ENCLOSURE 2
ATTACHMENT 7

SHINE MEDICAL TECHNOLOGIES, INC.

SHINE MEDICAL TECHNOLOGIES, INC. APPLICATION FOR CONSTRUCTION PERMIT
RESPONSE TO REQUEST FOR ADDITIONAL INFORMATION

1200-09-02, REVISION 0
SHINE TARGET SOLUTION QUALIFICATION PROGRAM

21 pages follow

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SHINE Target Solution Qualification Program

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1 INTRODUCTION

The purpose of this document is to describe the target solution qualification program for the SHINE target solution. The objective of the target solution qualification program is to demonstrate the safe and reliable operation of the SHINE target solution that will be used for the production of medical isotopes.

Unlike traditional research and power reactors, SHINE uses an aqueous fissile solution rather than solid fuel assemblies. Therefore, many aspects of traditional fuel qualification programs that are designed to ensure the mechanical stability and integrity of the fuel assembly do not apply to the SHINE target solution qualification process. As a solution, the SHINE target solution does not experience mechanical failures (e.g. pellet-clad interaction, grid-to-rod fretting, creep, and irradiation deformation).

The following items are reviewed in this report to demonstrate the safe and reliable operation of the SHINE target solution:

1. Properly characterizing the properties of the solution, which are necessary inputs to analyses of the nuclear, chemical, and mechanical process that the target solution undergoes
2. Demonstrating that the target solution will perform as expected through irradiation and chemical processing steps by experiment, testing, or previous demonstrations
3. Properly defining the limits of process operations to prevent adverse effects to the solution or process

Section 2 provides the history of target solution development.

Section 3 provides existing target solution physical parameter measurements and future testing needs.

Section 4 provides a SHINE facility process overview, which provides background on the nuclear, chemical, and mechanical steps the target solution will undergo.

Section 5 summarizes lab-scale testing of target solution that has been completed and is planned to be conducted by the National Laboratories.

Section 6 includes the process limits to ensure satisfactory target solution and process performances.

Section 7 describes the target solution testing requirements in the operating facility to ensure the target solution meets specifications. This will involve

1. Receipt inspection of uranium metal or uranium oxide
2. Control of chemical reagents
3. Testing of target solution pre-irradiation
4. In-line testing of target solution during irradiation
5. Testing of target solution during cleanup

Section 8 contains a list of references.

2 TARGET SOLUTION HISTORY

Concept designs of solution reactors utilizing uranyl sulfate as fuel were first proposed in the 1940s (IAEA, 2008). Both Oak Ridge National Laboratory (ORNL) and Los Alamos National Laboratory (LANL) initiated research activities on uranyl sulfate during that period (Secoy, 1948; Baker, 1944). These national laboratory research activities on uranyl sulfate continued during the 1950s (ORNL, 1952; Lee, 1952; Lane, 1958; Beall, 1954). Concurrent with the research performed at the national laboratories, uranyl sulfate research was performed at universities with research reactors (NCSU, 1955), Atomics International (Wilson, 1958), and elsewhere (Parkins, W., 1958; Secoy, 1955; Silverman, 1961; Gamble, 1959). Research on uranyl sulfate as a fuel solution has since continued and supports the concept of using uranyl sulfate as a target solution for the SHINE medical isotope facility.

Uranyl sulfate has been found to be a very soluble compound and completely stable under reactor radiation when in aqueous solution (Secoy, 1955).

Use of uranyl sulfate solutions in fission systems has also demonstrated that process and chemistry controls need to be in place to prevent the precipitation of uranyl peroxide. This is discussed further in Section 3.

Other historical work relevant to uranyl sulfate development is listed below.

1. IAEA, 2008. Homogeneous Aqueous Solution Nuclear Reactors for the Production of Mo-99 and Other Short Lived Radioisotopes, TECDOC-1601, International Atomic Energy Agency, September 2008.
2. Lane, 1958. Lane, J., Fluid Fuel Reactors, Part 1, Aqueous Homogeneous Reactors, Oak Ridge National Laboratory, June 1958.
3. LANL, 2004. MCNP5_RSICC_1.30, LA-UR-04-5921, MCNP Monte Carlo Team, X-5, Los Alamos National Laboratory, Los Alamos, NM, 2004.
4. Lee, 1952. Lee, J., et al., The Density of Uranyl Sulfate Solutions and the Determination of Uranium Concentration by Density Measurements, ORNL-1332, Oak Ridge National Laboratory, June 18, 1952.
5. NCSU, 1955. NCSCR-1, Raleigh Research Reactor Critical on September 1953, North Carolina State University, Shutdown June 1955.
6. ORNL, 1952. Physical Properties of Uranyl Sulfate at Atmospheric Pressure, CF52-3-253, Oak Ridge National Laboratory, March 10, 1052.
7. Parkins, W., 1958. Aqueous Homogeneous Type Research Reactors, Second International Conference on Peaceful Uses of Atomic Energy, March 19, 1958.
8. Secoy, 1948. Secoy, C., The System Uranyl Sulfate – Water, II. Temperature – Concentration Relationships above 250°C, ORNL-98, Oak Ridge National Laboratory, July 7, 1948.
9. Secoy, 1955. Secoy, C., Preprint65, Survey of Homogeneous Reactor Chemical Problems, Nuclear Engineering and Science Congress, American Chemical Society, December 12 – 16, 1955.

10. Silverman, 1961. Silverman, Louis, et al., Homogeneous Nuclear Reactor Fuel Composition, Patent No. 2,978,399, April 4, 1961.
11. Wilson, 1958. Wilson, R., et al., Aqueous Homogeneous Type Research Reactors, P/1543, Atomics International, June 1958.

3 TARGET SOLUTION PHYSICAL PARAMETERS

Target solution physical parameters are the measurable characteristics of the solution. These parameters are necessary inputs to the nuclear, chemical, and mechanical design of the SHINE facility systems.

Uranyl sulfate solutions have been studied extensively, including measurements of many of their physical properties over ranges of interest to the SHINE facility.

3.1 Density

A review and compilation of available density measurement data has been performed. This is documented in SHINE calculation CALC-2013-0011, Rev 0.

3.2 Viscosity

Viscosity measurements have been performed by Argonne National Laboratory are documented in “Mo Recovery Updates and Physical Properties of Uranyl Sulfate Solutions”, ANL/CSE-13/20 (Reference 3).

3.3 Specific heat

Specific heat measurements are required for thermal capacity determination. While historical values have been obtained from literature with sufficient accuracy to determine bounding values for safety analysis, more detailed values are desired for best-estimate models. These are planned to be determined through solution testing during the detailed design phase.

The additional data is not required to resolve any safety questions associated with structures, systems, or components.

3.4 Thermal conductivity

Thermal conductivity measurements are required for heat transfer and analyses of the thermal-hydraulics in the TSV. While historical values have been obtained from literature with sufficient accuracy to determine bounding values for safety analysis, more detailed values are desired for best-estimate models. These are planned to be determined through solution testing during the detailed design phase.

The additional data is not required to resolve any safety questions associated with structures, systems, or components.

3.5 Radiolytic gas generation rates

Radiolytic gas generation rates from fission product irradiation have been measured previously. This data is available in Fluid Fuel Reactors, Part 1 - Aqueous Homogeneous Reactors, by J. Lane. (Reference 21).

3.6 Solubility limits for fission products

Less than [Proprietary Information] of fission products per kg of target solution could precipitate based on thermodynamic modeling and [Proprietary Information] cycles of irradiation (Reference 15).

3.7 Solubility of uranyl peroxide

Based on preliminary research, if a steady-state hydrogen peroxide concentration of greater than 3x10-4 mol/kg was present uranyl peroxide could precipitate based on thermodynamic models (not accounting for kinetics effects) (Reference 15). Uranyl peroxide formation is expected to be avoided by [Proprietary Information]. Additional testing is being performed at Argonne National Laboratory to validate that kinetics effects are fully understood, which is scheduled to be completed in by Q3 2015.

4 SHINE FACILITY PROCESS OVERVIEW

4.1 Overview

The uranyl sulfate target solution is derived by one or both of the following means:

1. Procuring low-enriched uranium (LEU) metal, which is then dissolved in concentrated nitric acid, which is then processed into uranium oxide by thermal denitration. The uranium oxide is then dissolved in sulfuric acid to form the target solution.
2. Procuring LEU oxide, which is then dissolved in sulfuric acid to form the target solution.

After [Proprietary Information] cycles of irradiation and Molybdenum-99 extraction, the target solution is cleaned up by converting the uranyl sulfate to uranyl nitrate, removing the fission product impurities, and thermally denitrating the uranyl nitrate to produce uranium oxide. The recycled uranium oxide is re-dissolved in sulfuric acid to reconstitute the target solution. These processes are described in detail in the following sections.

4.2 Shipment and receipt of feed uranium

Special Nuclear Material (SNM) is received in the form of solid uranium metal pieces or uranium oxide from a Department of Energy (DOE) supplier.

Shipment of uranium metal is received on pallets containing transport containers. The transport containers contain three small convenience containers, which are removed from the transport container and placed in the receipt ventilation hood. Within the receipt ventilation hood, the convenience container is opened and the contents are verified. Uranium metal is then repackaged into the uranium metal storage can. The uranium metal storage can is designed to

be criticality-safe in this configuration. The uranium metal storage can is then transferred to the uranium metal storage rack prior to further processing.

Shipment of uranium oxide is received in containers that are transferred to the RCA. These containers are placed in the receipt ventilation hood. Within the receipt ventilation hood, the container is opened and the contents are verified. Uranium oxide is then repackaged into the uranium oxide storage can. The uranium oxide storage can is then transferred to the criticality-safe uranium oxide storage rack prior to further processing.

See Table 6.1 for uranium metal and uranium oxide specifications. The parameters contained in Table 6.1 have been developed from the following sources:

- Specifications from draft Low-Enriched Uranium (LEU) Specifications for uranium oxide from the DOE supplier.
- Barium, strontium, thorium, and silver limits were developed by SHINE to minimize the formation of precipitates in the target solution. Other elements likely to form low-solubility compounds (calcium and lead) had acceptable limits provided in the base specification from the DOE supplier.
- Particle size limits for uranium metal are intended to prevent violent reactions with nitric acid or nitrogen dioxide (Reference 1).
- Temperature limits for storage are intended to prevent exposure to extreme conditions.

4.3 Bulk Chemical Usage

Various chemicals will be used in the preparation and cleanup of target solution. A chemical control program will be developed to control chemical segregation and chemical inventories. Since many of these chemicals will be used in multiple processes in the facility, the chemicals will typically be received in a concentrated form and diluted as necessary for the appropriate process. The chemicals that will be used in the preparation and cleanup of target solution are as follows:

- Nitric acid (HNO_3)
- Sulfuric acid (H_2SO_4)
- [Proprietary Information]
- [Proprietary Information]
- Tributyl phosphate (TBP / $(CH_3(CH_2)_3O)_3PO$)
- n-Dodecane ($CH_3(CH_2)_{10}CH_3$)
- Acetohydroxamic acid (AHA / $CH_3CONHOH$)

Those chemicals with American Chemical Society (ACS) specifications will be obtained at the reagent grade to minimize the impurities introduced into the target solution. Those chemicals without ACS specifications are limited to the organic chemicals used in the uranium extraction (UREX) process and are not expected to be a significant source of contaminants into the

aqueous phase target solution. These chemicals will be obtained at a commercially available high purity. Bulk chemical specifications are similar to those used in a UREX demonstration involving reactor spent fuel (Reference 10). See Table 6.2 for bulk chemical specifications.

The molybdenum extraction [Proprietary Information] contain a fixed bed of [Proprietary Information]. The [Proprietary Information] will be procured from the supplier in accordance with specifications to be determined to avoid the introduction of impurities into the target solution.

4.4 Dissolution of Uranium Metal

Feed uranium in metal form is dissolved in concentrated nitric acid in the uranium metal dissolution tank (1-TSPS-02T) to form a uranyl nitrate solution. The uranyl nitrate solution is then transferred to the recycle uranyl nitrate hold tank (1-UNCS-06T) and then transferred to the thermal denitration (TDN) process to be processed into uranium oxide. Feed uranium will be used to prepare initial batches and replace uranium in the process, as needed.

The uranium metal dissolution tank (1-TSPS-02T) is maintained at an elevated temperature during dissolution. To accommodate various amounts of uranium metal to be dissolved, the nitric acid amount will be calculated for the specific uranium metal batch.

The uranium metal dissolution tank (1-TSPS-02T) and the associated piping containing fissile material is criticality-safe by geometry.

The uranium oxide produced from the dissolution and thermal denitration of uranium metal is stored in uranium oxide storage cans in a criticality-safe configuration within the uranium oxide storage rack. Uranium oxide is stored until needed by the facility for the production of target solution. The denitration process is described in Section 4.7 below.

See Table 6.3 for nitric acid specifications and process conditions for the dissolution of uranium metal. The specifications and process conditions are based on the following:

- Limits for nitric acid concentration are based on a maximum dissolution rate seen at high acid concentrations, and ineffective uranium dissolution at acid concentrations that are too low. Furthermore, nitric acid concentrations of less than 7.5M will produce predominantly nitrogen oxide (NO) when reacted with uranium metal (Reference 1).
- Limits for the volume of nitric acid required are based on minimizing the time required to dissolve uranium metal. Stoichiometrically, only 1.6 mL of 12M nitric acid is required to dissolve 1 g of uranium metal. An excess of nitric acid maximizes the dissolution rate (Reference 1).
- Limits on process temperatures are also based on minimizing dissolution time. The dissolution rate increases with increasing temperature, to a maximum temperature of approximately 86°C (the boiling point of pure nitric acid) (Reference 9).

4.5 Production of Target Solution from Uranium Oxide

Target solution (uranyl sulfate) is prepared in the target solution preparation system (TSPS) by dissolving uranium oxide in sulfuric acid. The vessels and piping containing fissile material in the TSPS are criticality-safe by geometry. Target solution must meet the chemical property

requirements discussed in Section 6 before it is transferred from the target solution hold tank (1-TSPS-03T) to the Target Solution Vessel (TSV). If the target solution is not within the required chemical specifications, operators make appropriate adjustments while the target solution is being prepared in the TSPS.

Target solution is prepared in the target solution preparation tank (1-TSPS-01T) by dissolving uranium oxide in sulfuric acid with the tank maintained at an elevated temperature and agitated until the uranium oxide is fully dissolved. The target solution will be prepared to accurately control the uranyl sulfate concentration. The pH of the target solution is also controlled by the addition of sulfuric acid.

The mass of uranium oxide used to prepare target solution is measured in the target solution preparation hood and transferred to the target solution preparation tank (1-TSPS-01T). The introduction of uranium oxide to the preparation tank occurs within a glovebox to reduce the potential for airborne contamination.

See Table 6.4 for specifications for target solution preparation and irradiation. The basis for the specifications are as follows:

- Uranium concentration is controlled to specifications and accuracy required for the subcritical assembly.
- Total mass and volume limits are based on subcritical assembly design.
- Temperature limits are imposed to minimize the formation of precipitates (Reference 11) and to prevent exposing the solution to extreme (freezing or boiling) conditions.
- pH values are based on minimizing corrosion and the formation of precipitates. Fission product precipitation becomes a concern at higher pH values (Reference 11). Corrosion rates of materials used in the SHINE facility have been tested at a pH of 1 and have been found to be acceptable (Reference 13), but corrosion rates of stainless steels in sulfuric acid rise as pH lowers (Reference 14). pH is temperature dependent, thus measurements taken at other temperatures will not necessarily conform to the limits provided in Section 6.
- Impurity limits are intended to minimize the formation of precipitates at room temperature and at TSV operating conditions (Reference 11).
- [Proprietary Information]

4.6 Irradiation

The target solution is transferred from the target solution hold tank (1-TSPS-03T) to the TSV during the startup of the irradiation process (Mode 1). During this process, the accelerator is not operating. The solution is delivered to the TSV in discrete steps, and reactivity is gradually increased to the target reactivity. The accelerator is then energized to begin neutron output. The accelerator target gas is gradually changed from deuterium to tritium by the tritium purification system (TPS) to slowly ramp up neutron yield and fission power. The maximum fission power generation in the target solution is up to [Proprietary Information]. The target solution undergoes

volumetric heating and gas generation, which aids in natural mixing. Heat is removed through the TSV walls [Proprietary Information]. Radiolytic and fission product gases are removed from the target solution continuously in the form of bubbles rising to the surface and being drawn into the TSV off-gas system (TOGS). Water vapor from the solution is condensed by the TOGS and returned to the solution. Radiolytic gases are recombined, condensed, and returned to the solution by the TOGS. Fission product gases are contained in the TOGS on the iodine removal beds or in the sweep gas itself. The TOGS sweep gas is purged to the noble gas removal system (NGRS) following each cycle.

Due to the stability of the uranyl sulfate and sulfuric acid under irradiation, no additions of acid, water, target solution, or other additives are made or required during irradiation. A small of amount of water hold up in the TOGS system during irradiation does not result in the target solution exceeding allowable parameters and is accounted for in the nuclear design.

Following a nominal irradiation period of 5.5 days, the solution is drained to the TSV dump tank. The solution is cooled through natural convection in the TSV dump tank as the tank is located in the light water pool. Following a minimum cooldown period of [Proprietary Information], the solution is transferred to the molybdenum extraction process within one of the SHINE supercells.

4.7 Cleanup of target solution

The target solution is recycled and irradiated [Proprietary Information] times before being cleaned up by the UNCS. This results in an average of [Proprietary Information] TSV batches of target solution being recycled to the TSVs each [Proprietary Information] and [Proprietary Information] TSV batches per [Proprietary Information] of target solution being converted to uranyl nitrate, processed through UREX, and converted to uranium oxide.

The target solution being recycled to the TSVs is staged in one of three recycle target solution tanks (1-UNCS-09T-A/B/C). From there, it is pumped to one of the target solution hold tanks (1-TSPS-03T-A-H) in the TSPS.

The spent target solution being converted to uranyl nitrate is reacted with [Proprietary Information] then [Proprietary Information]. The uranyl nitrate conversion tank (1-UNCS-01T-A/B) is mixed by a pump-around recycle. [Proprietary Information] is added to the batch solution first and is mixed for 1 hour at an elevated temperature. [Proprietary Information] is then added and mixed for 1 hour, also at an elevated temperature. The process temperature is achieved by recirculating the tank contents through an electrical heater. After the reaction steps are complete, the tank contents are cooled by recirculating them through a chilled water cooler. [Proprietary Information] both have low [Proprietary Information], while excess [Proprietary Information] remain dissolved in the uranyl nitrate solution. The reaction product slurry is pumped to a centrifuge, where the precipitated sulfates are separated from the uranyl nitrate solution. The solid product in the centrifuge is washed to achieve an overall uranium recovery of 99.75 percent. The filtrate is transferred to the UREX feed tank (1-UNCS-02T) where nitric acid is added to adjust the pH before being transferred to the target solution cleanup subsystem.

The target solution cleanup system uses a solvent extraction process (UREX) to separate uranium from fission products and transuranics with a very high specificity. The UREX solvent is

tri-butyl phosphate (TBP) in an n-dodecane carrier. The solvent extraction contacting and separation are performed in centrifugal contactors, arranged in series.

The UREX system is comprised of four distinct sections:

1. Extraction, in which the uranium in the uranyl nitrate feed is transferred from the aqueous to the solvent phase.
2. Scrubbing, in which impurities in the solvent, carried over from the extraction section, are returned to the aqueous phase.
3. Stripping, in which the uranium is transferred from the solvent to the aqueous phase.
4. Diluent washing, in which the uranyl nitrate product is washed with dodecane to remove organic impurities.

The uranium-rich HNO_3 solution resulting from the UREX process is routed to an anion exchange column, which removes the technetium and iodine from the stream.

The uranyl nitrate product from the anion exchange column is contacted with n-dodecane solvent to remove solvent degradation products and TBP from the aqueous stream. The uranyl nitrate stream from the diluent wash feeds the TDN process.

The TDN system first concentrates the uranyl nitrate solution in a thin-film evaporator. A recycle loop allows multiple passes through the evaporator to achieve the necessary concentration.

The concentrated uranyl nitrate from the evaporator is then sprayed into the thermal denitrator, which is a fluidized bed reactor. The thermal denitrator is fluidized by air that is pre-heated by an electrical heater.

The thermal denitrator uses heat to convert uranyl nitrate to uranium oxide. The TDN reaction is highly endothermic, so the thermal denitrator is heated using clamshell heaters around the denitrator walls and/or bayonet heaters within the bed. The uranium oxide generated in the thermal denitrator is loaded into cans to be recycled into target solution in the TSPS.

See Tables 6.5, 6.6, and 6.7 for specifications for the cleanup of target solution. The bases for the specifications are provided below:

<u>Uranyl sulfate to uranyl nitrate conversion</u>

- Temperature limits were selected based on experimental results indicating that 60°C is the most effective conversion temperature (Reference 7).
- Mole ratios of [Proprietary Information] to sulfate in the target solution are also based attaining the most efficient conversion while minimizing the excess [Proprietary Information] (Reference 7).

<u>UREX</u>

- Extraction, scrub and strip operating temperatures are based on experience with performing UREX on reactor spent fuel (Reference 10) and recommendations from Argonne National Laboratory for preferential Tc partitioning (Reference 16).

- Temperature safety limits for all phases are based on preventing the formation of red oil, where an explosive compound can be formed when high temperature TBP is in contact with concentrated nitric acid. (Reference 12)
- Extraction solvent composition is based on industry experience with liquid-liquid extraction, where TBP is used for metal nitrate extraction and was originally chosen over other organic solvents for its operation characteristics, safety, physical properties, radiation resistance and economics. TBP is diluted in another organic to reduce the solvent's viscosity and density, and n-dodecane is chosen because it is inert and radiation resistant. (Reference 12)
- The scrub solution composition is chosen based on UREX experience at ANL to reduce transition metals into forms that are not extractable into the organic solvent, removing contaminants from the uranium product. (Reference 16)
- The strip solution composition is chosen based on UREX experience at ANL to remove the uranium, technetium and iodine from the organic phase into an aqueous phase. (Reference 16)
- The wash solution composition is based on the need to remove residual TBP from the uranium product, which is known to be soluble in n-dodecane. (Reference 16)

Denitration

- Denitration temperature limits are based on the need to fully convert uranyl nitrate into uranium oxide. Uranyl nitrate is denitrated above 300°C. The desired form of uranium oxide is UO_3, which is easier to dissolve in sulfuric acid than U_3O_8. Hydrated UO_3 is converted to dry UO_3 above 400°C, but depending on the structural isomer form, UO_3 begins to decompose into U3O8 between 400 to 650°C. (References 17, 18, 19)
- The extent of denitration and dehydration of the UO_3 product needs to be determined to accurately calculate the mass of uranium used in further processes and to limit the carry-over of unwanted compounds into the process.

5 LAB-SCALE TESTING OF TARGET SOLUTION

Irradiations of uranyl sulfate and extractions of molybdenum-99 have been conducted at the National Laboratories in support of the development of the SHINE process. Studies performed at the Argonne and Los Alamos National Laboratories have been used as input for the specifications of the SHINE target solution. See tables in Section 6.

A summary of the supporting experiments is provided below:

- Mo Recovery Updates and Physical Properties of Uranyl Sulfate Solutions

  The density, pH, and viscosity of uranyl sulfate solutions were measured at several different temperatures and uranium concentrations.
- FY 2013 Progress Report on the Cleanup of Irradiated 130 g-U/L Uranyl Sulfate SHINE Target Solutions Final

The sulfate to nitrate conversion process was studied to determine the effectiveness of reagents for the target solution at a variety of reagent concentrations, reaction times and temperatures. Also studied were the partitioning of various isotopes expected to be in the target solution during the sulfate to nitrate conversion process.

- FY13 Progress Report on the Phase I Mini-SHINE Water Irradiations and Micro-SHINE Irradiations

  Samples of water, sodium bisulfate and uranyl sulfate were irradiated to study the gases produced via radiolysis, the pH of solutions pre and post-irradiation, and the effects of the addition of catalysts for the prevention of uranyl peroxide formation. Irradiated uranyl sulfate solutions were also used to conduct partitioning experiments of various isotopes when passed through a Mo-recovery column, and to conduct iodine speciation experiments.

- 2012-13 Blue Room Low Enriched Uranium Sample Irradiation, Associated Gas Handling System, and Subsequent Separation Chemistry.

  A sample of LEU sulfate solution was prepared and irradiated in order to produce Mo-99. Data was obtained on radiolytic gas production, isotopes produced from the irradiation, and Mo-99 recovery on a [Proprietary Information] column.

- Development of Recovery and Purification Processes for Mo-99 from an Accelerator-Driven Subcritical Target Solution: Determination of Distribution Coefficients for Competing Components and Micro-SHINE Tracer Column Results

  Batch and column studies were performed, which indicated that most components of the target solution will not strongly compete with Mo for adsorption sites on [Proprietary Information].

The corrosion resistance of the materials of construction of vessels and piping in contact with target solution is also currently being tested by Oak Ridge National Laboratory.

As described in section 3, testing is being performed at Argonne National Laboratory to ensure kinetic effects of peroxide formation and destruction in the SHINE solution are fully understood.

6 SPECIFICATIONS

The following tables provide specifications for the fresh uranium metal, uranium oxide, target solution, and other components that have the potential to affect the safe and reliable operation of the target solution. Operating limits for target solution irradiation and other processes are provided where they influence the performance of the target solution. Acceptance bands will be refined upon completion of the detailed design work for the SHINE facility.

Table 6.1 Uranium Metal and Oxide Specifications

Specified Item	Symbol	Units	Specification Limits LEU Metal / U_3O_8	Equivalent Boron Content (EBC) Factors
Uranium Purity	U	gU/g	[Proprietary Information]	N/A
U-232	U-232	µg/gU	[Proprietary Information]	N/A
U-234	U-234	µg/gU	[Proprietary Information]	N/A
U-235	U-235	wt. %	19.75 (± 0.2)	N/A
U-236	U-236	µg/gU	[Proprietary Information]	N/A
Tc-99 + Sr-90	Tc-99	Bq/gU	[Proprietary Information]	N/A
TRU (Alpha)	TRU	Bq/gU	[Proprietary Information]	N/A
Beta	Beta	Bq/gU	[Proprietary Information]	N/A
Activation Products	ActProd	Bq/gU	[Proprietary Information]	N/A
Fission Products	FissProd	Bq/gU	[Proprietary Information]	N/A
Moisture (U_3O_8 only)	H2O	ppm or µg/g oxide sample	[Proprietary Information]	N/A
Density (U_3O_8 only)	Density	g/cm^3	[Proprietary Information]	N/A
Surface Area (U_3O_8 only)		m^2/g	[Proprietary Information]	N/A
Particle Size (U metal only)		Mm	[Proprietary Information]	N/A
Temperature (storage)		°C	[Proprietary Information]	N/A
Impurities				
Aluminum	Al	µg/gU	[Proprietary Information]	0.0000
Antimony	Sb	µg/gU	[Proprietary Information]	
Arsenic	As	µg/gU	[Proprietary Information]	0.0008

Specified Item	Symbol	Units	Specification Limits LEU Metal / U_3O_8	Equivalent Boron Content (EBC) Factors
Barium	Ba	µg/gU	[Proprietary Information]	
Beryllium	Be	µg/gU	[Proprietary Information]	0.0000
Boron	Be	µg/gU	[Proprietary Information]	1.0000
Cadmium	Cd	µg/gU	[Proprietary Information]	0.3172
Calcium	Ca	µg/gU	[Proprietary Information]	0.0002
Carbon	C	µg/gU	[Proprietary Information]	0.0000
Cesium	Cs	µg/gU	[Proprietary Information]	
Chromium	Cr	µg/gU	[Proprietary Information]	0.0008
Cobalt	Co	µg/gU	[Proprietary Information]	0.0089
Copper	Cu	µg/gU	[Proprietary Information]	0.0008
Dysprosium	Dy	µg/gU	[Proprietary Information]	0.0818
Europium	Eu	µg/gU	[Proprietary Information]	0.4250
Gadolinium	Gd	µg/gU	[Proprietary Information]	4.3991
Hafnium	Hf	µg/gU	[Proprietary Information]	
Iron	Fe	µg/gU	[Proprietary Information]	0.0006
Lead	Pb	µg/gU	[Proprietary Information]	0.0000
Lithium	Li	µg/gU	[Proprietary Information]	0.1439
Magnesium	Mg	µg/gU	[Proprietary Information]	0.0000
Manganese	Mn	µg/gU	[Proprietary Information]	0.0034
Mercury	Mg	µg/gU	[Proprietary Information]	
Molybdenum	Mo	µg/gU	[Proprietary Information]	0.0004
Nickel	Ni	µg/gU	[Proprietary Information]	0.0011
Niobium	Nb	µg/gU	[Proprietary Information]	0.0002
Nitrogen	N	µg/gU	[Proprietary Information]	0.0019

Specified Item	Symbol	Units	Specification Limits LEU Metal / U_3O_8	Equivalent Boron Content (EBC) Factors
Phosphorus	P	µg/gU	[Proprietary Information]	0.0000
Potassium	K	µg/gU	[Proprietary Information]	0.0008
Samarium	Sm	µg/gU	[Proprietary Information]	0.5336
Silicon	Si	µg/gU	[Proprietary Information]	0.0000
Silver	Ag	µg/gU	[Proprietary Information]	0.0083
Sodium	Na	µg/gU	[Proprietary Information]	0.0003
Strontium	Sr	µg/gU	[Proprietary Information]	
Tantalum	Ta	µg/gU	[Proprietary Information]	
Thorium	Th	µg/gU	[Proprietary Information]	
Tin	Sn	µg/gU	[Proprietary Information]	0.0000
Titanium	Ti	µg/gU	[Proprietary Information]	
Tungsten	W	µg/gU	[Proprietary Information]	0.0014
Vanadium	V	µg/gU	[Proprietary Information]	0.0014
Zinc	Zn	µg/gU	[Proprietary Information]	0.0002
Zirconium	Zr	µg/gU	[Proprietary Information]	0.0000
TMI (Total Impuritities)		µg/gU	[Proprietary Information]	
Equivalent Boron Content	EBC		[Proprietary Information]	

[a] [Proprietary Information]
[b] "Not Measured" (NM)
[c] "To Be Reported" (TBR)
[d] EBC Factors are taken from ASTM C1233-09, "Standard Practice for Determining EBC of Nuclear Materials." EBC calculations will include: Boron, Cadmium, Dysprosium, Europium, Gadolinium, Lithium, and Samarium. Other EBC factors are provided for informational purposes only.
[e] [Proprietary Information]

Table 6.2 Stock or Bulk Chemicals

Chemical	Symbol	Specification
Nitric acid	HNO_3	ACS reagent, 70%
Sulfuric acid	H_2SO_4	ACS reagent, 95.0-98.0%
[Proprietary Information]	[Proprietary Information]	[Proprietary Information]
[Proprietary Information]	[Proprietary Information]	[Proprietary Information]
Tributyl phosphate	TBP / $(CH_3(CH_2)_3O)_3PO$	≥97% purity
n-Dodecane	$CH_3(CH_2)_{10}CH_3$	≥97% purity
Acetohydroxamic acid	AHA / $CH_3CONHOH$	≥98% purity

Note - ACS reagent grade chemicals to meet Current ACS Specification

Table 6.3 Uranium Metal Dissolution

Specified Item	Units	Specification Limits
Nitric acid		
Concentration	M	10 to 13
volume per 1g U	mL	10 to 20
Temperature	°C	75 to 85

Table 6.4 Target Solution Preparation and Irradiation

Property	Units	Specification Limit
Uranium concentration	gU/L	114 to 154
		+/- 1% of target concentration
Temperature	°C	20 to 80
Total Mass	kg/TSV batch	[Proprietary Information]
Total Volume	L/TSV batch	[Proprietary Information]
pH (at 20°C)	pH	[Proprietary Information]
[Proprietary Information]	[Proprietary Information]	[Proprietary Information]

Table 6.5 Uranyl sulfate to uranyl nitrate conversion

Property	Units	Specification Limit
Temperature	°C	55 to 65
[Proprietary Information]	[Proprietary Information]	[Proprietary Information]
[Proprietary Information]	[Proprietary Information]	[Proprietary Information]

Table 6.6 UREX

Property	Units	Specification Limit
Extraction solvent		
Composition		30 ± 1 vol% TBP in n-Dodecane
Temperature	°C	25 ± 5, safety limit ≤120
Scrub solution		
Composition		0.1M AHA in 0.3M HNO_3
Temperature	°C	25 ± 5, safety limit ≤120

Strip solution		
Composition		0.01M HNO_3
Temperature	°C	50 ± 5, safety limit ≤120
Wash solution		
Composition		n-Dodecane
Temperature	°C	safety limit ≤120

Table 6.7 Denitration

Property	Units	Specification Limit
Conversion Temperature	°C	300 to 400
Extent of Conversion		≥99%
Extent of Dehydration		TBD*

*Note – Dehydration measurement required only for confirmation of uranium mass fraction in uranium oxide

7 TARGET SOLUTION TESTING REQUIREMENTS

The following are testing requirements designed to ensure that fresh uranium and prepared target solution meet all required specifications to ensure safe and reliable performance. The test requirements may be revised based on the results of detailed design.

7.1 Receipt inspection of uranium metal and uranium oxide

Uranium metal will be received in a solid form from a Department of Energy (DOE) supplier. Upon receipt, the material will be visually inspected for any apparent defects or foreign material. Manufacturer certificates of analyses and other accompanying documentation will be reviewed to verify the material meets all specifications listed in Table 6.1.

If SHINE elects to obtain material in the form of uranium oxide, the material will be similarly inspected, and the documentation reviewed, to ensure the material complies with all required specifications.

7.2 Control of chemical reagents

All chemicals received at the facility intended to be used in the preparation, processing or cleanup of target solution will be controlled via the site chemical control program. Documentation will be reviewed upon receipt to ensure the chemical meets all specifications listed in Section 6. Procedures will be used to provide for the proper use of chemicals and to prevent the introduction of impurities. Testing and verification will be conducted as required for each process to ensure that the correct chemical with the correct specifications is used.

7.3 Testing of target solution pre-irradiation

After preparation of fresh target solution as described in Section 3, or after extraction of Molybdenum-99 and prior to re-irradiation of target solution, samples will be obtained and analyzed to ensure the solution meets the specifications outlined in Section 6. If the solution does not meet all specifications, it will be adjusted by the addition of components to meet

acceptance criteria if possible, or it will be cleaned up and reconstituted through the Uranyl Nitrate Conversion System.

The following testing or verification will be conducted:

- Solution pH
- Uranium concentration
- [Proprietary Information]
- Other parameters as deemed necessary based on detailed design

Additionally, the following parameters will be determined prior to irradiation:

- Total solution volume
- Total solution mass (inferred from volume and uranium concentration)

7.4 In-line testing of target solution during irradiation

During irradiation, all target solution will be monitored for the following parameters to ensure the solution meets operating conditions as specified in Table 6.4.

- Temperature
- Other parameters as deemed necessary based on detailed design

7.5 Testing of target solution during cleanup

Batches of target solution that are sent through the target solution cleanup process will be tested or monitored to ensure all conditions specified in Tables 6.5, 6.6 and 6.7 are met.

The following testing or monitoring will be performed:

- Temperature
- Other parameters as deemed necessary based on detailed design

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