]

- Irradiation temperature: Cladding surface temperature of 330°C

The cladding surface temperature was selected based on the following: The H. B. Robinson fuel/cladding was irradiated for seven cycles attaining a final fuel burnup of ~67 GWd/MTU. The H. B. Robinson plant is a 2500 MWt PWR. Recently, fuel/cladding from the Catawba nuclear power plant (a 3411 MWt PWR) was evaluated (PIE) at ORNL and extensive fuel performance analyses were performed. These fuel rod simulations (ORNL/MD/LTR-331 [draft] using the NRC's FRAPCON-3 code) for the examined Catawba fuel rods will be used to set the desired irradiation conditions (cladding temperature and approximate temperature gradient) for the cladding in HFIR (and the capsule design) since the Catawba/H. B. Robinson operating conditions are very similar (inlet/outlet coolant temperatures are close and initial rod average linear heat generation rates [ALHGRs] are close) and the Catawba fuel performance analyses are available. An irradiation time-step with a rod ALHGR of ~20 kW/m (6.1 kW/ft, approximate average operating conditions) was chosen for the cladding conditions. A plot of the axial cladding temperatures (and coolant temperature) is illustrated in Figure 3-2.

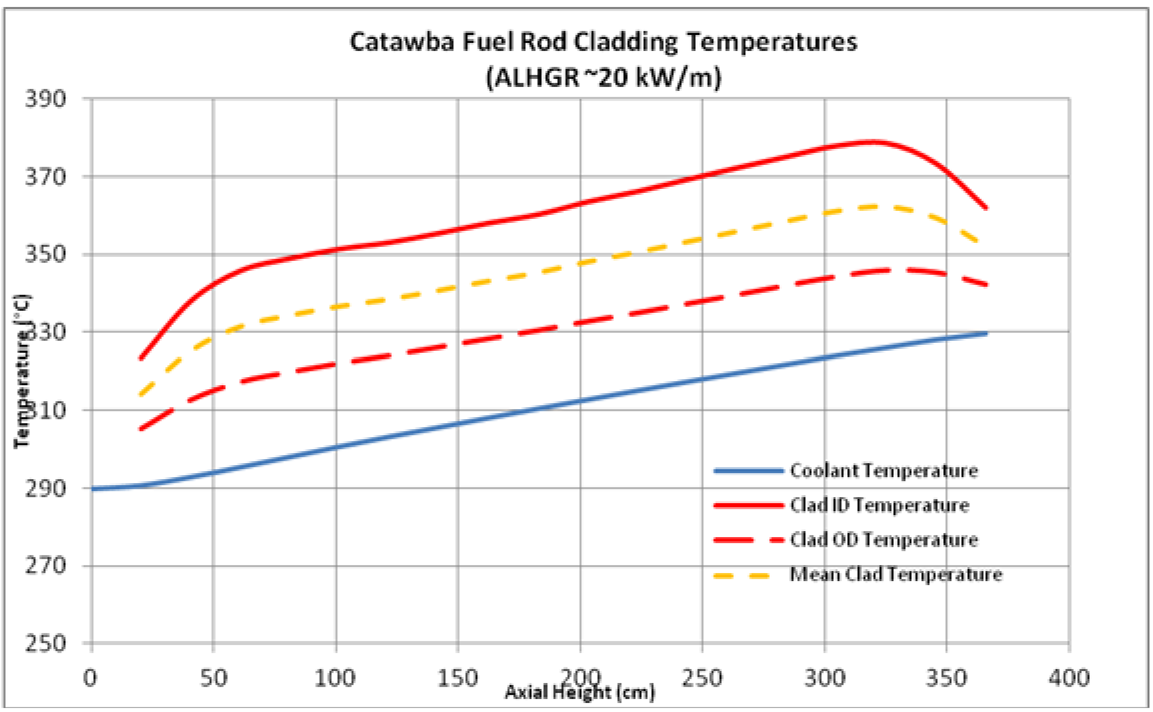


Figure 3-2. Axial Cladding and Coolant Temperatures from Catawba Fuel Performance Analysis.

The design point is taken at the midplane of the Catawba rod where the cladding surface temperature is approximately 330°C with a temperature gradient across the cladding of ~30°C. For the HFIR test irradiation, the capsule will be designed (gas gaps, fill gas, and internal heater [i.e., gamma heating in a Mo tube inside the cladding]) to achieve a clad surface temperature of 330°C (it would be over-specification of the problem to match both the surface temperature and the temperature gradient).

Note the Zircaloy-4 material from SNL appears to be typical of a 17×17 assembly (9.5 mm OD and thickness of 0.57 mm), and the H. B. Robinson benchmark material is from a 15×15 assembly

(10.77 mm OD and thickness of 0.762 mm); thus the diameters and cladding wall thicknesses differ (for the same LHGR, the H.B.Robinson rod would be slightly cooler [not significant] and the gradient would be slightly higher [not significant]).

3.1.3 Development of Hydriding Protocol

Unirradiated zirconium-based cladding tubes with a specified hydride concentration are needed for insertion into the HFIR. Hydrogen charging is accomplished using a furnace with a pressurized chamber. Protocols for sample preparation and operation of the furnace were developed and documented in *Procedure for Hydrogen-gas Charging of Unirradiated Zr Based Materials MET-NFM-SOG-40.*[4] This document is included as Attachment 1.

3.1.4 Sample Preparation and Hydriding

The results described in this report are from tests conducted with Zircaloy-4 tubing samples with an outer diameter of 9.50 mm and a wall thickness of 0.57 mm. The hydrogen concentration for this as-received tubing was ≈15 wppm. Table 3-2 lists the concentrations of major alloying elements and some impurities in nominal modern 17×17 Zircaloy-4.

Table 3-2. Nominal Composition of Commercial Cladding Zircaloy-4

Element	Sn, wt %	Nb, wt %	Fe, wt %	Cr, wt %	Ni, wt %	O, wt %	Zr
Zircaloy-4[a]	1.45	--	0.21	0.10	--	0.125	Balance

[a]R. Comstock et al.[5]

The 75-mm to 150-mm-long samples were cut from Zircaloy-4 tubing for hydrogen charging. The diameter of each sample was measured with a micrometer to an accuracy of ±0.01 mm at the axial center of the sample. Length measurements were also taken. The sample was first cleaned in distilled water in an ultrasonic bath for ≈200 s to clean residues and then were cleaned with ethanol. The sample was then etched by the use of hydrofluoric (HF) and nitric (HNO_3) acids, as described by ASTM G2/G2M06. This step provides a “window” for hydrogen absorption onto the cladding tubes, because residues and oxide scales are “barriers” to hydrogen adsorption. Figure 3-3 shows the etched Zircaloy-4 after the surface oxide layer was removed. Polishing was also tried to remove the surface oxide layer, but the etching process was more efficient. Sample weights were not measured before and after each test with a balance because the accuracy of our balance (±0.001 g) was not good enough for the weight gain due to hydrogen absorption.

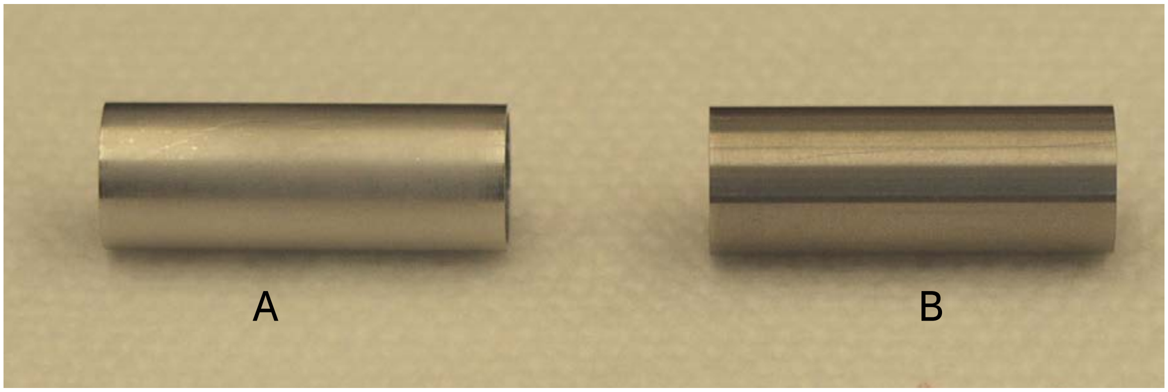


Figure 3-3. Photographs of (A) Acid Etched and (B) As-received Zircaloy-4 Cladding.

Figure 3-4. Fume Hood Used for Sample Etching with Hydrofluoric (HF) and Nitric (HNO_3) Acids.

The hydrogen content was measured with a LECO RH-404 Hydrogen Analyzer (see Figure 3-5) using the inert gas fusion method (ASTM E 1447-49). A weighed sample is melted in a graphite crucible in a stream of high-purity argon. Molecular hydrogen is released from the sample and is separated from any carbon monoxide and nitrogen liberated from the sample. A thermal conductivity cell was used as a detector for determining the hydrogen content from which the wt % of hydrogen in the sample is calculated. Before each hydrogen measurement, calibration is verified with standard reference materials of known hydrogen content.

Figure 3-5. LECO Hydrogen Analyzer.

Two-sided hydrogen charging was performed with the 901 Brew furnace (see Figure 3-6). The samples were placed in the 901 Brew furnace and exposed to a slightly positive pressure (<2 psig) flow of 30% H_2 in helium or 4% H_2 in argon at temperatures ≈400°C for various times to enable the adsorption/ diffusion process. The test conditions are detailed in Table 3-3.

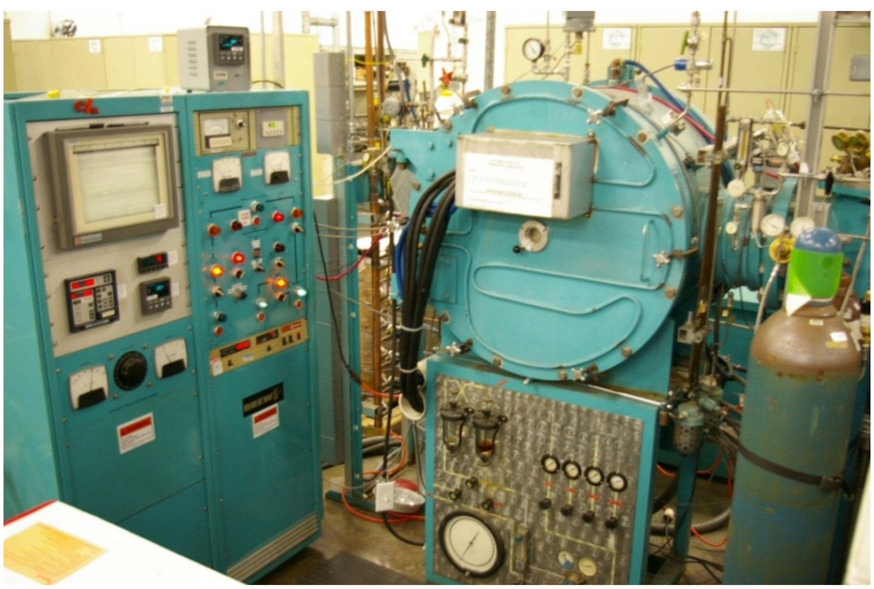


Figure 3-6. The 901 Brew Furnace for Materials Hydriding.

Table 3-3. Test Conditions for Materials Hydriding with the 901 Brew Furnace

Materials	17×17 Zircaloy-4
Charging gas	(a) 4% H_2 in argon; (b) 30% H_2 in helium
Cladding size	OD=9.5 mm; t=0.57 mm
Target hold temperature	400°C
Test time	Various
Heating RAMP	10-15°C /min.
Cooling rate	15±5°C /min. from 400 to 100 °C, followed by furnace cooling
Target post-test H content	500–800 ppm
Thermal cycling	For uniform hydrogen distribution

The target temperature and holding time for the tests have been modified to optimize the test condition for different lengths of Zircaloy-4 cladding. Cycling from 400°C to 100°C to 400°C was added for some tests after the samples were heated at 400°C in an attempt to improve hydrogen distribution. Hydrogen analyses performed on the post-test hydrided Zircaloy-4 samples indicated that, although the axial gradients in hydrogen content were still observed, the hydrogen distribution is improved by the thermal cycling. The hydrogen is typically symmetrically distributed to the middle plane. In order to achieve the target hydrogen content, various test conditions have been performed, by which the hydrogen content close to the target value (450-850 wppm) was obtained in the middle section of the two-sided hydrided samples. Figure 3-7 shows hydrided Zircaloy-4 cladding, as compared to as-received Zircaloy-4 cladding. A typical temperature history of materials hydriding is shown in Figure 3-8.

Eight two-sided hydrogen charging tests, plus some dry-run tests to calibrate/adjust the system, were conducted at 400°C for 90-480 minutes, by which pre-hydrided samples with hydrogen content from 450–820 wppm were generated. Seven samples (one 6-in. sample and six 1-in. samples) have been assembled in three sets for the HFIR irradiation. A schematic illustration of the three sets of the pre-hydrided samples is given in Figure 3-9, and the detailed sample descriptions are given in Table 3-4.

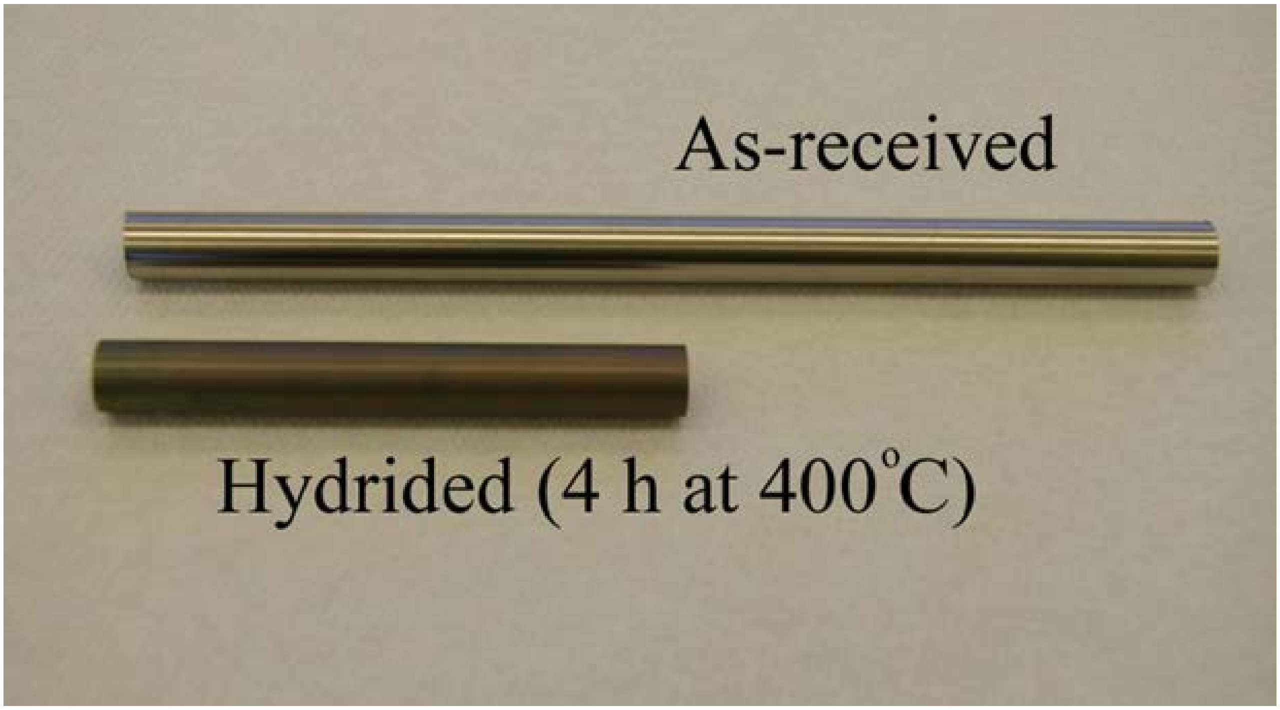


Figure 3-7. Photographs of (a) As-received and (b) Hydrided Zircaloy-4 Cladding.

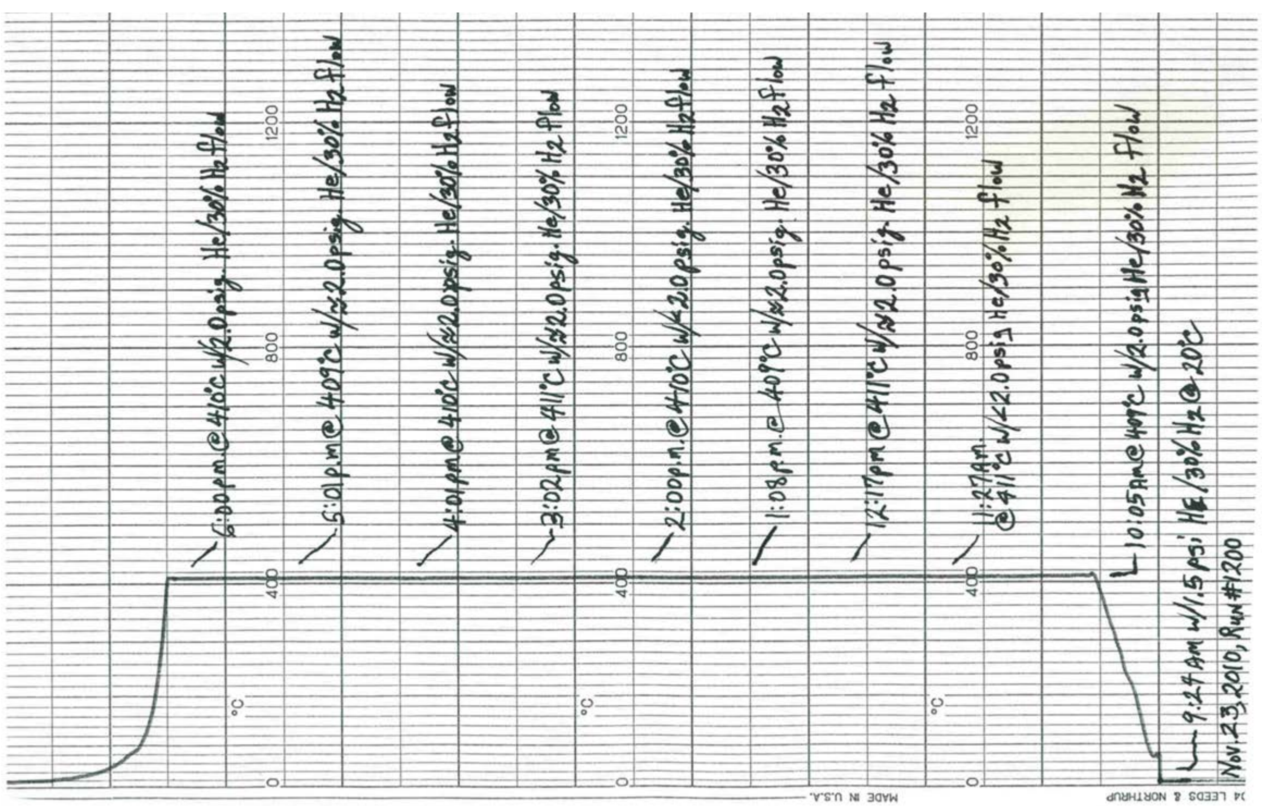


Figure 3-8. A Typical Temperature Profile for Hydriding Zircaloy-4 Cladding Materials.

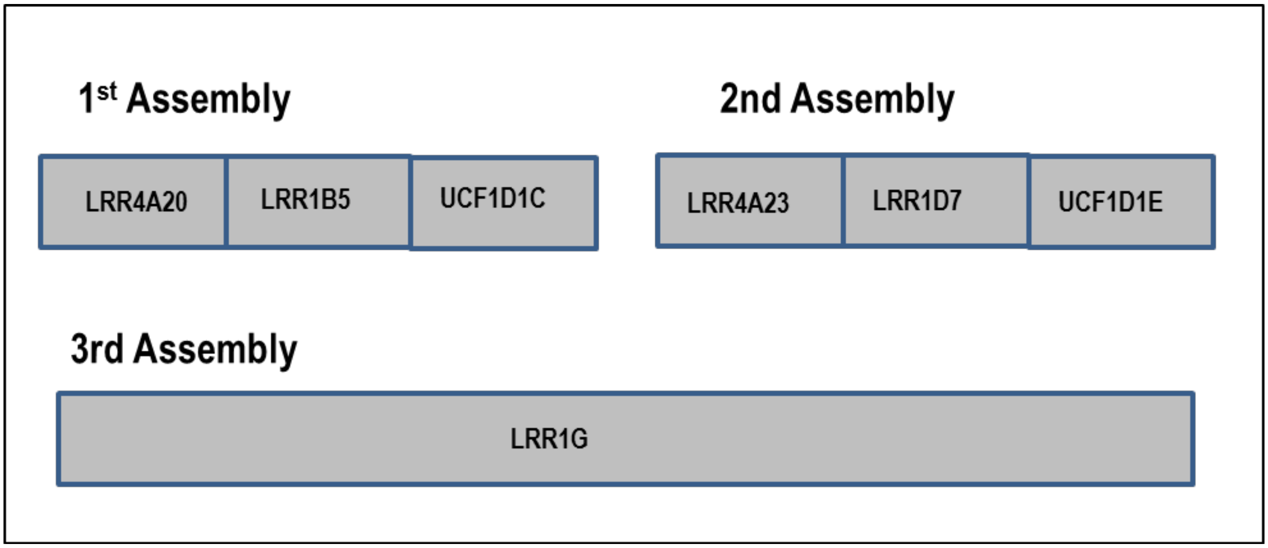


Figure 3-9. A Schematic Illustration of the Three Sets of the Pre-hydrided Samples for the HFIR Irradiation on March 26, 2012.

Table 3-4. Hydrided Samples for the HFIR Irradiation on March 26, 2012

Sample ID	Sample Length	Hydrogen Content	Comments
LRR4A20	≈1 in.	≈15 wppm	As-received*
LRR1B5	≈1 in.	≈820 wppm	
UCF1D1C	≈1 in.	≈450 wppm	
LRR4A23	≈1 in.	≈15 wppm	As-received*
LRR1D7	≈1 in.	≈550 wppm	
UCF1D1E	≈1 in.	≈450 wppm	
LRR1G	≈ 6 in.	≈770 wppm	Middle section

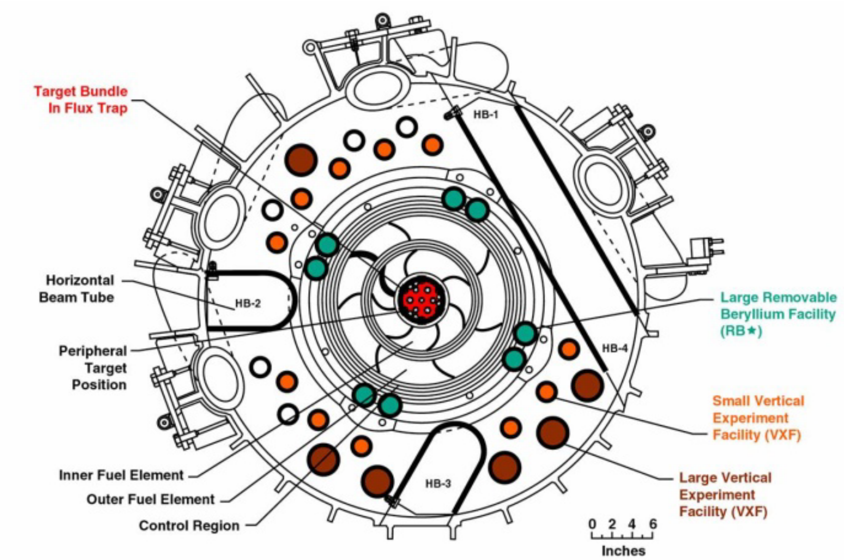
*As-received samples served as baseline data to be compared to hydrided samples.

Microstructural examinations on two-sided pre-hydrided samples and PIE on irradiated samples are to be conducted, and the instructions for these examinations will be given in a separate work plan.

3.2 High Flux Isotope Reactor Capsule Design Work

HFIR is a beryllium-reflected, pressurized, light-water-cooled and moderated flux-trap-type reactor. The core consists of aluminum-clad involute-fuel plates, which currently utilizes highly enriched ^{235}U fuel at a power level of 85 MWt.

The reactor core, illustrated in Figure 3-10, consists of two concentric annular regions, each approximately 61 cm in height. The flux trap is ~12.7 cm in diameter, and the outer fueled region is ~43.5 cm in diameter. The fuel region is surrounded by a beryllium annular reflector approximately 30.5 cm in thickness. The beryllium reflector is in turn backed up by a water reflector of effectively infinite thickness. In the axial direction, the reactor is reflected by water. The reactor core assembly is contained in a 2.44-m diameter pressure vessel, which is located in a 5.5-m cylindrical pool of water.



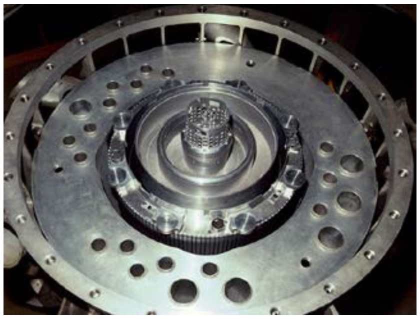


Figure 3-10. Cross Section through HFIR Illustrating the Primary Experimental Sites (left) and a Picture of the Reactor Core (right).

The Zircaloy-4 specimens in this design will be placed in the flux trap of HFIR in or near the outer ring of target positions shown in green in Figure 3-11. Table 3-5 summarizes the neutron flux characteristics of this location. The fast fluence is based on a typical 25-day cycle and 7 cycles per year.

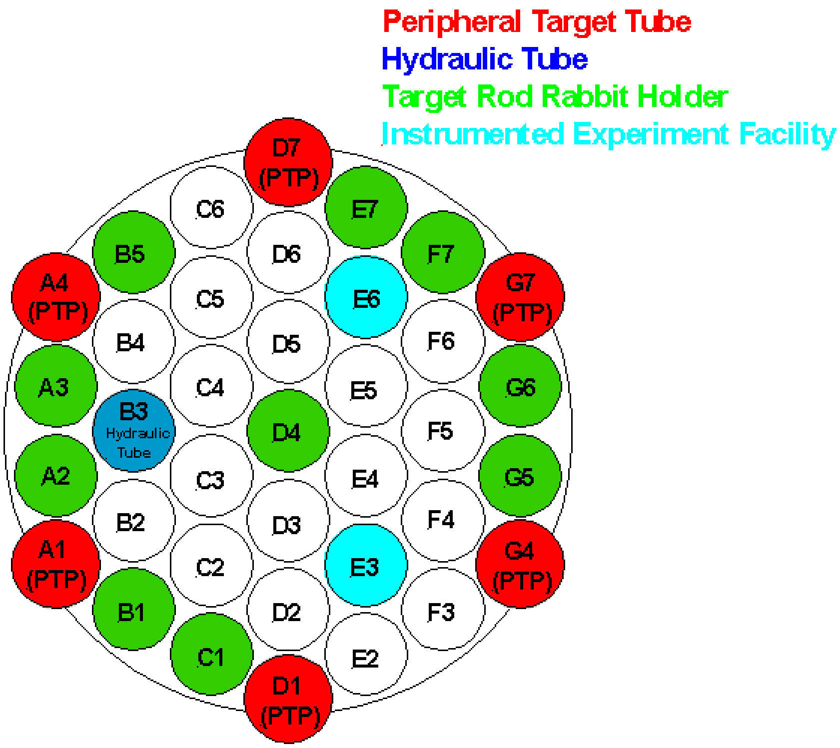


Figure 3-11. Flux Trap Irradiation Locations.

Table 3-5. Neutron Flux Characteristics of the Peripheral Target Tube (PTT) and Target Rod Rabbit Holder (TRRH) Irradiation Facilities

Parameter	**TRRH**(Greenwood, June 30, 1999)
Fast flux (10^{14} n/cm²·sec) [E > 1 MeV]	5.5
Fast flux (10^{14} n/cm²·sec) [E > 0.1 MeV]	10.8
Thermal flux (10^{14} n/cm²·sec) [E < 0.5 eV]	20.2
Fast fluence/cycle (10^{21} n/cm²) [E > 0.1 MeV]	2.33
Fast fluence/year (10^{21} n/cm²) [E > 0.1 MeV]	16.3
Axial peaking factor profile*	$1 - 1.06 \cdot 10^{-3} \cdot z^2$

*Peaking factor is the ratio of the local flux at a distance z from the reactor midplane (in cm) to the flux at the reactor midplane.

3.2.1 Experiment Design Description

The design assumes that the experiments will be placed in an outer ring position centered at the HFIR midplane. The specimen between these locations will be at ±7.62 cm (±3.00 in). The profile from Table 3-5 gives a peaking factor of 0.94-1.00 with an average of 0.98, resulting in a fast neutron flux of $10.6 \times \cdot 10^{14}$ n/cm²·sec [E > 0.1 MeV]. For a nominal 25-day cycle, the fluence (E>0.1 MeV) in each specimen will be approximately $2.3 \times \cdot 10^{21}$n/cm².

The design drawings for this experiment are included in Attachments 4 through 14 of this report. A schematic of the inner assembly is shown in Figure 3-12.

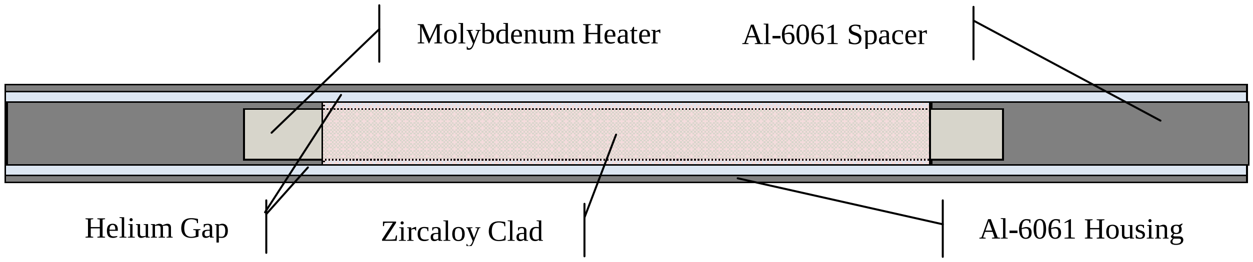


Figure 3-12. Experiment Assembly Schematic.

Coolant is directed to the experiment by the Al-6061 outer shroud, which is shown on Drawing X3E020977A608 (Attachment 11). The outer aluminum housing is the primary containment for the experiment and is fabricated from Al-6061. The housing is specified on Drawing X3E020977A612 Rev. A (Attachment 14), and the assembly is provided on Drawing X3E020977A608 (Attachment 11). The housing is made from No. 17, ½-in Al-6061 tubing, which has an inner diameter of 9.73 mm (0.383 in). The ends of the tubing are bored out to an inner diameter of 11.3 mm (0.445 in.) to meet the requirements of the existing design for the top and bottom caps and the approved weld procedures.

The Zircaloy-4 clad specimens have an outer diameter of 9.5 mm (0.3741 in) and an inner diameter of 8.35 mm (0.3287 in). The clad length ranges from 76 mm (3.00 in) to 152 mm (6.00 in). The clad will be fitted with a molybdenum rod, which acts as a heater for the cladding. Finite element calculations were performed to establish design diameters for the molybdenum heater rods to provide a sufficient mass to bring hydrided cladding specimens to a desired temperature of 330°C at the cladding surface for the three 1.00-in. and 6.00-in. clad specimens (see Attachment 2). The molybdenum rod is 102 mm (4 in.) long for the 76-mm clad case and 178 mm (7 in.) long for the 152-mm clad case. The axial location of the clad centroid is located at the reactor mid-plane. Spacers made from ⅜-in. Al-6061 tubing are used to ensure this placement. For the 76-mm clad case, the top and bottom spacers are 224 mm (8.82 in.) and 227 mm (8.95 in.) respectively. Similarly, for the 152-mm clad case, the top and bottom spacers are 183 mm (7.22 in.) and 189 mm (7.45 in.) respectively. Both spacer sets are counterbored 12 mm (0.5 in.) at the end oriented closest to the reactor centerline to hold the excess molybdenum heater rod while also keeping the clad in the proper location. Six equispaced pads are impressed into the ends of each spacer closest to the reactor center line. This feature produces a slightly larger diameter from the original outer diameter of the spacer tube, and this dimension is set to keep the experiment centered in the housing tube. See Figure 3-13 for an illustration of this centering device.

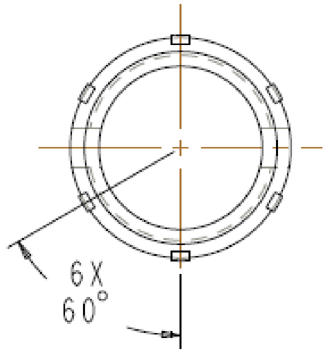


Figure 3-13. Centering Device.

3.2.2 Target Capsule Fabrication and Assembly

Three target capsules were fabricated and assembled in accordance with the design drawings. The outer housing tube and shroud were fabricated from Al-6061, and the cladding was fabricated from nuclear-grade Zirconium clad alloy (i.e., Zircaloy-4). The clad specimens used in the 3.00-in. case consisted of a line of three pieces; the center-most specimen being charged with hydrogen. The 6.00-in. specimen was a single tube that was charged with hydrogen. The center heater is fabricated from molybdenum or a molybdenum alloy. Figure 3-14 and Figure 3-15 show the assembled specimen configurations for both the 3.00- and 6.00-in. capsules, respectively.

Figure 3-14. 3-in. Target Capsule Specimen Configuration.

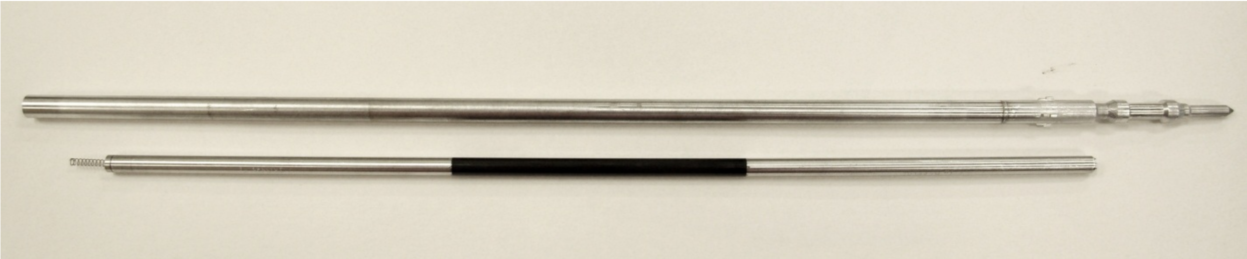


Figure 3-15. 6-in. Target Capsule Specimen Configuration.

3.2.3 Preparation of Safety Basis Documentation for HFIR

Experimental planning for HFIR includes an evaluation documenting that the proposed experiment does not exceed the reactor safety basis. For this experiment an analysis was developed to demonstrate that irradiating target capsules containing hydrided Zircaloy-4 cladding with a molybdenum heater rod could be exposed to a reactor power of 130% of 85 MW without exposing the capsule components to temperatures exceeding their respective melting temperatures. This evaluation is documented in Attachment 3, *Temperature Verification Calculation for Hydrided Cladding Specimens in the HFIR Target Region.*

3.2.4 Preliminary Estimation of Activity

The chemical composition of the Zircaloy-4 used in this estimate is taken from the specifications of ASTM B-351 for R60804 (Zircaloy-4) and summarized in Table 3-6. For the activity calculation, all non-zirconium elements are taken at their maximum allowable concentrations.

Table 3-6. Zircaloy-4 Elemental Composition

Element	Weight %		Element	Weight %
Zirconium	≈97.8		Tin	1.20-1.70
Chromium	0.07-0.13		Iron	0.18-0.24
Aluminum	0.0075		Magnesium	0.0020
Boron	0.00005		Manganese	0.0050
Cadmium	0.00005		Molybdenum	0.0050
Calcium	0.0030		Nickel	0.0070
Carbon	0.027		Niobium	0.0100
Cobalt	0.0020		Nitrogen	0.0080
Copper	0.0050		Silicon	0.0120
Hafnium	0.010		Tungsten	0.010
Hydrogen	0.0025		Titanium	0.0050
			Uranium	0.00035

The three initial experiments are slightly different in their loading and planned fluence. HYCD1 contains three 1-in.-long specimens with a total mass of 8.031 g and will be irradiated for 1 HFIR cycle. HYCD02 also contains three 1-in.-long specimens with a total mass of 8.026 g and will be irradiated for 2 HFIR cycles. HYCD03 contains one 6-in. specimen with a mass of 16.131 g and will be irradiated for 8 HFIR cycles.

Activity levels for the specimens in capsules HYCD01, 02, and 03 are shown in Figure 3-16 through Figure 3-18. Dose rate estimates are computed at a 1-ft. distance and are shown in Figure 3-19 through Figure 3-21.

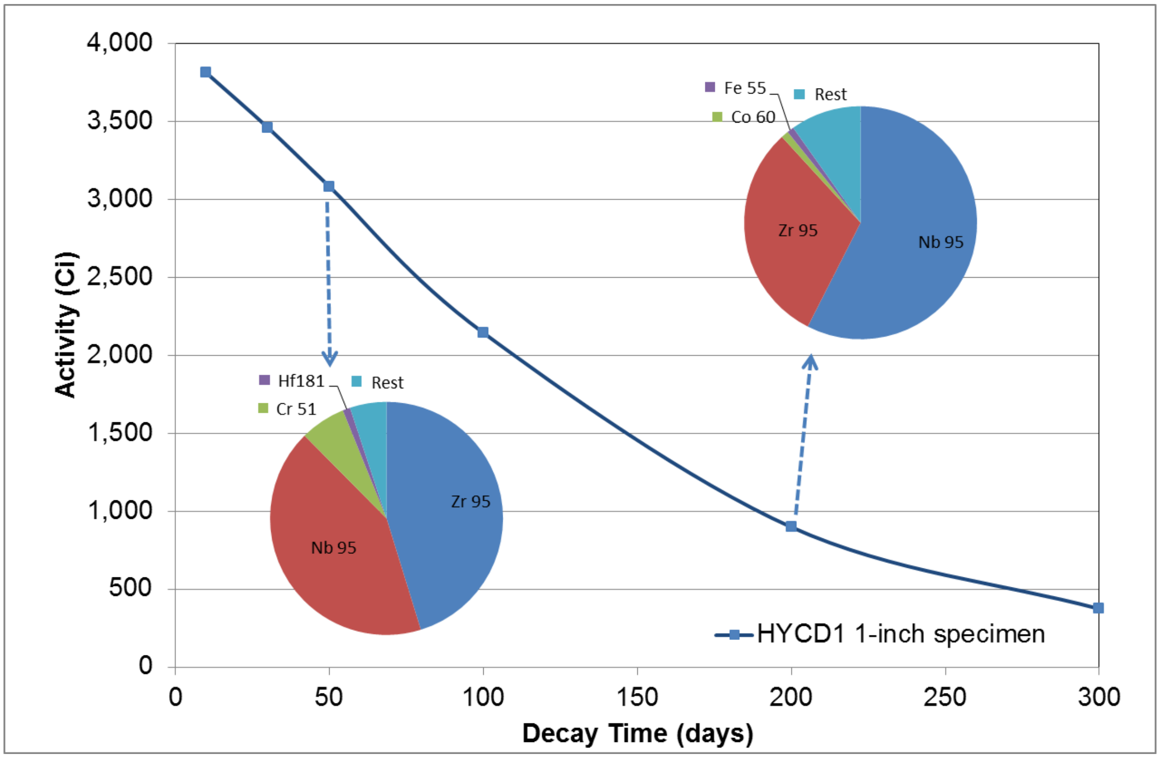


Figure 3-16. Activity Estimate for One 1-in. Zircaloy-4 Specimen in Capsule HYCD1 After 1 Irradiation Cycle.

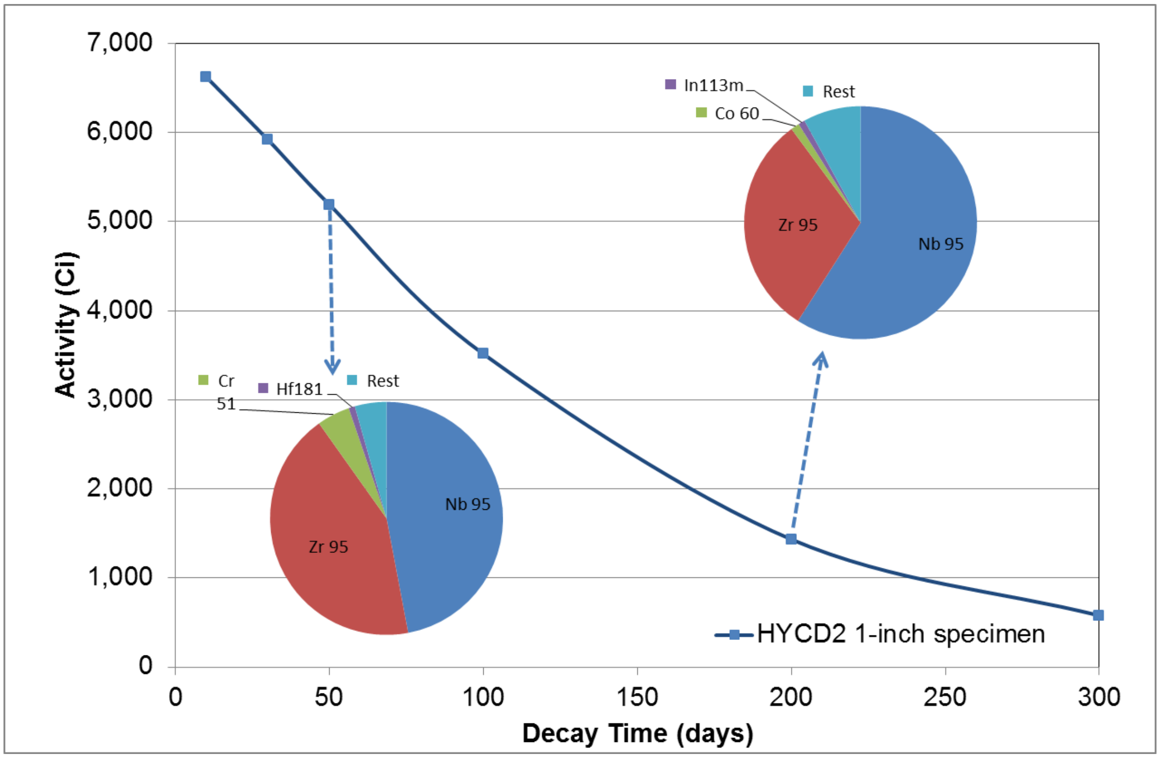


Figure 3-17. Activity Estimate for One 1-in. Zircaloy-4 Specimen in Capsule HYCD2 After 2 Irradiation Cycles.

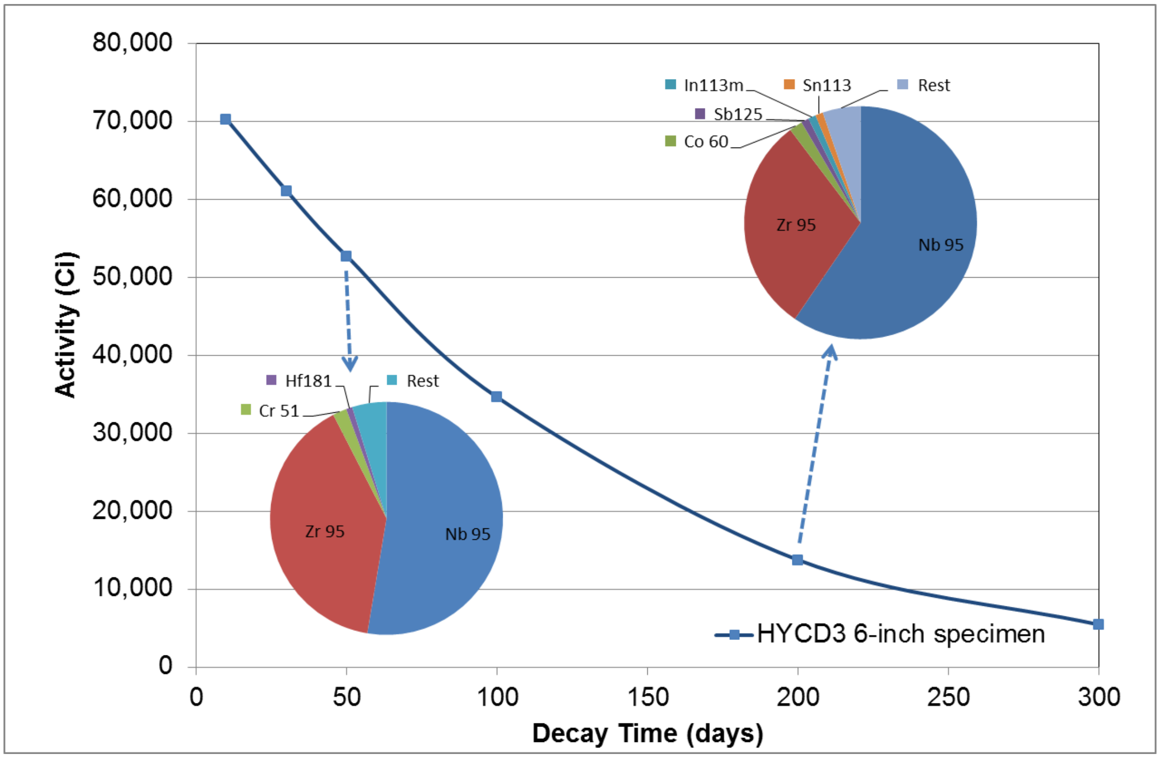


Figure 3-18. Activity Estimate for One 6-in. Zircaloy-4 Specimen in Capsule HYCD3 After 8 Irradiation Cycles.

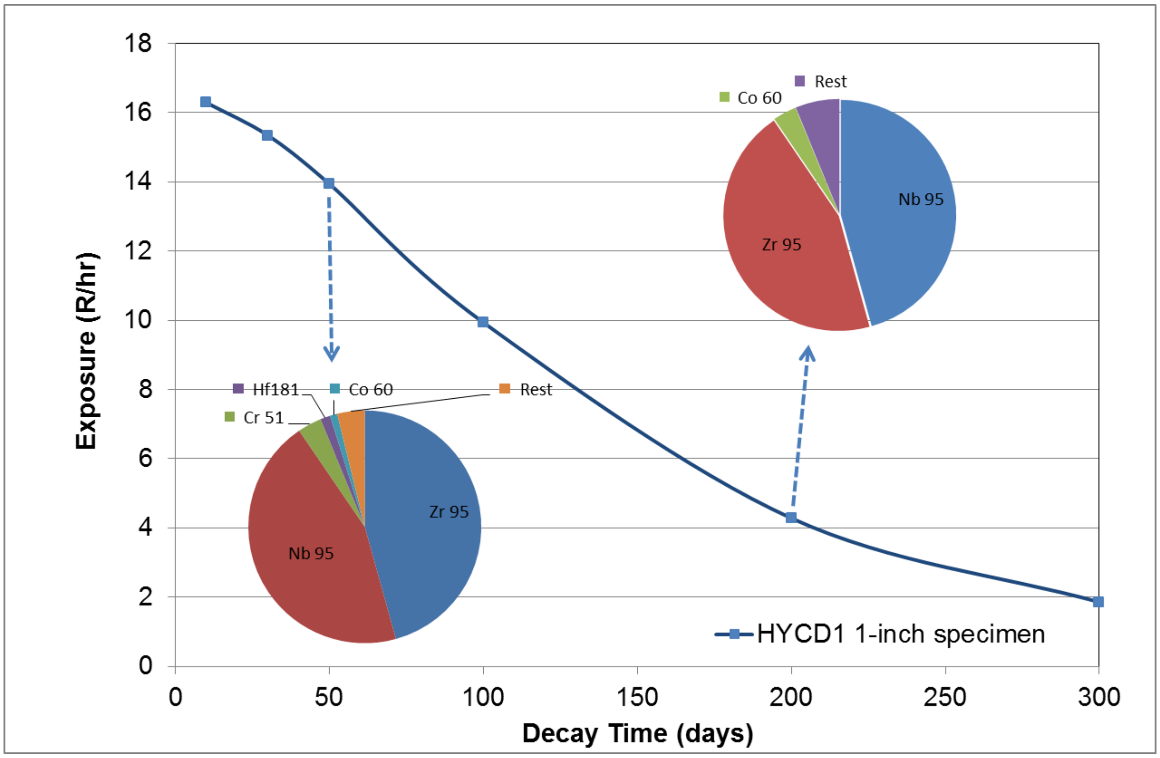


Figure 3-19. Exposure Estimate (at 1 foot) for One 1-in. Zircaloy-4 Specimen in Capsule HYCD1 After 1 Irradiation Cycle.

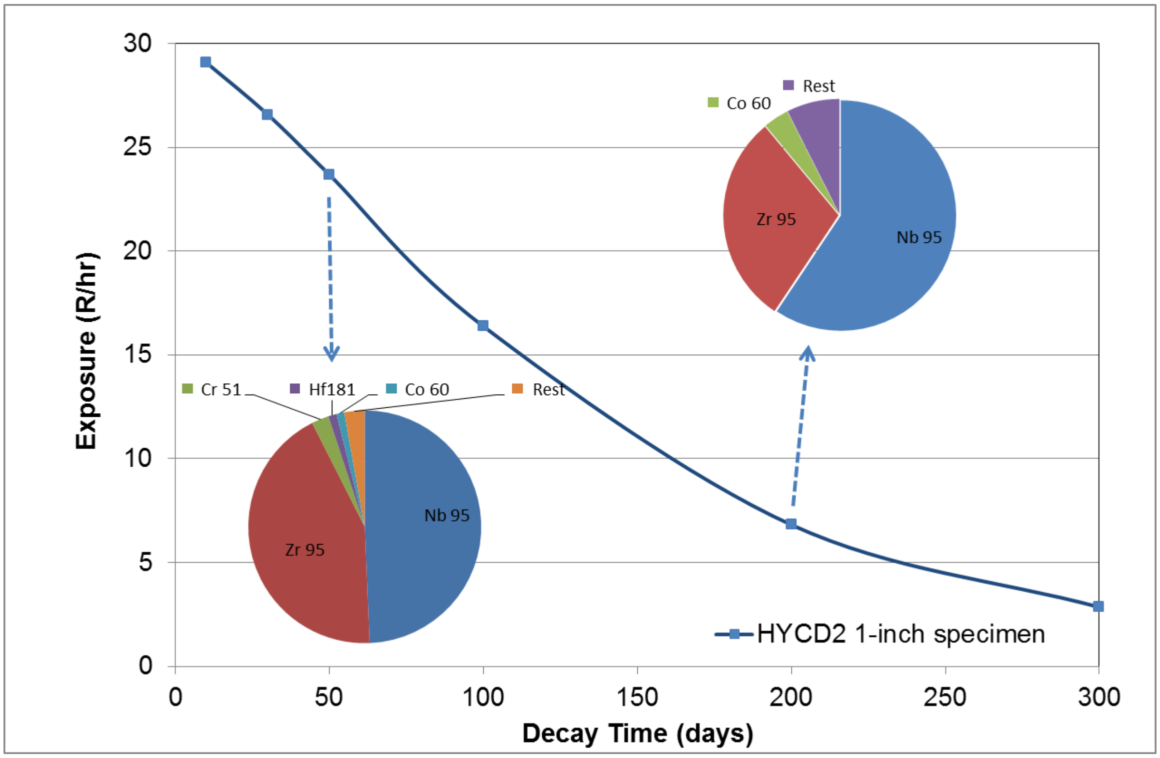


Figure 3-20. Exposure Estimate (at 1 foot) for One 1-in. Zircaloy-4 Specimen in Capsule HYCD2 After 2 Irradiation Cycles.

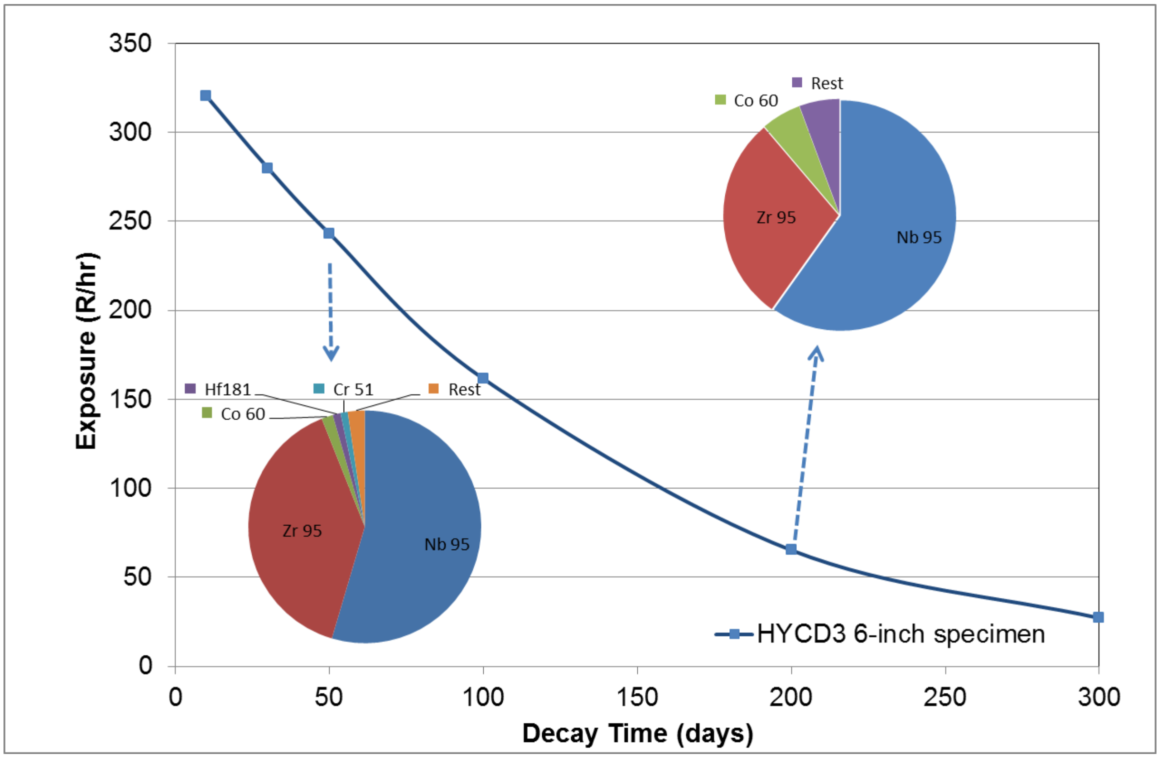


Figure 3-21. Exposure Estimate (at 1 foot) for One 6-in. Zircaloy-4 Specimen in Capsule HYCD3 After 8 Irradiation Cycles.

3.2.5 Insertion of Target Capsules into HFIR

The assembled target capsules have been delivered to HFIR and were inserted in the following flux trap locations: HYCD-1 is inserted in E3, HYCD-2 is inserted in E6, and HYCD-3 is inserted in C2 (see Figure 3-11).

3.2.6 Estimation of Cycle Time

From Ref. 3, the accumulated fluence for the seven cycle rods in the H. B. Robinson Assembly S-15H is illustrated in Figure 3-22 (based on Figures 3-26 through 3-34 in Ref. 3).

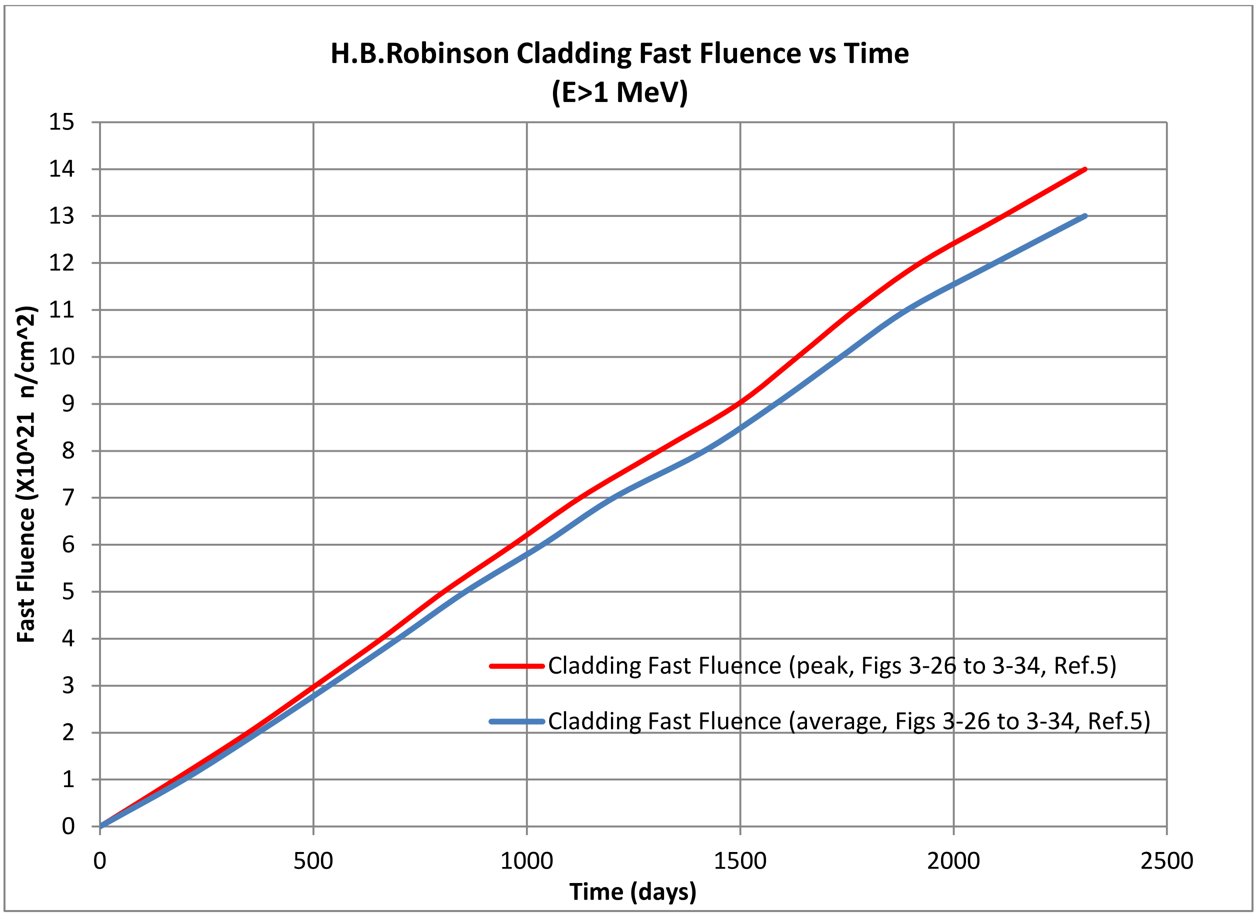


Figure 3-22. H. B. Robinson Cladding Fast Fluence (E>1 MeV) Versus Irradiation Time.

Based on a fast flux of 5.45×10^{14} n/cm²·sec (E>1 MeV, see Section 3.2) at the HFIR core centerline (also the specimen centerline) and a HFIR cycle length of 25 days, then the accumulated fast fluence in the specimen at the end of one HFIR cycle is approximately 1.177×10^{21} n/cm^2. In HFIR, the fluence would accumulate linearly with the numbers of HFIR cycles (assuming a constant cycle length). However, the cladding fluence in Figure 3-22 (above) is not quite linear; so via interpolation, the number of HFIR cycles required to attain the equivalent "average" curve in Figure 3-22 is illustrated in Figure 3-23.

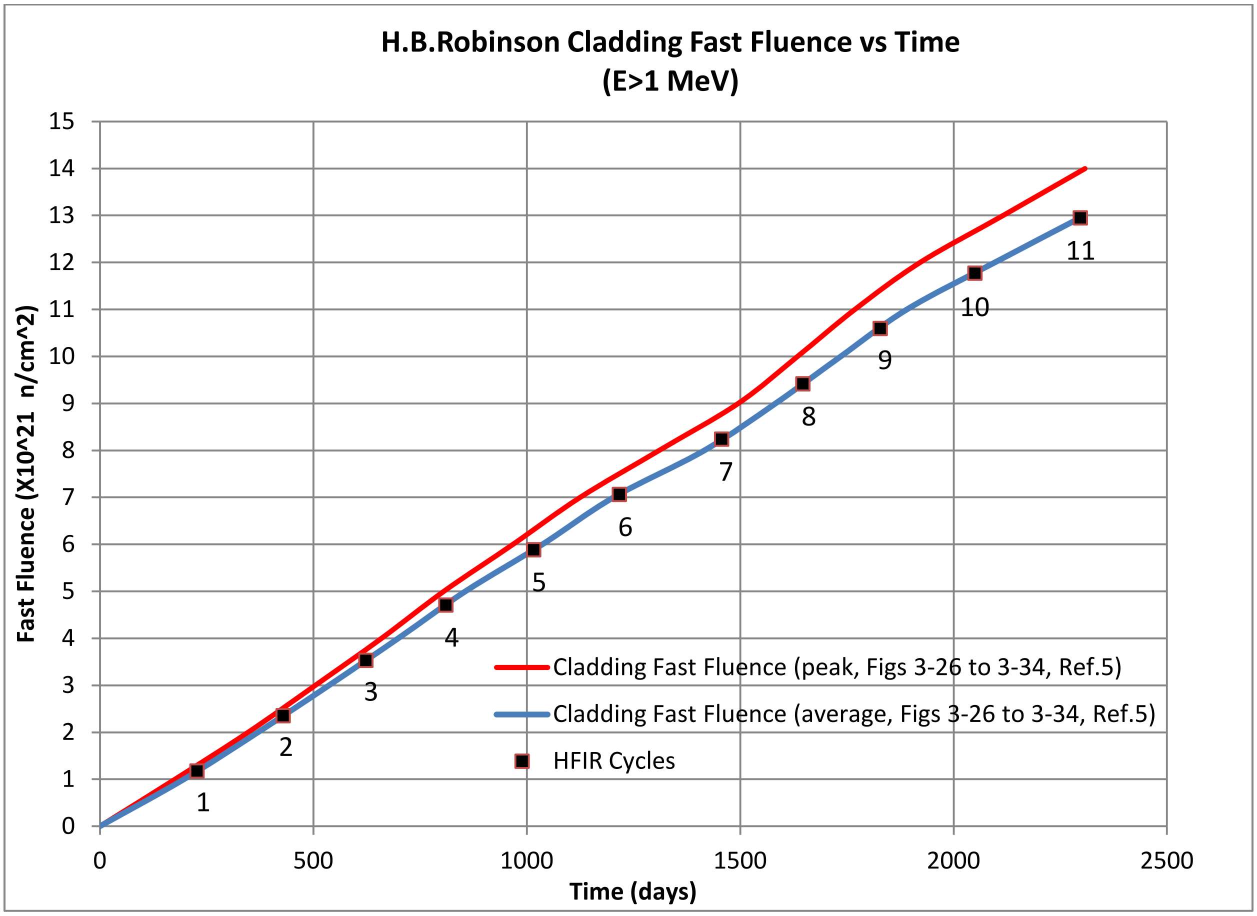


Figure 3-23. Number of HFIR Cycles Required to Attain the Equivalent Cladding Fast Fluence (E>1 MeV) in the H. B. Robinson Cladding.

Also, similarly (based on data from Table 3-1 of Ref. 3) the equivalent average fuel burnup (based on the equivalent cladding fluence in Figure 3-23) can be determined—this is illustrated in Figure 3-24.

Thus, using Figure 3-23 and Figure 3-24, the equivalent H. B. Robinson cladding fast fluence and fuel burnup can be determined for a given number of HFIR cycles.

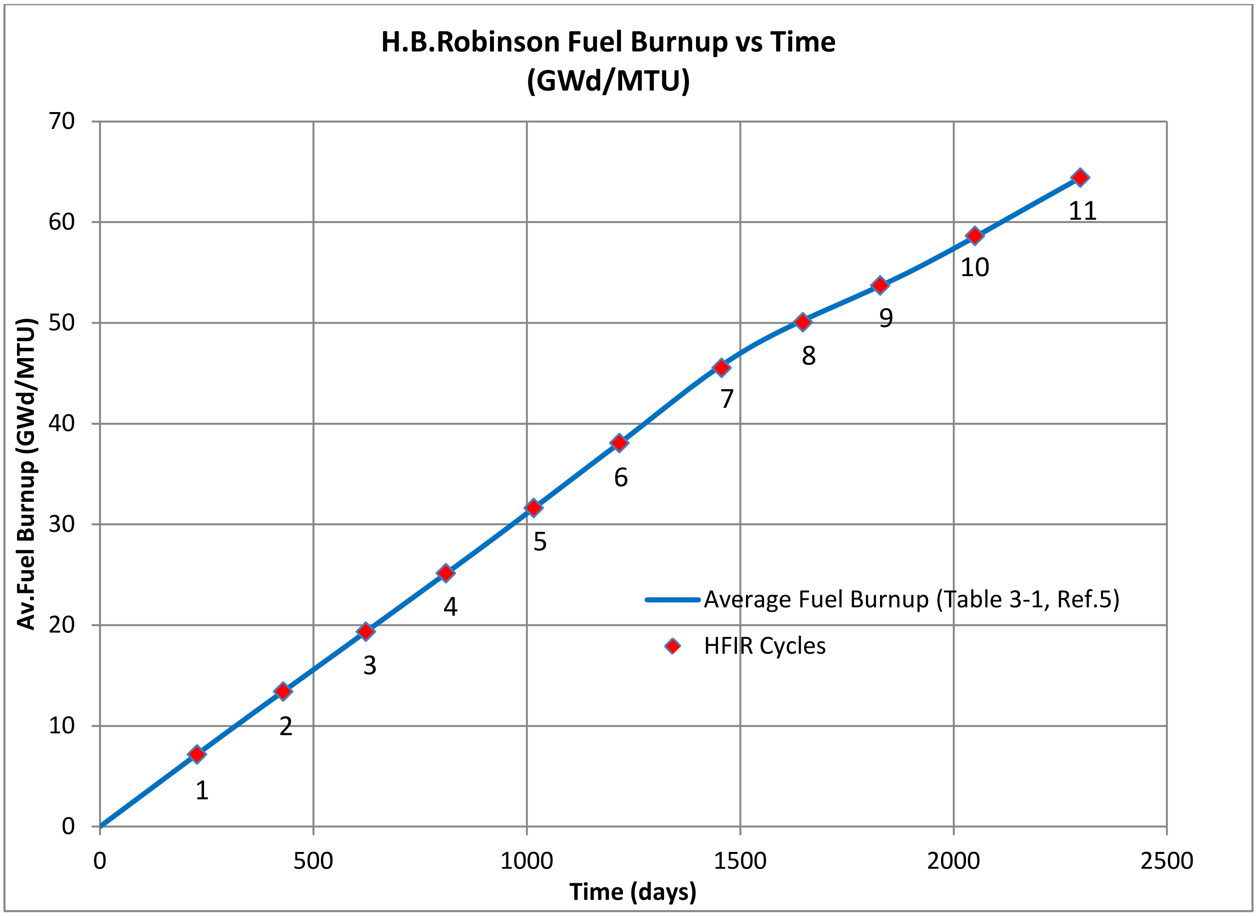


Figure 3-24. Equivalent Fuel Burnup after HFIR Cycles (H. B. Robinson Fuel Assembly S-15H).

4. References

1. DOE 2012. *Gap Analysis to Support Extended Storage of Used Nuclear Fuel,* FCRD-USED-2011-000136, Rev. 0, January 2012.

2. *Recovery of Irradiation Damage by Post-Irradiation Thermal Annealing:Relevance to Hydrogen Solubility and Dry Storage Issues*, TR-1013446, Electric Power Research Institute, Palo Alto, CA (2006).

3. *Design, Operation, and Performance Data for High Burnup PWR Fuel from the H. B. Robinson Plant for Use in the NRC Experimental Program at Argonne National Laboratory*, EPRI Technical Report 1001558, Electric Power Research Institute, Palo Alto, CA.

4. Y. Yan, "Procedure for Hydrogen-gas Charging of Unirradiated Zr-based Materials," MET-NFM-SOG-40, November 29, 2011.

5. R. J. Comstock, G. Schoenberger, and G. P. Sabol, "Influence of Processing Variables and Alloy Chemistry on the Corrosion Behavior of ZIRLO Nuclear Fuel Cladding," *Zirconium in the Nuclear Industry: Eleventh International Symposium, ASTM STP 1295*, E. R. Bradley and G. P. Sabol, Eds., American Society for Testing and Materials, 1996, pp. 710-725.

5. Attachments

Attachment No.	Title	
1	Operator Procedure, "Procedure for Hydrogen-gas Charging of Unirradiated Zr-based Materials Document," Document ID: MET-NFM-SOG-40, Irradiated Fuels Examination Laboratory, Oak Ridge National Laboratory, Oak Ridge, TN	
2	Design Analysis and Calculation, "Thermal Design Analysis for a Hydrided Clad Irradiation Experiment," Calculation ID: DAC-11-19-HYDRIDE01, Rev. 0, Reactor and Nuclear Systems Division, Oak Ridge National Laboratory, Oak Ridge, TN	
3	RRD Calculation, "Temperature Verification Calculation for Hydrided Cladding Specimens in the HFIR Target Region," Calculation ID: C-HFIR-2012-003, Rev. 0, Oak Ridge National Laboratory, Oak Ridge, TN	
	FCM Rabbit Design Drawings	
	Drawing No.	**Title**
4	X3E020977A570 Rev. 0	Shrouded Target Capsule Bottom Cap Assembly
5	X3E020977A571 Rev. 0	Shrouded Target Capsule Guide Pin Detail
6	X3E020977A572 Rev. 0	Shrouded Target Capsule Top Cap
7	X3E020977A573 Rev. 0	Shrouded Target Capsule Housing Tube
8	X3E020977A574 Rev. 0	Shrouded Target Capsule Rupture Sleeve
9	X3E020977A575 Rev. 0	Shrouded Target Capsule Shroud Tube
10	X3E020977A586 Rev. A	Target Capsule Housing and Shroud Weldment Subassembly
11	X3E020977A608 Rev. 0	Cladding Test Plan Hydriding Assembly
12	X3E020977A609 Rev. 0	Cladding Test Plan Hydriding Sample, Spacer, Rod Details
13	X3E020977A610 Rev. 0	Cladding Test Plan Hydriding Assembly Spacer Cap Detail
14	X3E020977A612 Rev. A	Cladding Test Plan Hydriding Housing Tube Detail

ATTACHMENT 1

OPERATOR PROCEDURE

Procedure for Hydrogen-gas Charging of Unirradiated Zr-based Materials

Prepared by: Date 3/27/2012
Yong Yan, FC&I Division

Reviewed by Date 28 MARCH 2012
Rob Howard, Reactor and Nuclear Systems Division, Program Manager

Approved by: Date 28 March 2012
Gary Bell, FC&I Division Nuclear Fuel Materials Group Leader

DSO Approval: Date 3-28-12
Mark Baldwin, FC&I Division Safety Officer

QA Approval: Date 3/28/12
M. C. Vance, QS & S Division Quality Assurance Representative

OPERATOR PROCEDURE

1. Purpose

The DOE Used Fuel Disposition Campaign (UFDC) has tasked ORNL to investigate the behavior of light-water-reactor fuel cladding material performance related to extended storage and transportation of used fuel. Fast neutron irradiation of pre-hydrided zirconium-alloy cladding in the High Flux Isotope Reactor (HFIR) at elevated temperatures will be used to simulate the effects of high burnup on used fuel cladding for use in understanding the material properties relevant to extended storage periods and subsequent transportation. The irradiated pre-hydrided metallic materials will generate data to benchmark hot-cell testing of high-burnup used fuel cladding, and more importantly, samples free of alpha contamination can be provided to the researchers/students in universities that do not have hot cell facilities to handle highly contaminated high-burnup used fuel cladding to support their research projects for the UFDC.

In order to accomplish this research, The Nuclear Fuel Materials Group needs to produce unirradiated zirconium-based cladding tubes with a certain hydrogen concentration. Therefore, a hydrogen-gas charging furnace and equipment for sample preparation are to be used for producing hydrogen-charged cladding.

2. Scope

The tasks described in this procedure are associated with the use of the 901 Brew Furnace in Lab 139, Building 4508.

3. Environmental, Safety and Health Concerns

ES&H hazards and controls are listed in the Research Safety Summary, RSS 1079, for activities occurring in Lab 139, Building 4508. Each person performing work is required to read and follow the RSS and be cognizant of specific requirements such as radiation permits.

Each person performing task work is responsible to ensure that their training is up to date as listed in their division training baseline. If deficiencies exist, do not perform this work until your training is brought up to date. Only individuals supervised or otherwise specified by the test engineer or project manager may perform the task work or operate equipment specified in this procedure. Modifications to task equipment and this procedure require the review and approval as specified in the Responsibilities Section.

4. Training and Qualification of Personnel

Appropriate training consists of self-study of this procedure, hands-on training, and demonstrated proficiency with the apparatus. Appropriate precautions should be taken to maintain recommended pressure and temperature limits as indicated in the manufacturer's operating manual. Do not operate the 901 Brew Furnace without specific instructions from trained personnel listed in Appendix B.

5. Responsibilities

All of the activities associated with this procedure will be conducted in Lab 139, Building 4508 and require the prior approval of the Lab Manager. Work will be conducted under the direction of the Principal Investigator and/or the relevant Project Manager.

6. Equipment

Verify that the 901 Brew Furnace (see Figure 1) is available and functioning properly.

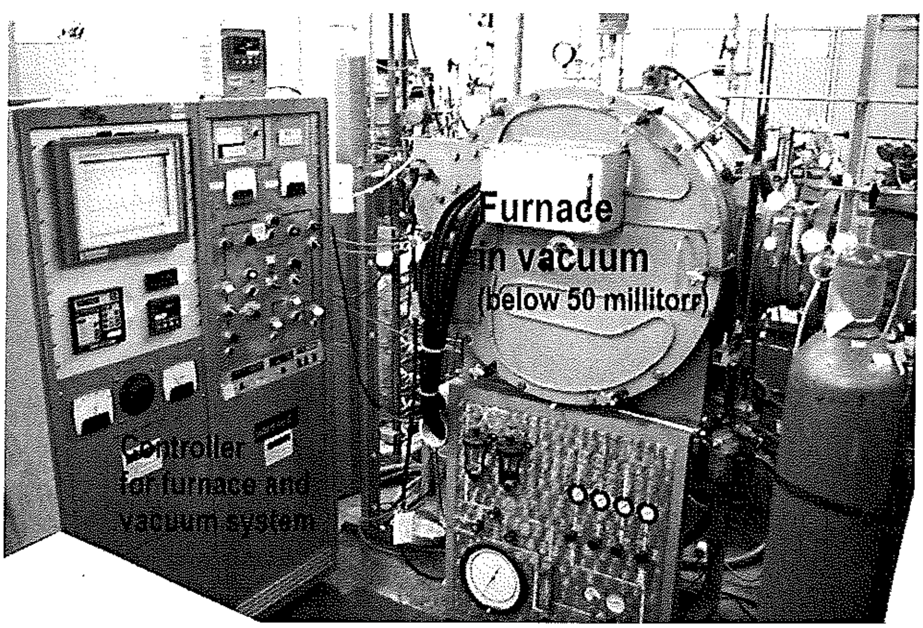


Figure 1. The 901 Brew Furnace for Materials Hydriding. The controller and vacuum chamber are labeled.

7. Using the 901 Brew Furnace for Hydrogen-gas Charging of Unirradiated Zr-based Materials

Samples (namely tubes with ≤0.43-inch outer diameter, ≤0.03-inch thickness, and ≤6-inch length) will first be prepared by treating the surfaces to clean residues and remove oxide scales. The sample should be etched by the use of hydrofluoric (HF) and nitric (HNO_3) acids, as described by ASTM G2 /G2M06. This first step is to provide a "window" for hydrogen absorption onto the cladding tubes; residues and oxide scales are "barriers" to hydrogen adsorption. Then, the samples will be placed in the 901 Brew furnace and exposed to a slightly positive pressure (<2 psig) flow of 30% H_2 in helium or 4% H_2 in argon at temperatures between 300-400°C for various times to enable the adsorption/ diffusion process. A datasheet will be provided to record the test conditions, such as the heating ramp, hold temperature, hold time, and cooling rate (see Appendix A). Samples will then be removed from the furnace and released for existing and approved UF-relevant testing. Appendix B "901 Brew Furnace Operating Guidelines in Hydrogen" describes in detail the following procedures:

- Leak-check the furnace piping system
- Check the gas supply
- Insert the sample into the furnace chamber
- Pump down the vacuum of the furnace chamber
- Setup time-temperature profiles
- Hydrogen-gas furnace charging of zirconium-based tubes
- Shut down the furnace and vacuum system, and
- Remove the sample when the furnace is cooled.

8. Records

Scientific notebooks or logbooks are used to record original research data with the goal of providing the information and data necessary to retrace the work processes and activities and confirm the results, or repeat the work processes and activities and achieve comparable results. Scientific logbooks will contain:

- original descriptions of ideas, concepts, data, calculations, notes, and sketches pertinent to the research
- equipment used,
- dates
- identification of individuals performing the research
- identification of samples or test articles
- any unusual measuring and test equipment calibration requirements
- a description of the work as it is being performed and the results obtained

- references to relevant research data and its location that cannot be permanently inserted into the logbook due to their size.

END OF PROCEDURE

Appendix A: Data Sheet for Materials Hydriding

Date: ______________________ Operator______________________

Program Name: ______________________ Test No.______________________

Material Information:

Heat/Composition____________________ Irradiation Conditions ____________

Specimen Information:

Specimen No. ____

Length (in./mm) ____________________ Specimen OD (in./mm)__________

Wall thickness (in./mm)______________ Etching or As Received __________

Testing Conditions:

Hold Temperature (°C)________________ Heating RAMP (°C/s) __________

Hold Time (Minutes)__________________ Cooling Rate (°C/s) ___________

Charging Gas ______________________ Purging Gas __________________

Comments:

____

____

____

Appendix B: 901 Brew Furnace Operating Guidelines in Hydrogen Charging

Jim Kiggans, Cliff Davisson, and Evan Ohriner

SCOPE

This operating guideline describes the activities associated with the use of the 901 Brew Furnace in Lab 139, Building 4508 for hydrogen gas use. This document is meant to serve as a guideline for safe operations but not as a procedure that lists some but not necessarily every valve number and part of the furnace.

ENVIRONMENTAL, SAFETY, AND HEALTH CONCERNS

Appropriate precautions should be taken to maintain recommended pressure and temperature limits as indicated in the manufacturer's operating manual.

RESPONSIBILITIES

Do not operate this equipment without specific instructions from trained personnel.

GUIDELINES

Power for 901 Brew Furnace
Main Power
480 Volts, 3∅ North Buss
Switch No. 901 on

Make sure switch 901-A located on transformer cabinet behind furnace is on.

Turn on Vacuum system

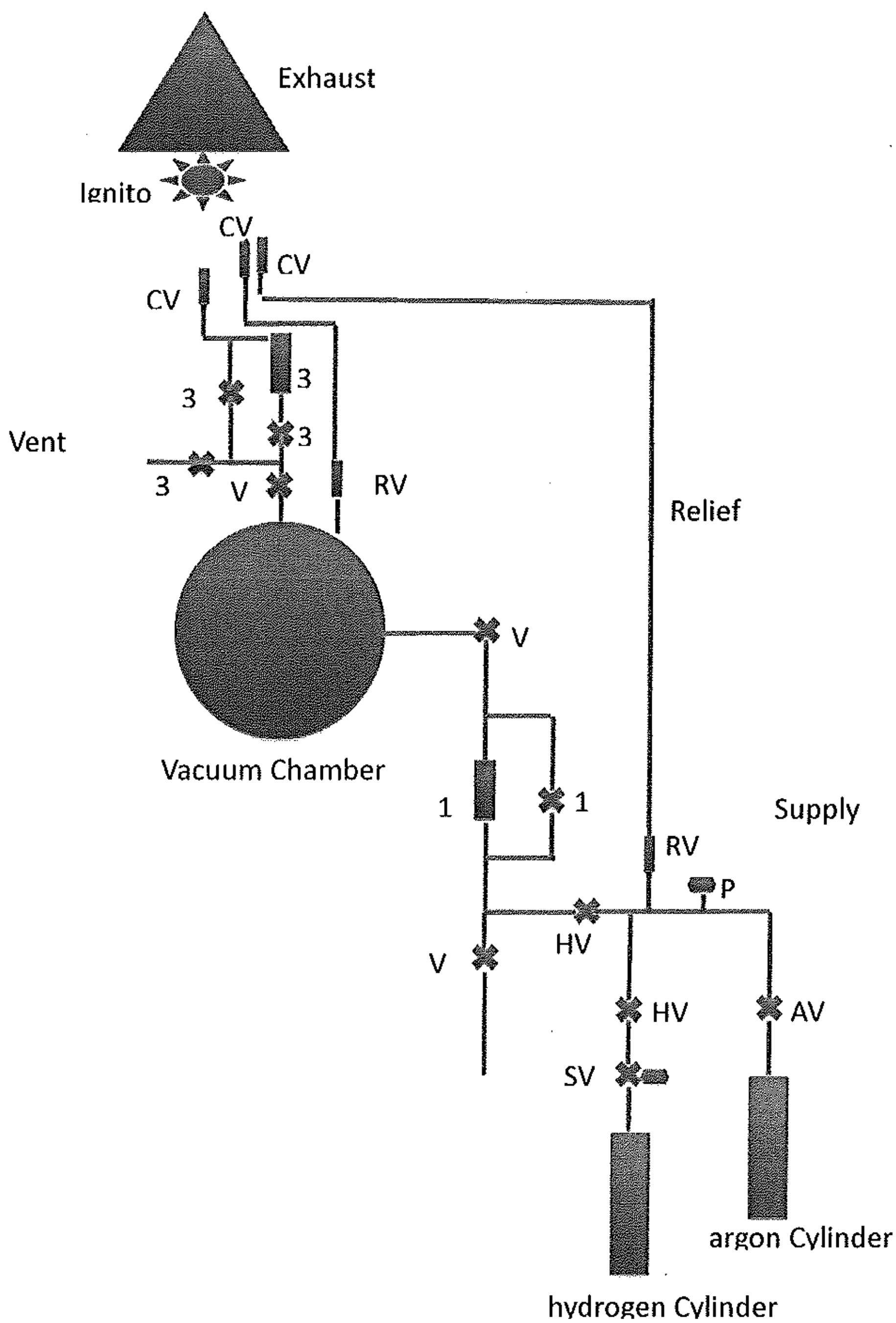
- Make sure door O-ring has vacuum grease and is in O-ring groove.

- Close door and lock down with clamps; close valves 1 through 11.
- Open valve 12 (water drain).
- Open valve 13 (furnace water light on graphic control panel should go out).
- Open valve 14 (pump water light on graphic control panel should go out).
- Start mechanical pump (graphic control panel); green light will come on.
- Check that gas supply and vent valves to the furnace are closed.
- Open roughing valves 1 and 2 on left side of graphic control panel; amber lights will come on. The furnace chamber will start to pump down through the mechanical pump.
- Switch to gauge 1 on the Varian 804-A thermocouple vacuum gauge, upper left of control panel. When vacuum in furnace chamber drops below 50 millitorr, close the vacuum valve to the chamber.
- Place vacuum interlock (located on left side of graphic control panel) in bypass position. If vacuum interlock switch is not in bypass position, the element will not energize. Turn the convectron switch to the by-pass mode.
- Place the Element Protection Interlock (EPI) switch into normal position. The function of this switch is to shut off the tungsten elements in the event of an unexpected drop in gas pressure below a safe operational level of 0.5 psig. The EPI switch is located directly above the furnace chamber.
- Set the over-temperature for furnace protection at ~ 50 °C above the desire process or setpoint temperature.
- Place samples in the chamber as needed.
- Install & tighten each of the furnace door bolts.
- Close the furnace vent valve 3.
- Close the furnace supply valve 2.
- After a vacuum of below 50 millitorr the furnace can be backfilled with argon.
- Adjust the pressure on the argon regulator to 20 PSIG.
- Open argon gas cylinder valve and argon ball valve AV1 to the hydrogen gas manifold.
- Close supply valve 1 to isolate the gas manifold used for regular furnace runs.
- Open valve HV2, valve 1B, and open valve V2 to fill the chamber to -10" argon pressure.
- Close the primary supply valve 2 and pump out the chamber the second time,
- Close the vacuum valve and refill the chamber to -10 " argon as before.
- Pump the chamber again and this time backfill the chamber to 1 psig overpressure.
- Open the vent valve V3.
- Close valves 3B and 3D
- Open the valve 3C .
- Regulate the valve 3A to maintain the desire flow.
- Adjust the flow to between 235-470 cc/min at valve 1A.

OPERATOR PROCEDURE

- Close 3C and open valve 3B.
- Connect the digital flowmeter to tubing and measure flow.
- Record the data.
- Close 3B and Open 3C to re-establish flow through the flow meter.
- Close the AV1 to isolate the argon cylinder on the argon-hydrogen manifold.
- Open the hydrogen gas cylinder.
- Adjust the pressure on hydrogen regulator to 20 PSIG.
- Open valve HV1.
- Check the pressure on the gas manifold for comparison.
- Adjust 1A as needed to control flow rate to desire value.
- Start the furnace run by engaging the elements and the furnace controller.
- Turn on the hydrogen burner.
- Heat the furnace using standard procedures.
- Upon completion of the heating cycle, close off the hydrogen cylinder and valve HV1.
- Immediately open the argon cylinder and isolation valve AV1 to flush out the hydrogen.
- Flow argon until the furnace is cool.
- Leave on the hydrogen burner until the flame can no longer be maintained at the burner. as indicated by visual observation and the thermocouple temperature drop at the burner.
- Purge the chamber for a minimum of two hours after the temperature reaches 50°C.
- Close the primary chamber vent valve V3 and supply valve V2.
- Pump the chamber to 50 millitorr.
- Backfill with argon gas to atmospheric pressure.
- Remove samples.

901 Brew Valves and Piping for Hydrogen Use



ATTACHMENT 2

Design Analysis and Calculation

Calculation No.:	DAC-11-19-HYDRIDE01
Calculation Title:	Thermal Design Analysis for a Hydrided Clad Irradiation Experiment
Organization:	Reactor & Nuclear Systems Division, Thermal Hydraulics & Irradiation Engineering Group
Project/Task:	Hydrided Clad Irradiation Experiment Thermal and Structural Design
Revision:	0
Prepared:	T Richard Howard 2/17/2012
Checked/Verified:	Joel McDuffee 2/17/2012
Group Leader:	[illegible] 2/23/12

Abstract:

The hydride clad irradiation experiments are designed to irradiate 3.00 to 6.00 in (7.62 cm to 15.2 cm) hydrided Zircaloy-4 samples (0.374 in OD). Under test irradiation conditions (temperature and temperature gradient across the cladding wall), the desired hydride morphology should be created within the cladding within a few days of the start of irradiation. The 3.00 in hydride-cladding samples are included in the initial HFIR insertion to demonstrate that the hydride morphology is attained early in the irradiation. The capsules with the 3.00 in samples will be removed from the reactor after the first and second cycles of irradiation for PIE (metallography) to determine the resulting hydride morphology. The 6.00 in cladding sample is included in the initial insertion (assuming the resulting hydride morphology is prototypic) to begin accumulating the required fast neutron fluence.

The experiment design is relatively straightforward. The clad will be contained within the outer aluminum 6061 housing with a small gap between the parts. A molybdenum rod will be placed inside the clad as a heat source. Clad temperature will be set using the combination of the wall thickness of the molybdenum rod (which defines the heat flux applied to the inner clad wall) and the size of the gas gap on the outside of the clad. A design temperature of 330°C on the outer clad wall is specified for this experiment. This calculation documents the overall design and the analyses performed to design the initial experiments.

CALCULATION REVISION LOG

TITLE: Thermal Design Analysis for a Hydrided Clad Irradiation Experiment		
CALCULATION IDENTIFIER: DAC-11-19-HYDRIDE01		
REVISION NUMBER	**DESCRIPTION OF REVISION**	**DATE APPROVED**
0	Initial issue	

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1. Purpose

The ORNL program for the Used Fuel Disposition Campaign testing of hydrided cladding requires an irradiation of hydrided test samples of Zircaloy-4 in the High Flux Isotope Reactor (HFIR). The initial irradiation plan calls for the insertion of 3 capsules in HFIR: two of these capsules will contain 3.00 in (7.62 cm) hydrided Zircaloy-4 samples (0.374 in OD) and one capsule will contain a 6.00 in (15.24 cm) hydrided Zircaloy-4 sample (0.374 in OD). Under test irradiation conditions (temperature and temperature gradient across the cladding wall), the desired hydride morphology should be created within the cladding within days of the start of irradiation. The purpose of the 3.00 in hydride-cladding samples is to demonstrate that the hydride morphology is attained early in the irradiation. The capsules with the 3.00 in samples will be removed from the reactor after the first and second cycles of irradiation for post-irradiation examination (PIE) to illustrate the resulting hydride morphology. The 6.00 in cladding sample is included in the initial insertion to begin accumulating the required fast neutron fluence. If the desired hydride morphology is confirmed from the PIE of the 3.00 in samples, then additional capsules containing 6.00 in samples will be inserted in HFIR at later dates.

The purpose of this calculation is to summarize the experiment design for the Zircaloy-4 hydrided specimens. The specimen temperature is controlled by the fill gas, the size of the gap between the clad and housing, and the thickness of the molybdenum heater rod. Helium is selected as the fill gas for all experiments.

2. Design Description

2.1. HFIR Target Facilities

HFIR is a beryllium-reflected, pressurized, light-water-cooled and moderated flux-trap-type reactor. The core consists of aluminum-clad involute-fuel plates, which currently utilizes highly enriched ^{235}U fuel at a power level of 85 MWt.

The reactor core, illustrated in Figure 2-1, consists of two concentric annular regions, each approximately 61 cm in height. The flux trap is ~12.7 cm in diameter, and the outer fueled region is ~43.5 cm in diameter. The fuel region is surrounded by a beryllium annular reflector approximately 30.5 cm in thickness. The beryllium reflector is in turn backed up by a water reflector of effectively infinite thickness. In the axial direction, the reactor is reflected by water. The reactor core assembly is contained in a 2.44 m diameter pressure vessel, which is located in a 5.5 m cylindrical pool of water.

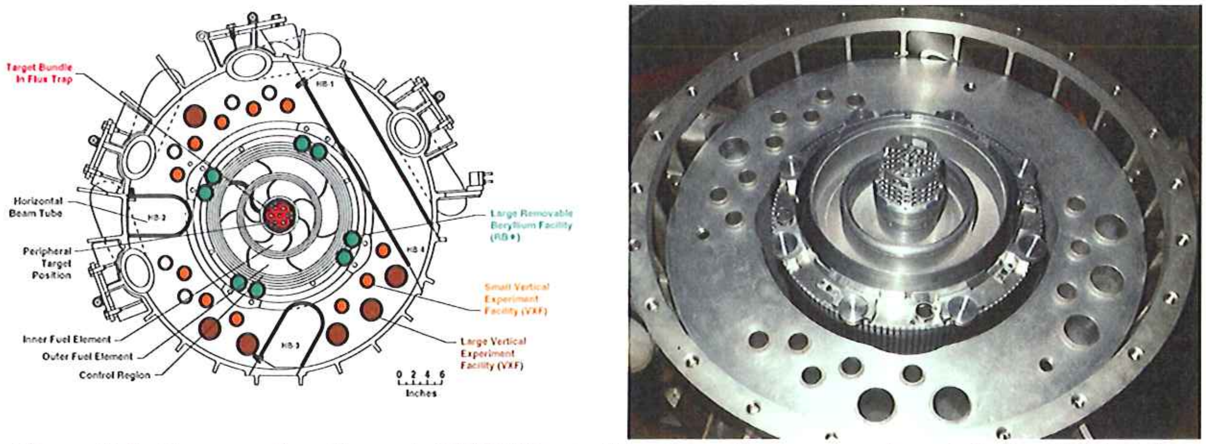

Figure 2-1. Cross section through HFIR illustrating the primary experimental sites (left) and a picture of the reactor core (right)

The Zircaloy-4 specimens in this design will be placed in the flux trap of HFIR in or near the outer ring of target positions shown in green in Figure 2-2. Table 2-1 summarizes the neutron flux characteristics of this location. The fast fluence is based on a typical 25 day cycle and 7 cycles per year.

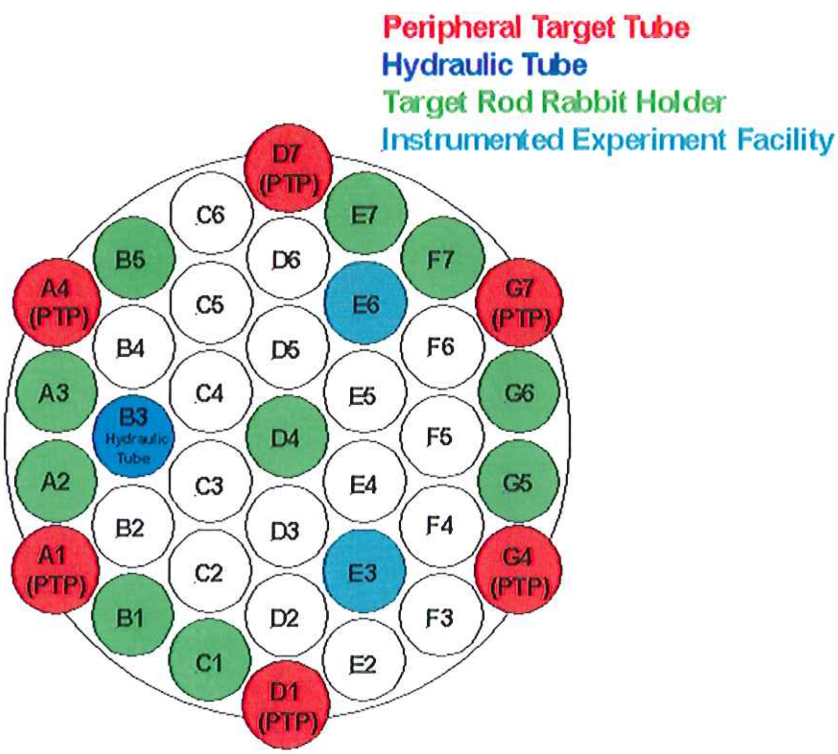

Figure 2-2. Flux Trap Irradiation Locations

Table 2-1. Neutron Flux Characteristics of the PTT and TRRH Irradiation Facilities

Parameter	TRRH (Greenwood, June 30, 1999)
Fast flux (10^{14} n/cm²·sec) [E > 1 MeV]	5.5
Fast flux (10^{14} n/cm²·sec) [E > 0.1 MeV]	10.8
Thermal flux (10^{14} n/cm²·sec) [E < 0.5 eV]	20.2
Fast fluence/cycle (10^{21} n/cm²) [E > 0.1 MeV]	2.33
Fast fluence/year (10^{21} n/cm²) [E > 0.1 MeV]	16.3
Axial peaking factor profile[1]	$1 - 1.06\cdot10^{-3}\cdot z^2$

1 peaking factor is the ratio of the local flux at a distance z from the reactor midplane (in cm) to the flux at the reactor midplane

The current design assumes that the experiments will be placed in an outer ring position centered at the HFIR midplane. The specimen between these locations will be at ±7.62 cm (±3.00 in). The profile from Table 2-1 gives a peaking factor of 0.94-1.00 with an average of 0.98, resulting in a fast neutron flux of $10.6\cdot10^{14}$ n/cm²·sec [E > 0.1 MeV]. For a nominal 25 day cycle, each specimen will receive $2.3\cdot10^{21}$ n/cm².

2.2. Experiment Design Description

The design drawings for this experiment are included in the attachments to this calculation. The inner assembly is shown in Figure 2-3.

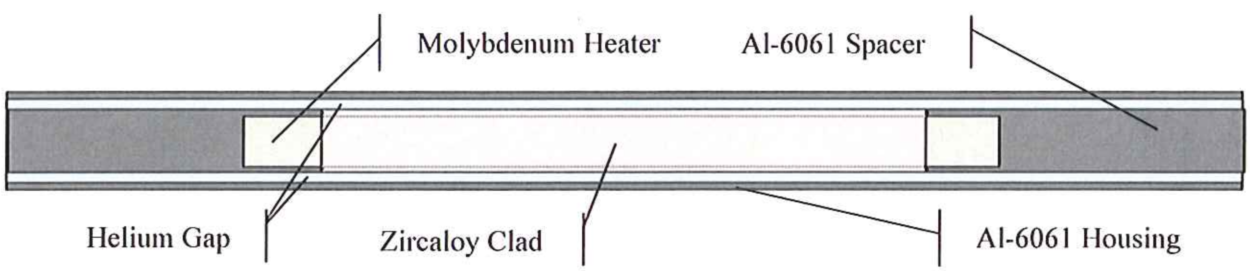

Figure 2-3. Experiment Assembly Schematic

Coolant is directed to the experiment by the Al-6061 outer shroud, which is shown on Drawing X3E020977A608. The outer aluminum housing is the primary containment for the experiment and is fabricated from Al-6061. The housing is specified on Drawing X3E020977A612 Rev A, and the assembly is provided on Drawing X3E020977A608. The housing is made from No. 17, ½-in Al-6061 tubing, which has an inner diameter of 9.73 mm (0.383 in). The ends of the tubing are bored out to an inner diameter of 11.3 mm (0.445 in) to meet the requirements of the existing design for the top and bottom caps and the approved weld procedures.

The Zircaloy-4 clad specimens have an outer diameter of 9.5 mm (0.3741 in) and an inner diameter of 8.35 mm (0.3287 in). The clad length will range from 76 mm (3.00 in) to 152 mm (6.00 in). The clad will be fitted with a molybdenum rod which acts as a heater for the cladding. The molybdenum rod is 102 mm (4 in) long for the 76 mm clad case and 178 mm (7 in) long for the 152 mm clad case. The axial location of the clad centroid is located at the reactor mid-plane. Spacers made from ⅜ in Al-6061 tubing are used to ensure this placement. For the 76 mm clad case, the top and bottom spacers are 224 mm (8.82 in) and 227 mm (8.95 in) respectively. Similarly, for the 152 mm clad case, the top and bottom spacers are 183 mm (7.22 in) and 189 mm (7.45 in) respectively. Both spacer sets are counterbored 12 mm (0.5 in) at the end oriented closest to the reactor centerline to hold the excess molybdenum heater rod while also keeping the clad in the proper location. Six equispaced pads are punched into the ends of each spacer closest to the reactor center line. This feature produces a slightly larger diameter from the original outer diameter of the spacer tube, and this dimension is set to keep the experiment centered in the housing tube. See Figure 2-4 for an illustration of this centering device.

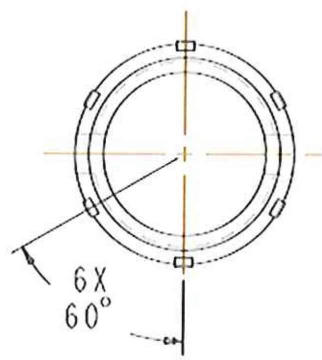

Figure 2-4. Centering Device

2.3. Design Drawings

Table 2-2 summarizes the design drawings and titles for the Zircaloy-4 hydride clad experiment.

Table 2-2. FCM Rabbit Design Drawings

Drawing No.	Title
X3E020977A570 Rev. 0	Shrouded Target Capsule Bottom Cap Assembly
X3E020977A571 Rev. 0	Shrouded Target Capsule Guide Pin Detail
X3E020977A572 Rev. 0	Shrouded Target Capsule Top Cap
X3E020977A573 Rev. 0	Shrouded Target Capsule Housing Tube
X3E020977A574 Rev. 0	Shrouded Target Capsule Rupture Sleeve
X3E020977A575 Rev. 0	Shrouded Target Capsule Shroud Tube
X3E020977A586 Rev. A	Target Capsule Housing and Shroud Weldment Subassembly
X3E020977A608 Rev. 0	Cladding Test Plan Hydriding Assembly
X3E020977A609 Rev. 0	Cladding Test Plan Hydriding Sample, Spacer, Rod Details
X3E020977A610 Rev. 0	Cladding Test Plan Hydriding Assembly Spacer Cap Detail
X3E020977A612 Rev. A	Cladding Test Plan Hydriding Housing Tube Detail

2.4. Materials of Construction

The outer housing tube and shroud are fabricated from Al-6061, and the cladding is fabricated from a nuclear-grade Zirconium clad alloy, such as Zircaloy-4. The center heater is fabricated from molybdenum or a molybdenum alloy. The spacers are fabricated from Al-6061. Material properties for this calculation are taken from the design and analysis calculations (DACs) shown in Table 2-3.

Table 2-3. Material Property References

Aluminum 6061	DAC-10-03-PROP_AL6061 Rev. 0
Helium	DAC-10-02-PROP_HELIUM Rev. 0
Zircaloy	DAC-11-03-PROP_ZIRCALOY Rev. 1
Molybdenum	DAC-10-11-PROP-MOLY Rev. 0

2.5. Thermal Boundary Conditions

The heat generation rates for capsule materials are summarized in Table 2-4. The convection parameters (heat transfer coefficient and bulk temperature) are also included.

Table 2-4. Thermal Boundary Conditions

Parameter	Value	Reference
Heat transfer coefficient	48.0 kW/m²·°C	DAC-10-19-JP03
Bulk fluid temperature (all regions)	60°C	DAC-10-19-JP03
Peak heat generation rate for AL6061	32.5 W/g	DAC-10-18-RAB02
Peak heat generation rate for Zircaloy	38.5 W/g	DAC-11-04-FCM01
Peak heat generation rate for Molybdenum	43.3 W/g	DAC-10-18-RAB02
Correlating parameter (σ)	30.07 cm	DAC-10-18-RAB02

The local heat generation rate is estimated with the following profile:

$$q(material, z) = q_{peak}(material) \cdot exp\left[-\left(\frac{z}{\sigma}\right)^2\right]$$

where:

q	—	local heat generation rate as a function of the material and axial location
q_{peak}	—	heat generation rate at the HFIR midplane as a function of material
z	—	axial location in HFIR, where the midplane is at zero
σ	—	correlating parameter (see Table 2-4)

2.6. Finite Element Model

The clad experiment uses relatively long specimens that are separated from the cool bottom of the aluminum housing by a centering piece and spacers. Therefore, axial heat flow will be minimized. A simple two dimensional model in the r-z plane should provide adequate estimates of operating temperatures. Symmetry about the reactor is also exploited, thus simplifying the model to only analyze the upper region of the experiment. The design temperature for all capsules is 330°C at the cladding outer surface.

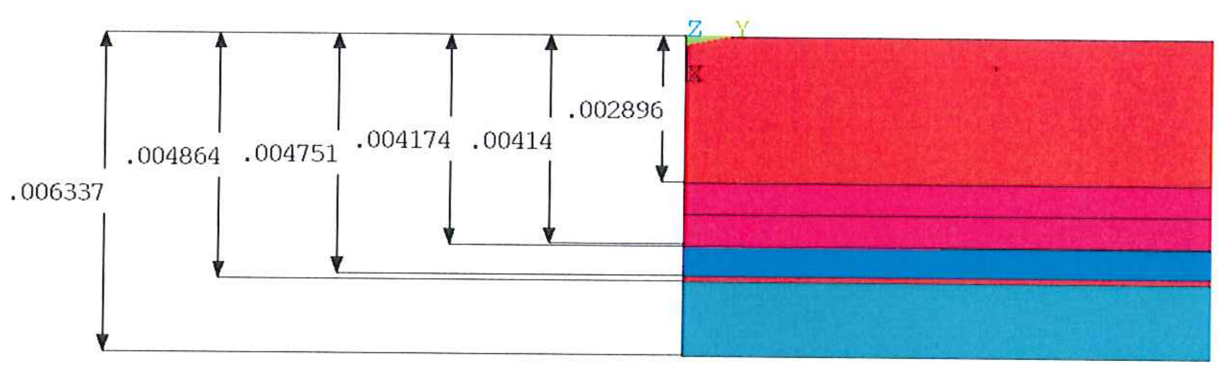

Figure 2-5. Radial Dimensions for Geometrical Model

The ANSYS input scripts used to create the specimen regions are included in Appendix A. Other ANSYS input scripts used to evaluate the models and summarize the results are documented elsewhere (McDuffee, 2010). Figure 2-5 shows the radial dimensions of geometrical model for the experiment in the r-z plane. These values, from smallest to largest, represent: molybdenum heater inner radius, molybdenum heater outer radius, Zircaloy cladding inner radius, Zircaloy cladding outer radius, housing tube inner radius, and housing tube outer radius. Figure 2-6 shows axial dimensions for the crucial parts along with part identifications. Note that the length of the Al-6061 spacer after the counterbore is not given. This dimension is not important to the analysis once it is sufficiently far away from the specimen. Therefore the spacer's axial length was set to be 0.0541 m (2.15 in). This dimension was selected by increasing the length of the part until the temperatures of the parts were no longer affected. All dimensions in both figures are shown in meters.

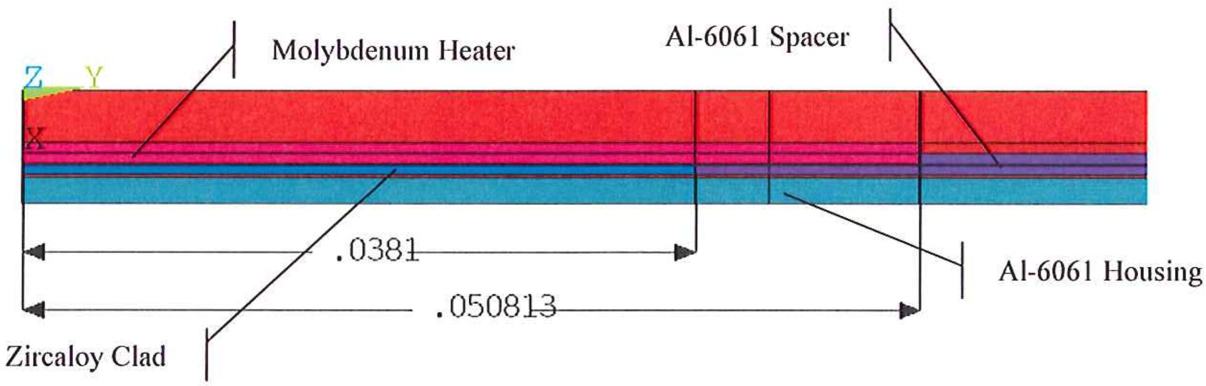

Figure 2-6. Axial Dimensions for Geometrical Model along with Part Identifications

3. Computations and Analyses

The sections below describe the results for each design. The design temperature for all models is 330°C at the cladding outer surface.

3.1. 3.00 in Hydrided Clad Capsule

The results for the 3.00 in cladding model are shown in Table 3-1. Figure 3-1 shows the temperature contours for the cladding in this case.

Table 3-1. Design Summary for 3.00 in Hydrided Clad Capsule

Design ID	Part	Temperature (°C) Average (Min-Max)
3.00 in Hydrided Clad	Housing	68 (63-75)
	Spacer	147 (117-267)
	Cladding	332 (279-350)
	Heater	395 (295-426)

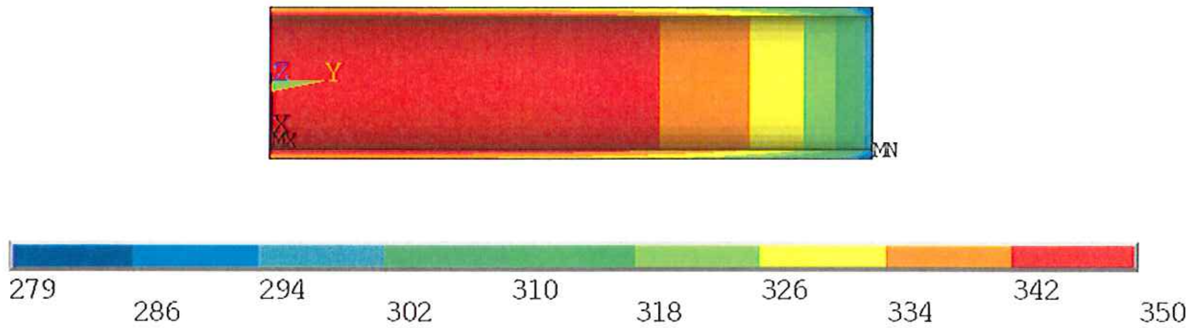

Figure 3-1. 3.00 in Hydrided Clad Temperature Contour Plot

3.2. 6.00 in Hydrided Clad Capsule

The results of the 6.00 in cladding are described in Table 3-2. Figure 3-2 shows the temperature contours for this cladding specimen.

Table 3-2. Design Summary for 6.00 in Hydrided Clad Capsule

Design ID	Part	Temperature (°C) Average (Min-Max)
6.00 in Hydrided Clad	Housing	69 (63-75)
	Spacer	142 (113-260)
	Cladding	333 (271-350)
	Heater	402 (285-427)

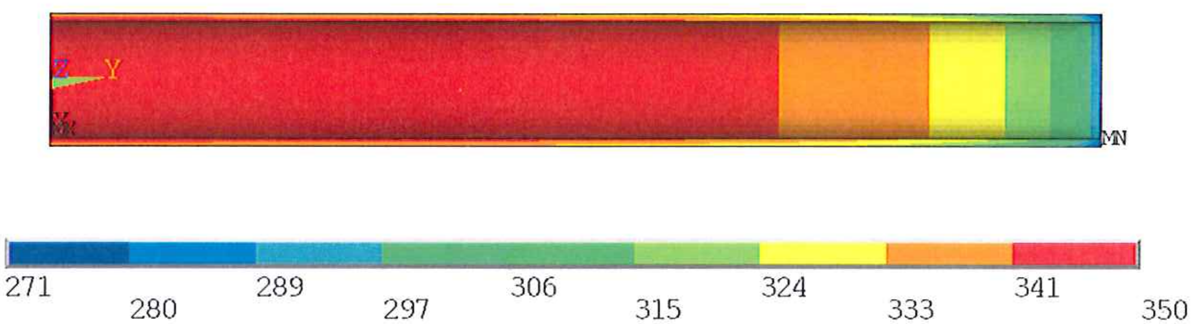

Figure 3-2. 6.00 in Hydrided Clad Temperature Contour Plot

4. .Summary of Results

Table 4-1 summarizes the key design temperatures for both of the clad types. The design temperature for the hydrided clad is 330°C at the clad surface. The analysis for both the 3.00 in and 6.00 in experiments reveal clad surface temperatures with less than a 10°C discrepancy at the reactor centerline (specimen hottest point) from the design temperatures.

Table 4-1. Design Summary for Hydrided Clad Capsules

Design ID	Molybdenum Design Inner Diameter	Cladding Specimen Temperature (°C) at Outer Surface at Reactor Centerline	Cladding Specimen Temperature (°C) Average (Min-Max)
3.00 in Hydrided Clad	5.79 mm (0.228 in)	332	332 (279-350)
6.00 in Hydrided Clad	5.79 mm (0.228 in)	333	333 (271-350)

5. Conclusions

This calculation establishes design diameters for the molybdenum heater rods to provide a sufficient mass to bring hydrided cladding specimens to a desired temperature of 330°C at the cladding surface for the 3.00 in and 6.00 in clad specimens. Helium fill gas proved to be the best heat transfer medium for this experiment. Due to the non-constant flux profile of the HFIR core, a uniform temperature in the specimen cannot be easily attained. Therefore, a slightly higher cladding surface temperature of ~333°C was achieved at the reactor centerline to ensure an average cladding surface temperature was reasonably close to the design constraint.

6. References

Greenwood, L R. June 30, 1999. *Neutron Dosimetry and Damage Calculations for the HFIR-CTR-62 and 63.* s.l. : Fusion Reactor Materials Program, Semi-annual Progress Report, June 30, 1999. DOE/ER-0313/26 - Volume 26.

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APPENDIX A

ANSYS Scripts Used to Create and Evaluate FEA Models

```
!*****************************************************************************
!*    MACRO HYDRIDE CLAD TARGET CAPSULE                                      *
!*                                                                           *
!* ARG1 - 0 = Perform Calculation with 3 in clad section.  (default)        *
!*        1 = Perform Calculation with 6 in clad section.                   *
!*                                                                           *
!*****************************************************************************

 FINISH
 /CLEAR
 /PREP7
 SHPP,MODIFY,1,500            ! Loosen tolerance on aspect ratio
 in = 0.0254                  !conversion from in to m ~> ##*in = ###m

!----------------------------------------------------------------------------
! INPUT SPECIFICATIONS
!----------------------------------------------------------------------------

 CRgap=0.0005*in      ! contact resistance gap
 Lbit=1E-06           ! a little bit
 PI=3.1415926536
 PF = 1.0
 SELTOL,Lbit/2        ! set the tolerance

! Heat Transfer Coefficient
 Hfilm=48040  !heat transfer coefficient (W/m²·°C) DAC-10-19-JP03
 Tcoolant=60  !bulk coolant temperature (°C)       DAC-10-19-JP03
 CASE_NUM = 3 + 3*ARG1 !used for report book keeping
!----------------------------------------------------------------------------
!     DEFINE MATERIALS ARRAY(S)
!----------------------------------------------------------------------------
nMats=5  !number of materials

!Define extra material property arrays
 xprpTmelt=
*DIM,xprpTmelt,ARRAY,nMats                    ! melting point
 xprpMatName=
*DIM,xprpMatName,CHAR,nMats                   ! material name
 xprpMolecularWeight=

!Define part name array
 PartName=
*DIM,PartName,STRING,20,nMats

!Define heat generation rate material array
 Qmass=
*DIM,Qmass,ARRAY,nMats,3

!----------------------------------------------------------------------------
! LOAD MATERIAL PROPERTIES
!----------------------------------------------------------------------------

 MAT_AL6061,      1,10                  ! Housing (AL6061)
 MAT_AL6061,      2,10                  ! Spacer(AL6061)
 MAT_HE,          3,10                  ! Fill Gas (Helium)
 MAT_ZIRC,        4,10                  ! Zircaloy
 MAT_MOLY,        5,10                  ! Molybdenum

!Define part names
 PartName(1, 1) ='Housing'
 PartName(1, 2) ='Spacer'
 PartName(1, 3) ='Fill Gas'
 PartName(1, 4) ='Zircaloy'
 PartName(1, 5) ='MOLY'

Qmass( 1,1)  = 32500                    ! Housing (AL6061) TRRH DAC-10-18-RAB02
Qmass( 2,1)  = 32500                    ! Spacer (AL6061)  TRRH DAC-10-18-RAB02
Qmass( 3,1)  =     0.                   ! Fill Gas (Helium)TRRH DAC-10-18-RAB02
```

```
 Qmass( 4,1)  = 38500                    ! Zircaloy          TRRH DAC-11-04-FCM01
 Qmass( 5,1)  = 43300                    ! Molybdenum        TRRH DAC-10-18-RAB02

!------------------------------------------------------------------------------
!  DIMENSIONAL SPECIFICATIONS
!------------------------------------------------------------------------------

!Housing dimensions:
 HOUSE_IR       = 0.383/2*in
 HOUSE_OR       = 0.499/2*in

 SPACER_IR      = 0.277/2*in
 SPACER_OR      = 0.375/2*in

 HEATER_OR      = 0.326/2*in

 CLAD_IR        = 0.3287/2*in
 CLAD_OR        = 0.3741/2*in

 SPACER_H       = 2.15*in
 PLUNGE_H       = 0.5*in

*IF,ARG1,EQ,0,THEN
 HEATER_H       = 2.00*in
 HEATER_IR      = 0.228/2*in
 CLAD_H         = 1.50*in
*ELSEIF,ARG1,EQ,1,THEN
 HEATER_H       = 3.50*in
 HEATER_IR      = 0.228/2*in
 CLAD_H         = 3.00*in
*ENDIF

!------------------------------------------------------------------------------
!  BUILD MODEL IN R-Z PLANE
!------------------------------------------------------------------------------

 Z_0 = 0.       $Z_1 = CLAD_H                  $SLICE
 Z_0 = Z_1      $Z_1 = Z_0 + CRgap             $SLICE
 Z_0 = Z_1      $Z_1 = Z_0 + PLUNGE_H/3        $SLICE
 Z_0 = Z_1      $Z_1 = Z_0 + PLUNGE_H*2/3      $SLICE
 Z_0 = Z_1      $Z_1 = Z_0 + CRgap             $SLICE
 Z_0 = Z_1      $Z_1 = Z_0 + SPACER_H          $SLICE

 APTN,ALL
 NUMCMP,AREA
 NUMCMP,LINE

!------------------------------------------------------------------------------
!SET UP LINE BREAKS
!------------------------------------------------------------------------------
 LSEL,S,LENGTH,,CLAD_H
 LESIZE,ALL,,,30,1/30,1

 LSEL,S,LOC,X,0,Lbit
 LSEL,R,LENGTH,,CLAD_H
 LESIZE,ALL,,,30,30,1

 LSEL,S,LENGTH,,CRgap
 LESIZE,ALL,,,5,,1

 LSEL,S,LENGTH,,PLUNGE_H/3
 LESIZE,ALL,,,10,10,1

 LSEL,S,LENGTH,,PLUNGE_H*2/3
 LESIZE,ALL,,,20,1/20,1

 LSEL,S,LENGTH,,SPACER_H
 LESIZE,ALL,,,50,50,1
```

```
LSEL,S,LOC,X,0,SPACER_IR
LSEL,R,LENGTH,,SPACER_IR
LESIZE,ALL,,,10,1/10,1

LSEL,S,LOC,X,0,SPACER_IR
LSEL,R,LENGTH,,SPACER_IR
LSEL,U,LOC,Y,0,Lbit
LESIZE,ALL,,,10,10,1

LSEL,S,LOC,Y,0,Lbit
LSEL,R,LENGTH,,HEATER_IR-SPACER_IR
LESIZE,ALL,,,2,,1

LSEL,S,LOC,Y,0,Lbit
LSEL,R,LENGTH,,HEATER_OR-HEATER_IR
LESIZE,ALL,,,5,,1

LSEL,S,LOC,Y,0,Lbit
LSEL,R,LENGTH,,CLAD_OR-CLAD_IR
LESIZE,ALL,,,5,,1

LSEL,S,LOC,Y,0,Lbit
LSEL,R,LENGTH,,HOUSE_IR-CLAD_OR
LESIZE,ALL,,,3,,1

LSEL,S,LOC,Y,0,Lbit
LSEL,R,LENGTH,,HOUSE_OR-HOUSE_IR
LESIZE,ALL,,,2,,1

LSEL,S,LOC,Y,Z_1-Lbit,Z_1
LSEL,R,LENGTH,,HEATER_IR-SPACER_IR
LESIZE,ALL,,,2,,1

LSEL,S,LOC,Y,Z_1-Lbit,Z_1
LSEL,R,LENGTH,,HEATER_OR-HEATER_IR
LESIZE,ALL,,,5,,1

LSEL,S,LOC,Y,Z_1-Lbit,Z_1
LSEL,R,LENGTH,,CLAD_OR-CLAD_IR
LESIZE,ALL,,,5,,1

LSEL,S,LOC,Y,Z_1-Lbit,Z_1
LSEL,R,LENGTH,,HOUSE_IR-CLAD_OR
LESIZE,ALL,,,3,,1

LSEL,S,LOC,Y,Z_1-Lbit,Z_1
LSEL,R,LENGTH,,HOUSE_OR-HOUSE_IR
LESIZE,ALL,,,2,,1

!-----------------------------------------------------------------------------
!ASSIGN MATERIALS TO AREAS
!-----------------------------------------------------------------------------

Z_0 = 0       $Z_1 = CLAD_H
ASEL,S,LOC,Y,Z_0,Z_1
AATT, 1
ASEL,U,LOC,X,HOUSE_IR,HOUSE_OR
AATT, 3
ASEL,U,LOC,X,CLAD_OR,HOUSE_OR
AATT, 4
ASEL,U,LOC,X,CLAD_IR,HOUSE_OR
AATT, 3
ASEL,U,LOC,X,HEATER_OR,HOUSE_OR
AATT, 5
ASEL,U,LOC,X,HEATER_IR,HOUSE_OR
AATT, 3
```

```
Z_0 = Z_1       $Z_1 = Z_0 + CRgap
ASEL,S,LOC,Y,Z_0,Z_1
AATT, 1
ASEL,U,LOC,X,HOUSE_IR,HOUSE_OR
AATT, 3
ASEL,U,LOC,X,HEATER_OR,HOUSE_OR
AATT, 5
ASEL,U,LOC,X,HEATER_IR,HOUSE_OR
AATT, 3

Z_0 = Z_1       $Z_1 = Z_0 + PLUNGE_H/3
ASEL,S,LOC,Y,Z_0,Z_1
AATT, 1
ASEL,U,LOC,X,HOUSE_IR,HOUSE_OR
AATT, 3
ASEL,U,LOC,X,CLAD_OR,HOUSE_OR
AATT, 2
ASEL,U,LOC,X,CLAD_IR,HOUSE_OR
AATT, 3
ASEL,U,LOC,X,HEATER_OR,HOUSE_OR
AATT, 5
ASEL,U,LOC,X,HEATER_IR,HOUSE_OR
AATT, 3

Z_0 = Z_1       $Z_1 = Z_0 + PLUNGE_H*2/3
ASEL,S,LOC,Y,Z_0,Z_1
AATT, 1
ASEL,U,LOC,X,HOUSE_IR,HOUSE_OR
AATT, 3
ASEL,U,LOC,X,CLAD_OR,HOUSE_OR
AATT, 2
ASEL,U,LOC,X,CLAD_IR,HOUSE_OR
AATT, 3
ASEL,U,LOC,X,HEATER_OR,HOUSE_OR
AATT, 5
ASEL,U,LOC,X,HEATER_IR,HOUSE_OR
AATT, 3

Z_0 = Z_1       $Z_1 = Z_0 + CRgap
ASEL,S,LOC,Y,Z_0,Z_1
AATT, 1
ASEL,U,LOC,X,HOUSE_IR,HOUSE_OR
AATT, 3
ASEL,U,LOC,X,CLAD_OR,HOUSE_OR
AATT, 2
ASEL,U,LOC,X,CLAD_IR,HOUSE_OR
AATT, 3

Z_0 = Z_1       $Z_1 = Z_0 + SPACER_H
ASEL,S,LOC,Y,Z_0,Z_1
AATT, 1
ASEL,U,LOC,X,HOUSE_IR,HOUSE_OR
AATT, 3
ASEL,U,LOC,X,CLAD_OR,HOUSE_OR
AATT, 2
ASEL,U,LOC,X,SPACER_IR,HOUSE_OR
AATT, 3
ALLSEL

!-------------------------------------------------------------------------------
!     MESH
!-------------------------------------------------------------------------------
ET,1,PLANE77,,,1

MSHAPE,0,2D              !Mesh with quadralateral-shaped elements in 2-D model
MSHKEY,1                 !Mapped meshing is used
AMESH,ALL
ALLSEL
```

```
!--------------------------------------------------------------------------------
!  DEFINE MACRO LIBRARY FOR SOLVING 2-D MODELS IN THE R-THETA PLANE
!--------------------------------------------------------------------------------
 *ULIB,'RZ_LIBRARY_R1','ULIB'
!--------------------------------------------------------------------------------
!      CREATE BOUNDARY CONDITION FILES
!--------------------------------------------------------------------------------
 CSYS,0
 ! Set convection nodes
 LSEL,S,LOC,X,HOUSE_OR-Lbit,HOUSE_OR
 NSLL,S,1
 ENTITY_SAVE,'NODE','CONVECT'
 /OUTPUT,'CONVECT','INP',,APPEND
 /COM, SF,ALL,CONV,Hfilm,Tcoolant
 /OUTPUT
 ALLSEL

 !Set Y-restraint
 LSEL,S,LOC,Y,0
 NSLL,S,1
 ENTITY_SAVE,'NODE','CONSTRNT'
 /OUTPUT,'CONSTRNT','INP',,APPEND
 /COM, D,ALL,UY,0.0
 /COM,
 /OUTPUT

 !Set X-restraint
 LSEL,S,LOC,X,0
 NSLL,S,1
 ENTITY_SAVE,'NODE','CONSTRNT',1
 /OUTPUT,'CONSTRNT','INP',,APPEND
 /COM, D,ALL,UX,0.0
 /OUTPUT

 ALLSEL

 ! Set up internal heat generation for element type 1
 *USE,HEATGEN,1

!--------------------------------------------------------------------------------
!      SOLVE
!--------------------------------------------------------------------------------

 *USE,SEQSOLVE,'CONVECT','CONSTRNT',1

!--------------------------------------------------------------------------------
!      POST PROCESSING
!--------------------------------------------------------------------------------
 /DELETE,'CONSTRNT','INP'
 /DELETE,'CONVECT','INP'

 *ULIB
 ALLSEL

 SAVE
 /POST1
 /GFORMAT,F,12,0
 PLNSOL,TEMP
 ESEL,S,MAT,,4
 /REPLOT

HYDRIDE_MAKEREPORT
SAVE
!--------------------------------------------------------------------------------
!      EOF
!--------------------------------------------------------------------------------
```

```
!**************************************************************************
!*     MACRO SLICE                                                        *
!*                                                                        *
!*     Prepares radial slices for HYDRIDE CLAD TARGET CAPSULE             *
!*     Requires a height interval (Z_0-Z_1)                               *
!*                                                                        *
!**************************************************************************
 /PREP7

 RECTNG,0,HEATER_IR,Z_0,Z_1
 RECTNG,0,SPACER_IR,Z_0,Z_1
 RECTNG,0,HEATER_OR,Z_0,Z_1
 RECTNG,0,CLAD_IR,Z_0,Z_1
 RECTNG,0,CLAD_OR,Z_0,Z_1
 RECTNG,0,HOUSE_IR,Z_0,Z_1
 RECTNG,0,HOUSE_OR,Z_0,Z_1
!-------------------------------------------------------------------------
!      EOF
!-------------------------------------------------------------------------

!**************************************************************************
!*                                                                        *
!*         MACRO HYDRIDE_MAKEREPORT                                       *
!*                                                                        *
!* This macro outputs key temperatures and other parameters for the capsule *
!*                                                                        *
!**************************************************************************


*ULIB,'RZ_LIBRARY_R1','ULIB'
*GET,strOutFile,ACTIVE,0,JOBNAM

/OUTPUT,strOutFile,'txt'
/COM, ***************************************************************************
/COM,       DESIGN ANALYSIS SUMMARY FOR HYDRIDED CLAD CAPSULES
/COM, ****************************************************************************
/COM
/COM, ---------------------------------------------------------------------------
/COM, DESCRIPTION
/COM
/COM, * %CASE_NUM% in Hydrided Clad Case
/COM, * 2-dimensional analysis (R-Z plane)
/COM, * %xprpMatName(3)% fill gas
/COM
/COM, BOUNDARY CONDITIONS
/COM
*VWRITE,Hfilm
  ('  Heat transfer coefficient = ',F7.0,' W/m²·°C')
*VWRITE,Tcoolant
  ('  Bulk coolant temperature  = ',F5.1,' °C')

/COM, ---------------------------------------------------------------------------
/COM, CONVERGENCE NOTE
/COM
/OUTPUT
*VLEN,1
*IF,Converge,EQ,0,THEN
     /OUTPUT,strOutFile'_'ARG1,'txt',,APPEND
     /COM, Solution is converged after %iFinal% iterations.
     *VWRITE,Terror(iFinal)
           ('       Maximum error = ',F5.3,'°C')
     /COM
     /OUTPUT
*ELSE
     /OUTPUT,strOutFile,'txt',,APPEND
     /COM, Solution is NOT converged after %iFinal% iterations.
     *VWRITE,Terror(iFinal)
           ('       Maximum error = ',F7.2,'°C')
```

```
     /COM
     /OUTPUT
*ENDIF

!------------------------------------------------------------------------------
! Heat generation rates
!------------------------------------------------------------------------------
/OUTPUT,strOutFile'_'ARG1,'txt',,APPEND
/COM, ------------------------------------------------------------------------------
/COM, HEAT GENERATION
*VWRITE,
     (36X,'-- Heat Generation --      -- Linear Heat Load --')
*VWRITE,
  Part                   Material     @Midplane    @Location    @Midplane     @Location
/COM,                                    (W/kg)       (W/kg)         (W)          (W)
*VWRITE,
(2X,'-------------------    --------   ---------   ---------    ---------    ---------')
/OUTPUT
 Qlinear_peak=0
 Qlinear_applied=0
*DO,iMat,1,nMats
     *IF,Qmass(iMat,1),GT,0.0,THEN
          *VLEN,1
          /OUTPUT,strOutFile'_'ARG1,'txt',,APPEND

*VWRITE,PartName(1,iMat),xprpMatName(iMat),Qmass(iMat,1),Qmass(iMat,1),Qmass(iMat,2),Qmass(iMat,3
)
  %-20C    %-8C    %8.0F    %8.0F     %8.0F    %8.0F
          /OUTPUT
           Qlinear_peak=Qlinear_peak+Qmass(iMat,2)
           Qlinear_applied=Qlinear_applied+Qmass(iMat,3)
     *ENDIF
*ENDDO
/OUTPUT,strOutFile'_'ARG1,'txt',,APPEND
*VWRITE,
(2X,'-------------------    --------   ---------   ---------    ---------    ---------')
*VWRITE,Qlinear_peak,Qlinear_applied
     (53X,'TOTAL',5X,F8.0,4X,F8.0)
/COM
*VWRITE,Qlinear_applied/(2*PI*HOUSE_OR*Z_1)
  Heat flux at location = %8.0F W/m²
*VWRITE,Qlinear_peak/(2*PI*HOUSE_OR*Z_1)
  Heat flux at midplane = %8.0F W/m²

!------------------------------------------------------------------------------
! Part temperature summary
!------------------------------------------------------------------------------
/COM
/COM, ------------------------------------------------------------------------------
/COM, CAPSULE TEMPERATURE SUMMARY
/COM
/COM, Name                     Material     Tavg    Tmin    Tmax     Tmelt
/COM,                                        (C)     (C)     (C)      (C)
/COM, -------------------    --------     -----   -----   -----    -----

/OUTPUT

*DO,iMat,1,nMats
      ESEL,S,TYPE,,1
      ESEL,R,MAT,,iMat
     *IF,ELNEXT(0),GT,0,AND,Qmass(iMat,1),GT,0.0,THEN
            TEMP_SUMMARY
           *VLEN,1
           /OUTPUT,strOutFile,'txt',,APPEND
           *VWRITE,PartName(1,iMat),xprpMatName(iMat),TempAvg,TempMin,TempMax,xprpTmelt(iMat)
  %-20C  %-10C   %5.0F   %5.0F   %5.0F    %5.0F
           /OUTPUT
     *ENDIF
```

```
*ENDDO
!---------------------------------------------------------------------------
!       EOF
!---------------------------------------------------------------------------
```

APPENDIX B

ANSYS Design Reports

Appendix B Table of Contents

B-1. Design 3.00 in Hydrided Clad

```
******************************************************************************
     DESIGN ANALYSIS SUMMARY FOR HYDRIDED CLAD CAPSULES
*******************************************************************************

------------------------------------------------------------------------------
DESCRIPTION

* 3 in Hydrided Clad Case
* 2-dimensional analysis (R-Z plane)
* Helium fill gas

BOUNDARY CONDITIONS

Heat transfer coefficient =  48040. W/m²·°C
Bulk coolant temperature  =  60.0 °C
------------------------------------------------------------------------------
CONVERGENCE NOTE

Solution is converged after 8 iterations.
     Maximum error = 0.042°C

------------------------------------------------------------------------------
HEAT GENERATION
                                 -- Heat Generation --      -- Linear Heat Load --
Part                   Material    @Midplane   @Location    @Midplane    @Location
                                    (W/kg)      (W/kg)        (W)          (W)
--------------------   --------   ---------   ---------    ---------    ---------
Housing                 AL-6061      32500.      32500.         480.         461.
Spacer                  AL-6061      32500.      32500.         172.         161.
Zircaloy                Zircaloy     38500.      38500.         155.         155.
MOLY                    Moly         43300.      43300.         619.         613.
--------------------   --------   ---------   ---------    ---------    ---------
                                                  TOTAL        1425.        1389.

Heat flux at location =  330792. W/m²
Heat flux at midplane =  339453. W/m²

------------------------------------------------------------------------------
CAPSULE TEMPERATURE SUMMARY

Name                   Material     Tavg    Tmin    Tmax     Tmelt
                                    (C)     (C)     (C)      (C)
--------------------   --------    -----   -----   -----    -----
Housing                AL-6061       68.     63.     75.     582.
Spacer                 AL-6061      147.    117.    267.     582.
Zircaloy               Zircaloy     332.    279.    350.    1825.
MOLY                   Moly         395.    295.    426.    2617.
```

B-2. Design 6.00 in Hydrided Clad

```
****************************************************************************
     DESIGN ANALYSIS SUMMARY FOR HYDRIDED CLAD CAPSULES
****************************************************************************

----------------------------------------------------------------------------
DESCRIPTION

* 6 in Hydrided Clad Case
* 2-dimensional analysis (R-Z plane)
* Helium fill gas

BOUNDARY CONDITIONS

Heat transfer coefficient =  48040. W/m²·°C
Bulk coolant temperature  =  60.0 °C
----------------------------------------------------------------------------
CONVERGENCE NOTE

Solution is converged after 7 iterations.
     Maximum error = 0.096°C

----------------------------------------------------------------------------
HEAT GENERATION
                                 -- Heat Generation --     -- Linear Heat Load --
Part                  Material   @Midplane   @Location    @Midplane    @Location
                                  (W/kg)      (W/kg)        (W)          (W)
--------------------  --------   ---------   ---------    ---------    ---------
Housing               AL-6061      32500.      32500.        653.         607.
Spacer                AL-6061      32500.      32500.        172.         149.
Zircaloy              Zircaloy     38500.      38500.        311.         304.
MOLY                  Moly         43300.      43300.       1082.        1052.
--------------------  --------   ---------   ---------    ---------    ---------
                                                 TOTAL      2218.        2111.

Heat flux at location =  369380. W/m²
Heat flux at midplane =  388008. W/m²

----------------------------------------------------------------------------
CAPSULE TEMPERATURE SUMMARY

Name                  Material     Tavg     Tmin     Tmax     Tmelt
                                   (C)      (C)      (C)      (C)
--------------------  --------     -----    -----    -----    -----
Housing               AL-6061       69.      63.      75.      582.
Spacer                AL-6061      142.     113.     260.      582.
Zircaloy              Zircaloy     333.     271.     350.     1825.
MOLY                  Moly         402.     285.     427.     2617.
```

ATTACHMENT 3

RRD Calculation

Title:	Temperature Verification Calculation for Hydrided Cladding Specimens in the HFIR Target Region		
Calculation ID: C-HFIR-2012-003			Safety related? ☒Yes ☐No
Revision:	0		
Prepared:	R.H. Howard R.H. Howard 2/17/12		
Checked:	JLMcDuffee 2/17/12		
Reviewed:	Kevin Cetiner 2/17/12 QwA 2/21/12		
Approved:	Kevin A Smith		
Date:	2/22/2012		
List all pages added by this revision:		N/A	
List all pages deleted by this revision:		N/A	
List all pages changed by this revision:		N/A	

Abstract:

This calculation considers the maximum temperature for target capsules containing hydrided cladding specimens and a molybdenum heater rod irradiated in the flux trap of the High Flux Isotope Reactor. The calculation demonstrates that the melting temperatures and dimensional constraints of internal components cannot be exceeded. Also, it is shown that this capsule is bounded by a previous calculation (C-HFIR-2011-020) ensuring that no flow excursion can occur under steady state normal operation, steady state local flow blockage, steady state at 130% power and full flow, LOOP and SBLOCA conditions.

MathCad is used to document calculations that are in a form suitable for hand calculation verification (MathCad is registered in the ORNL SRS (ID : 001232).

Revision Log

Title: Temperature Verification Calculation for Hydrided Cladding Specimens in the HFIR Target Region		
Calculation ID: C-HFIR-2012-003		
Revision Number	Description of Revision	Date Approved
0	Initial issue	2/22/2012

C-HFIR-2012-003 Rev. 0

TECHNICAL ADEQUACY REVIEW CHECKLIST

Y	N	NA	
☑	☐	☐	Is the calculation well organized, legible, and complete?
☑	☐	☐	If excerpts from other sources are included in the calculation, are the excerpts legible and properly referenced?
☑	☐	☐	Does the expressed purpose satisfy the requirements of the calculation? (Are all necessary elements included?)
☑	☐	☐	Is the method used appropriate considering the purpose and type of analysis and the use and acceptability of the results (i.e., margin to limits)?
☑	☐	☐	Is the method in accordance with codes, standards, and regulatory requirements?
☑	☐	☐	Has the method been employed similarly elsewhere in industry?
☑	☐	☐	Are assumptions necessary to perform the analysis adequately described, justified, and reasonable?
☑	☐	☐	Where necessary, are the assumptions identified for subsequent reverifications when the detailed design activities are completed?
☑	☐	☐	Are the inputs sufficient considering the purpose of the analysis?
☑	☐	☐	Are all codes used identified along with the source, computer type, inputs, and outputs?
☑	☐	☐	Has the code being used been adequately verified?
☑	☐	☐	Is the code suitable for the present analysis?
☑	☐	☐	Does the computer model (noding, time steps, etc.) adequately represent the physical systems?
☑	☐	☐	Is the magnitude of the result reasonable?
☑	☐	☐	Are the direction of trends reasonable?

Attached, Supporting Material	
Title/Description	**No. of Pages**
N/A	N/A

Comment number	Comment	Originator's resolution	Commentor's concurrence (if required)
	All comments resolved JLM 2/6/12		

CALCULATION INDEPENDENT REVIEW FORM

C-HFIR-2012-003 — 0

CALCULATION NO. — **REVISION**

METHOD OF INDEPENDENT REVIEW USED (CHECK METHOD USED):

√ **1. CALCULATION REVIEW**	In the calculation review method, justify the technical adequacy of the calculation and explain how the adequacy was verified (calculation is similar to another, based on accepted handbook methods, appropriate sensitivity studies included for confidence, etc.).
√ **2. ALTERNATE CALCULATION**	In the alternate calculation method, identify the pages where the alternate calculation has been included in the calculation package and explain why this method is adequate.
☐ **3. QUALIFICATION TEST**	In the qualification test method, identify the QA-documented source(s) where testing adequately demonstrate the adequacy of this calculation and explain.

Attached, Supporting Material		
Title/Description	**No. of Pages**	
Description of the independent calculation and comparison with the MATCAD calculation results.	6	
SBP-1300 Verification		
	Yes	**No**
The software configuration control requirements of SBP-1300 have been satisfied.	√	
Justification for "No" response to a question above:		
Independent Review Verification		
	Yes	**No**
Did you have any part in preparing the original calculation ?		√
Did you specify any analytic approach ?		√
Did you rule out any analytic considerations ?		√
Did you establish any input to the calculation being verified		√
Justification for any "Yes" response to a question above:		

N. O. Cetiner | 02/13/2012
INDEPENDENT REVIEWER | **DATE**

Independent Reviewer Comments

Independent analysis was performed using ANSYS 2-D model in the R-θ plane, exploiting 10° symmetry. The convective heat transfer coefficient, bulk fluid temperature, geometry input dimensions, heat generation rates were adapted from C-HFIR-2012-003/Rev0. Temperature dependent material property data files were used in the ANSYS model. This is different from the conservative properties used in the original calculation. The results summarized below gave an idea about the maximum temperatures that could be reached. The independent review showed that the temperatures reached at the original safety calculation are consistent, however original calculation have higher temperatures due to the conservatism used on the selected material property values. The calculation methodology in the C-HFIR-2012-003/Rev.0 is technically correct and it is true that temperature values do not exceed the melting temperatures.

The independent review also includes radial expansion results that agreed with the C-HFIR-2012-003/Rev0. Due to the restrictions on a 2-D model no axial expansion calculation was performed. The hot gap for the minimum radial gap calculation is 2.35 mils at the centerline location and 1.61 mils at the location that is 1.5 inches away from the centerline. These values are larger than the values in the C-HFIR-2012-003/Rev0 which are reported as 1.9 mils for the centerline location and 0.4 mils for the location 1.5 inches away from the centerline. As a conclusion internal components cannot produce radial stress on the capsule housing under the worst expected operating and expansion conditions. Calculation C-HFIR-2012-003/Rev0 is justified to be used as a bounding case.

Nevin Cetiner

N. O. Cetiner
2/13/12

****

INDEPENDENT REVIEW SUMMARY FOR HYDRIED CLAD TARGET EXPERIMENT

****

DESCRIPTION

* AL-6061 Housing
* Zircaloy Cladding
* Molybdenum Heater
* 2-dimensional analysis (r-theta plane)
* Helium fill gas

COLD MODEL DIMENSIONS

Outer housing radius = 6.290 mm (0.2476 in)
Inner housing radius = 4.860 mm (0.1913 in)
Outer clad radius = 4.720 mm (0.1858 in)
Inner clad radius = 4.190 mm (0.1650 in)
Outer heater radius = 4.130 mm (0.1626 in)
Inner heater radius = 2.870 mm (0.1130 in)

BOUNDARY CONDITIONS

Heat transfer coefficient = 49735. $W/m^2 \cdot °C$
Bulk coolant temperature = 67.7 °C
Reactor power factor = 1.26 (@110.5 MW) (Reactor centerline)

HEAT GENERATION

Part	Material	-- Heat Generation -- @Midplane (W/kg)	@Location (W/kg)	-- Linear Heat Load -- @Midplane (W/m)	@Location (W/m)
Housing	AL-6061	41350.	41350.	5592.	7054.
Cladding	Zircaloy	61000.	61000.	5928.	7477.
Heater	Molybdenum	63000.	63000.	17841.	22504.
			TOTAL	37036.	29361.

CAPSULE TEMPERATURE SUMMARY

Name	Material	Tavg (C)	Tmin (C)	Tmax (C)	Tmelt (C)
Housing	AL-6061	90.	87.	95.	582.
Cladding	Zircaloy	629.	617.	642.	1825.
Heater	Molybdenum	780.	777.	782.	2617.

PROPERTY SUMMARY AT THE AVERAGE PART TEMPERATURE

Name	Material	Thermal Conductivity (W/m·°C)	Expansion Coefficient (μm/m)	Emissivity (---)
Housing	AL-6061	170.156	24.21	0.050
Cladding	Zircaloy	20.213	4.90	0.699
Fill gas	Helium	0.357	0.00	0.000
Heater	Molybdenum	109.866	5.52	0.110

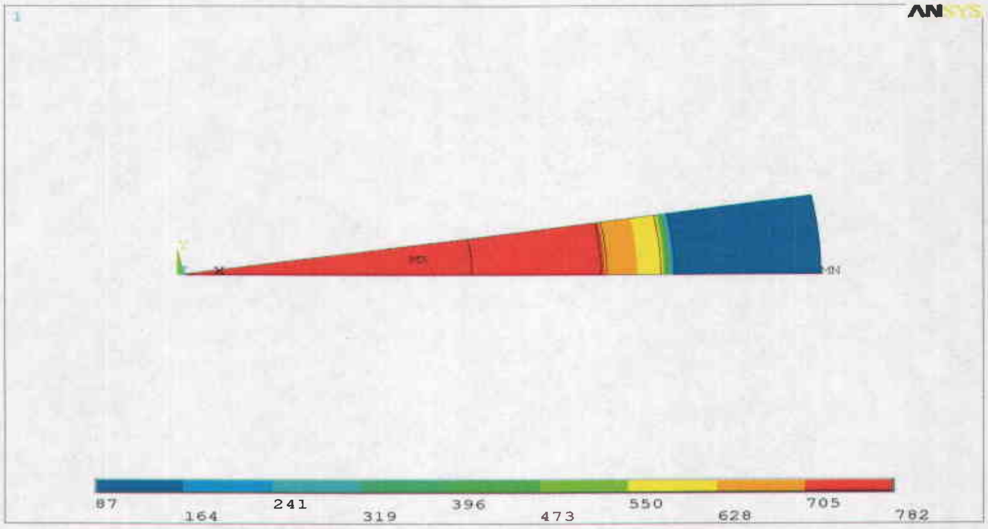

Figure 1: Contour plot for zircaloy cladding and molybdenum heater section at reactor centerline

****
INDEPENDENT REVIEW SUMMARY FOR HYDRIED CLAD TARGET EXPERIMENT
****

DESCRIPTION

----

* AL-6061 Housing
* AL-6061 Spacer
* Molybdenum Heater
* 2-dimensional analysis (r-theta plane)
* Helium fill gas

COLD MODEL DIMENSIONS

Outer housing radius = 6.290 mm (0.2476 in)
Inner housing radius = 4.860 mm (0.1913 in)
Outer spacer radius = 4.720 mm (0.1858 in)
Inner spacer radius = 4.180 mm (0.1646 in)
Outer heater radius = 4.130 mm (0.1626 in)
Inner heater radius = 2.870 mm (0.1130 in)

BOUNDARY CONDITIONS

Heat transfer coefficient = 49735. W/m²·°C
Bulk coolant temperature = 67.7 °C
Reactor power factor = 1.24 (@110.5 MW) (1.5 inches away from reactor centerline)

HEAT GENERATION

Part	Material	-- Heat Generation -- @Midplane (W/kg)	@Location (W/kg)	-- Linear Heat Load -- @Midplane (W/m)	@Location (W/m)
Housing	AL-6061	41350.	51439.	5592.	6957.
Spacer	AL-6061	41350.	51439.	1686.	2097.
Heater	Molybdenum	63000.	78372.	17841.	22194.
			TOTAL	31248.	25119.

CAPSULE TEMPERATURE SUMMARY

Name	Material	Tavg (C)	Tmin (C)	Tmax (C)	Tmelt (C)
Housing	AL-6061	87.	84.	90.	582.
Spacer	AL-6061	431.	429.	432.	582.
Heater	Molybdenum	658.	655.	660.	2617.

PROPERTY SUMMARY AT THE AVERAGE PART TEMPERATURE

Name	Material	Thermal Conductivity (W/m·°C)	Expansion Coefficient (μm/m)	Emissivity (---)
Housing	AL-6061	169.768	24.21	0.050
Spacer	AL-6061	176.000	26.69	0.060
Fill gas	Helium	0.329	0.00	0.000
Heater	Molybdenum	114.068	5.37	0.096

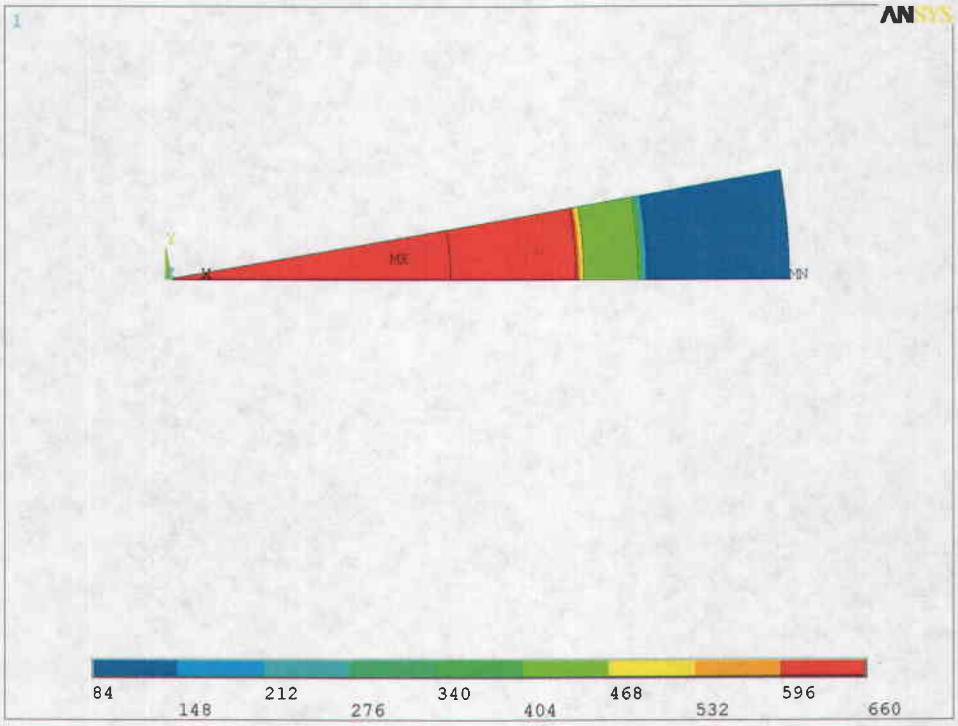

Figure 2: Contour plot for Al6061 spacer and molybdenum heater section at 1.5 inches away from the centerline

RADIAL DIMENSIONS AND GAP SUMMARY FOR THE CLADDING-HOUSING GAP

Outer Surface

Cold diameter = 9.720 mm (0.3827 in)
Average hot diameter = 9.737 mm (0.3833 in)
Minimum hot diameter = 9.737 mm (0.3833 in) at 1.0 degrees
Maximum hot diameter = 9.737 mm (0.3833 in) at 10.0 degrees

Inner Surface

Cold diameter = 9.600 mm (0.3780 in)
Average hot diameter = 9.617 mm (0.3786 in)
Minimum hot diameter = 9.617 mm (0.3786 in) at 1.0 degrees
Maximum hot diameter = 9.617 mm (0.3786 in) at 10.0 degrees

Gap

Cold gap = 60.00 µm (2.36 mils)
Average hot gap = 59.72 µm (2.35 mils)
Minimum hot gap = 59.72 µm (2.35 mils) at 1.0 degrees
Maximum hot gap = 59.72 µm (2.35 mils) at 10.0 degrees

RADIAL DIMENSIONS AND GAP SUMMARY FOR THE SPACER-HOUSING GAP

Outer Surface

Cold diameter = 9.720 mm (0.3827 in)
Average hot diameter = 9.736 mm (0.3833 in)
Minimum hot diameter = 9.736 mm (0.3833 in) at 1.0 degrees
Maximum hot diameter = 9.736 mm (0.3833 in) at 10.0 degrees

Inner Surface

Cold diameter = 9.600 mm (0.3780 in)
Average hot diameter = 9.654 mm (0.3801 in)
Minimum hot diameter = 9.654 mm (0.3801 in) at 1.0 degrees
Maximum hot diameter = 9.654 mm (0.3801 in) at 10.0 degrees

Gap

Cold gap = 60.00 µm (2.36 mils)
Average hot gap = 41.00 µm (1.61 mils)
Minimum hot gap = 41.00 µm (1.61 mils) at 1.0 degrees
Maximum hot gap = 41.00 µm (1.61 mils) at 10.0 degrees

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1. Purpose

The purpose of this analysis is to demonstrate the safety of irradiating target capsules containing hydrided zircaloy cladding with a molybdenum heater rod in a target position located in the High Flux Isotope Reactor (HFIR) flux trap. For the temperature and radial thermal expansion analysis, the capsule is assumed to operate at the position closest to the reactor midplane with the reactor power at 130% of 85 MW.

The scope of this evaluation is to demonstrate that the capsule can be exposed to extreme case of reactor power without exposing capsule components to temperatures exceeding their respective melting temperatures. Also the thermal expansion limits are reported to show that the internal configuration of the parts cannot expand and impart stress on the Al-6061 housing tube (containment).

2. Assumptions and Justifications

2.1. The minimum and maximum outer gas gap is 0.0025 in and 0.0055 in, respectively

For this calculation, the outer gas gap is specified to ensure proper heat transfer and design temperature achievement. The housing tube (Part 1, Drawing X3E020977A612, Rev. A (1)) inner diameter is set to the nominal 0.383 in, and the cladding/spacer-housing gap is set to 0.0055 in for maximum temperature calculations and 0.0025 in for minimum gap calculations. In practice, the outer gap and the thickness of the heater are selected based on the as-received dimensions of the spacers and housing. The larger drawing tolerances on the spacers and housing are defined so that these parts can be purchased from stock items from a vendor. A hold point will be placed in the final assembly for an independent reviewer to verify that the as-built dimensions meet the requirements/assumptions of this calculation.

3. Calculation Input and Sources of Input

3.1. Capsule Description

The target capsule considered in this calculation is generic in nature. The outer housing is detailed on drawing X3E020977A612, Rev. A (1); and the cladding, heater and spacers are detailed on drawing X3E020977A609, Rev 0 (2). The capsule is filled with the helium, which serves as the primary medium for heat transfer between the heater/clad assembly and the housing tube.

3.2. Materials and Material Properties

3.2.1. Al-6061

Al-6061 material properties are taken from DAC-10-03-PROP_AL6061, Rev. 1 (3). Specific values are summarized in Table 3-1.

Table 3-1. Thermophysical Properties for Al-6061

Property	Value	Comment
Density	2700 kg/m^3	
Thermal conductivity	161 W/m·°C	Value taken at 20°C.
Thermal expansion coefficient	$24.2 \cdot 10^{-6}$ /°C (min) $29.1 \cdot 10^{-6}$ /°C (max)	Minimum value taken at 20 °C -127°C Maximum value taken at 20 °C -627°C
Melting point	582°C	

3.2.2. Molybdenum

Molybdenum material properties are taken from DAC-10-11-PROP_MOLY, Rev. 0 (4). Specific values are summarized in Table 3-2.

Table 3-2. Thermophysical Properties for Molybdenum

Property	Value	Comment
Density	10220 kg/m^3	
Thermal conductivity	84 W/m·°C	Value taken at 2527°C.
Thermal expansion coefficient	$4.9 \cdot 10^{-6}$ /°C (min) $8.6 \cdot 10^{-6}$ /°C (max)	Minimum value taken at 20°C-127°C Maximum value taken at 20°C-2527°C
Melting point	2617°C	

3.2.3. Zircaloy

Zircaloy material properties are taken from DAC-10-06-PROP_ZIRC, Rev. 1 (5). Specific values are summarized in Table 3-3.

Table 3-3. Thermophysical Properties for Zircaloy

Property	Value	Comment
Density	6550 kg/m^3	
Thermal conductivity	12.6 W/m·°C	Value taken at 20°C
Thermal expansion coefficient	$1.8 \cdot 10^{-6}$ /°C (min) $5.5 \cdot 10^{-6}$ /°C (max)	Minimum value taken at 971°C Maximum value taken at 1825°C.
Melting point	1825 °C	

3.2.4. Helium

Inert gas material properties for helium are taken from DAC-10-02-PROP_HELIUM, Rev. 0 (6),. Specific values are summarized in Table 3-4.

Table 3-4. Thermophysical Properties for Helium

Property	Value	Comment
Thermal conductivity for Helium	0.15 W/m·°C	Value is for pure helium at 27°C (300 K)
	0.22 W/m·°C	Value is for pure helium at 227°C (500 K)
	0.28 W/m·°C	Value is for pure helium at 427°C (700 K)
	0.33 W/m·°C	Value is for pure helium at 627°C (900 K)

3.3. Heat Generation Rates

Table 3-5. Heat Generation Rates for Capsule Materials

Material	Value	Reference
Aluminum 6061	41.35 W/g	C-HFIR-2002-010, Rev. 0, p. 9 of 9. (7)
Molybdenum	63 W/g	C-HFIR-2008-039, Rev. 0, p. 3 of 3 (8)
Zircaloy	61 W/g	C-HFIR-2011-021, Rev. 0, p. 3 of 13. (9)

3.4. Thermal Boundary Conditions

A convective boundary condition is applied to the outer surface of the housing with a heat transfer coefficient of 49735 W/m²·°C and a bulk temperature of 67.7°C. These parameters are established in C-HFIR-2004-006, Rev. 0 page 9 of 23 (10).

3.5. Temperature Verification Capsule Model

For the first case of this calculation, a model in the r-θ plane at the reactor midplane is used to estimate the maximum temperatures in the specimen, specimen heater, and housing. The reactor axial power factor, which peaks at the reactor midplane, is ignored for these calculations. A uniform power factor of 1.26 reflects 130% nominal power (85 MW) at the reactor midplane.

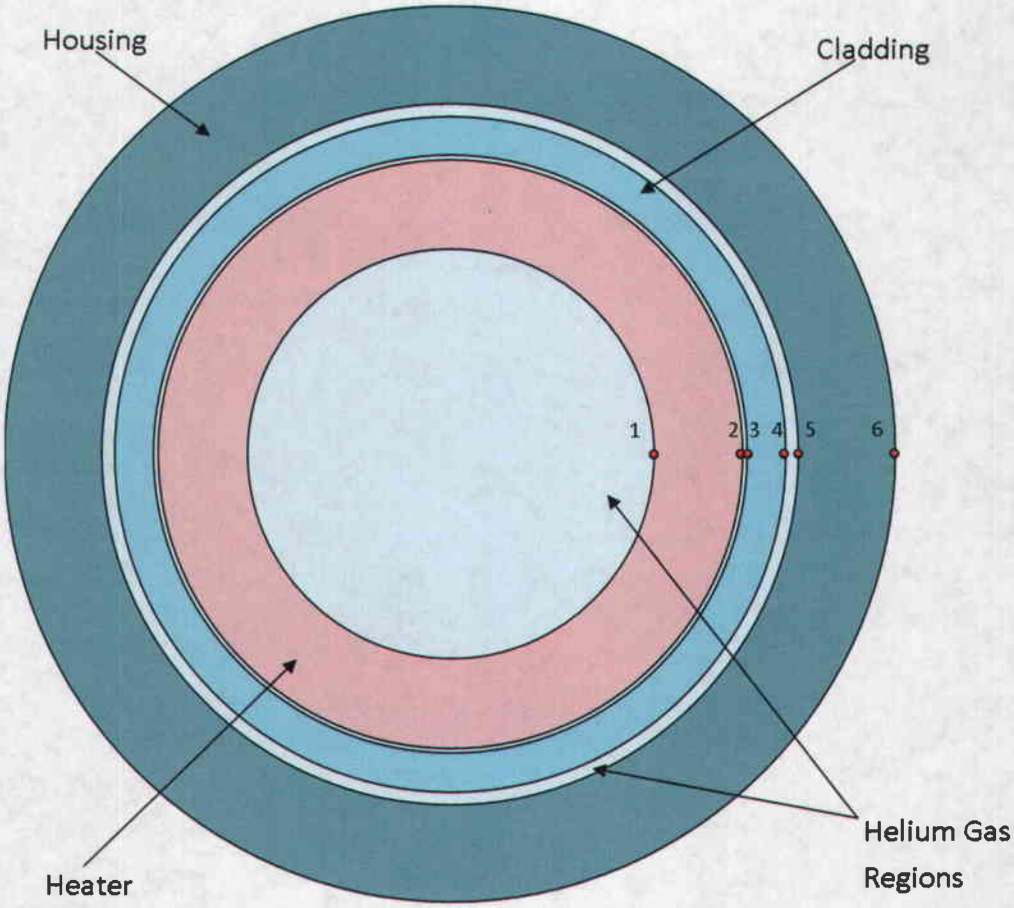

Figure 3-1. R-θ schematic for Reactor Midplane Case

A second case is investigated to estimate the temperatures of the molybdenum specimen heater and Al-6061 tubular spacer for a 3 in. specimen. This case bounds the subsequent 6 in. specimen case because the intersection is closer to the reactor midplane and, therefore, experiences a higher power level. The axial location for this case is 1.5 in. from the reactor midplane. The basic r-θ models for the midplane and offset cases are shown in Figure 3-1and Figure 3-2 respectively. The power factor for this location is calculated by using the following sinusoidal shape factor established in C-HFIR-2011-020, Rev 0, p. 6 of 44 (11).

$$pf(z) = 1.26 \cdot \cos(0.0423 \cdot z)$$

where:
pf — axial power factor for an axial location in centimeters
z — axial location in HFIR, where the midplane is at zero, z = 3.81 cm (1.5 in.)

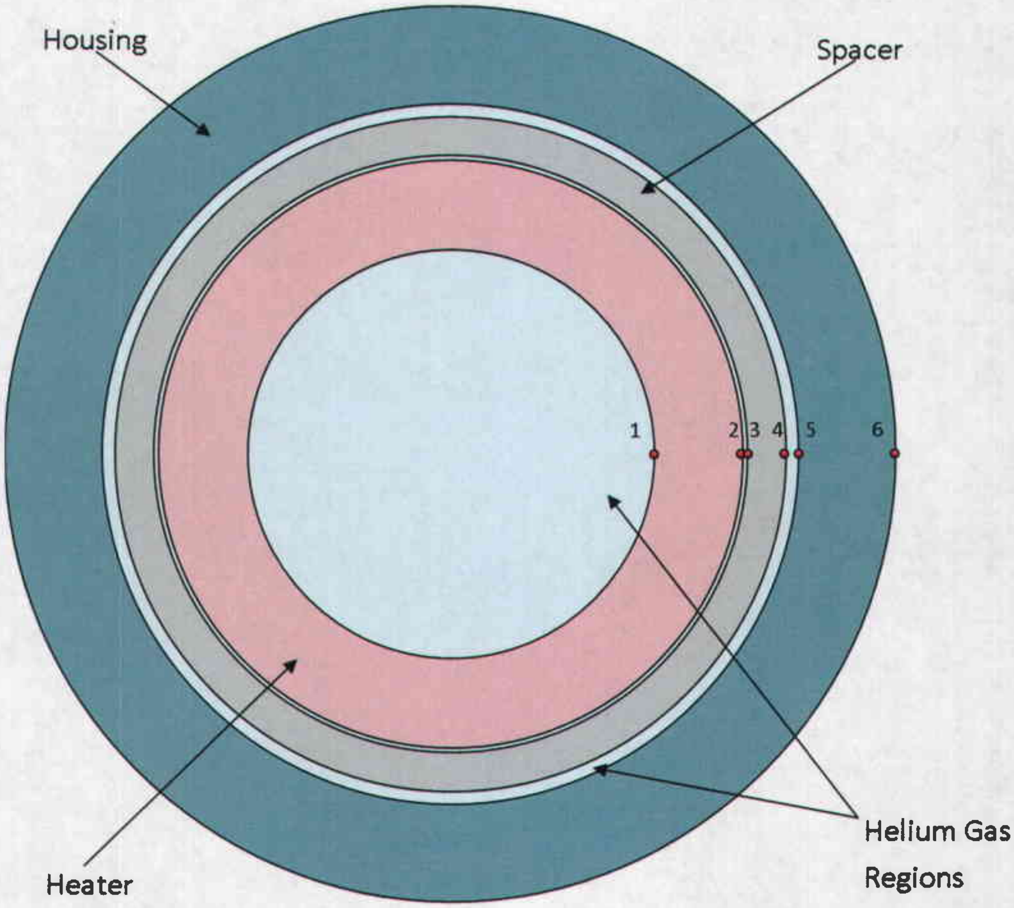

Figure 3-2. R-θ schematic for Z = 1.5 in. Case

There is a gas gap between the cladding/spacer part and the housing tube. This gap governs the radial heat transfer for the problem. There is also a small gap between the heater and the cladding/spacer part. This gap represents the slight difference in radial dimensions between the parts. Table 3-6 summarizes the cold dimensions for both cases.

Table 3-6. Temperature Verification Model Geometry

Node	Location	Radius (cm)	Reference
1	Heater inner radius	0.287	Minimum radius: drawing X3E020977A609 Rev. 0 (1)
2	Heater outer radius	0.413	Minimum radius: drawing X3E020977A609 Rev. 0
3	Cladding/Spacer inner radius	0.419/ 0.418	Maximum radius: drawing X3E020977A609 Rev. 0
4	Cladding/Spacer outer radius	0.472	Minimum radius, see assumption 2.1
		0.480	Maximum radius, see assumption 2.1
5	Housing inner radius	0.486	Nominal radius, see assumption 2.1
6	Housing outer radius	0.629	Minimum radius: drawing X3E020977A612 Rev. A (2)

4. Computations and Analyses

4.1. Maximum Temperatures

The model described above is evaluated using MathCad and is documented in Appendix A. Table 4-1 compares the maximum temperatures for each part with the melting point for each material. This analysis shows that internal part temperatures do not approach the melting point at 130% of 85 MW at the reactor midplane.

Table 4-1. Summary of maximum temperatures (°C) for all models

Part	Material	Maximum Temperature (C)	Melting Point (C)
Case 1: Maximum Temperature With Helium Fill Gas, Axial Location at Reactor Midplane			
Housing	Al 6061	95	582
Heater	Molybdenum	952	2617
Specimen	Zircaloy	783	1825
Case 2: Maximum Temperature With Helium Fill Gas, Axial Location at Z = 1.5 in.			
Housing	Al 6061	91	582
Heater	Molybdenum	733	2617
Spacer	Al 6061	457	582

4.2. Thermal Expansion

Both radial and axial expansions are considered in this calculation. The two axial locations (z =0 in. and z = 1.5 in) are considered for the radial case. The conservative maximum temperatures for both locations are used to evaluate the expansion rates. See Table 4-2 for the results of this analysis. The calculations can be found in the MathCad sheet included in Appendix A. It can be seen that neither the specimen nor the spacer collides with the inner radius of the housing tube.

Table 4-2. Summary of Radially Expanded Dimensions

Part	Material	Radial Dimension (cm)
Axial Location at Reactor Midplane		
Housing	Al 6061	0.487 (thermally expanded)
Specimen	Zircaloy	0.482 (thermally expanded)
Axial Location at Z = 1.5 in.		
Housing	Al 6061	0.487 (thermally expanded)
Spacer	Al 6061	0.486 (thermally expanded)

The axial expansion of the specimens and spacers are evaluated in similar fashion to that of the radial expansion case. The highest temperatures in the reactor midplane case and the temperature based on the integral average of the peaking factor (pf) are used to evaluate thermal expansion rates for the heater and the spacers respectively. Another configuration controlled by the expansion of the cladding was considered, but this arrangement was bounded by the expanded heater case. There are two experiments being performed for this project; the 3 in. clad (4 in. heater) and the 6 in. clad (7 in. heater). Both of these cases were analyzed, but the 7 in. heater case was the bounding scenario.

By using the maximum length of each part, based on drawing tolerances, the overall cold length of the internal configuration is 52.974 cm. The thermally expanded overall length is 53.279 cm. Drawing X3E020977A608, Rev 0 (12) has instructions to ensure a minimum 0.173 in. (0.439 cm) gap exists from the top of the internal stack to the end of the housing tube. The thermal expansion calculation reveals a difference of 0.120 in. (0.304 cm) between the cold and hot dimension. Therefore the specimen/spacer stack will not axially expand beyond the length of the housing tube, and into the containment. The particular details of this calculation can be found in the MathCad sheet in Appendix A.

4.3. Heat Generation and Stored Energy Calculations

Five transient scenarios are analyzed to calculate heat generation and stored energy with the target capsule which include: steady state normal operation, steady state local flow blockage, steady state at 130% power and full flow, LOOP and SBLOCA. This experiment is very similar to the JP-30 capsule and is bounded by its safety basis calculation from a flow excursion standpoint. Supporting details can be found in Appendix B.

Conclusions

This calculation demonstrates the safety of target capsules containing hydrided zircaloy cladding with a molybdenum heater. It shows that internal components cannot challenge or weaken the outer aluminum housing due to melting or thermal expansion. For this analysis, the capsules are assumed to operate with the reactor power at 130% of 85 MW.

5. References

1. **Oak Ridge National Laboratory, Thermal Hydraulics & Irradiation Engineering Group.** *Cladding Test Plan Hydriding Housing Tube Detail.* 2012. Drawing X3E020977A612 Rev.A.
2. —. *Cladding Test Plan Hydriding Sample, Spacer, Rod Details.* 2012. Drawing X3E020977A609 Rev.0.
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5. —. *Thermophysical Properties for Zircaloy.* 2011. DAC-11-03-PROP_ZIRCALOY, Rev 1.
6. —. *Thermophysical Properties for Helium.* 2010. DAC-10-02-PROP_HELIUM.
7. **Carbajo, J J.** *Heat generation inputs for the RELAP analysis of the PTT Irradiation Facility.* Oak Ridge, TN : Oak Ridge National Laboratory, Thermal Hydraulics & Irradiation Engineering Group, 2002. C-HFIR-2002-010, Rev. 0.
8. **McDuffee, J L.** *Molybdenum heat generation rate in a peripheral target position.* Oak Ridge, TN : Oak Ridge National Laboratory, Thermal Hydraulics & Irradiation Engineering Group, 2008. C-HFIR-2008-039, Rev. 0.
9. —. *Temperature Verification and Thermal Expansion Calculation for Surrogate.* 2011. C-HFIR-2011-021.
10. **Kim, S H.** *Safety Calculations for JP-27 Experiment.* 2004. C-HFIR-2004-006.
11. **Carbajo, J J.** *Safety Basis Calculation for the JP30/JP31 Target Experiment* . 2011. C-HFIR-2011-020.
12. **Oak Ridge National Laboratory, Thermal Hydraulics & Irradiation Engineering Group.** *Cladding Test Plan Hydriding Assembly.* 2012. Drawing X3E020977A608 Rev.0.
13. **McDuffee, J.L.** *Selenium Rabbit Irradiations in the HFIR Target Region.* s.l. : Oak Ridge National Laboratory, Research Reactors Division, 2007. C-HFIR-2007-043, Rev.0.

APPENDIX A

MathCad Evaluation of Cases 1-3

Calc Title: Temperature Verification Calculation for Hydrided Clad Capsules in the HFIR Target Region		Page A-2 of 12
Calc ID: C-HFIR-2012-003	Prep by: Rmn 2/6/12	Ck'd by: JLM 2/6/12

Properties (see Section 2.2)

Al-6061

$k_{Al} := 161 \cdot \frac{W}{m \cdot K}$ thermal conductivity of Al-6061

$\rho_{Al} := 2.7 \cdot \frac{gm}{cm^3}$ density of Al-6061

$\alpha_{Al\_max} := 29.1 \cdot 10^{-6} \cdot \frac{1}{K}$ maximum thermal expansion coefficient for Al-6061

$\alpha_{Al\_min} := 24.2 \cdot 10^{-6} \cdot \frac{1}{K}$ minimum thermal expansion coefficient for Al-6061

$Q_{v\_Al} := \left(41.35 \cdot \frac{W}{gm}\right) \cdot \rho_{Al}$ volumetric heat generation rate for Al-6061

Molybdenum

$k_{Mo} := 84 \cdot \frac{W}{m \cdot K}$ thermal conductivity of Molybdenum

$\rho_{Mo} := 10.22 \cdot \frac{gm}{cm^3}$ density of Molybdenum

$\alpha_{Mo\_max} := 8.6 \cdot 10^{-6} \cdot \frac{1}{K}$ maximum thermal expansion coefficient for Molybdenum

$\alpha_{Mo\_min} := 4.9 \cdot 10^{-6} \cdot \frac{1}{K}$ minimum thermal expansion coefficient for Molybdenum

$Q_{v\_Mo} := \left(63 \cdot \frac{W}{gm}\right) \cdot \rho_{Mo}$ volumetric heat generation rate for Molybdenum

Zircaloy

$k_{Za} := 12.6 \cdot \frac{W}{m \cdot K}$ thermal conductivity of Zircaloy

$\rho_{Za} := 6.55 \cdot \frac{gm}{cm^3}$ density of Zircaloy

$\alpha_{Za\_max} := 5.5 \cdot 10^{-6} \cdot \frac{1}{K}$ maximum thermal expansion coefficient for Zircaloy

$\alpha_{Za\_min} := 1.8 \cdot 10^{-6} \cdot \frac{1}{K}$ minimum thermal expansion coefficient for Zircaloy

$Q_{v\_Za} := \left(61 \cdot \frac{W}{gm}\right) \cdot \rho_{Za}$ volumetric heat generation rate for Zircaloy

Calc Title: Temperature Verification Calculation for Hydrided Clad Capsules in the HFIR Target Region		Page A-3 of 12
Calc ID: C-HFIR-2012-003	Prep by: Bun 2/6/12	Ck'd by: JiM 2/6/12

Inert Gas (helium)

The thermal conductivity of helium is subject to change, given the wide range of temperatures in the problem. The values will be selected conservatively based on the average gap temperature. These values will always be less than the gap average temperature.

Thermal boundary conditions (See Section 2.5)

$h_{film} := 49735 \cdot \frac{W}{m^2 \cdot K}$ heat transfer coefficient (W/m2-C)

$T_{bulk} := (67.7 + 273) \cdot K$ bulk temperature (C)

CASE 1: Target Capsule Maximum Temperatures at Reactor Centerline

Reactor power factor (130%)

$pf := 1.26$ reactor power factor = 130% of 85 MW

Volumetric heat generation rates (W/m³)

$Q_{v\_spec} := pf \cdot Q_{v\_Za}$ $Q_{v\_spec} = 503.4 \cdot \frac{W}{cm^3}$

$Q_{v\_htr} := pf \cdot Q_{v\_Mo}$ $Q_{v\_htr} = 811.3 \cdot \frac{W}{cm^3}$

$Q_{v\_hous} := pf \cdot Q_{v\_Al}$ $Q_{v\_hous} = 140.7 \cdot \frac{W}{cm^3}$

Initial cold dimensions

$R_{spec\_i} := \frac{0.330in}{2}$ specimen inner radius $R_{spec\_i} = 0.419 \cdot cm$

$R_{spec\_o} := \frac{0.372in}{2}$ $R_{spec\_o} = 0.472 \cdot cm$

specimen outer radius

$R_{spec\_max} := \frac{0.378in}{2}$ $R_{spec\_max} = 0.48 \cdot cm$

$R_{htr\_i} := \frac{0.226 \cdot in}{2}$ heater inner radius $R_{htr\_i} = 0.287 \cdot cm$

$R_{htr\_o} := \frac{0.325 \cdot in}{2}$ heater inner radius $R_{htr\_o} = 0.413 \cdot cm$

$R_{hous\_i} := \frac{0.383 \cdot in}{2}$ housing inner radius $R_{hous\_i} = 0.486 \cdot cm$

$R_{hous\_o} := \frac{0.495 \cdot in}{2}$ housing outer radius $R_{hous\_o} = 0.629 \cdot cm$

Calc Title: Temperature Verification Calculation for Hydrided Clad Capsules in the HFIR Target Region		Page A-4 of 12
Calc ID: C-HFIR-2012-003	Prep by: RHM 2/6/12	Ck'd by: JLM 2/6/12

$R_{spac\_i} := \frac{0.329in}{2}$ specimen inner radius $R_{spac\_i} = 0.418 \cdot cm$

$R_{spac\_o} := \frac{0.372in}{2}$ specimen outer radius $R_{spac\_o} = 0.472 \cdot cm$

$R_{spac\_max} := \frac{0.378in}{2}$ $R_{spac\_max} = 0.48 \cdot cm$

$L_{cap} := 0.14in$ max upper cap height $L_{cap} = 0.356 \cdot cm$

Total heat generated inside a section (W/m)

$Qgen_{spec} := Q_{v\_spec} \cdot \pi \cdot \left(R_{spec\_o}^{\ 2} - R_{spec\_i}^{\ 2}\right)$ specimen $Qgen_{spec} = 7521 \cdot \frac{W}{m}$

$Qgen_{htr} := Q_{v\_htr} \cdot \pi \cdot \left(R_{htr\_o}^{\ 2} - R_{htr\_i}^{\ 2}\right)$ holder $Qgen_{htr} = 22424 \cdot \frac{W}{m}$

$Qgen_{hous} := Q_{v\_hous} \cdot \pi \cdot \left(R_{hous\_o}^{\ 2} - R_{hous\_i}^{\ 2}\right)$ housing $Qgen_{hous} = 7009 \cdot \frac{W}{m}$

Total heat moving into a section (W/m)

$q_{in\_hous} := Qgen_{spec} + Qgen_{htr}$ $q_{in\_hous} = 29945 \cdot \frac{W}{m}$

$q_{in\_cool} := q_{in\_hous} + Qgen_{hous}$ $q_{in\_cool} = 36954 \cdot \frac{W}{m}$

Temperature calculation

$T_{hous\_o} := T_{bulk} + \frac{q_{in\_cool}}{h_{film} \cdot 2 \cdot \pi \cdot R_{hous\_o}}$ $T_{hous\_o} = 360\,K$

$$T_{hous\_i} := \frac{Q_{v\_hous}}{4 \cdot k_{Al}} \cdot \left(R_{hous\_o}^{\ 2} - R_{hous\_i}^{\ 2}\right) + \left(\frac{Q_{v\_hous} \cdot R_{hous\_i}^{\ 2}}{2 \cdot k_{Al}} - \frac{q_{in\_hous}}{2 \cdot \pi \cdot k_{Al}}\right) \cdot \ln\left(\frac{R_{hous\_i}}{R_{hous\_o}}\right) + T_{hous\_o} = 368\,K$$

$R_{hous\_i\_hot} := R_{hous\_i} \cdot \left[1 + \alpha_{Al\_max} \cdot \left(T_{hous\_i} - 293 \cdot K\right)\right]$ $R_{hous\_i\_hot} = 0.487 \cdot cm$

$T_{spec\_o} := 1018 \cdot K$ initial guess $k_{gas} := 0.220 \frac{W}{m \cdot K}$ Helium at 500 K

$R_{spec\_o\_hot} := R_{spec\_o} \cdot \left[1 + \alpha_{Za\_min} \cdot (T_{spec\_o} - 293 \cdot K)\right]$ $\qquad R_{spec\_o\_hot} = 0.473 \cdot cm$

$T_{spec\_o} := \left(\frac{-q_{in\_hous}}{2 \cdot \pi \cdot k_{gas}}\right) \cdot \ln\left(\frac{R_{spec\_o\_hot}}{R_{hous\_i\_hot}}\right) + T_{hous\_i}$ $\qquad T_{spec\_o} = 1018\,K$ good guess

$T_{spec\_i} := 1056 \cdot K$ initial guess

$R_{spec\_i\_hot} := R_{spec\_i} \cdot \left[1 + \alpha_{Za\_max} \cdot (T_{spec\_i} - 293 \cdot K)\right]$

$$T_{spec\_i} := \frac{Q_{v\_spec}}{4 \cdot k_{Za}} \cdot \left(R_{spec\_o\_hot}{}^2 - R_{spec\_i\_hot}{}^2\right) + \left(\frac{Q_{v\_spec} \cdot R_{spec\_i\_hot}{}^2}{2 \cdot k_{Za}} - \frac{Qgen_{htr}}{2 \cdot \pi \cdot k_{Za}}\right) \cdot \ln\left(\frac{R_{spec\_i\_hot}}{R_{spec\_o\_hot}}\right) \ldots + T_{spec\_o}$$

$T_{spec\_i} = 1056\,K$ good guess

$T_{spec\_max} := T_{spec\_i}$ $\qquad R_{spec\_o\_max} := R_{spec\_max} \cdot \left[1 + \alpha_{Za\_max} \cdot (T_{spec\_max} - 293 \cdot K)\right]$

$T_{htr\_o} := 1218 \cdot K$ initial guess $\qquad k_{gas} := 0.33 \frac{W}{m \cdot K}$ Helium at 900 K

$R_{htr\_o\_hot} := R_{htr\_o} \cdot \left[1 + \alpha_{Mo\_min} \cdot (T_{htr\_o} - 293 \cdot K)\right]$ $\qquad R_{htr\_o\_hot} = 0.415 \cdot cm$

$T_{htr\_o} := \left(\frac{-Qgen_{htr}}{2 \cdot \pi \cdot k_{gas}}\right) \cdot \ln\left(\frac{R_{htr\_o\_hot}}{R_{spec\_i\_hot}}\right) + T_{spec\_i}$ $\qquad T_{htr\_o} = 1218\,K$ good guess

$T_{htr\_i} := 1225 \cdot K$ initial guess

$R_{htr\_i\_hot} := R_{htr\_i} \cdot \left[1 + \alpha_{Mo\_min} \cdot (T_{htr\_i} - 293 \cdot K)\right]$ $\qquad R_{htr\_i\_hot} = 0.288 \cdot cm$

$$T_{htr\_i} := \frac{Q_{v\_htr}}{4 \cdot k_{Mo}} \cdot \left(R_{htr\_o\_hot}{}^2 - R_{htr\_i\_hot}{}^2\right) + \left(\frac{Q_{v\_htr} \cdot R_{htr\_i\_hot}{}^2}{2 \cdot k_{Mo}}\right) \cdot \ln\left(\frac{R_{htr\_i\_hot}}{R_{htr\_o\_hot}}\right) + T_{htr\_o}$$

$T_{htr\_i} = 1225\,K$ good guess

$R_{spec\_o\_max} = 0.482 \cdot cm$ $\quad R_{hous\_i\_hot} = 0.487 \cdot cm$ $\quad R_{spec\_o\_max} < R_{hous\_i}$ $\quad T_{max} := T_{htr\_i}$

CASE 2: Temperatures at Clad/ Spacer Transition for 3" Case (Z = 1.5")

$z := 1.5in$

$$pf := 1.26 \cdot \cos\left(\frac{0.0423}{cm} \cdot z\right) = 1.244$$

Volumetric heat generation rates (W/m³)

$Q_{v\_spac} := pf \cdot Q_{v\_Al}$ $\qquad Q_{v\_spac} = 138.8 \cdot \frac{W}{cm^3}$

$Q_{v\_htr} := pf \cdot Q_{v\_Mo}$ $\qquad Q_{v\_htr} = 800.8 \cdot \frac{W}{cm^3}$

$Q_{v\_hous} := pf \cdot Q_{v\_Al}$ $\qquad Q_{v\_hous} = 138.8 \cdot \frac{W}{cm^3}$

Total heat generated inside a section (W/m)

$Qgen_{spac} := Q_{v\_spac} \cdot \pi \cdot \left(R_{spac\_o}^{\ 2} - R_{spac\_i}^{\ 2}\right)$ specimen $\qquad Qgen_{spac} = 2121 \cdot \frac{W}{m}$

$Qgen_{htr} := Q_{v\_htr} \cdot \pi \cdot \left(R_{htr\_o}^{\ 2} - R_{htr\_i}^{\ 2}\right)$ holder $\qquad Qgen_{htr} = 22133 \cdot \frac{W}{m}$

$Qgen_{hous} := Q_{v\_hous} \cdot \pi \cdot \left(R_{hous\_o}^{\ 2} - R_{hous\_i}^{\ 2}\right)$ housing $\qquad Qgen_{hous} = 6919 \cdot \frac{W}{m}$

Total heat moving into a section (W/m)

$q_{in\_hous} := Qgen_{spac} + Qgen_{htr}$ $\qquad q_{in\_hous} = 24254 \cdot \frac{W}{m}$

$q_{in\_cool} := q_{in\_hous} + Qgen_{hous}$ $\qquad q_{in\_cool} = 31172 \cdot \frac{W}{m}$

Temperature calculation

$$T_{hous\_o} := T_{bulk} + \frac{q_{in\_cool}}{h_{film} \cdot 2 \cdot \pi \cdot R_{hous\_o}} \qquad T_{hous\_o} = 357\,K$$

$$T_{hous\_i} := \frac{Q_{v\_hous}}{4 \cdot k_{Al}} \cdot \left(R_{hous\_o}^{\ 2} - R_{hous\_i}^{\ 2}\right) + \left(\frac{Q_{v\_hous} \cdot R_{hous\_i}^{\ 2}}{2 \cdot k_{Al}} - \frac{q_{in\_hous}}{2 \cdot \pi \cdot k_{Al}}\right) \cdot \ln\left(\frac{R_{hous\_i}}{R_{hous\_o}}\right) + T_{hous\_o} = 364\,K$$

Calc Title: Temperature Verification Calculation for Hydrided Clad Capsules in the HFIR Target Region		Page A-7 of 12
Calc ID: C-HFIR-2012-003	Prep by: BRK 2/6/12	Ck'd by: JLM 2/6/12

$R_{hous\_i\_hot} := R_{hous\_i} \cdot \left[1 + \alpha_{Al\_max} \cdot \left(T_{hous\_i} - 293 \cdot K\right)\right]$ $\qquad R_{hous\_i\_hot} = 0.487 \cdot cm$

$T_{spac\_o} := 727 \cdot K$ initial guess $\qquad k_{gas} := 0.22 \dfrac{W}{m \cdot K}$ Helium at 500 K

$R_{spac\_o\_hot} := R_{spac\_o} \cdot \left[1 + \alpha_{Al\_min} \cdot \left(T_{spac\_o} - 293 \cdot K\right)\right]$ $\qquad R_{spac\_o\_hot} = 0.477 \cdot cm$

$$T_{spac\_o} := \left(\frac{-q_{in\_hous}}{2 \cdot \pi \cdot k_{gas}}\right) \cdot \ln\left(\frac{R_{spac\_o\_hot}}{R_{hous\_i\_hot}}\right) + T_{hous\_i}$$

$T_{spac\_o} = 727\,K$ good guess

$T_{spac\_i} := 730 \cdot K$ initial guess

$R_{spac\_i\_hot} := R_{spac\_i} \cdot \left[1 + \alpha_{Al\_max} \cdot \left(T_{spac\_i} - 293 \cdot K\right)\right]$ $\qquad R_{spac\_i\_hot} = 0.423 \cdot cm$

$$T_{spac\_i} := \frac{Q_{v\_spac}}{4 \cdot k_{Al}} \cdot \left(R_{spac\_o\_hot}{}^2 - R_{spac\_i\_hot}{}^2\right) + \left(\frac{Q_{v\_spac} \cdot R_{spac\_i\_hot}{}^2}{2 \cdot k_{Al}} - \frac{Qgen_{htr}}{2 \cdot \pi \cdot k_{Al}}\right) \cdot \ln\left(\frac{R_{spac\_i\_hot}}{R_{spac\_o\_hot}}\right) \ldots$$
$$+ T_{spac\_o}$$

$T_{spac\_i} = 730\,K$ good guess

$T_{spac\_max} := T_{spac\_i}$ $\qquad R_{spac\_o\_max} := R_{spac\_max} \cdot \left[1 + \alpha_{Al\_max} \cdot \left(T_{spac\_max} - 293 \cdot K\right)\right]$

$T_{htr\_o} := 1000K$ initial guess $\qquad k_{gas} := 0.28 \dfrac{W}{m \cdot K}$ Helium at 700 K

$R_{htr\_o\_hot} := R_{htr\_o} \cdot \left[1 + \alpha_{Mo\_min} \cdot \left(T_{htr\_o} - 293 \cdot K\right)\right]$ $\qquad R_{htr\_o\_hot} = 0.414 \cdot cm$

$$T_{htr\_o} := \left(\frac{-Qgen_{htr}}{2 \cdot \pi \cdot k_{gas}}\right) \cdot \ln\left(\frac{R_{htr\_o\_hot}}{R_{spac\_i\_hot}}\right) + T_{spac\_i}$$

$T_{htr\_o} = 1000\,K$ good guess

$T_{htr\_i} := 1006 \cdot K$ initial guess

$R_{htr\_i\_hot} := R_{htr\_i} \cdot \left[1 + \alpha_{Mo\_min} \cdot \left(T_{htr\_i} - 293 \cdot K\right)\right]$ $\qquad R_{htr\_i\_hot} = 0.288 \cdot cm$

$$T_{htr\_i} := \frac{Q_{v\_htr}}{4 \cdot k_{Mo}} \cdot \left(R_{htr\_o\_hot}^2 - R_{htr\_i\_hot}^2\right) + \left(\frac{Q_{v\_htr} \cdot R_{htr\_i\_hot}^2}{2 \cdot k_{Mo}}\right) \cdot \ln\left(\frac{R_{htr\_i\_hot}}{R_{htr\_o\_hot}}\right) + T_{htr\_o}$$

$T_{htr\_i} = 1006\,K$ good guess

$R_{spac\_o\_max} = 0.486 \cdot cm$ $\quad R_{hous\_i\_hot} = 0.487 \cdot cm$ $\quad R_{spec\_o\_max} < R_{hous\_i}$

CASE 3: Axial Expansion

3 A - 4 in. Heater Tube

$L_{htr} := 4.01 in$ max heater height $L_{htr} = 10.185 \cdot cm$

$R_{spac\_i} := \frac{0.274}{2} in$ min spacer radius $R_{spac\_i} = 0.348 \cdot cm$

$L_{l\_spac} := (8.956 - 0.49) in$ max lower spacer height $L_{l\_spac} = 21.504 \cdot cm$

$L_{u\_spac} := (8.83 - 0.49) in$ max upper spacer height $L_{u\_spac} = 21.184 \cdot cm$

$$L_{internal\_config\_cold} := L_{htr} + L_{u\_spac} + L_{l\_spac} + L_{cap} = 53.228 \cdot cm$$

$$pf := \frac{\displaystyle\int_0^{\frac{L_{internal\_config\_cold}}{2}} 1.26 \cdot \cos\left(\frac{0.0423}{cm} \cdot z\right) dz}{\frac{L_{internal\_config\_cold}}{2}} = 1.01$$

Volumetric heat generation rates (W/m³)

$Q_{v\_spac} := pf \cdot Q_{v\_Al}$ $\quad Q_{v\_spac} = 112.8 \cdot \frac{W}{cm^3}$

$Q_{v\_hous} := pf \cdot Q_{v\_Al}$ $\quad Q_{v\_hous} = 112.8 \cdot \frac{W}{cm^3}$

Total heat generated inside a section (W/m)

$Qgen_{spac} := Q_{v\_spac} \cdot \pi \cdot \left(R_{spac\_o}^2 - R_{spac\_i}^2\right)$ specimen $\quad Qgen_{spac} = 3618 \cdot \frac{W}{m}$

$Qgen_{hous} := Q_{v\_hous} \cdot \pi \cdot \left(R_{hous\_o}^{2} - R_{hous\_i}^{2}\right)$ housing $Qgen_{hous} = 5620 \cdot \frac{W}{m}$

Total heat moving into a section (W/m)

$q_{in\_hous} := Qgen_{spac}$ $q_{in\_hous} = 3618 \cdot \frac{W}{m}$

$q_{in\_cool} := q_{in\_hous} + Qgen_{hous}$ $q_{in\_cool} = 9238 \cdot \frac{W}{m}$

Temperature calculation

$$T_{hous\_o} := T_{bulk} + \frac{q_{in\_cool}}{h_{film} \cdot 2 \cdot \pi \cdot R_{hous\_o}} \qquad T_{hous\_o} = 345\,K$$

$$T_{hous\_i} := \frac{Q_{v\_hous}}{4 \cdot k_{Al}} \cdot \left(R_{hous\_o}^{2} - R_{hous\_i}^{2}\right) + \left(\frac{Q_{v\_hous} \cdot R_{hous\_i}^{2}}{2 \cdot k_{Al}} - \frac{q_{in\_hous}}{2 \cdot \pi \cdot k_{Al}}\right) \cdot \ln\left(\frac{R_{hous\_i}}{R_{hous\_o}}\right) + T_{hous\_o} = 347\,K$$

$$R_{hous\_i\_hot} := R_{hous\_i} \cdot \left[1 + \alpha_{Al\_max} \cdot \left(T_{hous\_i} - 293 \cdot K\right)\right] \qquad R_{hous\_i\_hot} = 0.487 \cdot cm$$

$T_{spac\_o} := 450 \cdot K$ initial guess $k_{gas} := 0.15 \frac{W}{m \cdot K}$ Helium at 300 K

$$R_{spac\_o\_hot} := R_{spac\_o} \cdot \left[1 + \alpha_{Al\_min} \cdot \left(T_{spac\_o} - 293 \cdot K\right)\right] \qquad R_{spac\_o\_hot} = 0.474 \cdot cm$$

$$T_{spac\_o} := \left(\frac{-q_{in\_hous}}{2 \cdot \pi \cdot k_{gas}}\right) \cdot \ln\left(\frac{R_{spac\_o\_hot}}{R_{hous\_i\_hot}}\right) + T_{hous\_i}$$

$T_{spac\_o} = 450\,K$ good guess

$T_{spac\_i} := 451 \cdot K$ initial guess

$$R_{spac\_i\_hot} := R_{spac\_i} \cdot \left[1 + \alpha_{Al\_min} \cdot \left(T_{spac\_i} - 293 \cdot K\right)\right] \qquad R_{spac\_i\_hot} = 0.349 \cdot cm$$

$$T_{spac\_i} := \frac{Q_{v\_spac}}{4 \cdot k_{Al}} \cdot \left(R_{spac\_o\_hot}^{2} - R_{spac\_i\_hot}^{2}\right) + \left(\frac{Q_{v\_spac} \cdot R_{spac\_i\_hot}^{2}}{2 \cdot k_{Al}}\right) \cdot \ln\left(\frac{R_{spac\_i\_hot}}{R_{spac\_o\_hot}}\right) \ldots$$
$$+ T_{spac\_o}$$

$T_{spac\_i} = 451\,K$ good guess

$L_{htr\_hot} := L_{htr} \cdot \left[1 + \alpha_{Mo\_max} \cdot \left(T_{max} - 293K\right)\right] = 10.267 \cdot cm$

$L_{u\_spac\_hot} := L_{u\_spac} \cdot \left[1 + \alpha_{Al\_max} \cdot \left(T_{spac\_i} - 293K\right)\right] = 21.281 \cdot cm$

$L_{l\_spac\_hot} := L_{l\_spac} \cdot \left[1 + \alpha_{Al\_max} \cdot \left(T_{spac\_i} - 293K\right)\right] = 21.602 \cdot cm$

$L_{cap\_hot} := L_{cap} \cdot \left[1 + \alpha_{Al\_max} \cdot \left(T_{spac\_i} - 293K\right)\right] = 0.357 \cdot cm$

$L_{internal\_config\_hot} := L_{htr\_hot} + L_{u\_spac\_hot} + L_{l\_spac\_hot} + L_{cap\_hot} = 53.508 \cdot cm$

$\Delta_{hot\_cold} := L_{internal\_config\_hot} - L_{internal\_config\_cold} = 0.279 \cdot cm$ $\Delta_{hot\_cold} = 0.11 \cdot in$

3 B - 7 in. Heater Tube

$L_{htr} := 7.01in$ max heater height $L_{htr} = 17.805 \cdot cm$

$L_{l\_spac} := (7.456 - 0.49)in$ max lower spacer height $L_{l\_spac} = 17.694 \cdot cm$

$L_{u\_spac} := (7.23 - 0.49)in$ max upper spacer height $L_{u\_spac} = 17.12 \cdot cm$

$L_{internal\_config\_cold} := L_{htr} + L_{u\_spac} + L_{l\_spac} + L_{cap} = 52.974 \cdot cm$

$$pf := \frac{\displaystyle\int_0^{\frac{L_{internal\_config\_cold}}{2}} 1.26 \cdot \cos\left(\frac{0.0423}{cm} \cdot z\right) dz}{\frac{L_{internal\_config\_cold}}{2}} = 1.012$$

Volumetric heat generation rates (W/m³)

$Q_{v\_spac} := pf \cdot Q_{v\_Al}$ $Q_{v\_spac} = 113 \cdot \frac{W}{cm^3}$

$Q_{v\_hous} := pf \cdot Q_{v\_Al}$ $Q_{v\_hous} = 113 \cdot \frac{W}{cm^3}$

Total heat generated inside a section (W/m)

$$Qgen_{spac} := Q_{v\_spac} \cdot \pi \cdot \left(R_{spac\_o}{}^2 - R_{spac\_i}{}^2\right)$$ specimen $$Qgen_{spac} = 3626 \cdot \frac{W}{m}$$

$$Qgen_{hous} := Q_{v\_hous} \cdot \pi \cdot \left(R_{hous\_o}{}^2 - R_{hous\_i}{}^2\right)$$ housing $$Qgen_{hous} = 5632 \cdot \frac{W}{m}$$

Total heat moving into a section (W/m)

$$q_{in\_hous} := Qgen_{spac}$$ $$q_{in\_hous} = 3626 \cdot \frac{W}{m}$$

$$q_{in\_cool} := q_{in\_hous} + Qgen_{hous}$$ $$q_{in\_cool} = 9258 \cdot \frac{W}{m}$$

Temperature calculation

$$T_{hous\_o} := T_{bulk} + \frac{q_{in\_cool}}{h_{film} \cdot 2 \cdot \pi \cdot R_{hous\_o}}$$ $$T_{hous\_o} = 345\,K$$

$$T_{hous\_i} := \frac{Q_{v\_hous}}{4 \cdot k_{Al}} \cdot \left(R_{hous\_o}{}^2 - R_{hous\_i}{}^2\right) + \left(\frac{Q_{v\_hous} \cdot R_{hous\_i}{}^2}{2 \cdot k_{Al}} - \frac{q_{in\_hous}}{2 \cdot \pi \cdot k_{Al}}\right) \cdot \ln\left(\frac{R_{hous\_i}}{R_{hous\_o}}\right) + T_{hous\_o} = 347\,K$$

$$R_{hous\_i\_hot} := R_{hous\_i} \cdot \left[1 + \alpha_{Al\_max} \cdot \left(T_{hous\_i} - 293 \cdot K\right)\right]$$ $$R_{hous\_i\_hot} = 0.487 \cdot cm$$

$$T_{spac\_o} := 451 \cdot K$$ initial guess

$$k_{gas} := 0.15 \frac{W}{m \cdot K}$$ Helium at 300 K

$$R_{spac\_o\_hot} := R_{spac\_o} \cdot \left[1 + \alpha_{Al\_min} \cdot \left(T_{spac\_o} - 293 \cdot K\right)\right]$$ $$R_{spac\_o\_hot} = 0.474 \cdot cm$$

$$T_{spac\_o} := \left(\frac{-q_{in\_hous}}{2 \cdot \pi \cdot k_{gas}}\right) \cdot \ln\left(\frac{R_{spac\_o\_hot}}{R_{hous\_i\_hot}}\right) + T_{hous\_i}$$ $$T_{spac\_o} = 450\,K$$ good guess

$$T_{spac\_i} := 451 \cdot K$$ initial guess

$$R_{spac\_i\_hot} := R_{spac\_i} \cdot \left[1 + \alpha_{Al\_min} \cdot \left(T_{spac\_i} - 293 \cdot K\right)\right]$$ $$R_{spac\_i\_hot} = 0.349 \cdot cm$$

$$T_{spac\_i} := \frac{Q_{v\_spac}}{4 \cdot k_{Al}} \cdot \left(R_{spac\_o\_hot}{}^2 - R_{spac\_i\_hot}{}^2\right) + \left(\frac{Q_{v\_spac} \cdot R_{spac\_i\_hot}{}^2}{2 \cdot k_{Al}}\right) \cdot \ln\left(\frac{R_{spac\_i\_hot}}{R_{spac\_o\_hot}}\right) \ldots + T_{spac\_o}$$

$T_{spac\_i} = 451\,K$ good guess

$$L_{htr\_hot} := L_{htr} \cdot \left[1 + \alpha_{Mo\_max} \cdot \left(T_{max} - 293K\right)\right] = 17.948 \cdot cm$$

$$L_{u\_spac\_hot} := L_{u\_spac} \cdot \left[1 + \alpha_{Al\_max} \cdot \left(T_{spac\_i} - 293K\right)\right] = 17.198 \cdot cm$$

$$L_{l\_spac\_hot} := L_{l\_spac} \cdot \left[1 + \alpha_{Al\_max} \cdot \left(T_{spac\_i} - 293K\right)\right] = 17.775 \cdot cm$$

$$L_{cap\_hot} := L_{cap} \cdot \left[1 + \alpha_{Al\_max} \cdot \left(T_{spac\_i} - 293K\right)\right] = 0.357 \cdot cm$$

$$L_{internal\_config\_hot} := L_{htr\_hot} + L_{u\_spac\_hot} + L_{l\_spac\_hot} + L_{cap\_hot} = 53.279 \cdot cm$$

$$\Delta_{hot\_cold} := L_{internal\_config\_hot} - L_{internal\_config\_cold} = 0.304 \cdot cm$$

$\Delta_{hot\_cold} = 0.12 \cdot in$

APPENDIX B

Supporting Material for Heat Generation and Stored Energy Calculations

Comparison of the Zr-Hydride Capsule and the JP-30 Capsule

JuanCarbajo

Rev. 1 - January 2012

The safety of the *JP-30 capsule* was studied in report C-HFIR-2011-020 (Ref. 1). Ref. 1 calculated heat generation, stored energy, and results of five different scenarios/transients (steady state normal operation, steady state local flow blockage, steady state at 130% power and full flow, LOOP and SBLOCA). The JP-30 capsule included 14 sub-capsules.

The *Zr-Hydride capsule* has a very simple configuration: a Zr-Hydride cladding tube, with a molybdenum rod inside, located between two aluminum spacers and surrounded by the aluminum housing. There are two different lengths of the Zr cladding tube: 3-in and 6-in. The 6-in tube with a 7-in molybdenum rod inside bounds the 3-in tube; thus, the 6-in long Zr-Hydride Tube is the one considered in this comparison study. Dimensions are taken from the drawings of Ref. 2.

Calculations are in Excel file **Hydride.xlsx** (Ref. 3). JP-30 values are taken from Excel file **JP30.xlsx** (Ref. 4) and from report C-HFIR-2011-020 (Ref. 1). A comparison of masses, heat generation, decay heat at time zero, maximum heat flux, and stored energy for the two capsules (Zr-Hydride and JP-30) is shown in the enclosed Table 1. The JP-30 capsule has more mass, more heat generation, more decay heat, higher heat flux and more stored energy than the Zr-Hydride capsule. The Zr-Hydride capsule has more aluminum (~35 g more) than the JP-30 capsule but the JP-30 has more steel (~202 g more). Therefore, the Zr-Hydride capsule is bounded by the JP-30 capsule and further safety studies are not needed for the Zr-Hydride capsule.

Table 1
Comparison of the Zr-Hydride and JP-30 Capsules

Variable	**Zr-Hydride**	**JP-30**
Model length (in)	23.9882	23.9882
(cm)	60.93	60.93
Masses (g)		
Al	135.15	100.65
Mo	51.33	–
Zr	16.71	–
Steel	0.49	202.4
SiC	–	4.2
V	–	8.6
Total (g)	**202.71**	**315.85**
Heat generation (W)	9,381	14,122
Decay Heat (W)	448.34	883.7
Max. heat flux (W/cm^2)	92.8	126.2
Stored Energy (J)	24,520	59,980

Notes

- JP-30 Data from C-HFIR-2011-020 and JP30.xlsx
- Steel mass in Zr-Hydride is for the spring, same as JP30
- Only the capsule (without the shroud) is considered, except for the stored energy in the JP-30 capsule that excludes also the housing and the end caps.
- Stored energy is calculated with reference to 0°C.

References

1. Juan J. Carbajo, "Safety Basis Calculation for the JP30/JP31 Target Experiment," RRD/ORNL Report **C-HFIR-2011-020**, July 2011.
2. UT-Battelle/ORNL Drawings for "Cladding Test Plan Hydriding:" **X3E020977A608, X3E020977A609**, and **X3E020977A612,** December 2011.
3. Juan J. Carbajo, Excel file "**Hydride.xlsx,**" January 2012.
4. Juan J. Carbajo, Excel file "**JP30.xlsx,**" July 2011.

HYDRIDE.XLSX

Component	z(in)	Z(cm)	f=cos	L(in)	L(cm)	Mo-d	Mo-D	Al/Zr-d	Al/Zr-D	Hous-d	Hous-D	V-Mo	rho*q	q-Mo	V-Al/Zr	rho*q	q-Al/Zr	V-hous	rho*q	qHous	Qtot(W)	Qtot*f(W)	q"(W/cm2)
HEAT GENERATED													10.2*84.51	0.488*61			2.7*41.35		2.7*41.35				
																	6.55*61						
top cap	11.7645	29.88183	0.302005	1.94095	4.930013					0	0.501							6.270192	111.645	700.0356	700.0356	211.4141	10.72666032
spring	10.567	26.84018	0.421825	0.454	1.15316					0.444	0.505			29.8				0.338254	111.645	37.76437	67.56437	28.50031	6.133170152
plug	10.215	25.9461	0.455805	0.25	0.635			0	0.375	0.444	0.505				0.452474	111.645	50.51645	0.186263	111.645	20.79536	71.31181	32.50427	12.7025744
top	6.795	17.2593	0.745129	6.59	16.7386			0.277	0.375	0.379	0.505				5.419386	111.645	605.0474	9.447116	111.645	1054.723	1659.771	1236.743	18.33518666
	3.25	8.255	0.939651	0.5	1.27	0.226	0.327	0.327	0.375	0.379	0.505	0.359424	862.002	309.8245	0.21684	111.645	24.2091	0.716777	111.645	80.02453	414.0582	389.0703	76.02377162
Center	0	0	1	6	15.24	0.226	0.327	0.328	0.375	0.379	0.505	4.313093	862.002	3717.894	2.551499	399.55	1019.452	8.60132	111.645	960.2943	5697.64	5697.64	**92.775884**
	3.25	8.255	0.939651	0.5	1.27	0.226	0.327	0.327	0.375	0.379	0.505	0.359424	862.002	309.8245	0.21684	111.645	24.2091	0.716777	111.645	80.02453	414.0582	389.0703	76.02377162
bottom	6.973	17.71142	0.732239	6.946	17.64284			0.277	0.375	0.379	0.505				5.712148	111.645	637.7328	9.957461	111.645	1111.701	1749.434	1281.003	18.01800276
cap bottom	10.8496	27.55798	0.394105	0.807244	2.0504					0	0.501							2.607782	111.645	291.1458	291.1458	114.742	13.99788569
Total				23.98819	60.93001																11065.02	**9380.687**	W
	minus caps			21.24																			

spring:0.488*61=29.8

L(in)		JP30-Qtot*	14122.41 W
1.342	DCT4	1564.248	113.8792002
1.342	DCT6	1724.519	125.5471284
1.342	DCT8	1733.554	**126.2048876**

STORED ENERGY

Component	L(in)	L(cm)	Mo-d	Mo-D	Al/Zr-d	Al/Zr-D	Hous-d	Hous-D	V-Mo	rho*cp*ΔT	E-Mo(J)	V-Al/Zr	rho*cp*ΔT	E-Al/Zr	V-hous	rho*cp*ΔT	E-Hous	E-Tot(J)
										10.2*0.277*431			2.7*1.034*262			2.7*0.943*76		
													6.55*0.331*353					
top cap	1.94095	4.930013					0	0.501							6.270192	193.5036	1213.305	1213.305
spring	0.454	1.15316					0.444	0.505						**133**	0.338254	193.5036	65.45337	198.4534
plug	0.25	0.635			0	0.375	0.444	0.505				0.452474	731.4516	330.9628	0.186263	193.5036	36.0426	367.0054
top	6.59	16.7386			0.277	0.375	0.379	0.505				5.419386	731.4516	3964.019	9.447116	193.5036	1828.051	5792.07
	0.5	1.27	0.226	0.327	0.327	0.375	0.379	0.505	0.359424	1217.7474	437.6881	0.21684	731.4516	158.608	0.716777	193.5036	138.6989	734.9949
Center	6	15.24	0.226	0.327	0.328	0.375	0.379	0.505	4.313093	1217.7474	5252.257	2.551499	765.3217	1952.718	8.60132	193.5036	1664.386	8869.362
	0.5	1.27	0.226	0.327	0.327	0.375	0.379	0.505	0.359424	1217.7474	437.6881	0.21684	731.4516	158.608	0.716777	193.5036	138.6989	734.9949
bottom	6.946	17.64284			0.277	0.375	0.379	0.505				5.712148	731.4516	4178.16	9.957461	193.5036	1926.805	6104.965
cap bottom	0.807244	2.0504					0	0.501							2.607782	193.5036	504.6152	504.6152
												0.488	**g-SS-spring**					
Total Vol									5.031941	cm3- Mo		12.01769	cm3-Al		38.84194	cm3-Al		**24519.76**
Total mass									**51.3258**	**g**		32.44776	g		104.8732	g		
															137.321	**g-Al-Tot**		
												2.551499	cm3-Zr					
												16.71232	**g**					

DECAY HEAT	g	Hydride		g	JP-30	Watts	
Al	135.146	427.0614			100.65	318.054	
Mo	51.3258	20.53032					
Steel	0.49	0.7448			202.4	307.648	
V					8.6	258	
TOTAL		**448.3365**	W			**883.702**	W

JP30.XLSX

Position	z(in)	z(cm)	Power f	Type	Mat	L (in)	L(in)adju	L (cm)	L (cm)adj	D (in)	D(cm)	d(in)	Vol(cm3)	rho	q(W/g)	Qhold(W)	Qhous(W)	Qspec(W)	Qtot(W)	Qshr(W)	Qshr(W)f	Qwat(W)f	fshroud	fwater	HS/Table	NODE #	
Capsu-1	8.758	22.24532	0.588999	SSJ3	Al	1.272		3.23088	3.23088	0.42	1.0668	0.3128	1.286052	2.7	41.35	143.5812	105.8068	478.6	727.98803	145.9863	85.98572	76.93575	56.74865	50.77587	211/5	Node 3	
spacer1	8.028	20.39112	0.650507		SS	0.186	0.188	0.47244	0.47752	0.244	0.61976	0.211	0.036331	8	61	17.7294	15.63811		33.367511	21.57659	14.03572	12.55847	9.263262	8.288306		4	
2	7.263	18.44802	0.710666	DCT	SS	1.342		3.40868	3.40868	0.4274	1.085596		3.155096	8	61	1539.687	111.6295		1651.3164	154.0201	109.4569	97.93661	72.23911	64.63596		5	
spacer2	6.4975	16.50365	0.766062		SS	0.186	0.189	0.47244	0.48006	0.244	0.61976	0.211	0.036524	8	61	17.82371	15.72129		33.544998	21.69135	16.61692	14.868	10.9668	9.812544		6	
3	5.767	14.64818	0.8141	SSJ3	Al	1.272		3.23088	3.23088	0.436	1.10744	0.3128	1.51027	2.7	41.35	168.6141	105.8068	478.6	753.02093	145.9863	118.8475	106.3388	78.43666	70.18122		7	
spacer3	5.1195	13.00353	0.852499		SS	0.022	0.023	0.05588	0.05842	0.244	0.61976	0.211	0.004445	8	61	2.169022	1.913173		4.0821956	2.639689	2.250331	2.013485	1.485168	1.328855		8	
4	4.437	11.26998	0.888505	DCT	SS	1.342		3.40868	3.40868	0.4423	1.123442		3.378916	8	61	1648.911	111.6295		1760.5406	154.0201	136.8476	122.4444	90.31633	80.81057		9	
spacer4	3.755	9.5377	0.919714		SS	0.022	0.022	0.05588	0.05588	0.244	0.61976	0.211	0.004251	8	61	2.074717	1.829992		3.9047088	2.52492	2.322204	2.077793	1.532603	1.371297		10	
5	3.03	7.6962	0.947475	M3PCCVN	Al	1.428		3.62712	3.62712	0.4412	1.120648	0.3277	1.603928	2.7	41.35	179.0706	118.7831	779	1076.8537	163.8902	155.2819	138.9386	102.4826	91.69633		11	
spacer5	2.243	5.69722	0.971102		SS	0.146	0.146	0.37084	0.37084	0.244	0.61976	0.211	0.028214	8	61	13.76858	12.14449		25.913067	16.75628	16.27205	14.55943	10.73919	9.608894		12	
6	1.499	3.80746	0.987059	DCT	SS	1.342		3.40868	3.40868	0.4405	1.11887		3.35147	8	61	1635.517	111.6295		1747.147	154.0201	152.0269	136.0261	100.3343	89.77416		13	
spacer6	0.8165	2.07391	0.996155		SS	0.022	0.023	0.05588	0.05842	0.244	0.61976	0.211	0.004445	8	61	2.169022	1.913173		4.0821956	2.639689	2.629538	2.35278	1.735436	1.552782		14	
7	0.169	0.42926	0.999835	SSJ3	Al	1.272		3.23088	3.23088	0.4328	1.099312	0.3128	1.464756	2.7	41.35	163.5327	105.8068	478.6	747.93948	145.9863	145.9622	130.5997	96.33177	86.19288		15	
spacer7	-0.4785	-1.21539	0.998679		SS	0.022	0.023	0.05588	0.05842	0.244	0.61976	0.211	0.004445	8	61	2.169022	1.913173		4.0821956	2.639689	2.636201	2.358742	1.739834	1.556717		16	
8	-1.161	-2.94894	0.99223	DCT	SS	1.342		3.40868	3.40868	0.4405	1.11887		3.35147	8	61	1635.517	111.6295		1747.147	154.0201	152.8234	136.7387	100.86	90.24451		17	Highest heat load
spacer8	-1.911	-4.85394	0.978995		SS	0.158	0.158	0.40132	0.40132	0.244	0.61976	0.211	0.030533	8	61	14.90024	13.14267		28.042909	18.13351	17.75263	15.88417	11.71634	10.48319		18	
9	-2.626	-6.67004	0.960461	SSJ3	Vn	1.272		3.23088	3.23088	0.4282	1.087628	0.3128	1.399917	6.11	69.05	590.6185	105.8068	478.6	1175.0253	145.9863	140.2141	125.4566	92.53818	82.79856		19	
spacer9	-3.3405	-8.48487	0.93628		SS	0.158	0.157	0.40132	0.39878	0.244	0.61976	0.211	0.03034	8	61	14.80594	13.05949		27.865422	18.01874	16.87059	15.09497	11.13421	9.962341		20	
10	-3.956	-10.0482	0.911022	M2PCCV	Al	1.074		2.72796	2.72796	0.4395	1.11633	0.3265	1.196472	2.7	41.35	133.5801	89.33687	592.1	815.01698	123.262	112.2944	100.4754	74.11177	66.31153		21	
spacer10	-4.504	-11.4402	0.885179		SS	0.022	0.022	0.05588	0.05588	0.244	0.61976	0.211	0.004251	8	61	2.074717	1.829992		3.9047088	2.52492	2.235005	1.999771	1.475053	1.319804		22	
11	-5.229	-13.2817	0.84629	M3PCCVN	Al	1.428		3.62712	3.62712	0.4402	1.118108	0.3277	1.587729	2.7	41.35	177.262	118.7831	779	1075.0451	163.8902	138.6987	124.1007	91.53801	81.90366		23	
spacer11	-5.954	-15.1232	0.802269		SS	0.022	0.022	0.05588	0.05588	0.244	0.61976	0.211	0.004251	8	61	2.074717	1.829992		3.9047088	2.52492	2.025665	1.812464	1.336893	1.196186		24	
12	-6.679	-16.9647	0.753383	M3PCCVN	Al	1.428		3.62712	3.62712	0.4396	1.116584	0.3277	1.578027	2.7	41.35	176.1789	118.7831	779	1073.962	163.8902	123.4721	110.4767	81.4888	72.91213		25	
spacer12	-7.404	-18.8062	0.699927		SS	0.022	0.022	0.05588	0.05588	0.244	0.61976	0.211	0.004251	8	61	2.074717	1.829992		3.9047088	2.52492	1.76726	1.581257	1.166352	1.043594		26	
13	-8.129	-20.6477	0.642227	M3PCCVN	Al	1.428		3.62712	3.62712	0.4378	1.112012	0.3277	1.549001	2.7	41.35	172.9382	118.7831	779	1070.7213	163.8902	105.2548	94.17673	69.46578	62.15453		27	
spacer13	-8.854	-22.4892	0.580632		SS	0.022	0.022	0.05588	0.05588	0.244	0.61976	0.211	0.004251	8	61	2.074717	1.829992		3.9047088	2.52492	1.466049	1.311748	0.96756	0.865724		28	Lowest heat load
14	-9.13	-23.1902	0.556237	TEM	Al	0.53		1.3462	1.3462	0.428	1.08712	0.2571	0.798662	2.7	41.35	89.1666	44.08617	148.4	281.65277	60.82761	33.83457	30.27349	22.33006	19.97983		29	
spacer14	-9.9205	-25.1981	0.483736		SS	1.051		2.66954	2.66954	0.244	0.61976	0.211	0.203104	8	61	99.11489	87.4237		186.53859	120.6223	58.3493	52.20806	38.50923	34.45615		30	
L-tot						19.833	19.84		50.3936								1650.32	W									
L-cent	18.6785					18.6715	18.6785										39.911	g									
																Q (W)	Fraction in HS10 or HS40										
Node 2	10.094	25.63876	0.467338	housing	Al	1.4		3.556	3.556	0.505	1.2827	0.444	1.043074	2.7	41.35	116.454	0.077744			160.6767	75.09025	67.18702	49.55788	44.34193		Node 2	
Node 1	11.76445	29.8817	0.30201	Top nod	Al	1.9409		4.93	4.93	0.501	1.27254	0	6.270175	2.7	41.35	700.0337	0.30201	Table10 HS10 Node1		222.7604	67.27586	62.73309	44.40056	41.40243		Node 1	TOP NODE
Node 31	-10.8496	-27.558	0.394105	Bottom	Al	0.8072		2.0504	2.0504	0.501	1.27254	0	2.607782	2.7	41.35	291.1459	0.163909	HS40 Node 31		92.64666	36.51249	34.047	24.09743	22.47026		Node 31	BOTTOM NODE
L-TOT						23.9881			60.93						Total Q*f	326.1591				Total Q	2047.109	1835.567					
											Radii used in RELAP5													Table 5 =	1.515203	Watts	
Node 2				Spring	SS	1.4			3.556				0.044284	8.02	61	21.66452											

Column Q & R 34-35

Heats for Nodes 1 and 31 - Table 10

Top and Bottom Solid Rod

Qhous =A*L*rho*q = 32.7486*L

Qhold for all capsules and spacers

Q for spacers is approximate

Qhold for capsules (including DCT) used in Sheet 3

Columns U, V and W

Heat generation in the shroud and in the water - structure HS211 - using Table 5

Qshr = A*L*rho*q =45.184674*L, A=0.404717cm2, rho*q=2.7*41.35W/cm3

Qwater = A*L*rho*q =42.1336*L for nodes 1 and 31, A=0.50399cm2

Qwater = 40.429*L for nodes 2-30, A=0.4836cm2, rho*q=83.6W/cm3

L (in m) used in CV110, HS 211, HS10-HS40

*0.01 conversion

Columns G and I - adjusted lengths for the spacers

Spacers 1, 2, 3, 6, 7 are LONGER than DESIGN values

Spacer 9 is SHORTER than DESIGN VALUE

Spacer volumes (and masses and Q) are approximate - Sheet 3 has the correct masses from measured values

RED NUMBERS USED IN RELAP5 INPUT: NOTE Node1 line 34, Node2 line 33, Node31 line 35

RELAP5 INPUTS: L(in m) for CV110 and HS211 and Table 5 (shroud and water), Table 10 (rod top-bottom) + factors for HS 10, 40 and 211

ATTACHMENTS

Selected Attachments

GENERAL DESIGN AND COMPUTATION SHEET

JOB		DATE	SHEET
C-HFIR-2007-043 Appendix C		6/18/2007	C-8 OF
ESO NO.	COMPUTED JLM 6/18/07	CHECKED BY	

$$T(r) = -\frac{\dot{q} r^2}{4K} + \left[-\frac{q'_{in}}{2\pi K} + \frac{\dot{q} r_i^2}{2K}\right]\ln r + \frac{\dot{q} r_o^2}{4K} - \left[\frac{-q'_{in}}{2\pi K} + \frac{\dot{q} r_i^2}{2K}\right]\ln r_o + T_o$$

$$= \frac{\dot{q}}{4K}\left(r_o^2 - r^2\right) + \left[\frac{\dot{q} r_i^2}{2K} - \frac{q'_{in}}{2\pi K}\right]\ln(r/r_o) + T_o$$

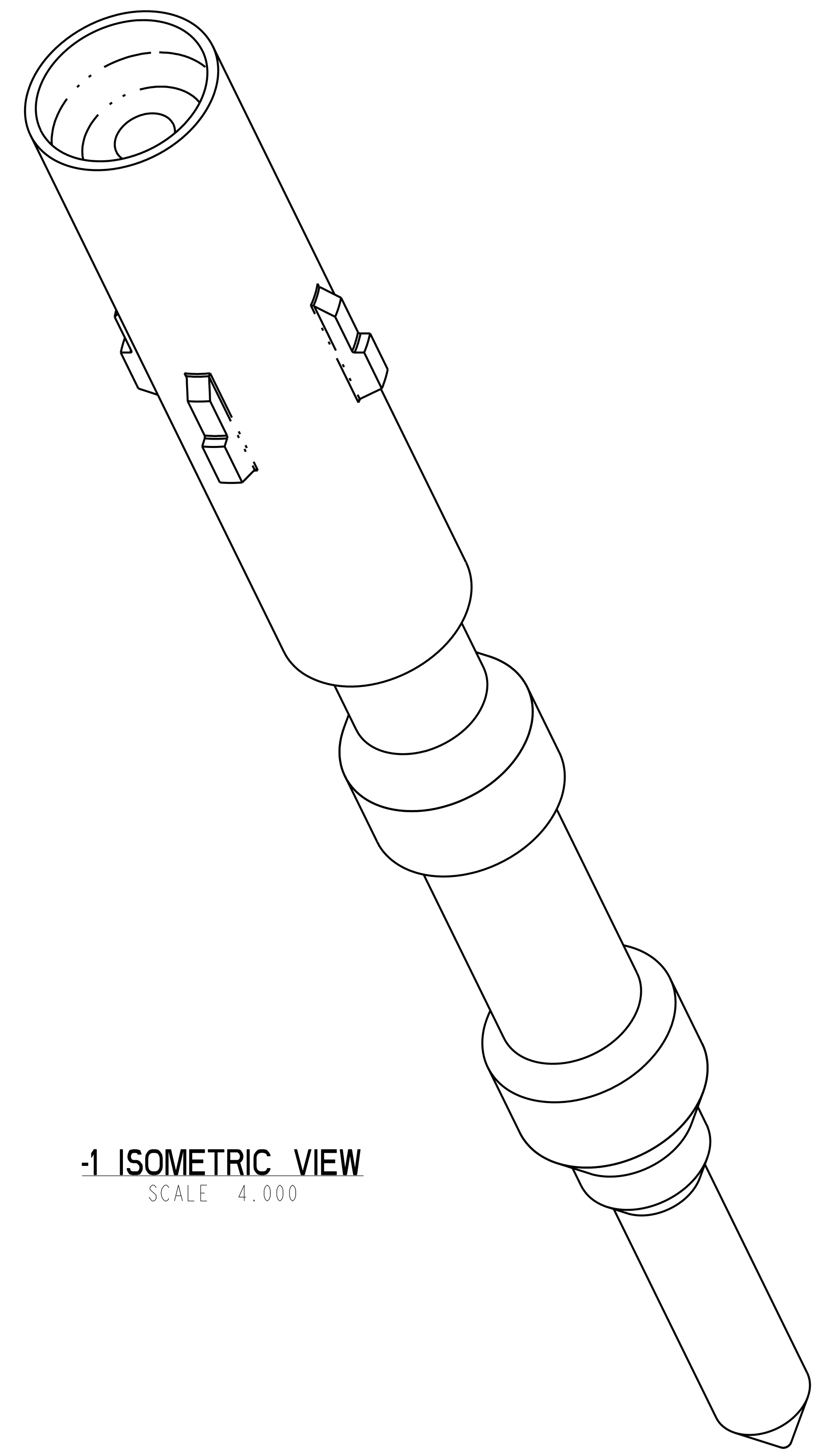
ORNL-229A (11-04)

ATTACHMENTS 4-14

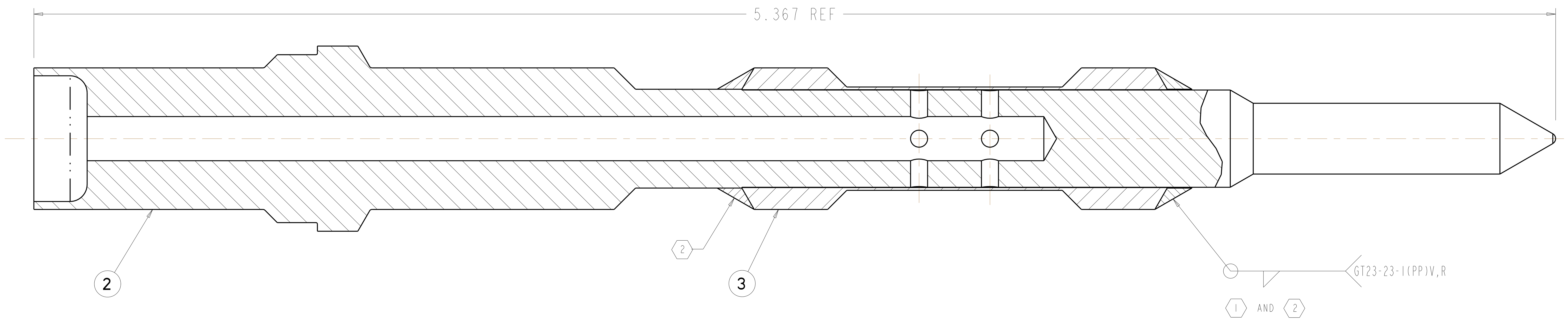
ATTACHMENT 4

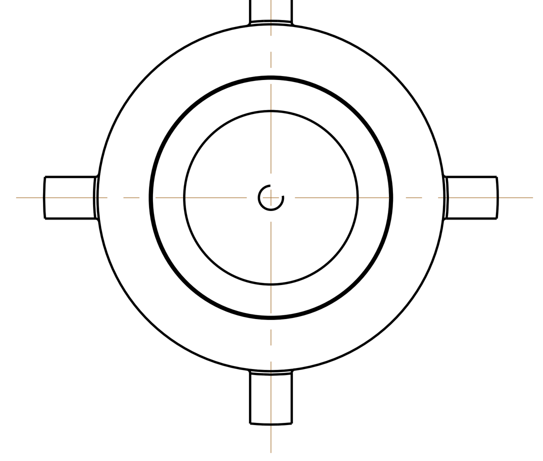
GENERAL NOTES:

1. CLEAN WITH ACETONE, FOLLOWED BY ALCOHOL PER RRD-JS-31.
2. DIMENSIONS ARE IN INCHES.
3. HELIUM LEAK TEST WELDS 1 AND 2 WITH A MASS SPECTROMETER DETECTOR. NO LEAKAGE GREATER THAN 1 X 10^{-7} STD CC/SEC PERMITTED AT ONE ATMOSPHERE PRESSURE DIFFERENTIAL.
4. ALL WELD INSPECTION SHALL BE DOCUMENTED USING FORM UNC-9989. IF WELDS ARE COMPLETED BY AN OUTSIDE VENDOR THE WELDING INSPECTOR SHALL BE AN AWS-CWI (AMERICAN WELDING SOCIETY CERTIFIED WELDING INSPECTOR). WELDING PROCEDURES AND WELDERS SHALL BE QUALIFIED PER ASME SECTION IX. WELD PROCEDURES SHALL BE APPROVED BY ORNL.



-1 ISOMETRIC VIEW
SCALE 4.000





SECTION A-A
-1 BOTTOM CAP ASSEMBLY
SCALE 6.000

2 LAST WELD

WELD INSPECTION SCHEDULE (SEE NOTE 4)						
WELD #	SPEC	VISUAL	DYE PENETRANT	RADIOGRAPH	He	HYDRO
1	GT23.23-1(PP)	FD-T-NDE-21		FD-T-JSP-43	SEE NOTE 3	
2	GT23.23-1(PP)	FD-T-NDE-21		FD-T-JSP-43		

		1	X3E020977A574-1	RUPTURE SLEEVE			3
		1	X3E020977A571-1	GUIDE PIN			2
		AR	-1	BOTTOM CAP ASSEMBLY			1
X3E020977 A576	-1	CAGE CODE	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL	SPECIFICATION	FIND NO
		NEXT ASSEMBLY		PARTS LIST			

CERTIFIED FOR CONSTRUCTION
ISSUE DATE:4/19/11

NO REPRESENTATION OR WARRANTY, EXPRESSED OR IMPLIED, IS MADE AS TO THE ACCURACY, COMPLETENESS OR USEFULNESS OF THE INFORMATION OR STATEMENTS CONTAINED IN THESE DRAWINGS, OR THAT THE USE OR DISCLOSURE OF ANY INFORMATION, APPARATUS, METHOD OR PROCESS DISCLOSED IN THESE DRAWINGS MAY NOT INFRINGE PRIVATE RIGHTS OF OTHERS. NO LIABILITY IS ASSUMED WITH RESPECT TO THE USE OF, OR FOR DAMAGES RESULTING FROM THE USE OF, ANY INFORMATION, APPARATUS, METHOD OR PROCESS DISCLOSED IN THESE DRAWINGS. DRAWINGS MADE AVAILABLE FOR INFORMATION TO BIDDER ARE NOT TO BE USED FOR OTHER PURPOSES, AND ARE TO BE RETURNED UPON REQUEST OF THE FORWARDING CONTRACTOR.

ALL FEATURES INDICATED BY X OR X SHALL BE INSPECTED AND RECORDED IN AN INSPECTION REPORT IN ACCORDANCE WITH RRD-JS-24, WITH THE EXCEPTION THAT SECTION 6 (NONCONFORMANCE REPORTING) DOES NOT APPLY TO THOSE DIMENSIONS INDICATED BY X

THIS DRAWING PRODUCED ON PRO-ENGINEER

CAUTION NUCLEAR MATERIAL

ANY PROCESS OR MATERIAL (INCLUDING PACKAGING AND SHIPPING MATERIAL) THAT HAS THE POSSIBILITY OF LEAVING A RESIDUE CONTAINING ANY OF THE HALIDE ELEMENTS (PRIMARILY CHLORIDE AND FLUORIDE), METALLIC ELEMENTS (PRIMARILY COPPER, LEAD, NICKLE, SILVER, THORIUM AND TIN) OR CARBON/GRAPHITE ON THE SURFACE OF ANY HFIR COMPONENT AFTER FINAL CLEANING SHALL NOT BE USED. MERCURY IN ANY FORM SHALL BE SPECIFICALLY PRECLUDED IN THE PROCURMENT OF ALUMINUM RAW MATERIALS AND IN ALL PROCESSING AND MANUFACTURING OPERATIONS.

REV	DESCRIPTION	ZONE	BY	CHK	TL	HFIR	HFIR	NQR	QARRD

SCALE

TOLERANCES UNLESS OTHERWISE SPECIFIED
FRACTIONS :
XX DECIMALS ±.01
XXX DECIMALS ±.005
ANGLES ±0°15′
BREAK SHARP EDGES .02 MAX
FINISH 63 RMS 1
FILLETS .02 MAX 2

DRAWING APPROVALS		DATE
DES	D.W.HEATHERLY	08/11/10
DRW	D.W.SPARKS	08/11/10
CHK	D.W.HEATHERLY	4/13/11
TL	J.L.McDUFFEE	4/13/11
WELDING	J.C.POOLE	4/19/11
HFIR CM	Y.S. KWON	4/19/11
RRD SAFETY	R.W HOBBS	4/15/11
HFIR R	D.L.PINKSTON	4/16/11
HFIR OP	E.L.FOGLE	4/19/11
NQR	W.G.ASKEW	4/14/11
QA RRD	L.C.SMITH	4/14/11

UT-BATTELLE

Oak Ridge National Laboratory
managed for the DEPARTMENT OF ENERGY under
U.S. GOVERNMENT contract DE-AC05-00OR22725
UT-BATTELLE, LLC. Oak Ridge, Tennessee

PROJECT NAME
HFIR TARGET IRRADIATION CAPSULES

SHROUDED
TARGET CAPSULE
BOTTOM CAP ASSEMBLY

VERSION NO.	PLANT	BLDG	FL	SHT	OF	TYPE	CLASS
		79	1	1	1	A	U

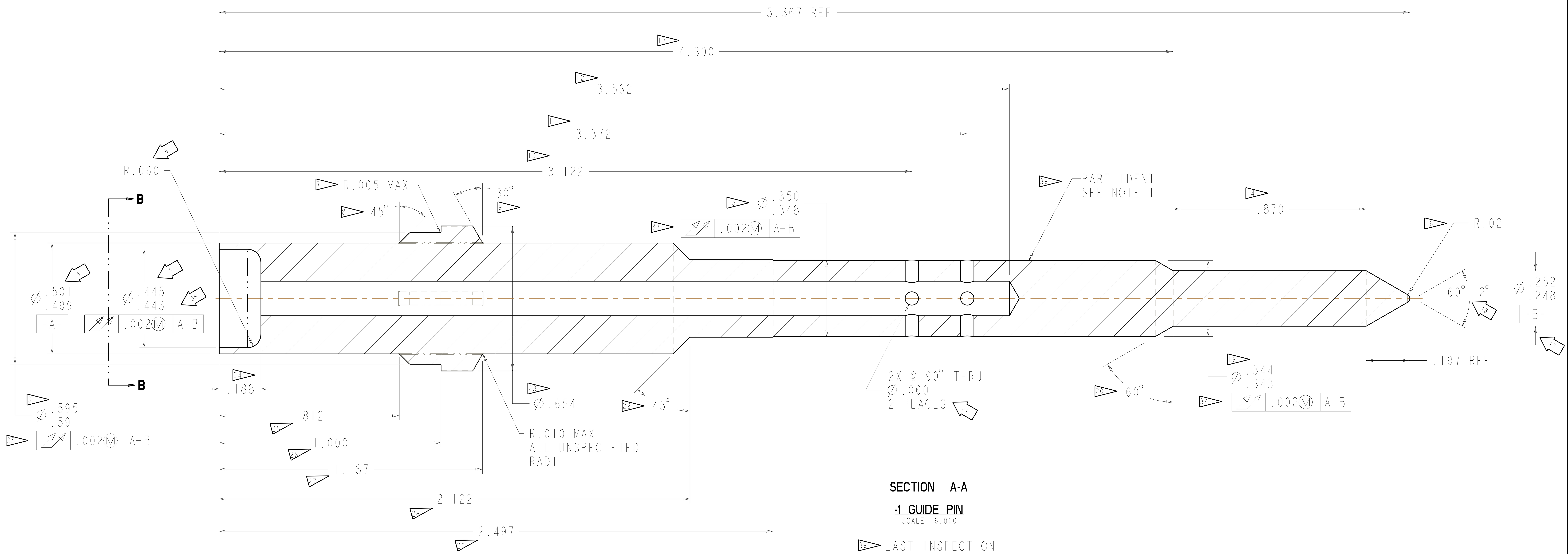
RELEASE LEVEL	EJN		REV
		X3E020977A570	0

X3E020977A570

NEXT ASS'Y: FINAL ASS'Y:

GENERAL NOTES: ATTACHMENT 5

1. PART IDENTIFICATION SHALL BE OF THE FORM "DRAWING NO.-PART NO.-SERIAL NO." OR AN INSPECTION REQUEST NO. (I.R.N.) TRACEABLE TO MATERIAL AND/OR PART DOCUMENTATION AND BE ETCHED ON PART. OPTIONALLY, PART MAY BE PLACED IN A SEALABLE PLASTIC BAG WITH A TAG INDICATING PART IDENTIFICATION.
2. CLEAN WITH ACETONE, FOLLOWED BY ALCOHOL PER RRD-JS-31.
3. DIMENSIONS ARE IN INCHES.
4. DOCUMENTATION REQUIRED:
   RRD-MS-52------ APPENDIX 1 (OR EQUIVALENT), APPENDIX 2
   RRD-JS-31------ APPENDIX A CLEANLINESS REPORT
   RRD-JS-24------ INSPECTION PLAN AND DIMENSIONAL INSPECTION REPORT

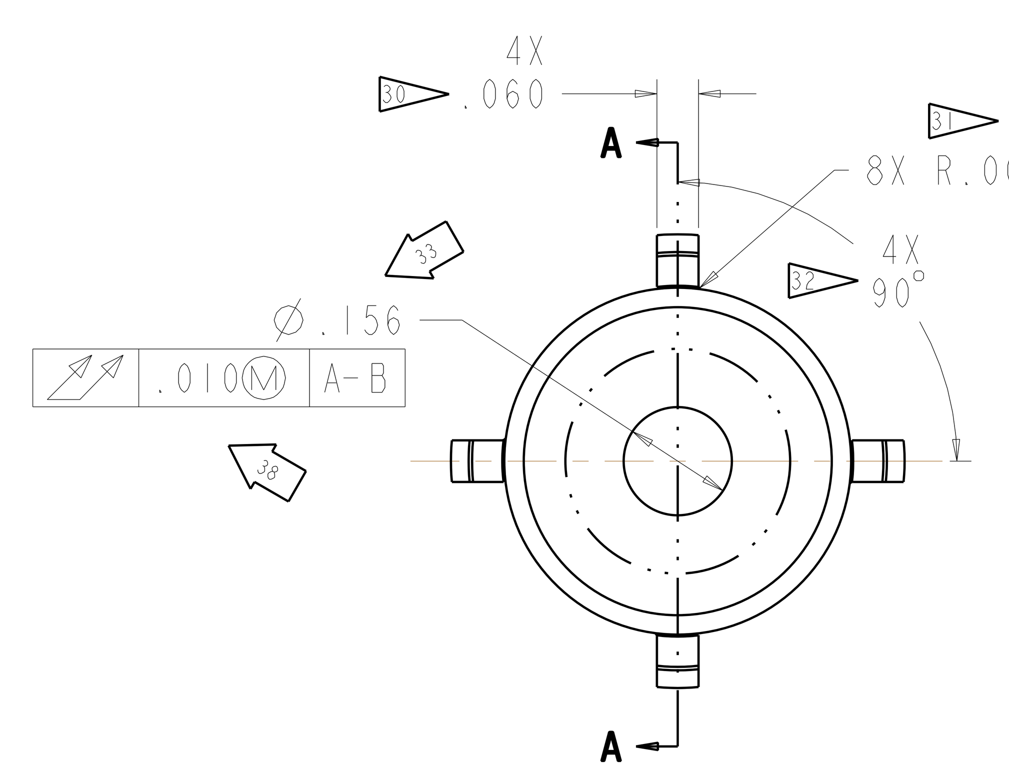


SECTION A-A

-1 GUIDE PIN

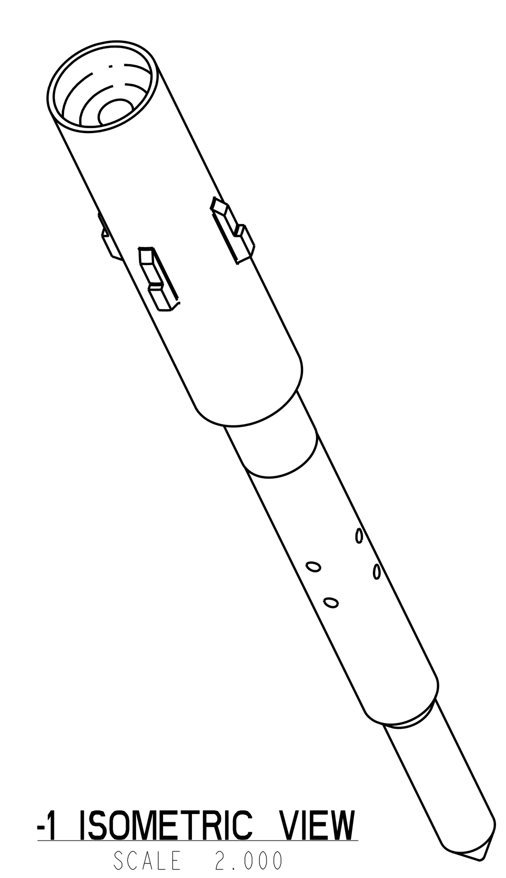
SCALE 6.000

LAST INSPECTION



VIEW B-B

SCALE 6.000



-1 ISOMETRIC VIEW

SCALE 2.000

AR		-1	GUIDE PIN	AL 6061-T6		
X3E020977 A570	CAGE CODE	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL	SPECIFICATION	FIND NO
	NEXT ASSEMBLY		PARTS LIST			

CERTIFIED FOR CONSTRUCTION

ISSUE DATE: 4/19/11

ALL FEATURES INDICATED BY X OR X SHALL BE INSPECTED AND RECORDED IN AN INSPECTION REPORT IN ACCORDANCE WITH RRD-JS-24, WITH THE EXCEPTION THAT SECTION 6 (NONCONFORMANCE REPORTING) DOES NOT APPLY TO THOSE DIMENSIONS INDICATED BY X

THIS DRAWING PRODUCED ON PRO-ENGINEER

CAUTION NUCLEAR MATERIAL

ANY PROCESS OR MATERIAL (INCLUDING PACKAGING AND SHIPPING MATERIAL) THAT HAS THE POSSIBILITY OF LEAVING A RESIDUE CONTAINING ANY OF THE HALIDE ELEMENTS (PRIMARILY CHLORIDE AND FLUORIDE), METALLIC ELEMENTS (PRIMARILY COPPER, LEAD, NICKLE, SILVER, THORIUM AND TIN) OR CARBON/GRAPHITE ON THE SURFACE OF ANY HFIR COMPONENT AFTER FINAL CLEANING SHALL NOT BE USED. MERCURY IN ANY FORM SHALL BE SPECIFICALLY PRECLUDED IN THE PROCURMENT OF ALUMINUM RAW MATERIALS AND IN ALL PROCESSING AND MANUFACTURING OPERATIONS.

REV	DESCRIPTION	ZONE	BY	CHK	TL	HFIR	HFIR	NQR	QARRD

SCALE		
TOLERANCES UNLESS OTHERWISE SPECIFIED		
FRACTIONS	:	
XX DECIMALS	±.01	
XXX DECIMALS	±.005	
ANGLES	±0°15′	
BREAK SHARP EDGES	.02 MAX	
FINISH	63 RMS	1
FILLETS .02 MAX		2

DRAWING APPROVALS		DATE
DES	DWH/JLM/KRT	08/23/10
DRW	D.W.SPARKS	08/23/10
CHK	D.W.HEATHERLY	4/13/11
TL	J.L.McDUFFEE	4/13/11
HFIR CM	Y.S. KWON	4/19/11
RRD SAFETY	R.W HOBBS	4/15/11
HFIR R	D.L.PINKSTON	4/16/11
HFIR OP	E.L.FOGLE	4/19/11
NQR	W.G.ASKEW	4/14/11
QA RRD	L.C.SMITH	4/14/11

UT-BATTELLE

Oak Ridge National Laboratory managed for the DEPARTMENT OF ENERGY under U.S. GOVERNMENT contract DE-AC05-00OR22725 UT-BATTELLE, LLC. Oak Ridge, Tennessee

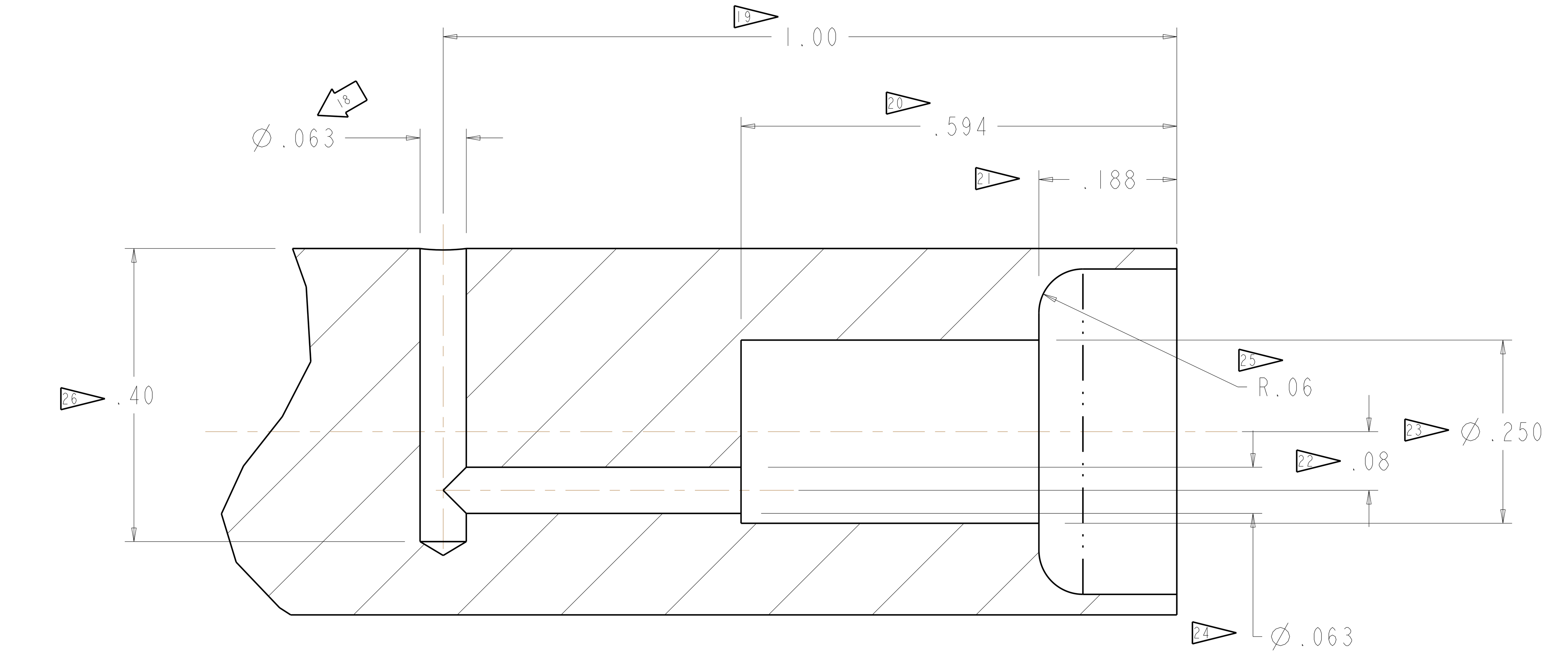
PROJECT NAME: HFIR TARGET IRRADIATION CAPSULES

SHROUDED TARGET CAPSULE GUIDE PIN DETAIL

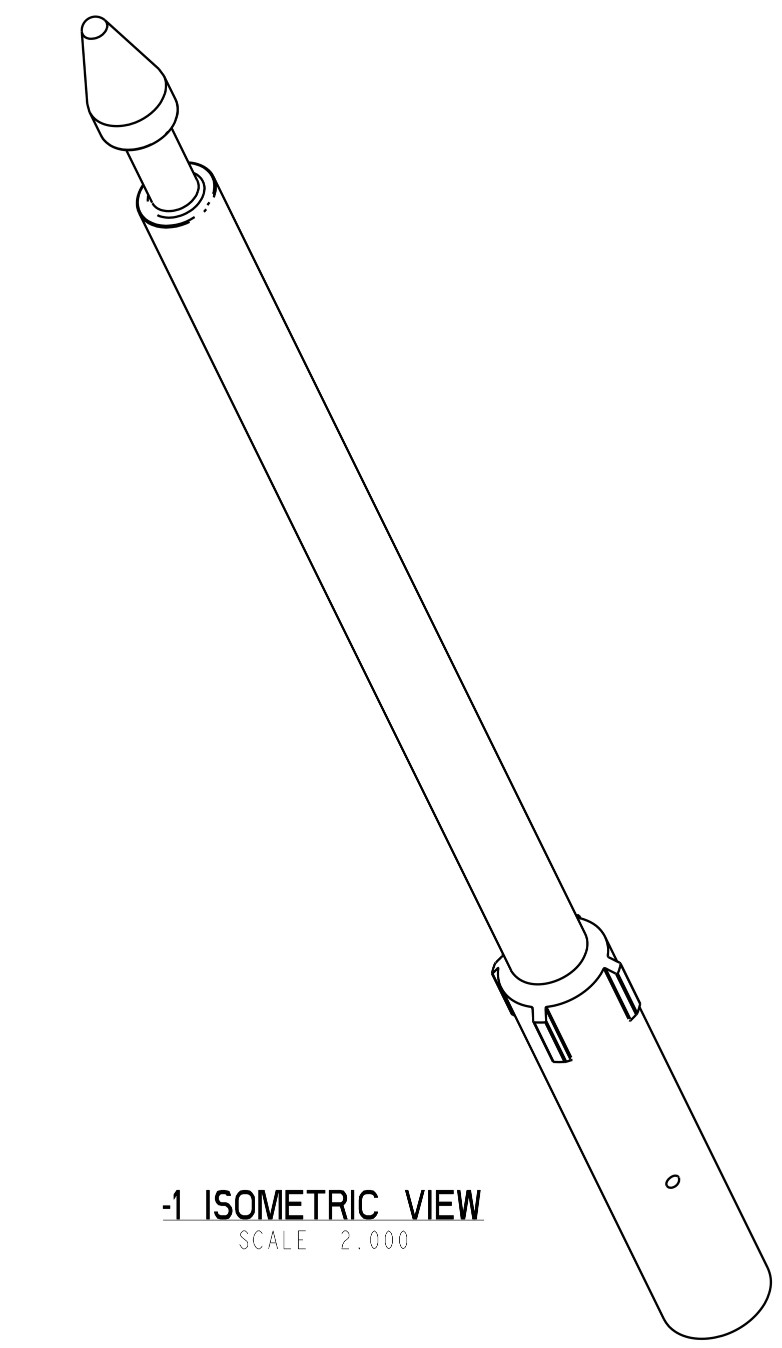
VERSION NO.	PLANT	BLDG	FL	SHT	OF	TYPE	CLASS
	ORNL	7900	1	1	1	D	U
RELEASE LEVEL	EJN	X3E020977A571					REV 0

X3E020977A571

ATTACHMENT 6



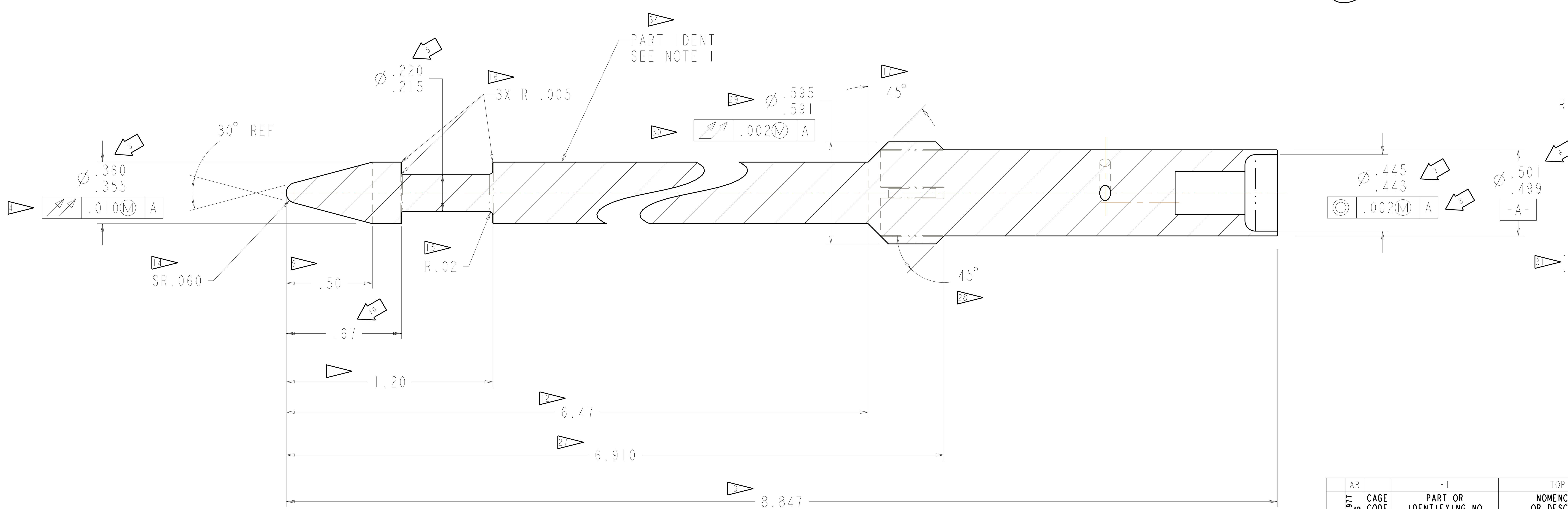
SECTION B-B
SCALE 10.000

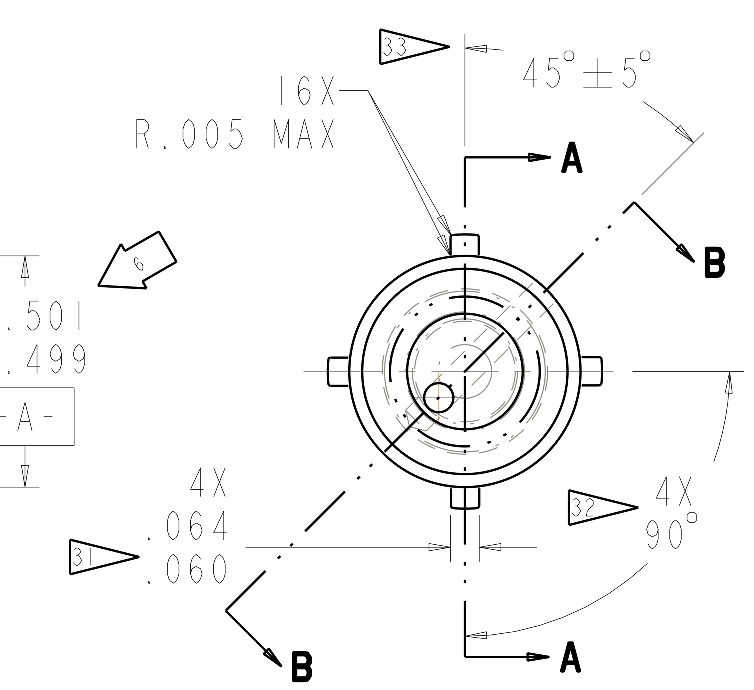


-1 ISOMETRIC VIEW
SCALE 2.000

GENERAL NOTES:

1. PART IDENTIFICATION SHALL BE OF THE FORM "DRAWING NO.-PART NO. -SERIAL NO." OR AN INSPECTION REQUEST NO. (I.R.N.) TRACEABLE TO MATERIAL AND/OR PART DOCUMENTATION AND BE ETCHED ON PART. OPTIONALLY, PART MAY BE PLACED IN A SEALABLE PLASTIC BAG WITH A TAG INDICATING PART IDENTIFICATION.
2. CLEAN WITH ACETONE, FOLLOWED BY ALCOHOL PER RRD-JS-31.
3. DIMENSIONS ARE IN INCHES.
4. DOCUMENTATION REQUIRED:
   RRD-MS-52------ APPENDIX 1 (OR EQUIVALENT), APPENDIX 2
   RRD-JS-31------ APPENDIX A CLEANLINESS REPORT
   RRD-JS-24------ INSPECTION PLAN AND DIMENSIONAL INSPECTION REPORT





AR		-1	TOP CAP	AL 6061-T6		1
X3E020977 A576	CAGE CODE	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL	SPECIFICATION	FIND NO
	NEXT ASSEMBLY		PARTS LIST			

SECTION A-A
-1 TOP CAP
SCALE 4.000

34 LAST INSPECTION

CERTIFIED FOR CONSTRUCTION
ISSUE DATE: 4/19/11

NO REPRESENTATION OR WARRANTY, EXPRESSED OR IMPLIED, IS MADE AS TO THE ACCURACY, COMPLETENESS OR USEFULNESS OF THE INFORMATION OR STATEMENTS CONTAINED IN THESE DRAWINGS, OR THAT THE USE OR DISCLOSURE OF ANY INFORMATION, APPARATUS, METHOD OR PROCESS DISCLOSED IN THESE DRAWINGS MAY NOT INFRINGE PRIVATE RIGHTS OF OTHERS. NO LIABILITY IS ASSUMED WITH RESPECT TO THE USE OF, OR FOR DAMAGES RESULTING FROM THE USE OF, ANY INFORMATION, APPARATUS, METHOD OR PROCESS DISCLOSED IN THESE DRAWINGS. DRAWINGS MADE AVAILABLE FOR INFORMATION TO BIDDER ARE NOT TO BE USED FOR OTHER PURPOSES, AND ARE TO BE RETURNED UPON REQUEST OF THE FORWARDING CONTRACTOR.

ALL FEATURES INDICATED BY X OR X SHALL BE INSPECTED AND RECORDED IN AN INSPECTION REPORT IN ACCORDANCE WITH RRD-JS-24, WITH THE EXCEPTION THAT SECTION 6 (NONCONFORMANCE REPORTING) DOES NOT APPLY TO THOSE DIMENSIONS INDICATED BY X

THIS DRAWING PRODUCED ON PRO-ENGINEER

CAUTION NUCLEAR MATERIAL

ANY PROCESS OR MATERIAL (INCLUDING PACKAGING AND SHIPPING MATERIAL) THAT HAS THE POSSIBILITY OF LEAVING A RESIDUE CONTAINING ANY OF THE HALIDE ELEMENTS (PRIMARILY CHLORIDE AND FLUORIDE), METALLIC ELEMENTS (PRIMARILY COPPER, LEAD, NICKLE, SILVER, THORIUM AND TIN) OR CARBON/GRAPHITE ON THE SURFACE OF ANY HFIR COMPONENT AFTER FINAL CLEANING SHALL NOT BE USED. MERCURY IN ANY FORM SHALL BE SPECIFICALLY PRECLUDED IN THE PROCURMENT OF ALUMINUM RAW MATERIALS AND IN ALL PROCESSING AND MANUFACTURING OPERATIONS.

REV	DESCRIPTION	ZONE	BY	CHK	TL	HFIR	HFIR	NQR	QARRD

SCALE

TOLERANCES UNLESS OTHERWISE SPECIFIED

FRACTIONS	:
XX DECIMALS	±.01
XXX DECIMALS	±.005
ANGLES	±0°15′
BREAK SHARP EDGES	.02 MAX
FINISH	63 RMS 1
FILLETS .02 MAX	2

DRAWING APPROVALS		DATE
DES	DWH/JLM/KRT	08/23/10
DRW	D.W.SPARKS	08/23/10
CHK	D.W.HEATHERLY	4/13/11
TL	J.L.McDUFFEE	4/13/11
HFIR CM	Y.S. KWON	4/19/11
RRD SAFETY	R.W.HOBBS	4/15/11
HFIR R	D.L.PINKSTON	4/15/11
HFIR OP	E.L.FOGLE	4/19/11
NQR	W.G.ASKEW	4/14/11
QA RRD	L.C.SMITH	4/14/11

UT-BATTELLE

Oak Ridge National Laboratory
managed for the DEPARTMENT OF ENERGY under U.S. GOVERNMENT contract DE-AC05-00OR22725
UT-BATTELLE, LLC. Oak Ridge, Tennessee

PROJECT NAME
HFIR TARGET IRRADIATION CAPSULES

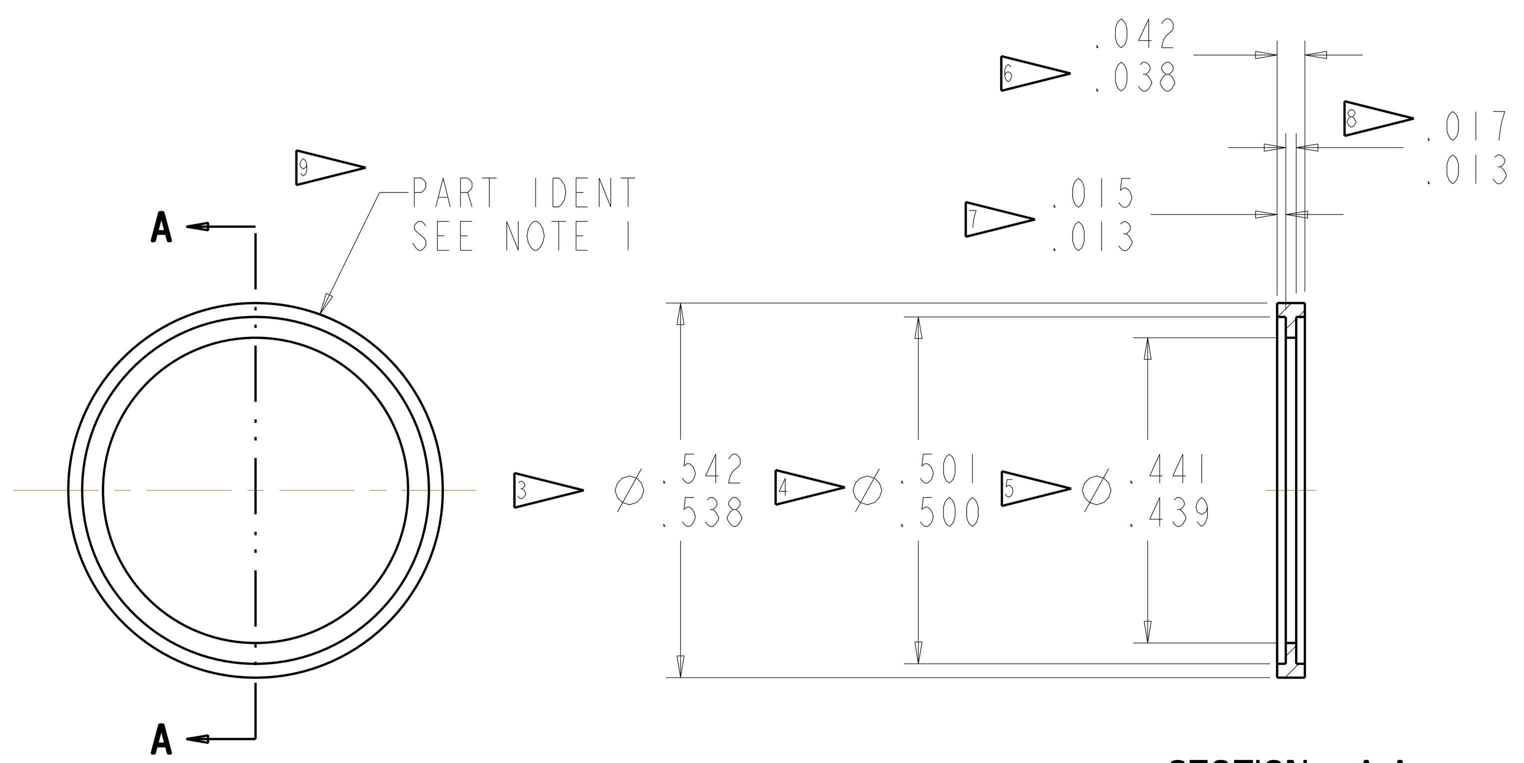
SHROUDED
TARGET CAPSULE
TOP CAP

VERSION NO.	PLANT	BLDG	FL	SHT	OF	TYPE	CLASS
12	ORNL	7900	1	1	1	D	U

RELEASE LEVEL	EJN		REV
WIP		X3E020977A572	0

X3E020977A572

ATTACHMENT 7



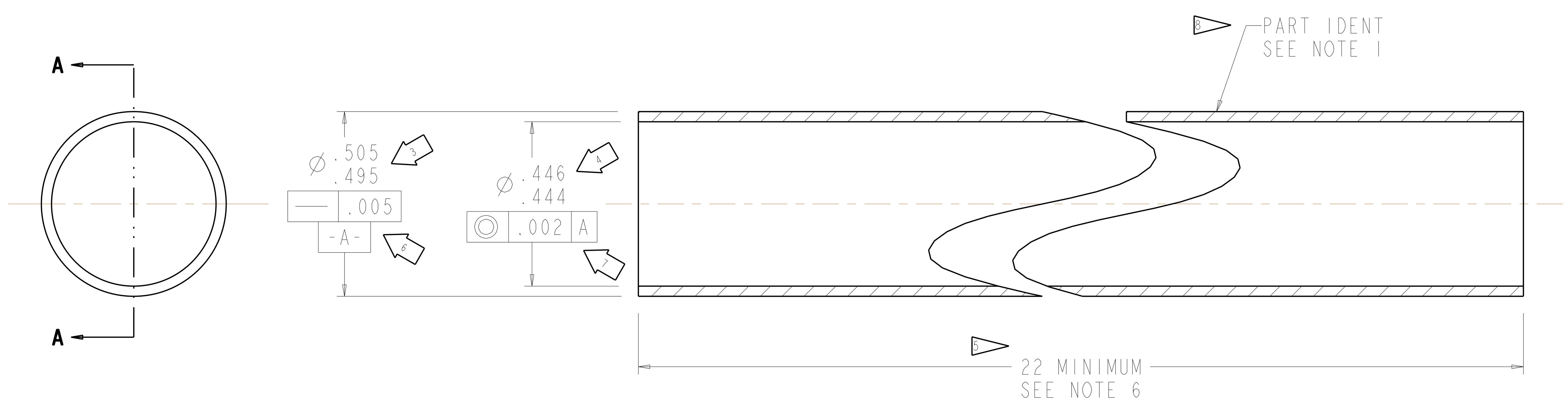
SECTION A-A

-2 WELD RING
SCALE 6.000

LAST INSPECTION

GENERAL NOTES:

1. PART IDENTIFICATION SHALL BE OF THE FORM "DRAWING NO.-PART NO. -SERIAL NO." OR AN INSPECTION REQUEST NO. (I.R.N.) TRACEABLE TO MATERIAL AND/OR PART DOCUMENTATION AND BE ETCHED ON PART. OPTIONALLY, PART MAY BE PLACED IN A SEALABLE PLASTIC BAG WITH A TAG INDICATING PART IDENTIFICATION.
2. CLEAN WITH ACETONE FOLLOWED BY ALCOHOL PER RRD-JS-31.
3. DIMENSIONS ARE IN INCHES.
4. DOCUMENTATION REQUIRED:
   RRD-MS-52------ APPENDIX 1 (OR EQUIVALENT), APPENDIX 2 (APPLIES TO PARTS 1 AND 2 ONLY)
   RRD-JS-31------ APPENDIX A CLEANLINESS REPORT
   RRD-JS-24------ INSPECTION PLAN AND DIMENSIONAL INSPECTION REPORT
5. WELD RING (FIND #2) TO BE FABRICATED FROM 4043 ALUMINUM WELD FILLER MATERIAL. CERTIFIED CHEMICAL ANALYSIS OF MATERIAL REQUIRED.
6. THE HOUSING TUBE SHOWN ON THIS DRAWING HAS EXCESS LENGTH. THE FINAL HOUSING TUBE LENGTH WILL BE DETERMINED WHEN THE PART IS USED ON A CAPSULE ASSEMBLY.



SECTION A-A

-1 HOUSING TUBE
SCALE 6.000

LAST INSPECTION

5	AR		-2	WELD RING	AL 4043	SEE NOTE 5	2
	AR		-1	HOUSING TUBE ∅.500 X .028 WALL TUBE	AL 6061-T6	ASTM B210 OR B221	1
	X3E020977 A576	CAGE CODE	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL	SPECIFICATION	FIND NO
			NEXT ASSEMBLY	PARTS LIST			

CERTIFIED FOR CONSTRUCTION
ISSUE DATE:4/19/11

X3E020977A573

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THIS DRAWING PRODUCED ON PRO-ENGINEER

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REV	DESCRIPTION	ZONE	BY	CHK	TL	HFIR	HFIR	NQR	QARRD

SCALE

TOLERANCES UNLESS OTHERWISE SPECIFIED
FRACTIONS :
XX DECIMALS ±.01
XXX DECIMALS ±.005
ANGLES ±0°15′
BREAK SHARP EDGES .02 MAX
FINISH 63 RMS 1
FILLETS .02 MAX 2

DRAWING APPROVALS		DATE
DES	DWH/JLM/KRT	08/30/10
DRW	D.W.SPARKS	8/30/10
CHK	D.W.HEATHERLY	4/13/11
TL	J.L.McDUFFEE	4/13/11
HFIR CM	Y.S. KWON	4/19/11
RRD SAFETY	R.W HOBBS	4/15/11
HFIR R	D.L.PINKSTON	4/15/11
HFIR OP	E.L.FOGLE	4/19/11
NQR	W.G.ASKEW	4/14/11
QA RRD	L.C.SMITH	4/14/11

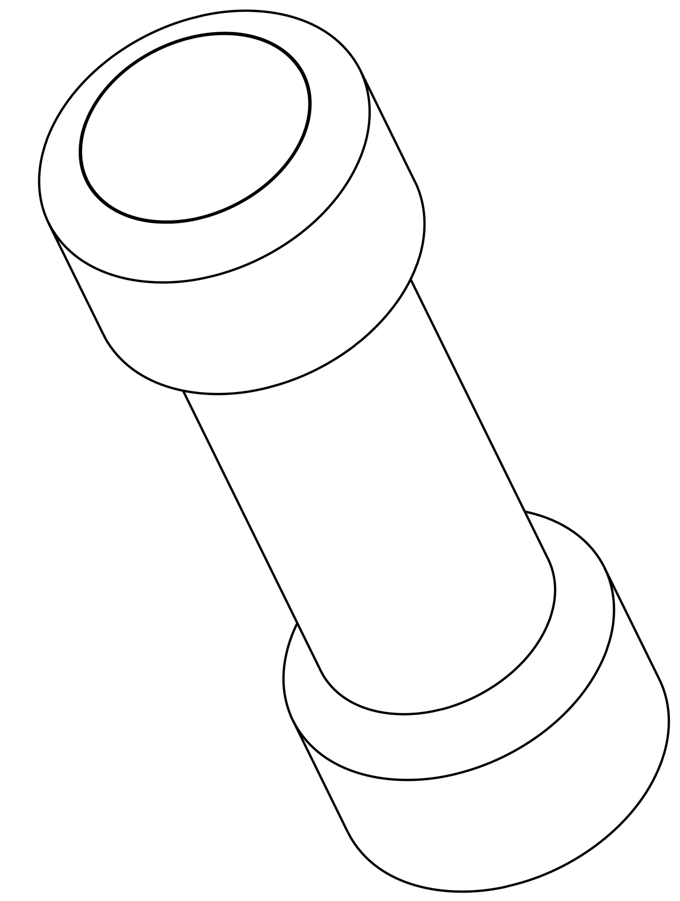
UT-BATTELLE
Oak Ridge National Laboratory
managed for the DEPARTMENT OF ENERGY under U.S. GOVERNMENT contract DE-AC05-00OR22725
UT-BATTELLE, LLC. Oak Ridge, Tennessee

PROJECT NAME
HFIR TARGET IRRADIATION CAPSULES

SHROUDED
TARGET CAPSULE
HOUSING TUBE

VERSION NO.	PLANT	BLDG	FL	SHT OF	TYPE	CLASS
9	ORNL	7900	1	1 1	D	U
RELEASE LEVEL WIP	EJN	X3E020977A573				REV 0

ATTACHMENT 8



-1 ISOMETRIC VIEW
SCALE 6.000

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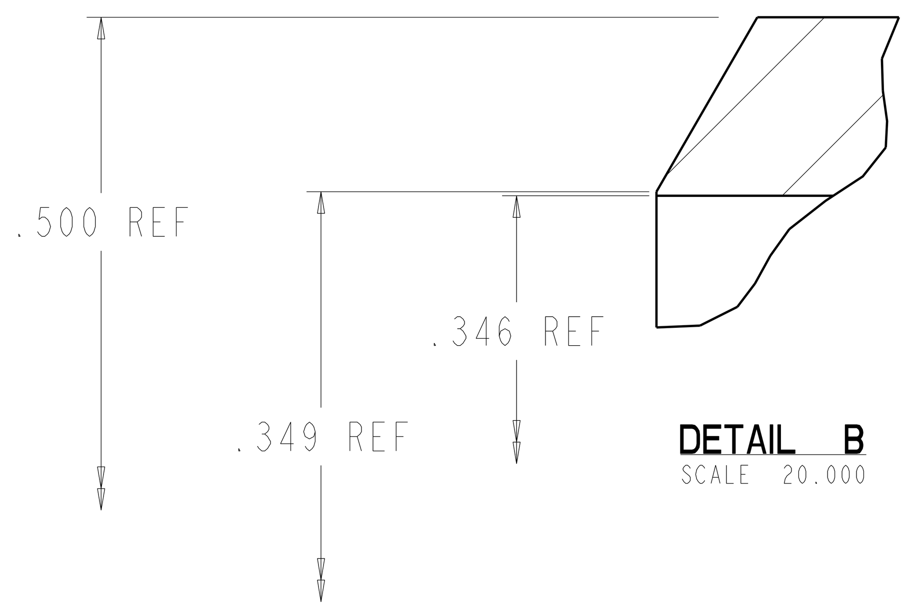
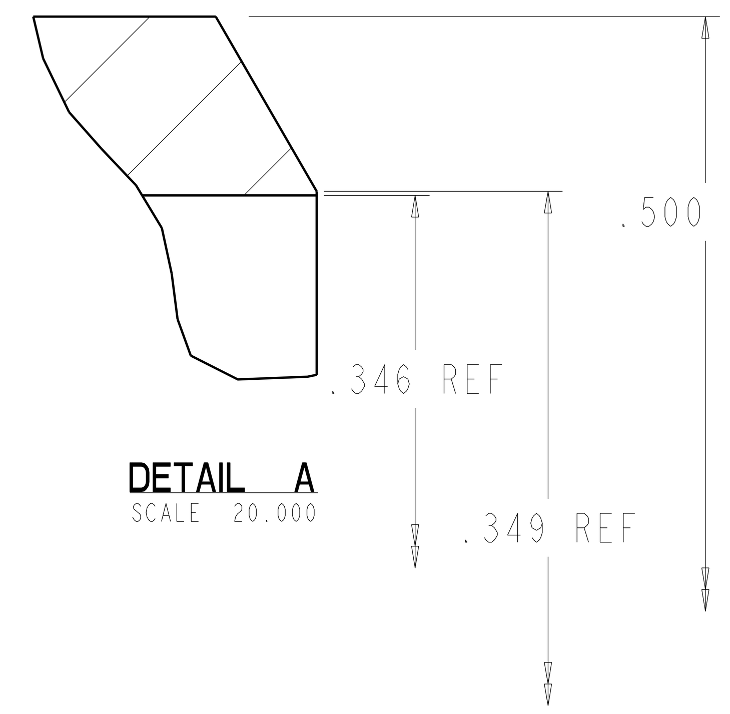
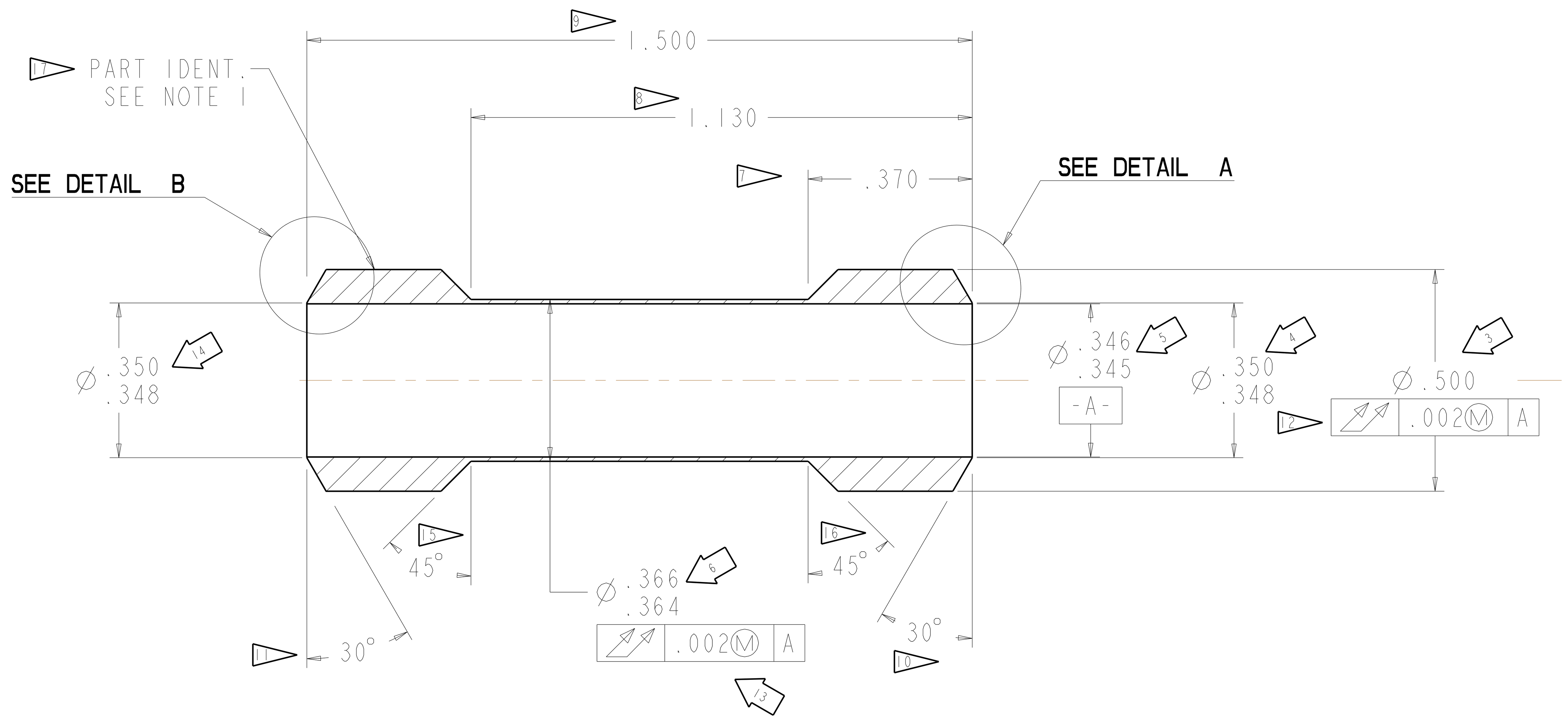
   RRD-JS-31------ APPENDIX A CLEANLINESS REPORT
   RRD-JS-24------ INSPECTION PLAN AND DIMENSIONAL INSPECTION REPORT



DETAIL B
SCALE 20.000

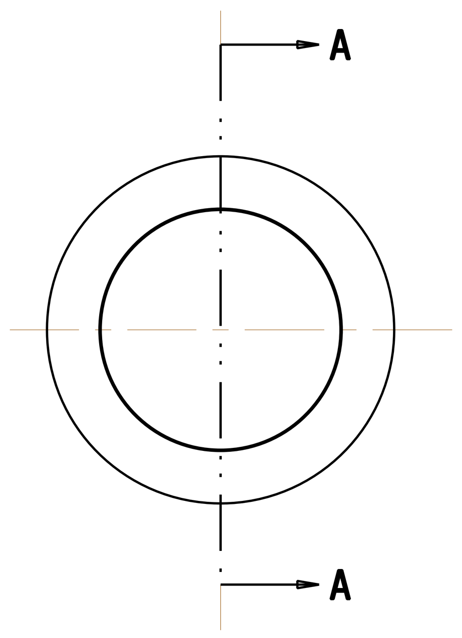


DETAIL A
SCALE 20.000



SECTION A-A
-1 RUPTURE SLEEVE
SCALE 6.000

LAST INSPECTION



AR		-1	RUPTURE SLEEVE	AL 1100-H14	ASTM B210	1
X3E020977 A570	CAGE CODE	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL	SPECIFICATION	FIND NO
	NEXT ASSEMBLY		PARTS LIST			

X3E020977A574

CERTIFIED FOR CONSTRUCTION

ISSUE DATE:4/19/11

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REV	DESCRIPTION	ZONE	BY	CHK	TL	HFIR	HFIR	NQR	QARRD

SCALE		DES DWH/JLM/KRT	08/30/10
TOLERANCES UNLESS OTHERWISE SPECIFIED		DRW D.W.SPARKS	08/30/10
		CHK D.W.HEATHERLY	4/13/11
		TL J.L.McDUFFEE	4/13/11
FRACTIONS	:		
XX DECIMALS	±.01		
XXX DECIMALS	±.005	HFIR CM Y.S. KWON	4/19/11
ANGLES	±0°15′	RRD SAFETY R.W HOBBS	4/15/11
BREAK SHARP EDGES	.02 MAX	HFIR R D.L.PINKSTON	4/16/11
FINISH	63 RMS 1	HFIR OP E.L.FOGLE	4/19/11
FILLETS .02 MAX	2	NQR W.G.ASKEW	4/14/11
		QA RRD L.C.SMITH	4/14/11
		DRAWING APPROVALS	DATE

UT-BATTELLE

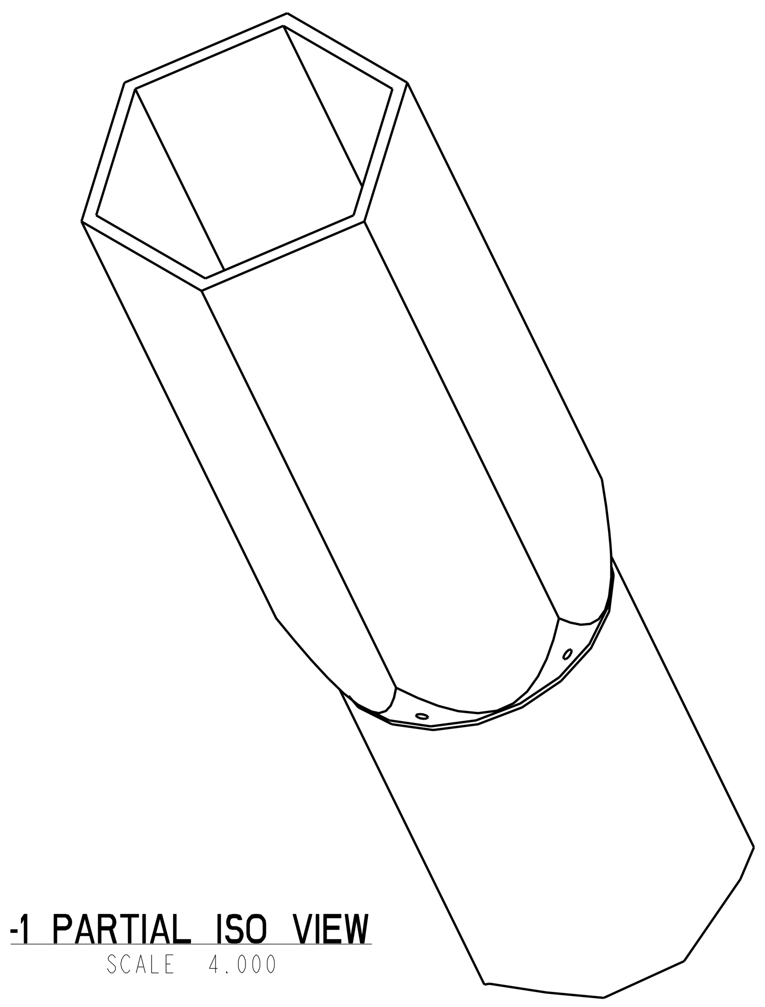
Oak Ridge National Laboratory
managed for the DEPARTMENT OF ENERGY under
U.S. GOVERNMENT contract DE-AC05-00OR22725
UT-BATTELLE, LLC. Oak Ridge, Tennessee

PROJECT NAME
HFIR TARGET IRRADIATION CAPSULES

SHROUDED
TARGET CAPSULE
RUPTURE SLEEVE

VERSION NO.	PLANT	BLDG	FL	SHT	OF	TYPE	CLASS
	ORNL	7900	1	1	1	D	U
RELEASE LEVEL	EJN	X3E020977A574					REV 0

ATTACHMENT 9



-1 PARTIAL ISO VIEW
SCALE 4.000

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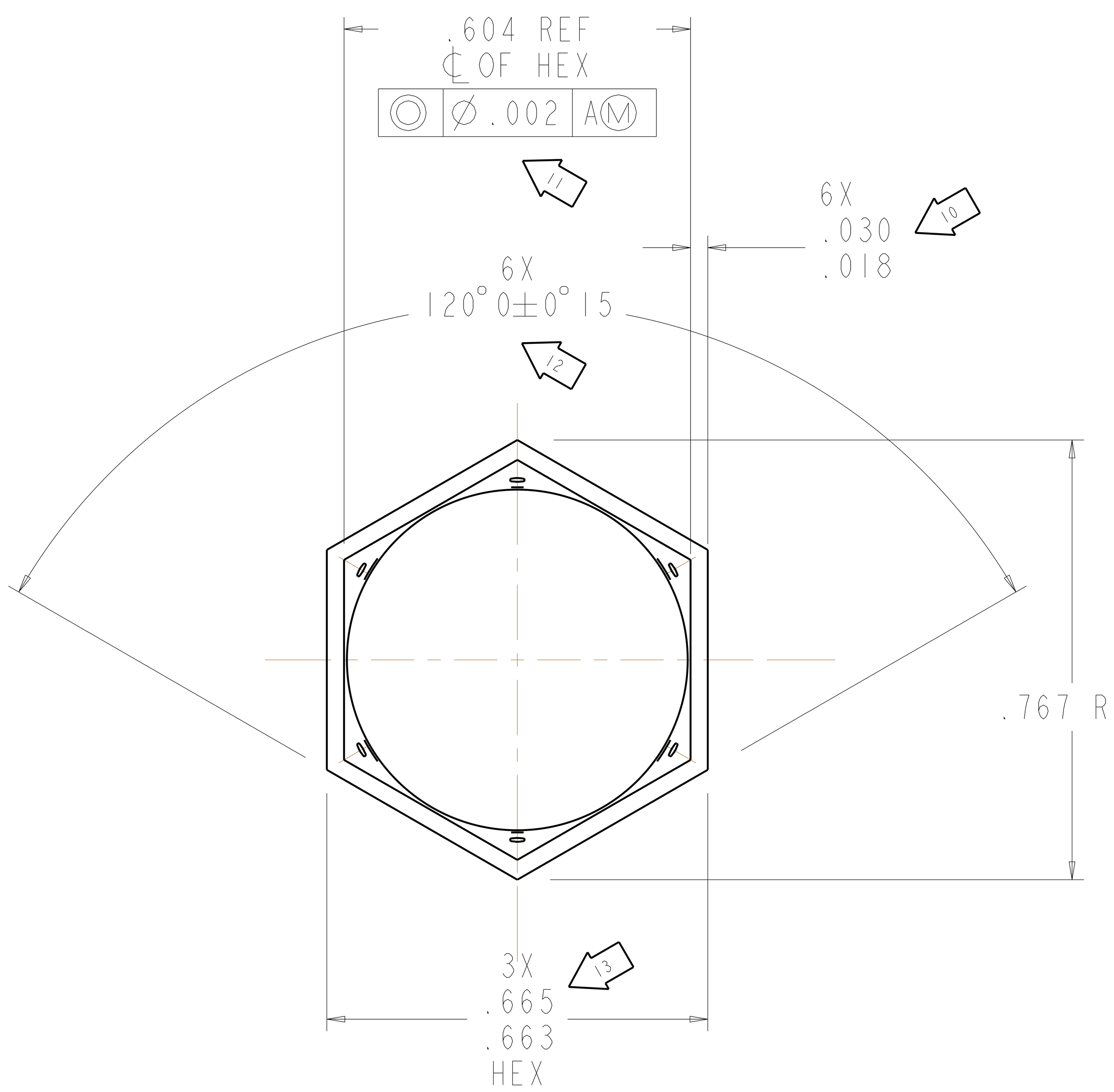
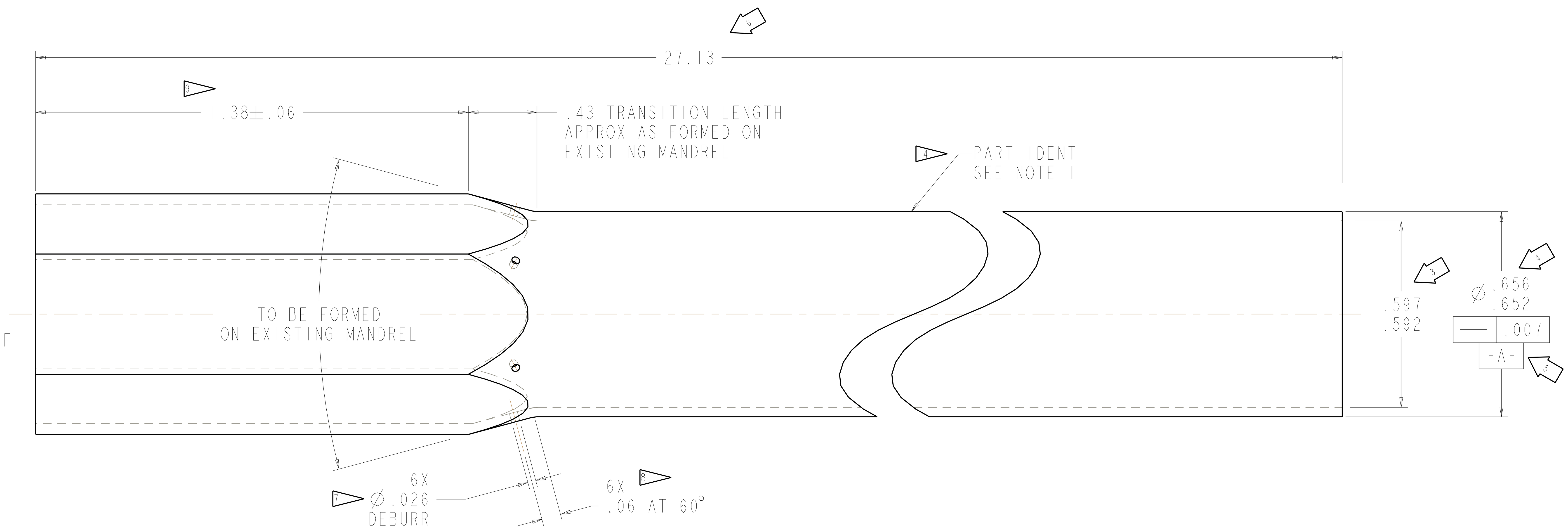
2. CLEAN WITH ACETONE, FOLLOWED BY ALCOHOL PER RRD-JS-31.
3. DIMENSIONS ARE IN INCHES.
4. FOR DIMENSIONAL INSPECTION SEE NOTE IN LOWER LEFT CORNER OF THIS DRAWING.





-1 SHROUD TUBE
SCALE 6.000

LAST INSPECTION

AR	-1	SHROUD TUBE	AL 6061-0	PER RRD-MS-52	1
CAGE CODE	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL	SPECIFICATION	FIND NO
NEXT ASSEMBLY		PARTS LIST			

X3E020977A576

X3E020977A575

CERTIFIED FOR CONSTRUCTION

ISSUE DATE: 02/08/11

DIMENSIONAL INSPECTION NOTE

ALL FEATURES INDICATED BY X OR X SHALL BE INSPECTED AND RECORDED IN AN INSPECTION REPORT IN ACCORDANCE WITH RRD-JS-24, WITH THE EXCEPTION THAT SECTION 6 (NONCONFORMANCE REPORTING) DOES NOT APPLY TO THOSE DIMENSIONS INDICATED BY X

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REV	DESCRIPTION	ZONE	BY	CHK	TL	HFIR	HFIR	NQR	QARRD

SCALE

TOLERANCES UNLESS OTHERWISE SPECIFIED

FRACTIONS	:
XX DECIMALS	±.01
XXX DECIMALS	±.005
ANGLES	±0° 15′
BREAK SHARP EDGES	.02 MAX
FINISH	63 RMS 1
FILLETS	.02 MAX 2

DRAWING APPROVALS		DATE
DES	DWH/JLM/KRT	08/30/10
DRW	D.W.SPARKS	08/30/10
CHK	D.W.HEATHERLY	01/20/11
TL	D.W.HEATHERLY	01/20/11
CHK	J.L.McDUFFEE	01/21/11
HFIR CM	Y.S.KWON	02/08/11
RRD SAFETY	R.W.HOBBS	02/03/11
HFIR R	D.L.PINKSTON	01/25/11
HFIR R	F.L.FOGEL	02/08/11
NQR	W.G.ASKEW	02/07/11
QA RRD	L.C.SMITH	01/25/11

UT-BATTELLE

Oak Ridge National Laboratory
managed for the DEPARTMENT OF ENERGY under
U.S. GOVERNMENT contract DE-AC05-00OR22725
UT-BATTELLE, LLC. Oak Ridge, Tennessee

PROJECT NAME
HFIR TARGET IRRADIATION CAPSULES

SHROUDED
TARGET CAPSULE
SHROUD TUBE

VERSION NO.	PLANT	BLDG	FL	SHT	OF	TYPE	CLASS
	ORNL	7900	1	1	1	D	U
RELEASE LEVEL	EJN	X3E020977A575					REV 0

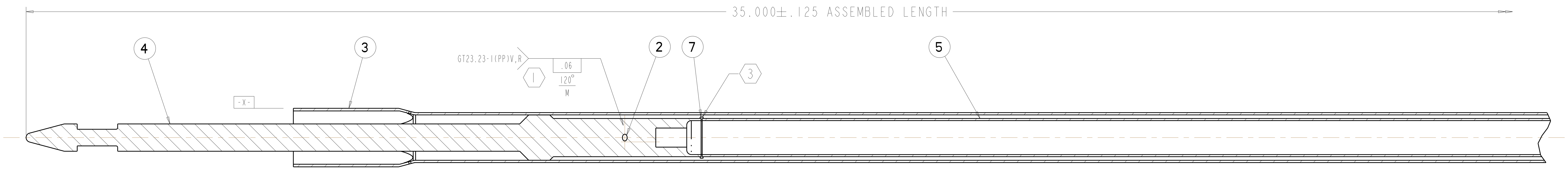
ATTACHMENT 10

GENERAL AND ASSEMBLY NOTES:

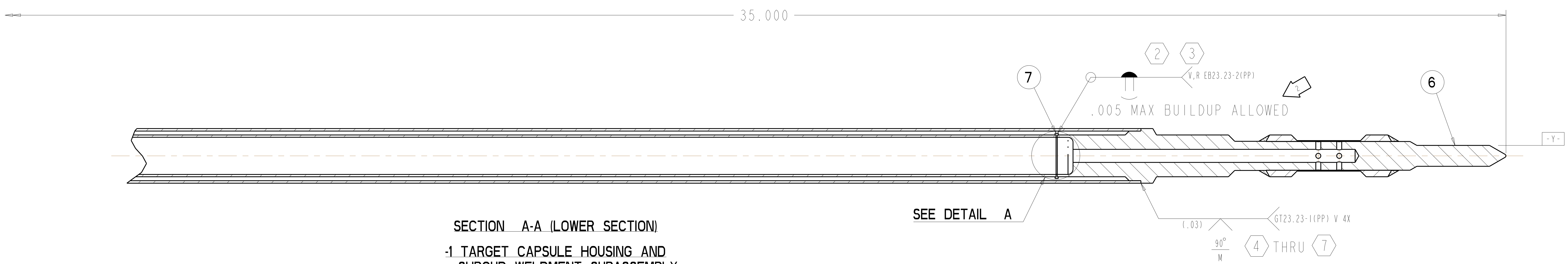
1. DIMENSIONS ARE IN INCHES UNLESS NOTED OTHERWISE.
2. HELIUM TEST WELDS 1,2,3 AND COMPLETE ASSY WITH A MASS SPECTROMETER DETECTOR.
   NO LEAKAGE GREATER THAN 1 X 10^{-7} STD CC/SEC PERMITTED AT ONE ATMOSPHERE PRESSURE DIFFERENTIAL.
3. EXTERNAL HYDROSTATIC PRESSURE TEST THE COMPLETE ASSEMBLY AT 1050 PSIG. HOLD PRESSURE $\geq$ 1050 PSIG FOR 10 MIN FOLLOWED BY HELIUM LEAK TEST PER NOTE 2 ABOVE.
4. FINAL ASSEMBLY SHALL BE STRAIGHT WITHIN .010 TIR BETWEEN DATUMS -X- AND -Y- OR OPTIONALLY FINAL ASSEMBLY CAN BE FUNCTIONALLY FIT TESTED IN THE HFIR TARGET CAPSULE INSPECTION GAUGE FROM DRAWING M-10070-OC-368-E.

NOTES CONTINUED:

5. CONTAINMENT DESIGN CONDITIONS:
   EXTERNAL PRESSURE - 690 P.S.I.
   TEMPERATURE- 200°F.
   SEE CALCULATION DAC-10-13-JP02.
6. FINAL CLEANING OF OVERALL ASSEMBLY SHALL BE COMPLETED USING ACETONE AND ALCOHOL AS PER RRD-JS-31.
7. ALL WELD INSPECTION SHALL BE DOCUMENTED USING FORM UNC-9989. IF WELDS ARE COMPLETED BY AN OUTSIDE VENDOR THE WELDING INSPECTOR SHALL BE AN AWS-CWI (AMERICAN WELDING SOCIETY CERTIFIED WELDING INSPECTOR). WELDING PROCEDURES AND WELDERS SHALL BE QUALIFIED PER ASME SECTION IX. WELD PROCEDURES SHALL BE APPROVED BY ORNL.
8. HOUSING TUBE (PART 5) FOR SHALL BE FABRICATED FROM TUBING DOCUMENTED IN IR -19461 OR AN APPROVED EQUAL MATERIAL WITH SAME I.D. AS THE MATERIAL ON IR-19461. HOLDER DIMENSIONS AND RADIAL GAS GAPS ARE BASED ON USE OF THIS MATERIAL.
9. HOUSING TUBE, FIND #5, TO BE CUT TO DESIGNED LENGTH AT ASSEMBLY TO MEET DIMENSION QC #2 ON THIS DRAWING.
10. INTERPRET DIMENSIONS AND TOLERANCES PER ANSI Y14.5M 1994.



SECTION A-A (UPPER SECTION)
SCALE 2.000



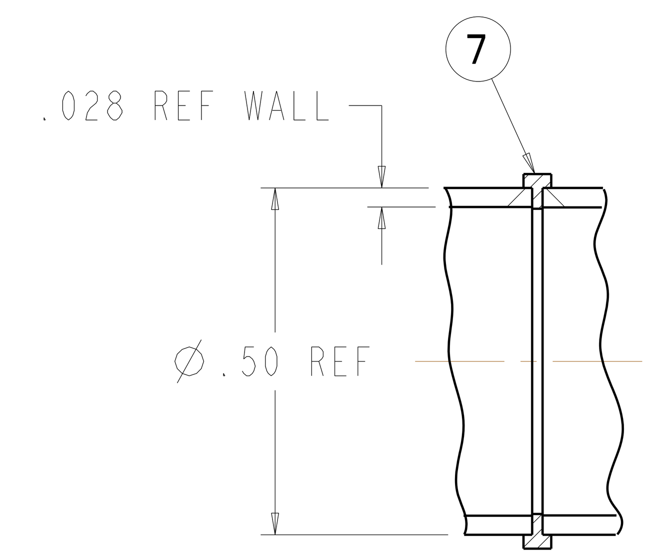
SEE DETAIL A

SECTION A-A (LOWER SECTION)

-1 TARGET CAPSULE HOUSING AND SHROUD WELDMENT SUBASSEMBLY
SCALE 2.000

3 LAST QUALITY CONTROL INSPECTION NUMBER

7 LAST WELD



DETAIL A (TYP WELD JOINTS 2 & 3)
SCALE 6.000

					2	X3E020977A573-2	WELD RING			7

QTY	CAGE CODE	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL	SPECIFICATION	FIND NO
2		X3E020977A573-2	WELD RING			7
1		X3E020977A570-1	SHROUDED BOTTOM CAP ASSEMBLY			6
8 1		X3E020977A573-1	HOUSING TUBE (SEE NOTES 8 AND 9)			5
1		X3E020977A572-1	SHROUDED TOP CAP			4
1		X3E020977A575-1	SHROUD TUBE			3
1		-2	WIRE-∅.064 X .406 LG 120° CONE ONE END	5356 AL. FILLER ROD PER RRD-MS-52		2
X		-1	TARGET CAPSULE HOUSING AND SHROUD WELDMENT SUBASSEMBLY			1
- -	CAGE CODE	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL	SPECIFICATION	FIND NO
	NEXT ASSEMBLY		PARTS LIST			

WELD INSPECTION SCHEDULE (SEE NOTE 7)						
WELD #	SPEC	VISUAL	DYE PENETRANT	RADIOGRAPH	He	HYDRO
1	GT23.23-1(PP)	FD-T- NDE-21		ORNL JSP-43	SEE NOTE 2	SEE NOTE 3
2	EB23.23-2(PP)	FD-T- NDE-21		ORNL JSP-43		
3	EB23.23-2(PP)	FD-T- NDE-21		ORNL JSP-43		
4	GT23.23-1(PP)	FD-T- NDE-21				
5	GT23.23-1(PP)	FD-T- NDE-21				
6	GT23.23-1(PP)	FD-T- NDE-21				
7	GT23.23-1(PP)	FD-T- NDE-21				

CERTIFIED FOR CONSTRUCTION
ISSUE DATE:4/19/11
REV A ISSUE DATE:01/09/12

ALL FEATURES INDICATED BY X OR X SHALL BE INSPECTED AND RECORDED IN AN INSPECTION REPORT IN ACCORDANCE WITH RRD-JS-24, WITH THE EXCEPTION THAT SECTION 6 (NONCONFORMANCE REPORTING) DOES NOT APPLY TO THOSE DIMENSIONS INDICATED BY X

THIS DRAWING PRODUCED ON PRO-ENGINEER

CAUTION NUCLEAR MATERIAL

ANY PROCESS OR MATERIAL (INCLUDING PACKAGING AND SHIPPING MATERIAL) THAT HAS THE POSSIBILITY OF LEAVING A RESIDUE CONTAINING ANY OF THE HALIDE ELEMENTS (PRIMARILY CHLORIDE AND FLUORIDE), METALLIC ELEMENTS (PRIMARILY COPPER, LEAD, NICKLE, SILVER, THORIUM AND TIN) OR CARBON/GRAPHITE ON THE SURFACE OF ANY HFIR COMPONENT AFTER FINAL CLEANING SHALL NOT BE USED. MERCURY IN ANY FORM SHALL BE SPECIFICALLY PRECLUDED IN THE PROCURMENT OF ALUMINUM RAW MATERIALS AND IN ALL PROCESSING AND MANUFACTURING OPERATIONS.

REV	DESCRIPTION	ZONE	BY	CHK	TL	HFIRS	HFIRR	NQR	QARRD	HFIRR	HFIRCM
A	REMOVED FINISH & FILLET INSPECTION REQUIREMENT		DWS 1/3/12	JLM 1/31/12	RHH 1/31/12	RWH 1/05/12	ELF 1/09/12	WGA 1/05/12	LCS 1/09/12	DLP 1/09/12	YSK 1/09/12

SCALE

TOLERANCES UNLESS OTHERWISE SPECIFIED
FRACTIONS :
XX DECIMALS ±.01
XXX DECIMALS ±.005
ANGLES ±0°15′
BREAK SHARP EDGES .02 MAX
FINISH 63 RMS
FILLETS .02 MAX

DRAWING APPROVALS		DATE
DES	D.W.HEATHERLY	02/23/11
DRW	D.W.SPARKS	02/23/11
CHK	D.W.HEATHERLY	4/13/11
TL	J.L.McDUFFEE	4/13/11
WELDING	J.C.POOLE	4/19/11
HFIR CM	Y.S. KWON	4/19/11
RRD SAFETY	R.W HOBBS	4/15/11
HFIR R	D.L.PINKSTON	4/18/11
HFIR R	E.L.FOGLE	4/19/11
NQR	W.G.ASKEW	4/14/11
QA RRD	L.C.SMITH	4/14/11

UT-BATTELLE

Oak Ridge National Laboratory
managed for the DEPARTMENT OF ENERGY under U.S. GOVERNMENT contract DE-AC05-00OR22725
UT-BATTELLE, LLC. Oak Ridge, Tennessee

PROJECT NAME
HFIR TARGET IRRADIATION CAPSULES

TARGET CAPSULE HOUSING AND SHROUD WELDMENT SUBASSEMBLY

VERSION NO.	PLANT	BLDG	FL	SHT OF	TYPE	CLASS
	ORNL	7900	A	1 1	A	U
RELEASE LEVEL	EJN	X3E020977A586				REV A

NEXT ASS'Y: FINAL ASS'Y:

X3E020977A586

ATTACHMENT 11

NEXT ASS'Y: FINAL ASS'Y:

GENERAL AND ASSEMBLY NOTES:

1. DIMENSIONS ARE IN INCHES UNLESS NOTED OTHERWISE.
2. ASSEMBLY TO BE FILLED WITH 99.9% PURE HELIUM (MOISTURE FREE) AT 3 TO 5 PSIG BEFORE FINAL CLOSURE IS MADE.
3. REFERENCE ASSEMBLY PROCEDURE AP-RNSD-20977-030.
4. CONTAINMENT DESIGN CONDITIONS:
   EXTERNAL PRESSURE - 690 P.S.I.
   TEMPERATURE- 200° - 350° C.
   SEE CALCULATION DAC-10-13-JP02.

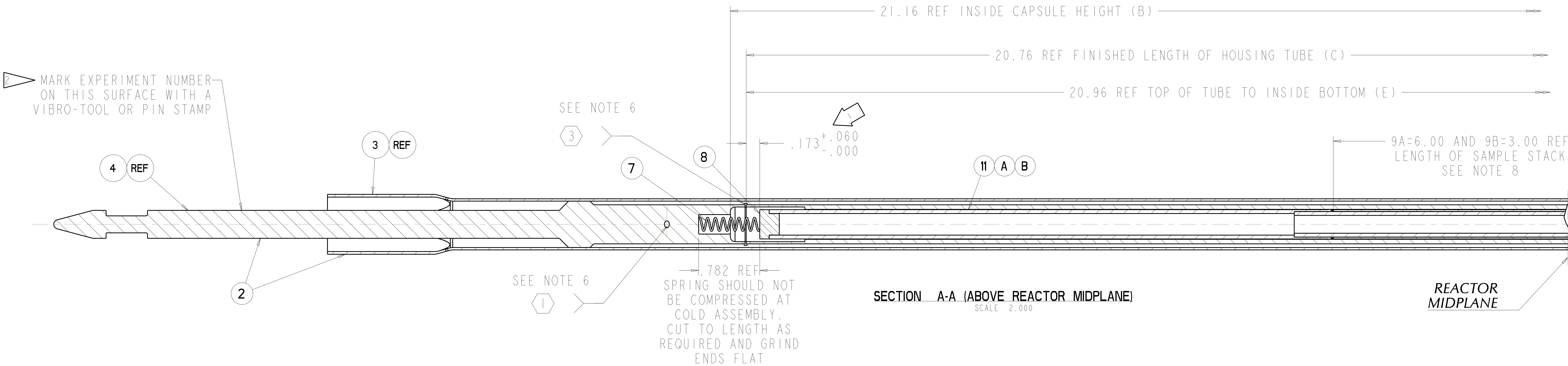
NOTES CONTINUED:

5. INTERPRET DIMENSIONS AND TOLERANCES PER ANSI Y14.5M-1994.
6. ASSEMBLY REQUIREMENTS ON THIS DRAWING ARE IN ADDITION TO ALL REQUIREMENTS ON DRAWING X3E020977A586, EXCEPT REPLACE PART 5 (HOUSING TUBE) ON DRAWING X3E020977A586 WITH PART 5 FROM THIS DRAWING. ALL REQUIREMENTS FROM BOTH THIS DRAWING AND X3E020977A586 SHALL BE MET.
7. MATERIAL CERTIFICATION INCLUDING CHEMICAL COMPOSITION IS REQUIRED FOR ALL MATERIALS AND SPECIMENS SUPPLIED BY CUSTOMER.

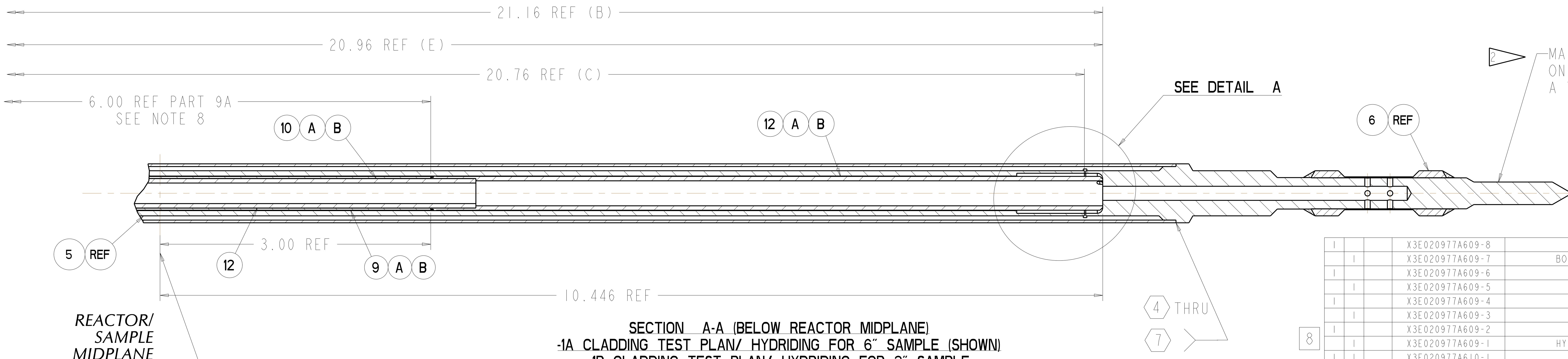
8 MULTIPLE SAMPLES MAY BE COMBINED TO ATTAIN THE SPECIFIED 6" OR 3" SPECIMEN DIMENSION (PARTS 9A AND 9B).

VENDOR NOTE:

ASSOCIATED SPRING RAYMOND, BARNES GROUP INC.
1705 INDIAN WOOD CIRCLE- SUITE 210
MAUNEE, OH 43537

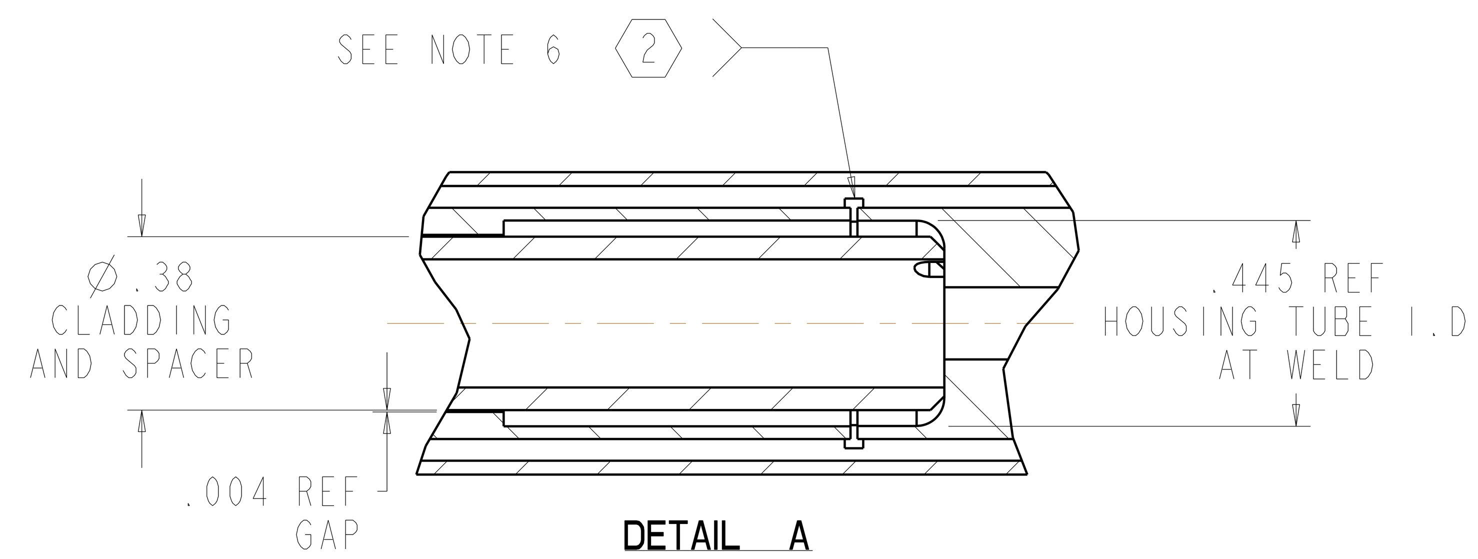


SECTION A-A (ABOVE REACTOR MIDPLANE)
SCALE 2.000



SECTION A-A (BELOW REACTOR MIDPLANE)
-1A CLADDING TEST PLAN/ HYDRIDING FOR 6" SAMPLE (SHOWN)
-1B CLADDING TEST PLAN/ HYDRIDING FOR 3" SAMPLE
SCALE 2.000

2 LAST QUALITY CONTROL INSPECTION NUMBER



DETAIL A
SCALE 4.000

PARTS LIST

-1B	-1A	CAGE CODE	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL	SPECIFICATION	FIND NO
1			X3E020977A609-8	BOTTOM TUBULAR SPACER (8.946 LONG)			12B
	1		X3E020977A609-7	BOTTOM TUBULAR SPACER (7.446 LONG) SHOWN			12A
1			X3E020977A609-6	TOP TUBULAR SPACER REF (8.82 LONG)			11B
	1		X3E020977A609-5	TOP TUBULAR SPACER (7.22 LONG) SHOWN			11A
1			X3E020977A609-4	CENTER MOLY ROD REF (4" LONG)			10B
	1		X3E020977A609-3	CENTER MOLY ROD (7" LONG) SHOWN			10A
1			X3E020977A609-2	HYDRIDED CLADDING SAMPLE (3" LONG)			9B
	1		X3E020977A609-1	HYDRIDED CLADDING SAMPLE (6" LONG) SHOWN			9A
1	1		X3E020977A610-1	TOP SPACER CAP			8
1	1		C0180-020-1250S .777 FL X .18 OD	COMPRESSION SPRING SEE VENDOR NOTE	SS302	SELLER CERTS	7
1	1		X3E020977A586-6	SHROUDED BOTTOM CAP ASSEMBLY (REF)			6
1	1		X3E020977A612-1	HOUSING TUBE			5
1	1		X3E020977A586-4	SHROUDED TOP CAP (REF)			4
1	1		X3E020977A586-3	SHROUD TUBE (REF)			3
1	1		X3E020977A586-1	TARGET CAPSULE HOUSING AND SHROUD WELDMENT SUBASSEMBLY			2
X			-1B	CLADDING/ HYDRIDING IRRAD CAPSULE FOR 3" SAMPLE			1B
	X		-1A	CLADDING/ HYDRIDING IRRAD CAPSULE FOR 6" SAMPLE			1A

NEXT ASSEMBLY

8

CERTIFIED FOR CONSTRUCTION
ISSUE DATE:01/09/12

ALL FEATURES INDICATED BY X OR X SHALL BE INSPECTED AND RECORDED IN AN INSPECTION REPORT IN ACCORDANCE WITH RRD-JS-24, WITH THE EXCEPTION THAT SECTION 6 (NONCONFORMANCE REPORTING) DOES NOT APPLY TO THOSE DIMENSIONS INDICATED BY X

THIS DRAWING PRODUCED ON PRO-ENGINEER

CAUTION NUCLEAR MATERIAL

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REV	DESCRIPTION	ZONE	BY	CHK	TL	HFIR CM	HFIRS	QA	QARRD

SCALE

TOLERANCES UNLESS OTHERWISE SPECIFIED
FRACTIONS :
XX DECIMALS ±.01
XXX DECIMALS ±.005
ANGLES ±0°15'
BREAK SHARP EDGES .02 MAX
FINISH 63 RMS 1
FILLETS .02 MAX 2

DRAWING APPROVALS		DATE
DES	L.J. OTT	10/20/2011
DRW	D.W.SPARKS	10/20/2011
CHK	J.L.McDUFFEE	01/03/12
TL	R.H.HOWARD	01/03/12
HFIR CM	Y.S.KWON	01/09/12
RRD SAFETY	R.W.HOBBS	01/05/12
HFIR R	E.L.FOGLE	01/09/12
HFIR R	D.L.PINKSTON	01/09/12
QA	W.G.ASKEW	01/05/12
QA RRD	L.C.SMITH	01/05/12

UT-BATTELLE

Oak Ridge National Laboratory
managed for the DEPARTMENT OF ENERGY under U.S. GOVERNMENT contract DE-AC05-00OR22725
UT-BATTELLE, LLC. Oak Ridge, Tennessee

PROJECT NAME
HFIR IRRADIATION CAPSULE

CLADDING TEST PLAN
HYDRIDING
ASSEMBLY

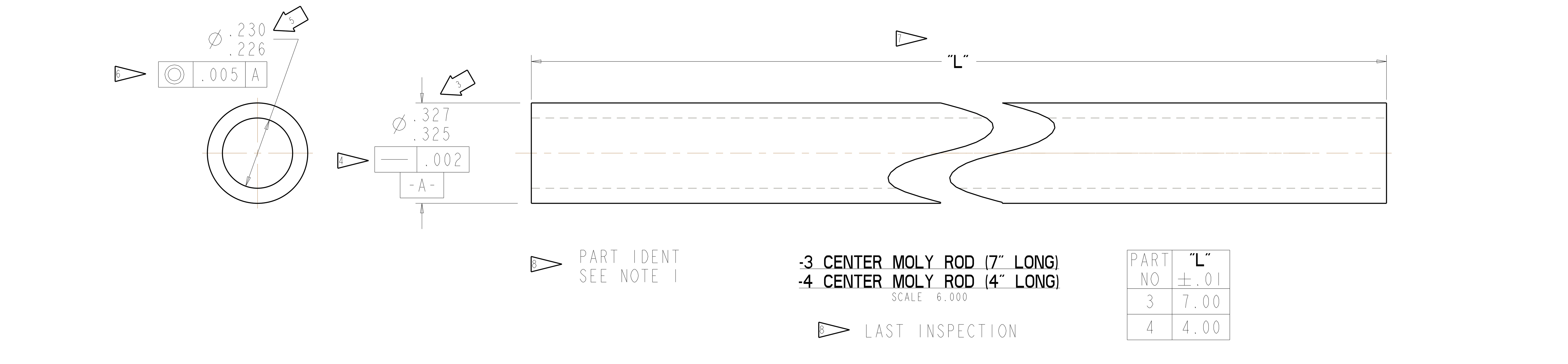
VERSION NO.	PLANT	BLDG	FL	SHT 1 OF 1	TYPE	CLASS
	ORNL	7900	A		A	U

RELEASE LEVEL | EJN | X3E020977A608 | REV 0

ATTACHMENT 12

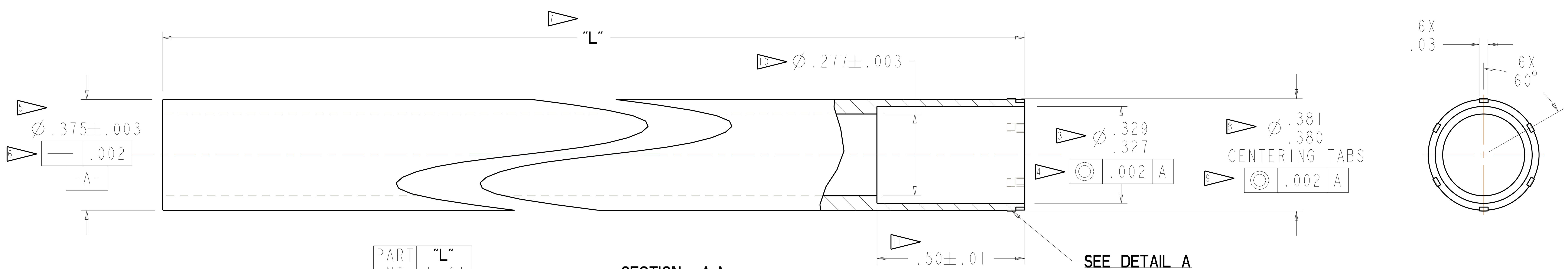
GENERAL NOTES:

1. PART IDENTIFICATION SHALL BE OF THE FORM "DRAWING NO.-PART NO. -SERIAL NO." OR AN INSPECTION REQUEST NO. (I.R.N.) TRACEABLE TO MATERIAL AND/OR PART DOCUMENTATION AND BE ETCHED ON PART. OPTIONALLY, PART MAY BE PLACED IN A SEALABLE PLASTIC BAG WITH A TAG INDICATING PART IDENTIFICATION.
2. CLEAN WITH ACETONE, FOLLOWED BY ALCOHOL PER RRD-JS-31.
3. DIMENSIONS ARE IN INCHES.



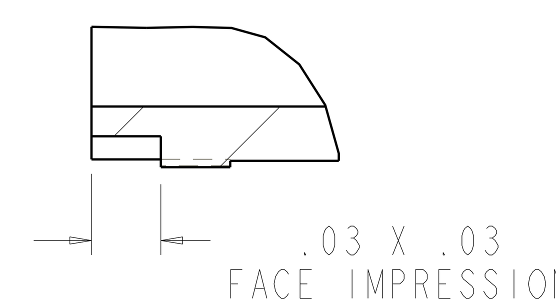
-3 CENTER MOLY ROD (7" LONG)
-4 CENTER MOLY ROD (4" LONG)
SCALE 6.000

PART NO	"L" ±.01
3	7.00
4	4.00



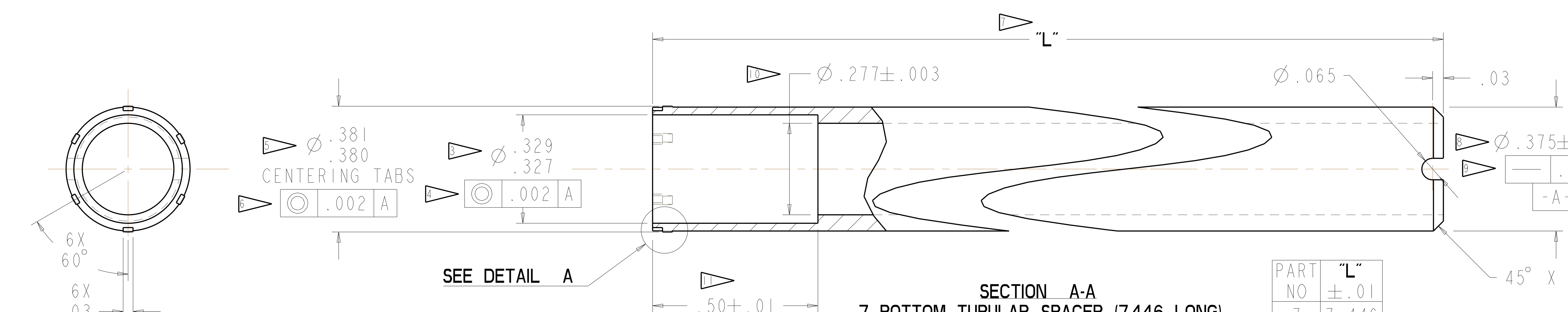
PART NO	"L" ±.01
5	7.22
6	8.82

SECTION A-A
-5 TOP TUBULAR SPACER (7.22 LONG)
-6 TOP TUBULAR SPACER (8.82 LONG)
SCALE 6.000



DETAIL A
SCALE 20.000

1. ON PARTS 3, 4, 5 AND 6 IMPRESS 6 POINTS (SPACED AS SHOWN) FOR THE PURPOSE OF RAISING MATERIAL TO ESTABLISH CENTERING TABS.
2. MACHINE DOWN TO REQUIRED DIA.



SECTION A-A
-7 BOTTOM TUBULAR SPACER (7.446 LONG)
-8 BOTTOM TUBULAR SPACER (8.946 LONG)
SCALE 6.000

PART NO	"L" ±.01
7	7.446
8	8.946

-1 HYDRIDED CLADDING SAMPLE (6" LONG)
-2 HYDRIDED CLADDING SAMPLE (3" LONG)
SCALE 6.000

NOTE
MULTIPLE SAMPLES MAY BE COMBINED TO ATTAIN THE SPECIFIED 6" OR 3" SPECIMEN DIMENSION

PART NO	"L" ±.01
1	6.00
2	3.00

		CAGE CODE	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL	SPECIFICATION	FIND NO
	AR		-8	BOTTOM TUBULAR SPACER (7.946 LONG)	AL TUBE FURNISHED BY CUSTOMER		8
	AR		-7	BOTTOM TUBULAR SPACER (7.446 LONG)	AL TUBE FURNISHED BY CUSTOMER		7
	AR		-6	TOP TUBULAR SPACER (8.82 LONG)	AL TUBE FURNISHED BY CUSTOMER		6
	AR		-5	TOP TUBULAR SPACER (7.22 LONG)	AL TUBE FURNISHED BY CUSTOMER		5
	AR		-4	CENTER MOLY ROD (4" LONG)	MOLY FURNISHED BY CUSTOMER		4
	AR		-3	CENTER MOLY ROD (7" LONG)	MOLY FURNISHED BY CUSTOMER		3
	AR		-2	HYDRIDED CLADDING SAMPLE (3" LONG)	FURNISHED BY CUSTOMER		2
	AR		-1	HYDRIDED CLADDING SAMPLE (6" LONG)	FURNISHED BY CUSTOMER		1
	A609-1	NEXT ASSEMBLY		PARTS LIST			

CERTIFIED FOR CONSTRUCTION
ISSUE DATE: 01/09/12

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REV	DESCRIPTION	ZONE	BY	CHK	TL	HFIR	HFIR	QA	QARRD

SCALE
TOLERANCES UNLESS OTHERWISE SPECIFIED
FRACTIONS :
XX DECIMALS ±.1
XXX DECIMALS ±.05
ANGLES ±0°15'
BREAK SHARP EDGES .02 MAX
FINISH 63 RMS
FILLETS .02 MAX

DRAWING APPROVALS		DATE
DES	L.J.OTT	11/30/11
DRW	D.W.SPARKS	11/30/11
CHK	J.L.McDUFFEE	01/03/12
TL	R.H.HOWARD	01/03/12
HFIR CM	Y.S.KWON	
RRD SAFETY	R.W.HOBBS	01/05/12
HFIR R	E.L.FOGLE	01/09/12
HFIR R	D.L.PINKSTON	01/09/12
QA	W.G.ASKEW	01/05/12
QA RRD	L.C.SMITH	01/05/12

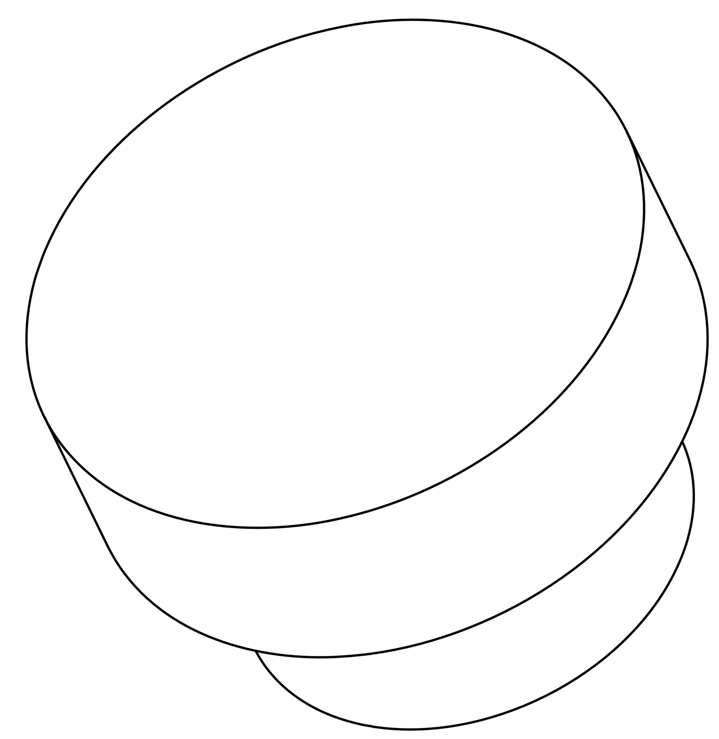
UT-BATTELLE
Oak Ridge National Laboratory
managed for the DEPARTMENT OF ENERGY under U.S. GOVERNMENT contract DE-AC05-00OR22725
UT-BATTELLE, LLC. Oak Ridge, Tennessee

PROJECT NAME
HFIR IRRADIATION CAPSULE

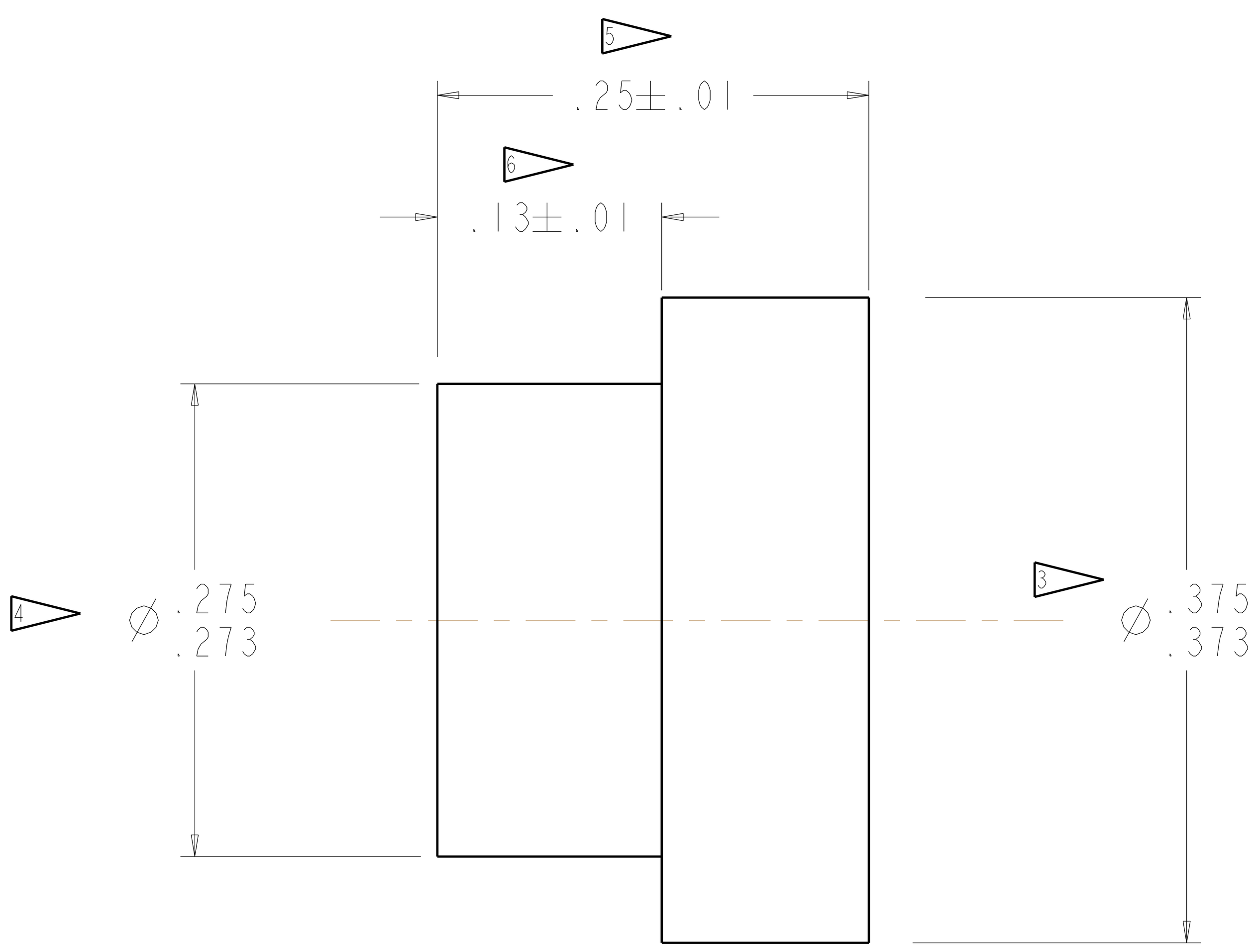
CLADDING TEST PLAN
HYDRIDING
SAMPLE, SPACER, ROD DETAILS

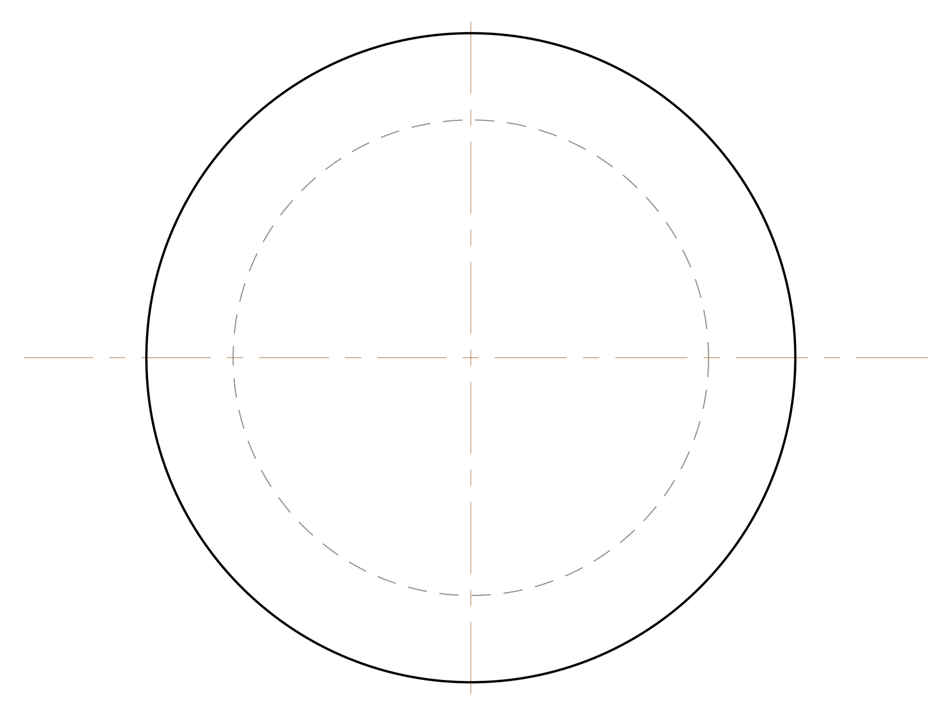
VERSION NO.	PLANT	BLDG	FL	SHT	OF	TYPE	CLASS
	ORNL	7900	A	1	1	D	U
RELEASE LEVEL	EJN	X3E020977A609					REV 0

ATTACHMENT 13



-2 ISO VIEW
SCALE 15.000





-1 TOP SPACER CAP
SCALE 15.000

PART IDENT
SEE NOTE 1

LAST INSPECTION

GENERAL NOTES:

1. PART IDENTIFICATION SHALL BE OF THE FORM "DRAWING NO.-PART NO. -SERIAL NO." OR AN INSPECTION REQUEST NO. (I.R.N.) TRACEABLE TO MATERIAL AND/OR PART DOCUMENTATION AND BE ETCHED ON PART. OPTIONALLY, PART MAY BE PLACED IN A SEALABLE PLASTIC BAG WITH A TAG INDICATING PART IDENTIFICATION.
2. CLEAN WITH ACETONE, FOLLOWED BY ALCOHOL PER RRD-JS-31.
3. DIMENSIONS ARE IN INCHES.

	AR		-1	TOP SPACER CAP	AL 6061		1
	A609-1	CAGE CODE	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL	SPECIFICATION	FIND NO
		NEXT ASSEMBLY		PARTS LIST			

CERTIFIED FOR CONSTRUCTION
ISSUE DATE:01/09/12

X3E020977A610

NO REPRESENTATION OR WARRANTY, EXPRESSED OR IMPLIED, IS MADE AS TO THE ACCURACY, COMPLETENESS OR USEFULNESS OF THE INFORMATION OR STATEMENTS CONTAINED IN THESE DRAWINGS, OR THAT THE USE OR DISCLOSURE OF ANY INFORMATION, APPARATUS, METHOD OR PROCESS DISCLOSED IN THESE DRAWINGS MAY NOT INFRINGE PRIVATE RIGHTS OF OTHERS. NO LIABILITY IS ASSUMED WITH RESPECT TO THE USE OF, OR FOR DAMAGES RESULTING FROM THE USE OF, ANY INFORMATION, APPARATUS, METHOD OR PROCESS DISCLOSED IN THESE DRAWINGS. DRAWINGS MADE AVAILABLE FOR INFORMATION TO BIDDER ARE NOT TO BE USED FOR OTHER PURPOSES, AND ARE TO BE RETURNED UPON REQUEST OF THE FORWARDING CONTRACTOR.

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REV	DESCRIPTION	ZONE	BY	CHK	TL	HFIR	HFIR	QA	QARRD

SCALE

TOLERANCES UNLESS OTHERWISE SPECIFIED

FRACTIONS	:
XX DECIMALS	±.01
XXX DECIMALS	±.005
ANGLES	±0°15′
BREAK SHARP EDGES	.02 MAX
FINISH	63 RMS 1
FILLETS .02 MAX	2

DRAWING APPROVALS		DATE
DES	L.J.OTT	11/30/11
DRW	D.W.SPARKS	11/30/11
CHK	J.L.McDUFFEE	01/03/12
TL	R.H.HOWARD	01/03/12
HFIR CM	Y.S.KWON	01/09/12
RRD SAFETY	R.W.HOBBS	01/05/12
HFIR R	E.L.FOGLE	01/09/12
HFIR R	D.L.PINKSTON	01/09/12
QA	W.G.ASKEW	01/05/12
QA RRD	L.C.SMITH	01/05/12

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Oak Ridge National Laboratory
managed for the DEPARTMENT OF ENERGY under
U.S. GOVERNMENT contract DE-AC05-00OR22725
UT-BATTELLE, LLC. Oak Ridge, Tennessee

PROJECT NAME
HFIR IRRADIATION CAPSULE

CLADDING TEST PLAN
HYDRIDING
SPACER CAP DETAIL

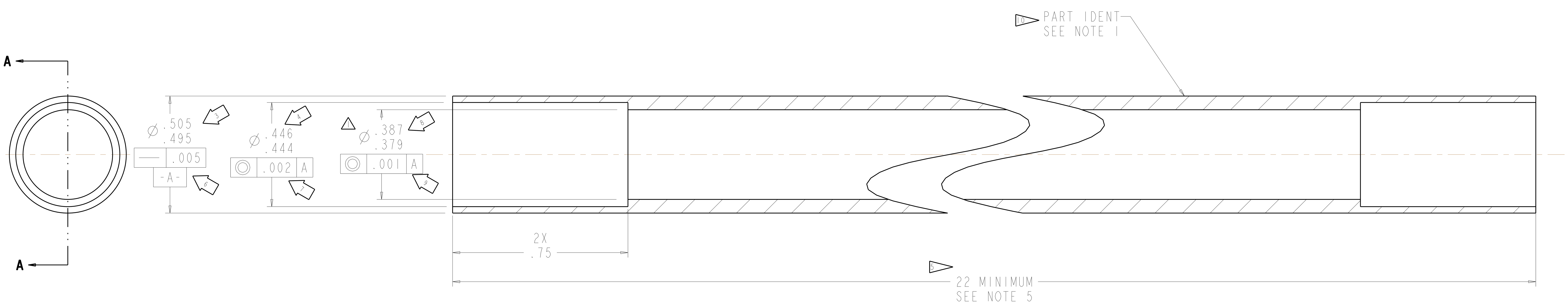
VERSION NO.	PLANT	BLDG	FL	SHT	OF	TYPE	CLASS
	ORNL	7900	A	1	1	D	U

RELEASE LEVEL	EJN		REV
		X3E020977A610	0

ATTACHMENT 14

GENERAL NOTES:

1. PART IDENTIFICATION SHALL BE OF THE FORM "DRAWING NO.-PART NO.-SERIAL NO." OR AN INSPECTION REQUEST NO. (I.R.N.) TRACEABLE TO MATERIAL AND/OR PART DOCUMENTATION AND BE ETCHED ON PART. OPTIONALLY, PART MAY BE PLACED IN A SEALABLE PLASTIC BAG WITH A TAG INDICATING PART IDENTIFICATION.
2. CLEAN WITH ACETONE FOLLOWED BY ALCOHOL PER RRD-JS-31.
3. DIMENSIONS ARE IN INCHES.
4. DOCUMENTATION REQUIRED:
   RRD-MS-52------ APPENDIX 1 (OR EQUIVALENT), APPENDIX 2
   RRD-JS-31------ APPENDIX A CLEANLINESS REPORT
   RRD-JS-24------ INSPECTION PLAN AND DIMENSIONAL INSPECTION REPORT
5. THE HOUSING TUBE SHOWN ON THIS DRAWING HAS EXCESS LENGTH. THE FINAL HOUSING TUBE LENGTH WILL BE DETERMINED WHEN THE PART IS USED ON A CAPSULE ASSEMBLY.



SECTION A-A

-1 HYDRIDING CLADDING HOUSING TUBE

SCALE 6.000

LAST INSPECTION

AR		-1	HOUSING TUBE REF Ø.500" X .058" WALL	AL 6061-T6	ASTM B210 OR B221	
A608	CAGE CODE	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL	SPECIFICATION	FIND NO
next assy		NEXT ASSEMBLY	PARTS LIST			

CERTIFIED FOR CONSTRUCTION

ISSUE DATE:01/09/12
REV A ISSUE DATE:1/31/12

REV	DESCRIPTION	ZONE	BY	CHK	TL	HFIR CM	RRD S	HFIR R	HFIR R	QA	QA RRD
A	1 I.D. TOL WAS ±.005		DWS 1/17/12	JLM 1/31/12	RHH 1/31/12	YSK 1/29/12	RWH 1/17/12	ELF 1/23/12	DLP 1/30/12	WGA 1/29/12	LCS 1/23/12

SCALE

TOLERANCES UNLESS OTHERWISE SPECIFIED
FRACTIONS :
XX DECIMALS ±.01
XXX DECIMALS ±.005
ANGLES ±0°15′
BREAK SHARP EDGES .02 MAX
FINISH 63 RMS 1
FILLETS .02 MAX 2

DRAWING APPROVALS		DATE
DES	L.J.OTT	12/02/11
DRW	D.W.SPARKS	12/02/11
CHK	J.L.McDUFFEE	01/03/12
TL	R.H.HOWARD	01/03/12
HFIR CM	Y.S.KWON	01/09/12
RRD SAFETY	R.W.HOBBS	01/05/12
HFIR R	E.L.FOGLE	01/09/12
HFIR R	D.L.PINKSTON	01/09/12
QA	W.G.ASKEW	01/05/12
QA RRD	L.C.SMITH	01/05/12

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UT-BATTELLE, LLC. Oak Ridge, Tennessee

PROJECT NAME
HFIR IRRADIATION CAPSULE

CLADDING TEST PLAN
HYDRIDING
HOUSING TUBE DETAIL

VERSION NO.	PLANT	BLDG	FL	SHT	OF	TYPE	CLASS
	ORNL	7900	A	1	1	A	U

RELEASE LEVEL	EJN		REV
		X3E020977A612	A

X3E020977A612

ALL FEATURES INDICATED BY X OR X SHALL BE INSPECTED AND RECORDED IN AN INSPECTION REPORT IN ACCORDANCE WITH RRD-JS-24, WITH THE EXCEPTION THAT SECTION 6 (NONCONFORMANCE REPORTING) DOES NOT APPLY TO THOSE DIMENSIONS INDICATED BY X

THIS DRAWING PRODUCED ON PRO-ENGINEER

CAUTION NUCLEAR MATERIAL

ANY PROCESS OR MATERIAL (INCLUDING PACKAGING AND SHIPPING MATERIAL) THAT HAS THE POSSIBILITY OF LEAVING A RESIDUE CONTAINING ANY OF THE HALIDE ELEMENTS (PRIMARILY CHLORIDE AND FLUORIDE), METALLIC ELEMENTS (PRIMARILY COPPER, LEAD, NICKLE, SILVER, THORIUM AND TIN) OR CARBON/GRAPHITE ON THE SURFACE OF ANY HFIR COMPONENT AFTER FINAL CLEANING SHALL NOT BE USED. MERCURY IN ANY FORM SHALL BE SPECIFICALLY PRECLUDED IN THE PROCURMENT OF ALUMINUM RAW MATERIALS AND IN ALL PROCESSING AND MANUFACTURING OPERATIONS.