ENCLOSURE 2

SHINE MEDICAL TECHNOLOGIES, LLC

SHINE MEDICAL TECHNOLOGIES, LLC APPLICATION FOR AN OPERATING LICENSE SHINE RESPONSE TO REQUEST FOR ADDITIONAL INFORMATION 4A-4

PUBLIC VERSION

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

RAI 4a-4

The ISG Augmenting NUREG-1537, Part 2, Section 4a2.2.1, "Reactor Fuel," states that information provided should include various phenomena that results in potential fuel precipitation.

SHINE FSAR Section 4a2.6.3.5, "Limiting Core Configuration," states that uranyl peroxide is known to precipitate out of uranyl sulfate solution under certain conditions of irradiation due to the presence of hydrogen peroxide formed from radiolysis effects. The formation of uranium precipitates is dependent on the rates of hydrogen peroxide production, the peroxide solubility, and the rate of decomposition. The key factors influencing these parameters include the solution chemistry (including pH and catalysts), temperature, and power density. The NRC staff needs more information to understand how these parameters associated with solubility are monitored and maintained to prevent uranium precipitation from the target solution.

Explain how solubility, temperature, pH, power density, and any other target solution parameters are measured, monitored, and maintained within acceptable limits at zero power with cold conditions to prevent precipitation of uranium from the target solution.

SHINE Response

The key parameters that affect the peroxide decomposition rate are temperature and catalyst concentration, while the peroxide solubility is primarily affected by pH and to a much lesser extent by the uranium concentration. The full operating range of these parameters were considered in the development of SHINE's power density limits.

The pH, catalyst concentration, and uranium concentration are measured parameters of the target solution, maintained within the limits defined in the Target Solution Qualification Program and the technical specifications. At a minimum, sampling is performed after preparation of a new batch of target solution and after making adjustments to an existing batch of target solution, prior to transferring the batch to the TSV. Unlike nitric acid systems, sulfuric acid is stable under

irradiation, and [ ]PROP/ECI. Therefore, the target solution chemistry (i.e., pH, catalyst concentration, and uranium concentration) does not change during irradiation, other than the small effects of water holdup in the target solution vessel (TSV) off-gas system (TOGS).

Uranium concentration has two competing effects with respect to precipitation. Higher uranium concentration results in a lower peroxide solubility limit, but also decreases the peroxide generation rate based on a lower G value. These effects are small in comparison to the effects from the other parameters and do not need to be accounted for in the power density limits based on the limited operating range and the small, competing effects. Bounding uranium concentrations are used when evaluating the acceptability of the limits with respect to the other parameters.

While the limits for pH and uranium concentration are dictated by the process needs to allow the subcritical assembly and extraction process to operate efficiently, the catalyst concentration limit is defined such that it will counteract the effects of increasing pH in the prevention of uranyl peroxide precipitation. Higher pH in the target solution decreases the peroxide solubility. The catalyst concentration is correspondingly increased for higher pH target solution to increase the destruction rate of the peroxide, to keep the peroxide concentration under the solubility limit. With the catalyst concentration compensating for the pH effects, the parameters of concern are then limited to power density and temperature.

Because the peroxide decomposition rate is highly dependent on temperature, the acceptable power density is also highly dependent on temperature. A curve for the acceptable steady-state power density as a function of temperature in the SHINE system was developed with experimental data from Argonne National Laboratory (ANL), Oak Ridge National Laboratory (ORNL), and the Kinetics Experiments on Water Boilers (KEWB), Argus, L-8, and L-54 uranyl sulfate systems. The data from these experiments and correlations for peroxide decomposition rates and peroxide solubility developed at ORNL were used to generate data points at conditions equivalent to SHINE's operating conditions by taking into account differences in key parameters. These data points define a region of safe operation and confirm the SHINE power density limit curve was conservatively defined.

During steady-state operation at power, the thermal hydraulic properties of the system result in an inherent relationship between the power density and temperature. Based on the minimum primary closed loop cooling system (PCLS) supply temperature (see Table 5a2.2-1 of the Final Safety Analysis Report [FSAR]), the system maintains approximately 30 percent margin between the steady-state power and the power density limit. At the nominal PCLS temperature, the system maintains approximately 90 percent margin.

At zero power with cold conditions, there is not significant peroxide being generated in the target solution and the system remains well below the peroxide solubility limit. During the transition from zero power cold conditions to steady-state operation, the power density as a function of temperature exceeds that of steady-state operation because the target solution is still heating up. The technical specifications define the acceptable region for power density and temperature during this transition (i.e., power ramp up).

In addition to the inherent thermal hydraulic properties of the system and the maximum power of the system, the peroxide concentration is also affected by the [ ]PROP/ECI and PCLS flow rate during the ramp up phase. The [ ]PROP/ECI and PCLS flow rate will be adjusted during the ramp up, as necessary, to maintain the system within the acceptable region of the power density limit versus temperature curve, defined in the technical specifications.

Failure to control power density and temperature in accordance with the technical specifications, while not an anticipated event, would not cause damage to the primary system boundary. Calculations show that the uranyl peroxide precipitation for this uncontrolled event is less than [ ]PROP/ECI. During irradiation, the bubble-driven flow would keep the precipitate distributed throughout the target solution, having minimal effect on the reactivity of the system. Following irradiation, the precipitate would drain with the target solution to the TSV dump tank. The TSV dump tank, as well as the other target solution-containing piping and tanks downstream, are designed to be geometrically favorable for the most reactive uranium concentration, preventing any safety impacts from the precipitate.

During a driver drop out event, the lack of bubble-driven flow could result in the settling of precipitate, resulting in either an increase or decrease to the system reactivity, depending on the location of the precipitate within the TSV. This reactivity effect is expected to be small, and the system is protected by the neutron flux detectors and the TSV reactivity protection system (TRPS). If the reactivity effects result in the system exceeding either the wide range neutron flux or power range neutron flux limits, the TRPS will initiate an IU Cell Safety Actuation.

In responding to this request, SHINE re-evaluated the power density limits of the SHINE system to account for both the ramp up and steady-state phases of operation. A mark-up of the FSAR, incorporating the revised evaluation, is provided in Attachment 1. SHINE has also revised the technical specifications to incorporate this curve which defines the acceptable region for power density and temperature both during the transition from zero power cold conditions to steady-state operation and at steady-state operation. The revision to the technical specifications also provides clarification of the applicability of the transient average power density limit previously provided in the technical specifications. A mark-up of the technical specifications is provided in Attachment 2. SHINE will provide a revision to the technical specifications incorporating the mark-up, as well as corresponding technical specification bases, by August 31, 2020.

References

1. NRC letter to SHINE Medical Technologies, LLC, "Issuance of Request for Additional Information Related to the SHINE Medical Technologies, LLC Operating License Application (EPID No. L-2019-NEW-0004)," dated May 26, 2020 (ML20148M278)

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

ENCLOSURE 2
ATTACHMENT 1

SHINE MEDICAL TECHNOLOGIES, LLC

SHINE MEDICAL TECHNOLOGIES, LLC APPLICATION FOR AN OPERATING LICENSE
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FINAL SAFETY ANALYSIS REPORT CHANGES
PUBLIC VERSION
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3 pages follow

Combined with the analyses described in Subsection 4a2.6.3.7, the target solution can be shut down safely and maintained in a safe shutdown condition.

4a2.6.3.5 Limiting Core Configuration

The limiting core configuration is that core that produces the highest power density possible for the target solution. This power density is then compared to power density limits determined from historical stability data and solution chemistry effects to ensure acceptability.

Power Density Limits

The power density is important for ensuring thermal hydraulic stability. If the average power density is too high, the bubbles generated through radiolysis can cause surface effects such as sloshing from turbulent liquid contacting the vessel walls. Section 3.2 of IAEA-TECDOC-1601 (IAEA, 2008) summarizes historical data on power density instabilities. Based on experiments conducted at historic aqueous homogeneous reactor (AHR) facilities (Russian ARGUS facility and French SILENE facility), steady state, stable core conditions could be sustained at power densities below approximately 1.8 thermal kilowatts/liter (kW/L) (BNL, 2010; IAEA, 2008; Barbry Francis, 2007). The SHINE system is designed to ensure that power density is maintained less than [ ]PROP/ECI. However, the chemical stability data below provides additional restriction on the limiting power densities.

Power density is a key parameter for chemical stability. Uranyl peroxide is known to precipitate out of uranyl sulfate solution under certain conditions of irradiation, due to the presence of hydrogen peroxide formed from radiolysis effects. The formation of uranium precipitates is dependent on the rates of hydrogen peroxide production, the peroxide solubility, and the rate of decomposition. The key factors influencing these parameters include the solution chemistry (including pH and catalysts), temperature, and power density. SHINE has evaluated the available literature and found that in operating within the power density limits presented in Table 4a2.6-9 and the other operating limits of Table 4a2.2-2, formation of significant uranyl peroxide precipitates is not expected. Supporting literature is from existing operating reactor data and experimental investigations. The average steady-state power density limit to prevent precipitation is determined to be [ ]PROP/ECI at cold conditions of 68°F (20°C). The transient power density limit is determined to be [ ]PROP/ECI at cold conditions of 68°F (20°C), the duration of which is limited by the high time-average neutron flux trip within the TRPS.

The operational limits related to preventing uranyl peroxide precipitation include a correlation for the steady-state power density as a function of temperature, a correlation for the minimum concentration of [ ]PROP/ECI catalyst required as a function of pH, and a transient power density limit.

Peroxide decomposition rates are highly dependent on temperature and catalyst concentrations, while peroxide solubility is highly dependent on the pH of the solution. Uranium concentration also has a lesser effect on peroxide solubility but a compensating effect in the rate of hydrogen production, as a result the power density limits are independent of uranium concentration over the operating range.

For higher pH in the target solution, the peroxide solubility decreases, requiring an increase in the catalyst concentration to achieve a corresponding increase in the peroxide decomposition rate. A correlation for the [ ]PROP/ECI catalyst concentration required as a function of pH is

provided in Table 4a2.6-9. A minimum concentration of [ ]$^{PROP/ECI}$ is imposed in addition to the correlation.

With the appropriate catalyst to compensate for pH, the power density limit is solely a function of the average temperature in the target solution. The correlation for the limiting average steady-state power density is provided in Table 4a2.6-9. A maximum value of [ ]$^{PROP/ECI}$ is also imposed due to the thermal hydraulic stability concerns discussed previously.

Although an extensive history of transient testing with AHRs has shown that precipitation will not occur with transient power densities in excess of 100 kW/L, the transient power density limit for the SHINE system is set to the maximum steady-state power density limit of [ ]$^{PROP/ECI}$. The averaging time of the high time-average neutron flux trip was determined by evaluating the temperature effects of transients at this power density and ensuring the limiting event would not challenge the safety limits for the system.

Precipitation of the uranium from the solution is undesired due to potential for significant reactivity insertion and the possibility of difficulties in dumping the solution. Remaining below the power density limits and within the chemistry and temperature limits in Table 4a2.6-9 and Table 4a2.2-2 results in hydrogen peroxide concentrations below those that may result in precipitation.

Limiting Core Configuration Results

The limiting core configuration for a given power level is the core configuration that has the highest allowable power density. It was determined that the limiting core configuration is set by the thermal hydraulics analysis as the minimum volume to ensure that target solution boiling does not occur.

The limiting core configuration occurs at a minimum volume of [ ]$^{PROP/ECI}$. This fill volume has a calculated uranium concentration of [ ]$^{PROP/ECI}$ and a cold fill height of approximately [ ]$^{PROP/ECI}$ in the TSV. At a TSV power level of 125 kW, this results in an average power density of less than [ ]$^{PROP/ECI}$. The local peak power density is less than [ ]$^{PROP/ECI}$. The limiting core configuration is summarized in Table 4a2.6-10.

The aspect ratio of the TSV and the startup method of using the 1/M curve to fill to approximately 5 percent by volume below critical, results in core configurations with smaller fill volumes having lower reactivity. This is due to the fact that although the volume margin is proportional and smaller with smaller core configurations, the final fill height is in a location of higher target solution worth, resulting in an overall larger reactivity margin to critical. With the lower reactivity in this system, it is estimated that a neutron source strength ~~approximately~~of [ ]$^{PROP/ECI}$ ~~above the expected maximum of 1.5E+14 n/sec~~ would be needed to reach the operating limit of 125 kW.

The peak flux density in the limiting core configuration is less than [ ]$^{PROP/ECI}$.

The average power density has greater than [ ]$^{PROP/ECI}$ margin from the [ ]$^{PROP/ECI}$, and greater than [ ]$^{PROP/ECI}$ margin to the average steady-state power density limit of [ ]$^{PROP/ECI}$ that was determined based on an anticipated solution temperature of 128°F (53°C).

Table 4a2.6-9 – Power Density Limits for Target Solution

	Correlation	Additional Bounds
Steady-state average power density limit (kW/L)	[ ]PROP/ECI	[ ]PROP/ECI
Minimum [ ]PROP/ECI concentration required (ppm)	[ ]PROP/ECI	[ ]PROP/ECI
Transient average power density limit (kW/L)	[ ]PROP/ECI	N/A

ENCLOSURE 2
ATTACHMENT 2

SHINE MEDICAL TECHNOLOGIES, LLC

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TECHNICAL SPECIFICATIONS CHANGES
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LCO 3.1.6	Temperature and average power density of the target solution in the TSV shall be within the "Acceptable" region of Figure 3.1.6, defined by the following equation: Power Density Limit (kW/L) =[ ]PROP/ECI Note – This LCO does not apply during loss of driver and restart transients, see LCO 3.1.7 for the transient average power density limit.
Applicability	Associated IU in Mode 2
Action	According to Table 3.1.6
SR 3.1.6	Verify temperature and average power density of the target solution in the TSV is within the "Acceptable" region of Figure 3.1.6 hourly. Note – This SR is only required to be performed during power ramp up [ ]PROP/ECI.

Table 3.1.6 Power Density Limit Actions

	Action (per IU)	Completion Time
1.	If the power density-temperature conditions are not within the acceptable region, Place the associated IU in Mode 3.	Immediately

Figure 3.1.6 Target Solution Average Power Density vs Temperature

[ ]PROP/ECI

~~LCO 3.1.6~~ LCO 3.1.7	Transient a~~A~~verage power density of target solution within the TSV shall be [ ]PROP/ECI
Applicability	Associated IU in Mode 2
Action	~~If the power density limit is exceeded, place the associated IU in Mode 3.~~According to Table 3.1.7
~~SR 3.1.6~~ SR 3.1.7	Verify transient average power density of the target solution in the TSV ~~is~~did not exceed [ ]PROP/ECI ~~daily~~following any driver restart after a loss of driver event.

Table 3.1.7 Transient Average Power Density Actions

	Action (per IU)	Completion Time
1.	If the transient average power density limit is exceeded, Place the associated IU in Mode 3.	Immediately

DF 4.3.2	1. The subcritical assembly system principally consists of the TSV, subcritical assembly support structure (SASS), neutron multiplier and TSV dump tank, and is described in FSAR Section 4a2.2. 2. Redundant overflow tubes are provided for the TSV to protect the TSV headspace to allow for TOGS operation.

~~DF 4.3.3~~	~~The characteristics of the cooling in the subcritical assembly are designed to maintain the relationship between average TSV target solution power density and average TSV target solution temperature within the "Acceptable" region shown in the power density limit curve (Figure 4.3.3). As designed, the PCLS maintains an approximately 50% margin between steady-state power and the power density limit at the corresponding temperature.~~

~~Figure 4.3.3 – Target Solution Average Power Density vs. Average Temperature~~

PROP/ECI