ENCLOSURE 2

SHINE TECHNOLOGIES, LLC

SHINE TECHNOLOGIES, LLC APPLICATION FOR AN OPERATING LICENSE RESPONSE TO REQUEST FOR ADDITIONAL INFORMATION NON-PUBLIC VERSION

The NRC staff determined that additional information was required (Reference 1) to enable the staff’s continued review of the SHINE Technologies, LLC (SHINE) operating license application (Reference 2). The following information is provided by SHINE in response to the NRC staff’s request.

Chapter 4 – Irradiation Unit and Radioisotope Production Facility Description

RAI 4a-15

The referenced embrittlement studies, “The Effects of Neutron Radiation on Structural Materials,” and “Radiation Effects Design Handbook: Section 7,” used for evaluating radiation damage in the SHINE target solution vessel (TSV) and the subcritical assembly support structure (SASS) use neutron fluence above 1 megaelectron volt (MeV) as a measure for radiation damage. However, the implicit correlation between fluence and displacement per atom in the radiation effects data may not be the same as the actual SHINE neutron spectrum because of the 14.1 MeV neutron source used in the SHINE irradiation units.

Provide a complete energy spectrum of neutrons expected in the limiting areas of the SHINE TSV and the SASS, including expected relative populations of thermal and fast neutrons that will contribute to radiation damage. The limiting areas depend on a combination of limiting local stresses during normal conditions and design basis events and the local radiation fluence. Provide spectrum diagrams, including comparison(s) to prototypical light water reactor spectrums, and accompanying descriptions demonstrating that the expected energy spectrums would not result in radiation damage, as supported by the referenced embrittlement studies.

This information is necessary for the NRC staff to determine the relevancy of the embrittlement studies used by SHINE to predict radiation damage in the SHINE TSV and SASS. Further, this information is necessary for the NRC staff to find that SHINE has included adequate descriptions and analyses of the structures, systems, and components of the facility to show that safety functions will be accomplished, consistent with the requirements of 10 CFR 50.34(b)(2).

SHINE Response

The complete neutron energy spectrum for the target solution vessel (TSV) inner shell, TSV outer shell, subcritical assembly system (SCAS) support structure (SASS) outer shell, and [ ]$^{\text{PROP/ECI}}$ is provided in Figure 4a-15-1. The flux is calculated at the mid-height of the target solution as this area will see the highest flux. The areas of limiting local stresses during normal conditions and design basis events are near nozzles and supports. Applying the highest calculated flux to the areas of limiting local stresses is conservative. The embrittlement studies referenced in the FSAR have shown that austenitic stainless steels have increased yield strength, ultimate tensile strengths, and retain sufficient ductility below 100°C and at fast fluences on the order of [ ]$^{\text{PROP/ECI}}$. These conditions are consistent with normal and off-normal conditions for the areas of limiting local stresses within the TSV and SASS at the highest calculated flux.

The relative expected neutron populations for the TSV inner shell, TSV outer shell, SASS outer shell, and [ ]$^{\text{PROP/ECI}}$ are provided in Table 4a-15-1. Driver neutrons are defined as anything greater than 10 MeV.

The neutron energy spectrum for the TSV inner shell is plotted against the H.B. Robinson spectrum from NUREG/CR-6453 (Reference 3) in Figure 4a-15-2. The neutron energy spectrum for the TSV inner shell is similar to that of the H.B. Robinson spectrum other than the small fraction of neutrons above 10 MeV.

Table 4a-15-1 – SHINE Relative Expected Neutron Population

Location	Energy	Relative Population [%]
TSV Inner Shell	Thermal	15
	Fast	18
	Driver	0.3
TSV Outer Shell	Thermal	26
	Fast	20
	Driver	0.1
SASS Outer Shell	Thermal	41
	Fast	14
	Driver	0.1
[ ]PROP/ECI	Thermal	35
	Fast	18
	Driver	0.1

Figure 4a-15-1 – SHINE Neutron Energy Spectra

Figure 4a-15-2 – Light Water Reactor Comparison

RAI 4a-16

In SHINE FSAR Section 4a2.4.1.1, “Design Considerations,” SHINE states, in part, the following:

> Radiation effects and corrosion testing has been performed at Oak Ridge National Laboratory (ORNL) to determine the characteristics of stainless steel for TSV relevant conditions. The results of the radiation effects testing, corrosion testing, and literature data were used as input for the final TSV design.

However, SHINE does not describe the types and results of the corrosion and irradiation testing performed by ORNL. Further, SHINE does not adequately demonstrate within the FSAR how the TSV and SASS will fulfill their design basis requirements over their intended lifetimes. Therefore:

a) Identify the types and results of the corrosion and irradiation testing performed at ORNL on the TSV and SASS materials and how these test results have been used to demonstrate the adequacy of the TSV and SASS components over the components’ intended design lifetimes. Provide relevant references to studies and reports used to support the evaluation of the adequacy of these components.

b) Demonstrate that the design requirements will be maintained over the intended operating lifetimes of the TSV and SASS by evaluating the potential effects of material degradation due to the operating environment (i.e., operating temperature, cooling water chemistry, and radiation damage).

This information is necessary for the NRC staff to determine that SHINE has included adequate descriptions and analyses of the structures, systems, and components of the facility to show that safety functions will be accomplished, consistent with the requirements of 10 CFR 50.34(b)(2).

SHINE Response

a) Oak Ridge National Laboratory (ORNL) performed irradiation and corrosion testing for TSV and SASS relevant conditions as documented in ORNL/TM-2015/498, “Interim Progress Report on the Irradiation Test Results of Structural Components in Support of an Accelerator Driven Subcritical Assembly for the Production of Mo-99” (Reference 4), and ORNL/TM-2015/704, “Corrosion Assessment of Candidate Materials for the SHINE Subcritical Assembly Vessel and Components – FY 2015 Report” (Reference 5).

   The TSV is constructed from 347 stainless steel. The SASS is constructed from 304L stainless steel. Oak Ridge National Laboratory performed irradiation and corrosion testing on 316L stainless steel (References 4 and 5) which is an 18-8 alloy similar to 347 and 304L stainless steels. Alloys 316L, 347, and 304L are all austenitic stainless steels and are expected to behave similarly in a given environment.

   As described in Reference 5, the stress-corrosion cracking (SCC) susceptibility of 316L stainless steel was examined using standard U-bend test specimens as well as slow-strain rate (SSR) mechanical testing. The U-bend test concluded that no evidence of cracking was observed, general corrosion rates were very low, no increases in surface roughness or localized corrosion were observed, and no unexpected discoloration (i.e., the discoloration patterns resulting from minor oxidation were expected). Results of the SSR testing concluded that none of the alloys mechanically tested in the prototypic environments revealed any change in fracture characteristic compared to identical specimens pulled to failure in water.

As described in Reference 5, electrochemical polarization testing was used to assess and compare passive film stability and corrosion characteristics as a function of fluid velocity. In a polarization test, the specimen is exposed to a large range of electrochemical potentials representing the full gamut of oxidizing and reducing conditions that might be encountered upon exposure to the generalized solution chemistry of interest. The polarization data collected for the 316L stainless steel suggests extraordinary passivity over a wide range consistent with immeasurably low corrosion rates and with little or no influence of fluid velocity over the range of stagnant-to-turbulent conditions. Thus, while extreme fluid velocity is not expected within the SHINE process conditions, it appears unlikely that fluid velocity is a sensitive factor for consideration in the design and corrosion allowances that are developed.

As described in Reference 5, vibratory horn testing was used to examine potential cavitation characteristics. The goal of this testing was to compare erosion-corrosion conditions for solution with and without uranyl sulfate to consider any potential changes in compatibility that might result from fluid handling of these solutions. The results indicated that the uranium component of the solution does not add a significant component to potential cavitation or related velocity effects in solution. Cavitation conditions within the fluids are not expected in the SHINE process.

As described in Reference 5, potential effects of radiolysis were analyzed using small corrosion test containers that were exposed in the spent fuel pool at the High Flux Isotope Reactor (HFIR) in an area designed specifically for material assessments. Dosimetry indicated that the corrosion test containers were irradiated at an equilibrium temperature of approximately 65°C and a gamma dose rate of approximately 2 MRad/hr. Data suggests that an increase in corrosion rate is associated with the radiolysis exposure conditions, but the increase is minimal. The 316L stainless steel studied was shown to be resistant to solution changes resulting from radiolysis.

As described in Reference 4, irradiation testing of 316L stainless steel showed an increase in ultimate strength and yield strength and a decrease in total elongation. Examination the fracture of the specimens suggests that ductility was maintained after irradiation.

The results of the corrosion and irradiation testing performed at ORNL (References 4 and 5) for materials similar to the TSV and SASS materials demonstrate the adequacy of the TSV and SASS materials over the intended design lifetime.

b) SHINE has demonstrated that design requirements will be maintained over the operating lifetimes of the TSV and SASS by evaluating the potential effects of material degradation due to the operating environment, including the following:

  - The corrosion and irradiation testing performed at ORNL (References 4 and 5) demonstrate the adequacy of the TSV and SASS materials.

  - As described in Subsection 4a2.4.1.1 of the FSAR, the TSV is designed and fabricated in accordance with the American Society of Mechanical Engineers

(ASME) Boiler and Pressure Vessel Code (BPVC), Section VIII, Division 1 (Reference 6). Pressure retaining components of the SASS are also designed and fabricated in accordance with the ASME, BPVC, Section VIII, Division 1. ASME pressure vessel code calculations for the design and construction of the TSV and SASS include analysis of the vessels at the design temperature of the vessel, assuming maximum corrosion.

- Corrosion data from ORNL-630, “Homogeneous Reactor Experiment Report for the Quarter Ending February 28, 1950” (Reference 7), and ORNL-1221, Homogeneous Reactor Project Quarterly Progress Report for the Period Ending November 15, 1951” Reference 8), is used to determine the corrosion allowance of the TSV over the 30-year lifetime; the corrosion allowance is approximately 31 mils for TSV components interfacing with the target solution. The corrosion allowance for the SASS (in contact with cooling water) is 1.5 mils over the 30 year lifetime based on standard literature data for 304L stainless steel in water. These corrosion allowances are incorporated into the ASME pressure vessel code calculations for the design and construction of the TSV and SASS, which demonstrate the design requirements will be maintained.

- Embrittlement studies, which demonstrate the adequacy of the materials used for the TSV and SASS, are discussed in the SHINE Response to RAI 4a-15.

RAI 4a-17

SHINE FSAR Figure 4a2.7-1, “Target Solution Vessel Heat Transfer Surfaces,” shows that cooling channel 3 (CC3) provides forced water to cool the TSV outer wall. FSAR Chapter 4a2.7.3.1, “General Characteristics,” states, in part, that “(CC3) is the annular gap between the TSV and the SASS inner baffle.” FSAR Figure 4a2.7-1 shows a gap/area between the SASS inner baffle and the SASS inner wall that could create stagnant water flow zones that may subsequently lead to degradation (e.g., cracking) of the inner baffle and inner wall components. However, the SHINE FSAR does not describe the impacts of such potential degradation on the ability of the primary closed loop cooling system (PCLS) and SASS to fulfill their design requirements over the intended service life.

Therefore, confirm whether stagnate flow zones are created in the area between the SASS inner baffle and SASS inner wall that may lead to degradation (e.g., cracking) of either component. If stagnate flow zones are created, demonstrate that the PCLS and SASS design requirements continue to be met over the intended service life of those components.

This information is necessary for the NRC staff to determine that SHINE has included adequate descriptions and analyses of the structures, systems, and components of the facility to show that safety functions will be accomplished, consistent with the requirements of 10 CFR 50.34(b)(2).

SHINE Response

Stagnant flow zones are not expected in the area between the SASS inner baffle and SASS inner wall. This channel is filled with cooling water from the primary closed loop cooling system (PCLS), and while the PCLS does not force water through this channel, flow is provided via natural convection and bubbles from radiolysis. The channel is closed on the bottom and open on the top; cooling water can flow to/from the SASS upper plenum. Natural convection is driven by the temperature gradient between the cooling water temperature and the wall temperature. Heat is generated in the channel cooling water from absorption of radiation and from heat transfer from the SASS inner baffle. The PCLS water quality standards identified in Table 5a2.2-1 of the FSAR provide additional protection against potential degradation of the SASS inner baffle and the SASS inner wall.

RAI 4a-18

Paragraph (b)(6)(iv) of 10 CFR 50.34 requires that an applicant's FSAR include information regarding the "[p]lans for conduct of normal operations, including maintenance, surveillance, and periodic testing of structures, systems, and components."

Section 4a2.4.1.5, "Chemical Interactions and Neutron Damage," of the SHINE FSAR states, in part, the following:

> The TSV, TSV dump tank, TOGS, and associated components act as the PSB and are safety-related. Surveillance and inspection capabilities for these structures, systems, and components (SSCs) are provided in order to assess mechanical integrity and verify corrosion rates are acceptable. The surveillance and inspection program ensures the integrity of the PSB components is not degraded below acceptable limits due to radiation damage, chemical damage, erosion, pressure pulses, or other deterioration.

However, SHINE does not describe the surveillance, testing, and inspection program(s) that will be implemented to monitor the integrity of the TSV and SASS over the design life.

Provide descriptions of the following aspects of surveillance, testing, and inspection program(s) that will be in place to monitor the integrity of the TSV and SASS over the design life:

- Surveillance Program: Describe the objectives of the surveillance program, identify the locations within the TSV containing surveillance specimens, and provide the bases for choosing these locations. Then, describe the surveillance program planned at each TSV surveillance location. This description should include the following information:
    - Type, size, number, and purpose of each unique specimen-type
    - Extraction and testing periodicity for each unique specimen type

- Testing and evaluation to be performed for each unique specimen type and the associated standards that will be used to govern the testing and evaluation.

- Inspection Program: Describe the objectives of the inspection programs for the TSV and SASS, identify the planned inspection locations within the TSV and SASS, and provide the bases for choosing these locations. Then, describe the inspection program planned at each TSV and SASS location. This description should include the following information:
    - Inspection method(s) and associated periodicity
    - Inspection coverage (i.e., surface area or volume)
    - Applicable codes and standards governing the inspection methods and the interpretation of inspection results
    - Accessibility constraints or challenges that may limit inspection coverage

- The intended use of results from both the surveillance and inspection programs to update the initial programs, if necessary, should also be described.

This information is necessary for the NRC staff to determine that SHINE has the appropriate program(s) in place to monitor the integrity of the TSV and SASS consistent with the requirements of 10 CFR 50.34(b)(6)(iv).

SHINE Response

SHINE has implemented a surveillance, testing, and inspection program to monitor the integrity of the target solution vessel (TSV) and the subcritical assembly support structure (SASS). The program describes the requirements for coupon testing and inspections, including required periodicity, methods of testing, and acceptance criteria. The objectives of the surveillance, testing, and inspection program is to ensure that the mechanical integrity of the TSV and SASS are maintained throughout the design life. The program is updated, if needed, based on the results of the surveillances, tests, and inspections.

Surveillances

Each TSV is equipped with a material coupon tree that allows for the attachment of specifically designed TSV material samples. The testing tree is connected to a blind flange near the top of each TSV by a threaded connection, allowing the samples to be removed for analysis. During normal operation, the samples are submerged in target solution. Coupon samples located within the TSV are exposed to a flux and corrosion environment that is representative of the TSV inner shell flux and corrosion environment. The material coupons are milled from the same heat of material as the associated TSV inner shell. Two types of coupons are present: fracture samples and tension samples.

Corrosion Testing

Prior to undergoing specific fracture or tension testing, each sample removed from the TSV undergoes corrosion testing. This corrosion testing aims to identify early warning signs of unanticipated or excessive corrosion and to determine trends and processes that may be creating a more corrosive environment. Corrosion monitoring also serves to measure the effectiveness of corrosion prevention methods and to determine which techniques may be used to minimize the corrosion rate within the TSV. Assessment of TSV corrosion rates is performed via non-destructive testing (NDT) methods.

Tension Samples

Following corrosion testing, tension samples are analyzed to identify early warning signs of unanticipated or excessive deterioration of the TSV inner shell via radiation damage, chemical damage, or other forms of deterioration. Destructive testing of the tension samples is performed using methods from American Society for Testing and Materials (ASTM) E8/E8M-21 “Standard Test Methods for Tension Testing of Metallic Materials” (Reference 9). Tension samples are approximately 4.75 inches (in.) wide and 0.5 in. tall. Twenty-five tension samples are manufactured for each TSV, 24 of which are installed inside the TSV prior to initial operation. The remaining sample serves as a control sample. The coupon tree allows for the attachment of tension samples at 6 elevations in 4 equally spaced orientations around the tree.

Fracture Samples

Following corrosion testing, fracture samples are analyzed to identify early warning signs of unanticipated or excessive radiation damage to the TSV inner shell. The fracture samples also allow for the monitoring of changes in material properties with respect to operational conditions. Destructive testing of the fracture samples is performed using methods from ASTM E399-20a “Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness of Metallic Materials”

(Reference 10), and ASTM E1820-20b “Standard Test Method for Measurement of Fracture Toughness” (Reference 11). Fracture samples are approximately 1.5 in. wide and 0.75 in. tall. Thirteen fracture samples are manufactured for each TSV, 12 of which are installed inside the TSV prior to initial operation. The remaining sample serves as a control sample. The coupon tree allows for the attachment of fracture samples at 4 elevations in 3 equally spaced orientations around the tree.

Testing Periodicity

Testing coupons are removed based on Effective Full Power Years (EFPY) of the TSV. Planned frequency of removal is shown in the following table:

Coupon Test Number	TSV EFPYs of Operation	Number of Fracture Samples Removed (Cumulative Total)	Number of Tension Samples Removed (Cumulative Total)
1	1	1	2
2	2	2	4
3	3	3	6
4	4	4	8
5	5	5	10
6	10	6	12
7	15	7	14
8	20	8	16
9	30	9	18

Inspections

Inspections of each TSV and SASS will occur approximately once every EFPY, not to exceed two calendar years between inspections.

TSV Inspections

Each TSV contains two inspection ports that permit inspection of the interior surfaces of the TSV. At a minimum, each periodic visual inspection of the TSV interior must include representative portions of the TSV interior surfaces. While a minimum surface area or volume is not defined for TSV inspections, the TSV representative portions that are inspected include weld locations, the liquid level line, piping connections, areas of the TSV interior that are expected to receive the highest levels of chemical damage, areas of the TSV that are expected to be the most susceptible to deterioration from pressure pulses, and areas of the TSV that are expected to receive the highest levels of radiation damage.

SASS Inspections

At a minimum, each periodic visual inspection of the SASS must include representative portions of the exterior primary system boundary (PSB) surfaces. While a minimum surface area or volume is not defined for SASS inspections, the SASS representative portions that are inspected include weld locations and mechanical connections of the PSB exterior surfaces.

Accessibility constraints and challenges include dimensional constraints. Due to the required inspection locations and dimensional constraints, inspections of the TSV and SASS will normally be accomplished via remote visual inspections methods. Interior inspections will be accomplished by use of a borescope. Exterior inspections will be accomplished by use of a borescope or robotic divers. Visual inspections include documentation of abnormalities or areas of concern identified, such as pitting, cracking, or discoloration. Weld inspections are performed in accordance with American Welding Society (AWS) B1.11M/B1.11:2015, “Guide for the Visual Examination of Welds” (Reference 12).

The surveillance, testing, and inspection program will be updated, if needed, based on the surveillance and inspection results (e.g., the frequency may be adjusted based on inspection results or coupon sample analysis results). Changes to the surveillance and inspection frequencies require approval by both Operations and Engineering management.

References

1. NRC letter to SHINE Medical Technologies, LLC, “SHINE Medical Technologies, LLC – Request for Additional Information Related to Radiation Damage (EPID No. L-2019-NEW-0004),” dated December 23, 2021 (ML21355A360)

2. SHINE Medical Technologies, LLC letter to the NRC, “SHINE Medical Technologies, LLC Application for an Operating License,” dated July 17, 2019 (ML19211C143)

3. U.S. Nuclear Regulatory Commission, “H. B. Robinson-2 Pressure Vessel Benchmark,” NUREG/CR-6453, October 1997

4. Oak Ridge National Laboratory, “Interim Progress Report on the Irradiation Test Results of Structural Components in Support of an Accelerator Driven Subcritical Assembly for the Production of Mo-99,” ORNL/TM-2015/498, September 2015

5. Oak Ridge National Laboratory, “Corrosion Assessment of Candidate Materials for the SHINE Subcritical Assembly Vessel and Components – FY 2015 Report,” ORNL/TM-2015/704, January 2016

6. American Society of Mechanical Engineers, “Boiler & Pressure Vessel Code - Rules for Construction of Pressure Vessels, Section VIII,” July 1, 2010

7. Oak Ridge National Laboratory, “Homogeneous Reactor Experiment Report for the Quarter Ending February 28, 1950,” ORNL-630, April 1950

8. Oak Ridge National Laboratory, “Homogeneous Reactor Project Quarterly Progress Report for the Period Ending November 15, 1951,” ORNL-1221, March 1952

9. American Society for Testing and Materials, “Standard Test Methods for Tension Testing of Metallic Materials,” ASTM E8/E8M-21, February 2021

10. American Society for Testing and Materials, “Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness of Metallic Materials,” ASTM E399-20a, December 2020

11. American Society for Testing and Materials, “Standard Test Method for Measurement of Fracture Toughness,” ASTM E1820-20b, September 2020

12. American Welding Society, “Guide for the Visual Examination of Welds,” AWS B1.11M/B1.11:2015, September 2014