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Abstract

On January 3, 1961, at the National Reactor Testing Station, in Idaho Falls, Idaho, the Stationary Low Power Reactor No. 1 (SL-1) experienced a major nuclear excursion, killing three people, and destroying the reactor core. The SL-1 reactor, a 3 MW_t boiling water reactor, was shut down and undergoing routine maintenance work at the time. This paper presents an analysis of the SL-1 reactor excursion using the RELAP5-3D thermal-hydraulic and nuclear analysis code, with the intent of simulating the accident from the point of reactivity insertion to destruction and vaporization of the fuel. Results are presented, along with a discussion of sensitivity to some reactor and transient parameters (many of the details are only known with a high level of uncertainty).

Introduction

The SL-1 excursion involved a water-covered core in a subcritical mode at low temperatures that experienced a large reactivity insertion resulting from a control rod withdrawal. This reactivity insertion caused the core to achieve prompt criticality in a very short period of time. The inner module fuel temperatures quickly passed the vaporization point, causing fuel destruction. Because the fuel was highly enriched uranium, there is minimal Doppler reactivity feedback. Therefore, the only mechanisms for curtailing the excursion were heating of the water moderator, through direct heating and convective heat transfer from the fuel element to the moderator, and disassembly damage of the reactor, thus changing its geometry. Due to the relatively long time constants associated with fuel element heat conduction and convection, this mechanism was not a dominant contributor in the initial phases of the transient. Once the fuel elements failed, the resulting liquid and solid fragments had considerably shorter heat transfer time constants and vastly increased heat transfer area. The resulting flashing of the water to steam caused a water slug to impact the top of the reactor vessel, sending all unsecured material flying as projectiles (including the central control rod which initiated the event), breaking all piping connections, raising the reactor vessel nine feet, and destroying much of the fuel and core materials. The steam formation and destruction and vaporization of the fuel ended the excursion, and all water was expelled from the vessel. Three workers were killed as a result.[1,2,3,4,5,6]

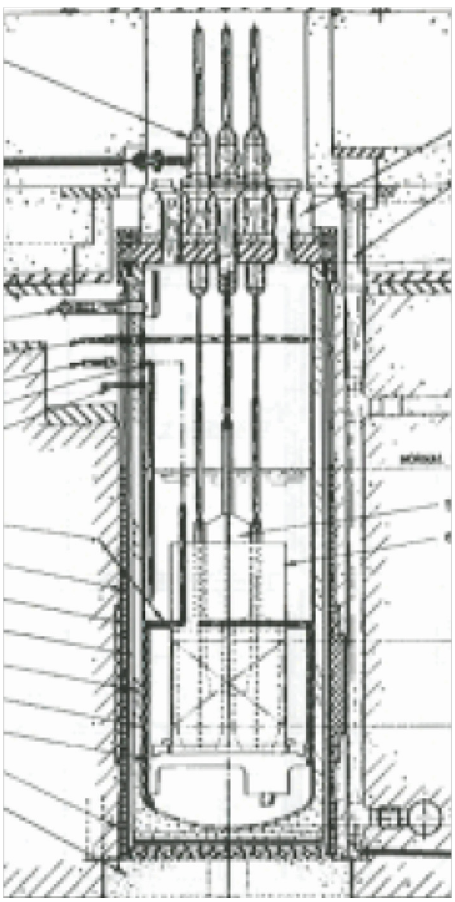
Information on the SL-1 reactor and accident was gathered through a collection of Atomic Energy Commission (AEC) reports made available through the Freedom of Information Act (FOIA), as well as other reports on nuclear criticality excursions and events.

Description of the Model

The following section describes the RELAP5-3D model used in the SL-1 analysis, including assumptions and approximations based on available data.

Since SL-1 was a boiling water reactor, and shutshut downdown at the time of the accident, the RELAP5-3D model boundary is defined as containing the reactor vessel only, including the core and all voids above it. The SL-1 accident occurred with no flow to the core, in a scrammed configuration, and with the vessel head open to the environment. For purposes of the modeling, the piping to and from the reactor vessel is not required for simulation. Figure 1 is a drawing of the SL-1 reactor vessel.[3]

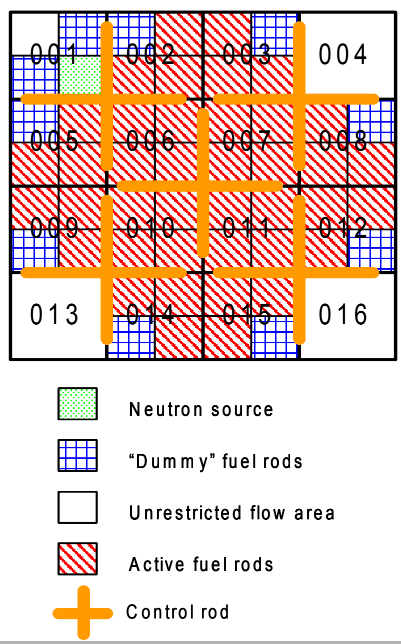
Figure 1: SL-1 Reactor Vessel



The period of the accident reactivity transient is generally accepted to be on the order of 3 to 5 ms.[7] The reactivity insertion is modeled as a ramp change over 4 ms. The system is assumed to be at steady-state initial conditions. The amount of reactivity insertion is estimated at 2.4 $\pm$ 0.3 \$ of reactivity. For the base SL-1 RELAP5-3D model, a reactivity insertion of 2.4 \$ over 4 ms was used. Table 1 contains a list of all relevant parameters for the SL-1 core and accident transient and identifies the sources for each parameter.

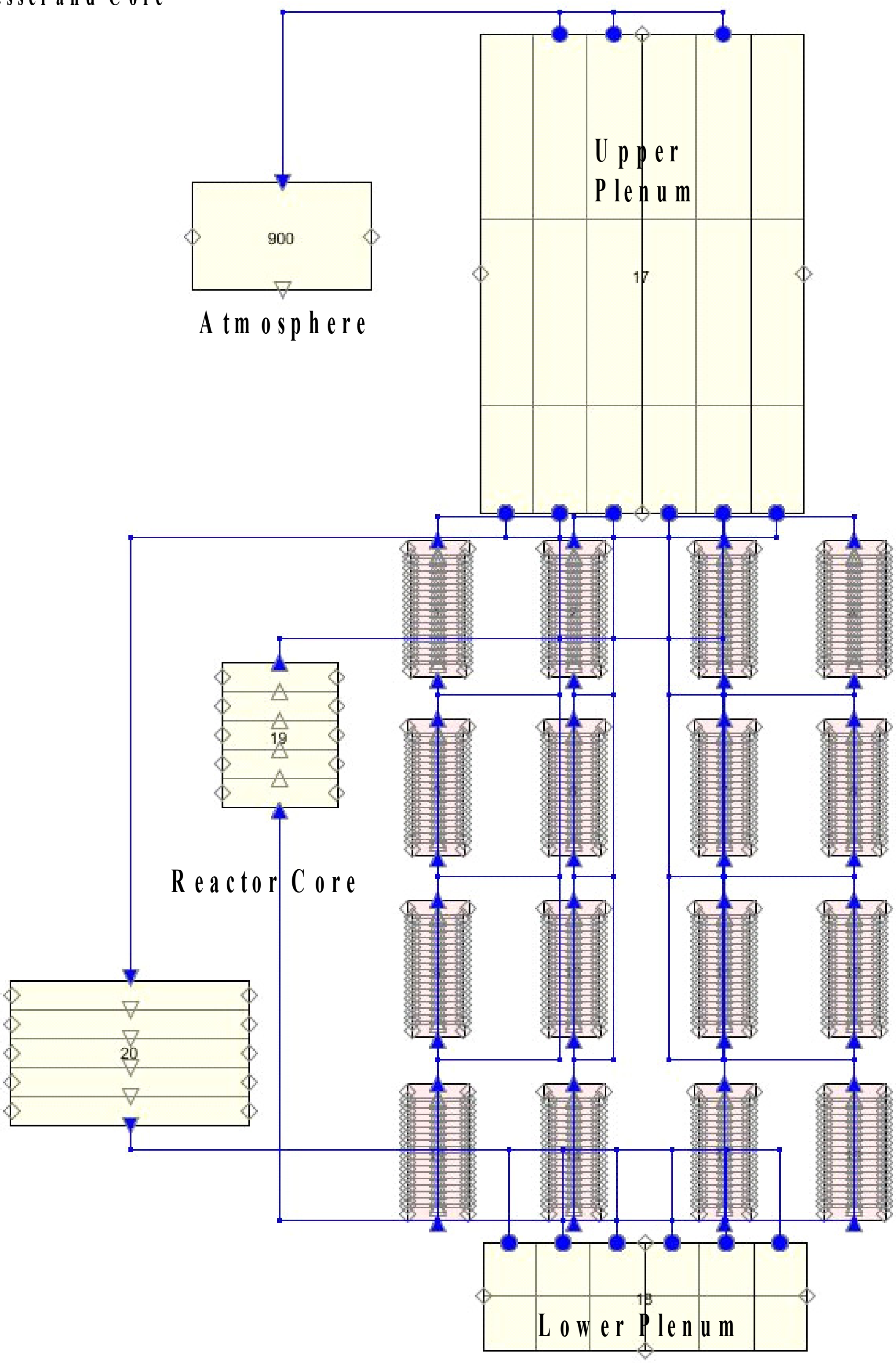
The SL-1 reactor vessel could contain a total of 59 fuel rods, 1 neutron source, 5 cruciform control rods, and 4 T-shaped control rods. At the time of the accident, 40 fuel modules were in place, with dummy non-fueled modules occupying some of the additional spaces. All 5 cruciform control rods were installed, and none of the T-shaped control rods were installed. The reactor core was divided into 16 partitions for modeling purposes. Figure 2 is a plan view of the SL-1 reactor core, indicating how it was divided up for the model.

Figure 2: SL-1 Reactor Core Model Schematic



The RELAP5-3D nodalization of the SL-1 reactor model is shown in Figure 3.

Figure 3: RELAP5-3D Nodalization Diagram of SL-1 Reactor Vessel and Core



The sixteen regions in the reactor core were each modeled using a 20-volume pipe component. Multi-dimensional components were used for the reactor vessel area (upper plenum, core region including downcomer, and lower plenum). The plenums and reactor core were connected using multiple junction components.

The fuel plates were 120 mils in thickness (70 mils of clad and 50 mils of meat). The dummy non-fuel elements were an aluminum-nickel X-8001 alloy material. Aluminum-nickel was also used for the flow boxes in the unrestricted flow areas. Uranium aluminum-nickel alloy material properties were used for active fuel plates. The neutron source was treated as a dummy fuel plate. Heat structure components for dummy and active fuel plates were modeled using 20 axial nodes and 4 radial nodes. The control rod metal material was considered to be negligible and was not explicitly modeled using heat structures.

Melting and vaporization of the fuel plates was accounted for by adjusting the volumetric heat capacity of the fuel meat and aluminum alloy material. The heat of vaporization and heat of fusion were assumed to result in a 10 ^{o}F temperature rise. The volumetric heat capacity tables were adjusted to reflect this assumption. The appropriate thermal conductivity for each phase was modeled as well.

The heat source was distributed over active fuel rods only, using a sine distribution for axial power shape. In the radial direction, 60% of the total power was contained in the center 4 modules (006, 007, 010, 011), and the remaining 40% was distributed over the remaining active fuel modules.

Key nuclear parameters included in the model were estimated based to the available data. A value of 0.007 was used for the effective delayed neutron fraction, β-bar. A prompt neutron generation time of 6×10^{-5} sec^{-1} was used. The ANS79-1 fission product standard option was used, assuming an energy release of 200 MeV/fission. The 931.5 MWD of core operation time, including 11 days of shut down time prior to the accident, was included in the model. A log-density feedback coefficient of 15.037 dollars was used. Doppler feedback was included in the model, using a fuel temperature coefficient of -0.001 dollars/sqrt(^{o}F). The fuel temperature coefficient was not calculated using available SL-1 data, but was estimated through sensitivity calculations, starting with 100% uranium-235, and increasing this coefficient to account for the presence of uranium-238 and nickel in the SL-1 reactor core.

Discussion of Results

Based on the available data from AEC reports on the SL-1 accident, the following estimated key accident conditions were used for comparison to the RELAP5-3D model results. The power is estimated to have peaked at $1.9 \times 10^{10} \pm 0.4 \times 10^{10}$ W. Total energy generated was 130 ± 10 MW-sec, with the preliminary estimates indicating a range of 80 to 270 MW-sec. The vaporization temperature of the fuel plates at centerline was 3740 ^{o}F, with peak temperatures reaching 4721 ^{o}F. The peak water hammer effect was 10000 pounds impact, with steam pressure reaching 500 psia. The upward water velocity following the excursion was approximately 160 ft/sec.[1,2,3,4,5,6]

These results were analyzed using the RELAP5-3D SL-1 model. Figures 4 through 17 show the key parameters throughout the transient. In Figures 12 through 17, the void fraction and temperatures for a representative hot and cold element are presented over 16 axial heights.

Table 2 contains the estimated SL-1 reactor transient parameters and the calculated results from the RELAP5-3D model. A range of calculated values generated by varying modeling parameters is included.

For the base case using the model conditions described above, the key transient parameters are consistent with conditions calculated by the AEC following the accident. Peak power and energy release are higher in the RELAP5-3D model by over an order of magnitude. The RELAP5-3D model results show that the fuel vaporizes or melts throughout the entire core. In reality, the SL-1 reactor core was only partially melted or vaporized, with the majority of damage in the very center of the core (5% of the central core region reached the vaporization temperature of 3740 ^{o}F at the fuel plate centerline). Since RELAP5-3D assumes an intact geometry throughout the transient, the negative reactivity effects of the core disassembly damage could not be modeled accurately, thus resulting in an over-prediction of the damage. Similarly, the over-prediction in fuel temperature is the result of not being able to model the fragmentation of the fuel and the associated decrease in conduction and convection time constants and, more importantly, the increase in overall heat transfer area.

Sensitivity studies were made to try and understand better the fuel temperature behavior during the transient. This was performed by adjusting various core parameters, including Doppler fuel temperature coefficients, which seemed to have the largest effect. It was possible to achieve fuel temperatures that more closely resemble expected temperatures (per the AEC investigation) during the transient by increasing the Doppler fuel temperature coefficients, but this also reduced the overall magnitude of the transient in terms of energy released and power peaks. In these cases, the other key parameters, such as total and maximum power, energy released, and pressures, did not match accident conditions. It is believed that this inability to model the fuel temperatures in the core accurately is a result of the approximations made in development of the model. These approximations (e.g., feedback coefficients, prompt neutron generation time, material properties, and power distribution) were made due to lack of detailed information on certain nuclear and physical characteristics of the SL-1 core.

Conclusions

On January 3, 1961, at the National Reactor Testing Station, in Idaho Falls, Idaho, the Stationary Low Power Reactor No. 1 (SL-1) experienced a major nuclear excursion, killing three people, and destroying the reactor core. The SL-1 reactor, a 3 MW_t boiling water reactor, was shut down and undergoing routine maintenance work at the time.

A RELAP5-3D analysis of the SL-1 reactor excursion, was performed using information available from the AEC event reports. Key characteristics of the transient were reasonably well matched, with the exception of fuel temperatures during the transient. The RELAP5-3D model predicted the peak power and energy release during the transient over an order of magnitude higher, although the general trends matched the expected accident scenario. However, the fuel temperatures were not well predicted due to the inability to properly model the destruction and vaporization of the fuel.

Acknowledgements

The authors wish to acknowledge the contributions of Dr. Larry Foulke and Dr. Bruce Berquist for their assistance in development of the SL-1 RELAP5-3D model.

References

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2. "SL-1 Recovery Operations, January 3 Thru May 20, 1961," IDO-19301 (CEND-1007), June 30, 1961.
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4. Islitzer, Norman F., "The Role of Meteorology Following the Nuclear Accident in Southeast Idaho," IDO-19310, May 1962.
5. "Final Report of SL-1 Recovery Operation," IDO-19311, July 27, 1962.
6. "Additional Analysis of the SL-1 Excursion, Final Report of Progress July through October 1962," IDO-19313, November 21, 1962.
7. "The Technology of Nuclear Reactor Safety," Volume 1, Reactor Physics and Control, T. J. Thompson and J. G. Beckerley, Eds., pp.653-707, The M.I.T. Press, Cambridge, Massachusetts, 1964.

Table 1: Key SL-1 Reactor and Transient Parameters

Parameter	Value	Source	Range of Values
Reactivity Insertion Time (ms)	4	IDO-19311	3 to 5
Delayed neutron fraction	0.007	IDO-19311	0.0065 to 0.007
Prompt neutron lifetime (sec)	6×10^{-5}	IDO-19311	4×10^{-5} to 8×10^{-5}
Excess reactivity insertion ($)	2.4	IDO-19311	2.1 to 2.7
Log-density coefficient ($) (based on $\alpha_T = -5 \times 10^{-5}$ /K)	15.037	IDO-19311	15.037 to 19.1698
Doppler fuel temperature coefficient ($/sqrt($^oF$))	-0.001	Estimated by Calculation	-0.06 to -0.0002

Table 2: Comparison of SL-1 Accident to RELAP5-3D Model Results

Parameter	SL-1 Accident Value	RELAP5-3D Base Model Value	RELAP5-3D Model Range of Values
Total fissions	2×10^{18}	9.34×10^{19}	6.2×10^{18} to 1.1×10^{20}
Upward water slug velocity (max) (ft/sec)	159	170	~0 to ~250
Energy released by the nuclear excursion (MW-sec)	130	299	~20 to 330
Peak Power (MW)	19000	183300	6000 to 280000
Peak Fuel Temperature (Central Region of Core) (^oF)	4721	>10000	3740 to >10000

Figure 4. SL-1 - Power Generated

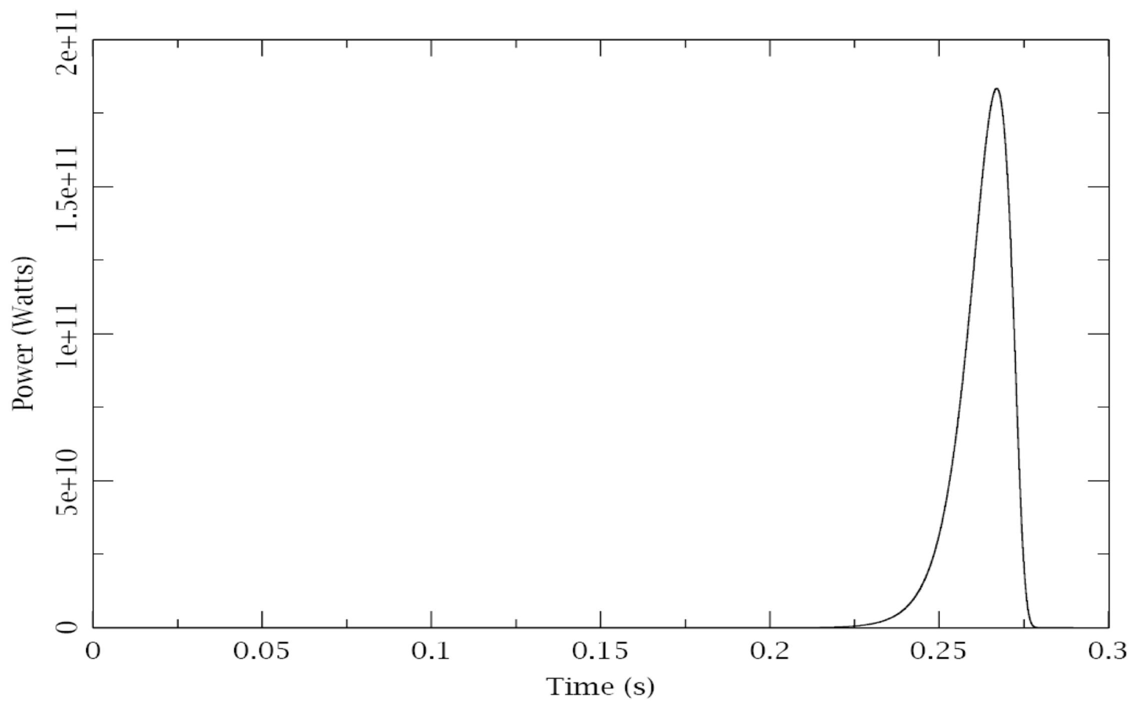

Figure 5. SL-1 - Reactivity

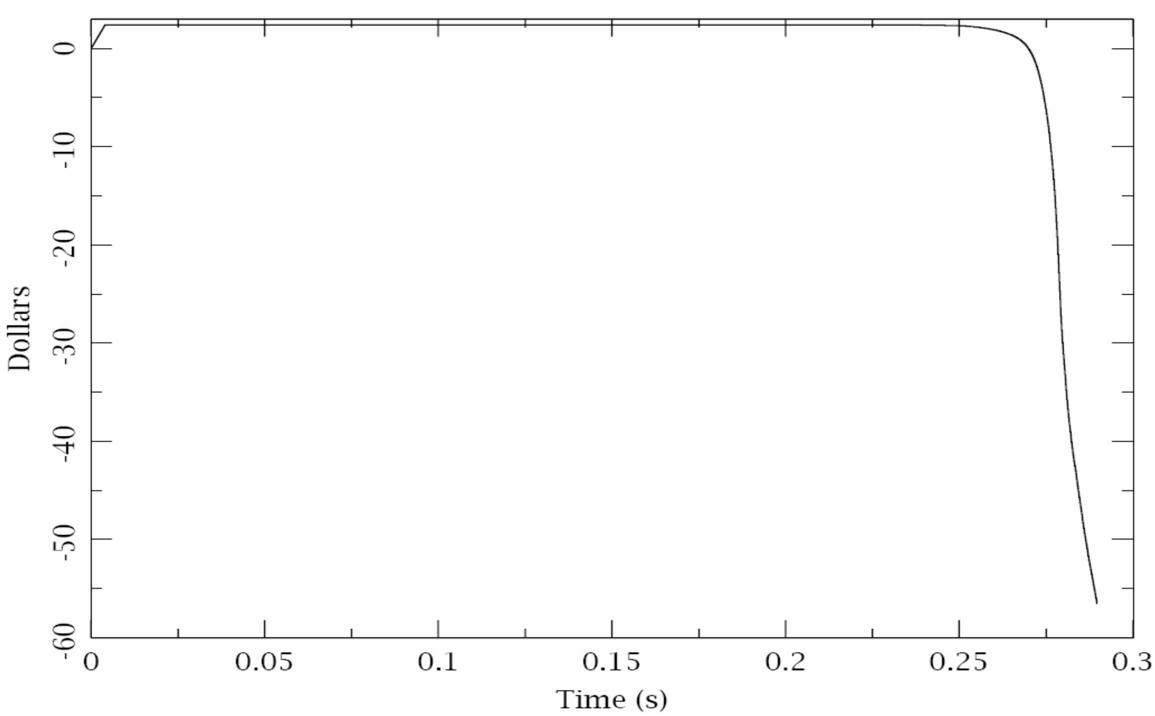

Figure 6. SL-1 - Energy Deposited

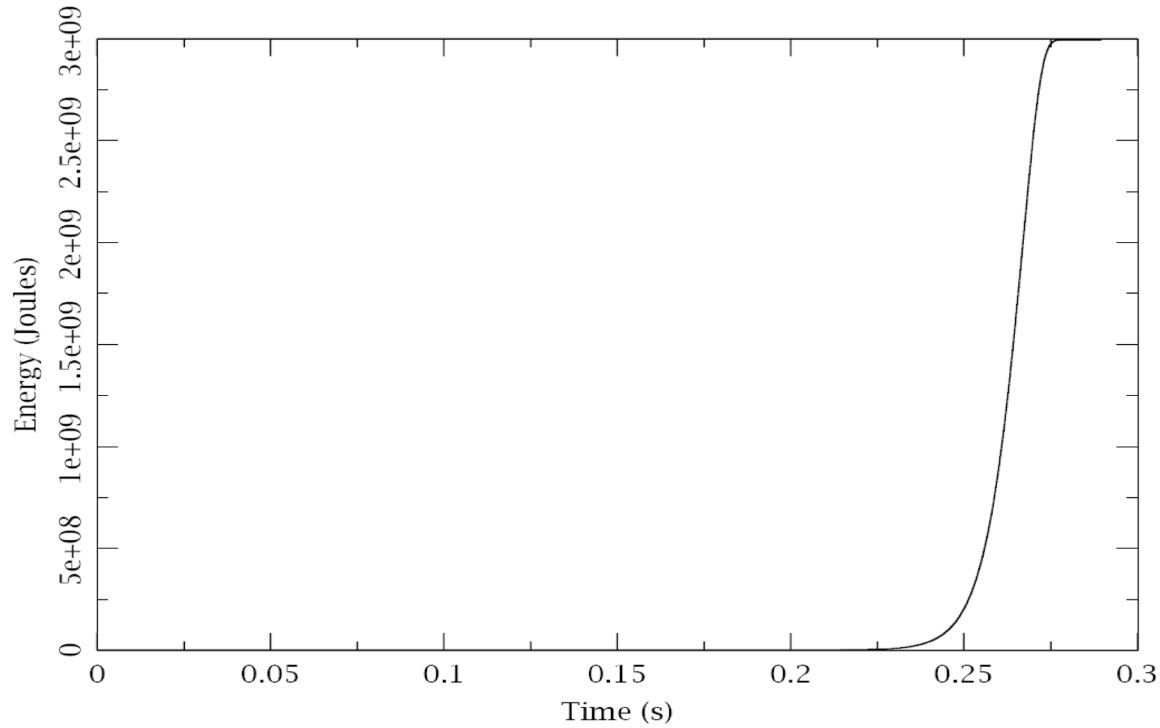

Figure 7. SL-1 - Total Fissions

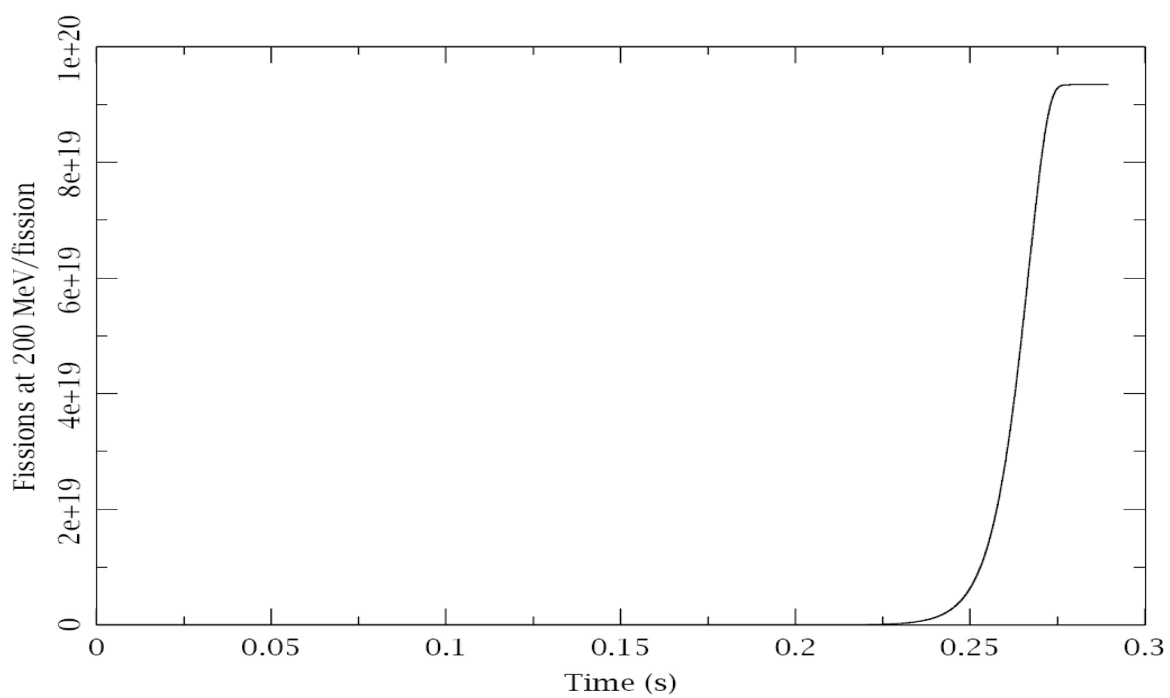

Figure 8. SL-1 - Maximum Power

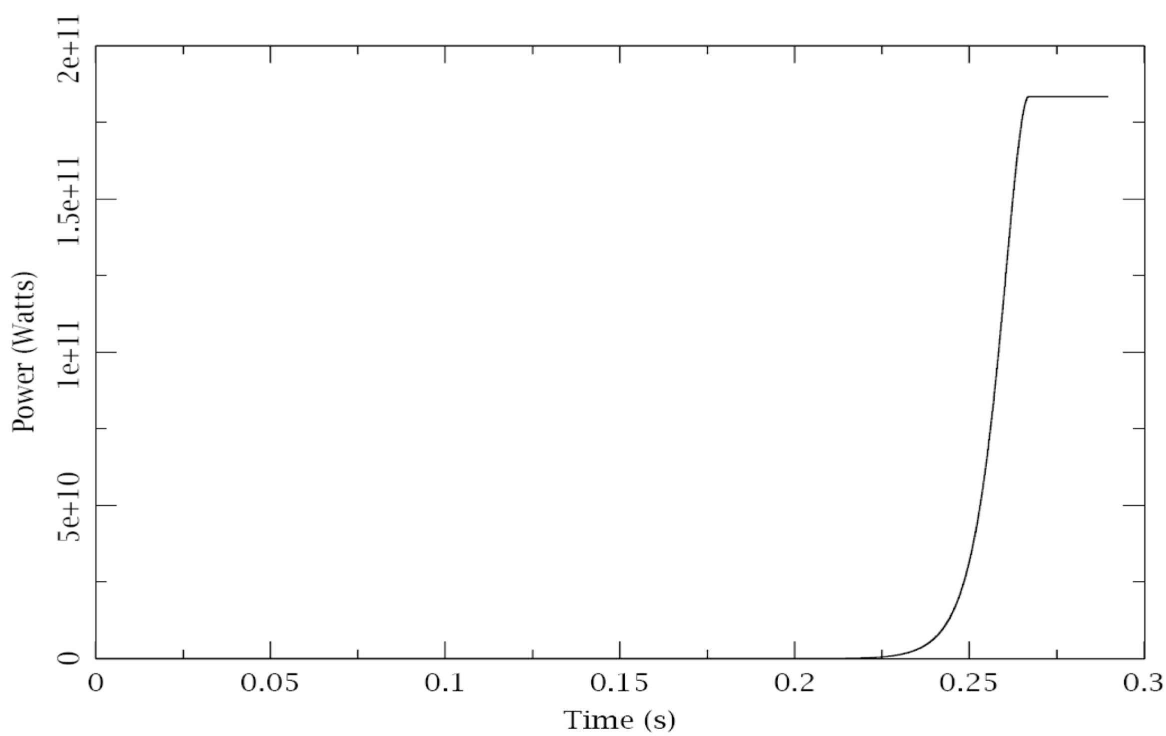

Figure 9. SL-1 - Pressure Below Head

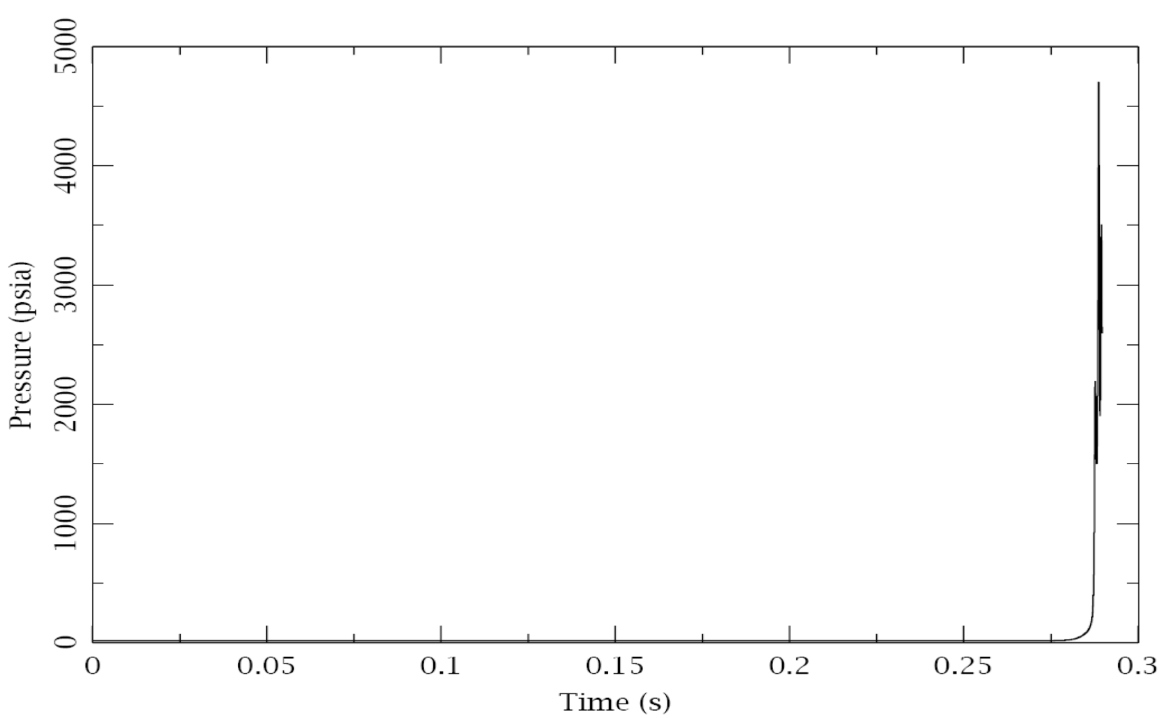

Figure 10. SL-1 - Fluid Fraction Below Head

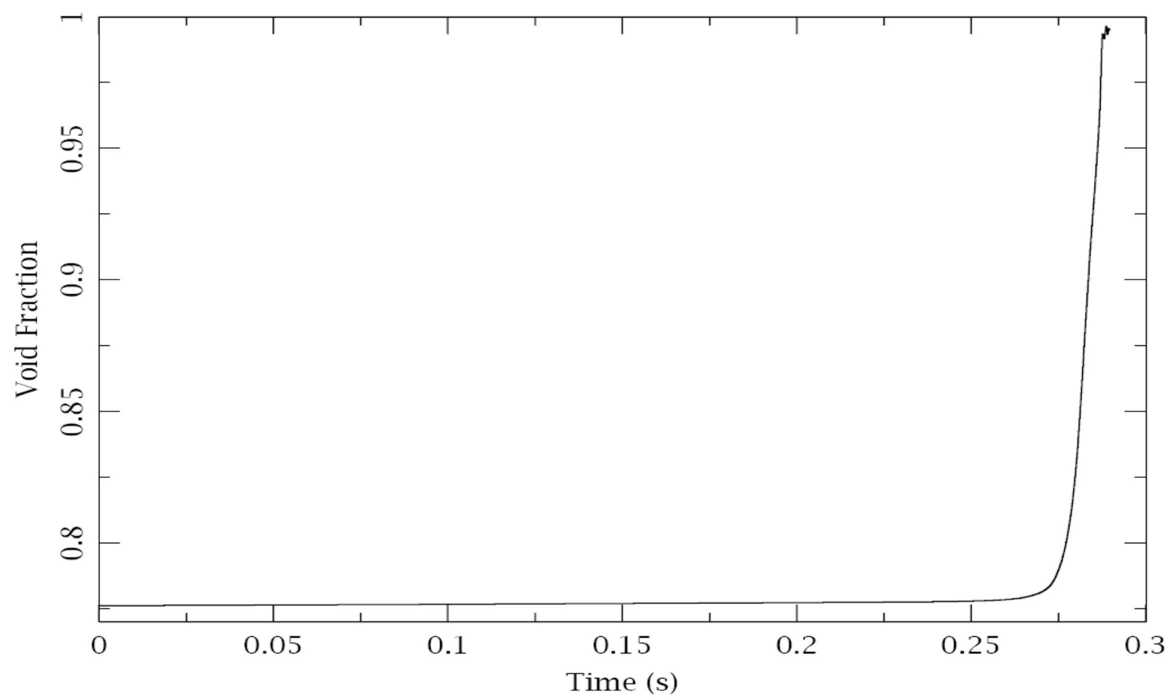

Figure 11. SL-1 - Water Slug Velocity

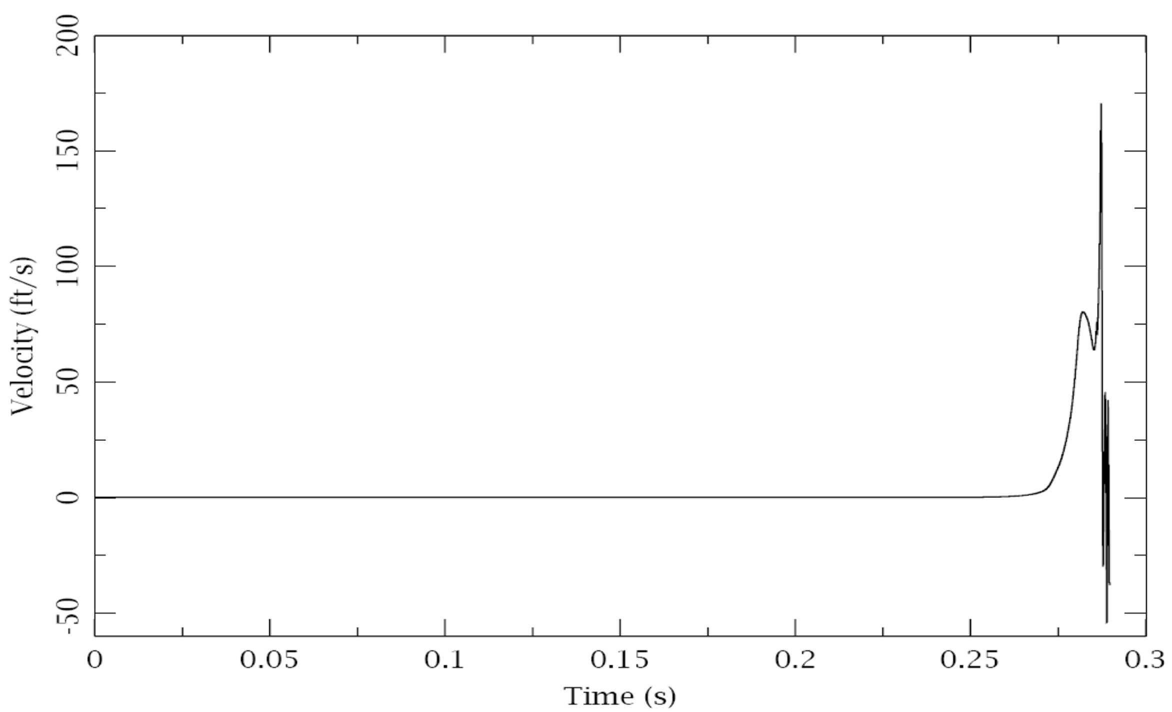

Figure 12. SL-1 - Hot Module Void Fraction

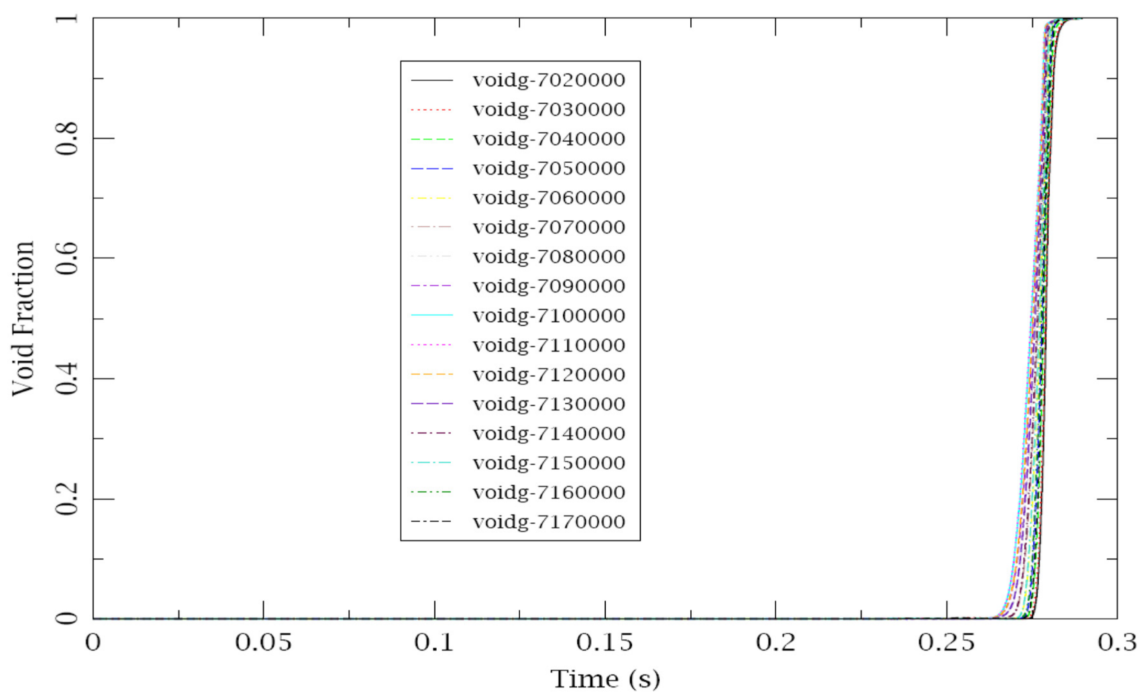

Figure 13. SL-1 - Cold Module Void Fraction

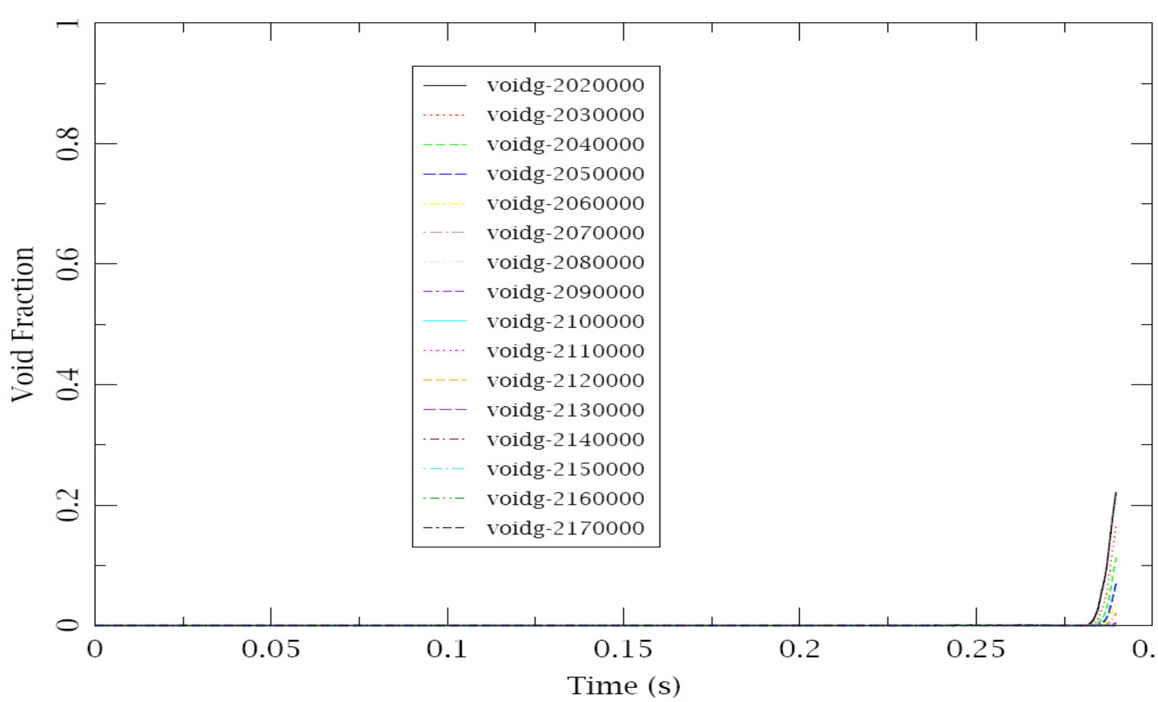

Figure 14. SL-1 - Hot Element Centerline Temperature

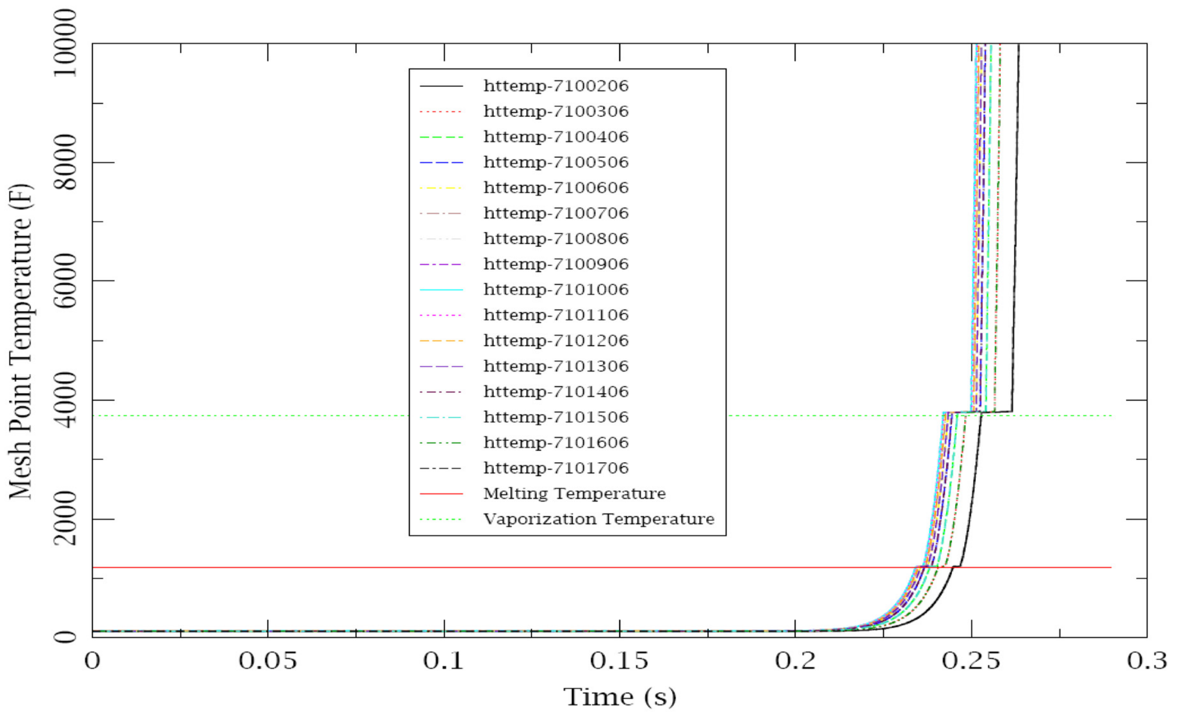

Figure 15. SL-1 - Hot Element Surface Temperature

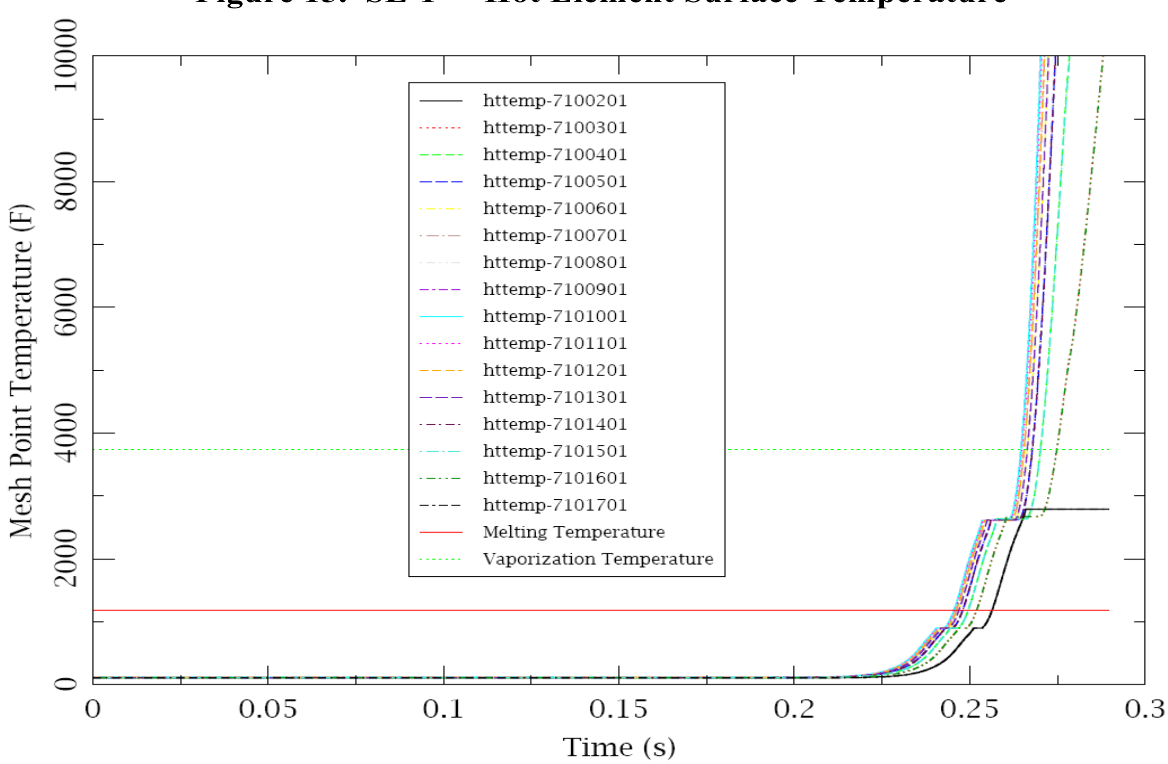

Figure 16. SL-1 - Cold Element Centerline Temperature

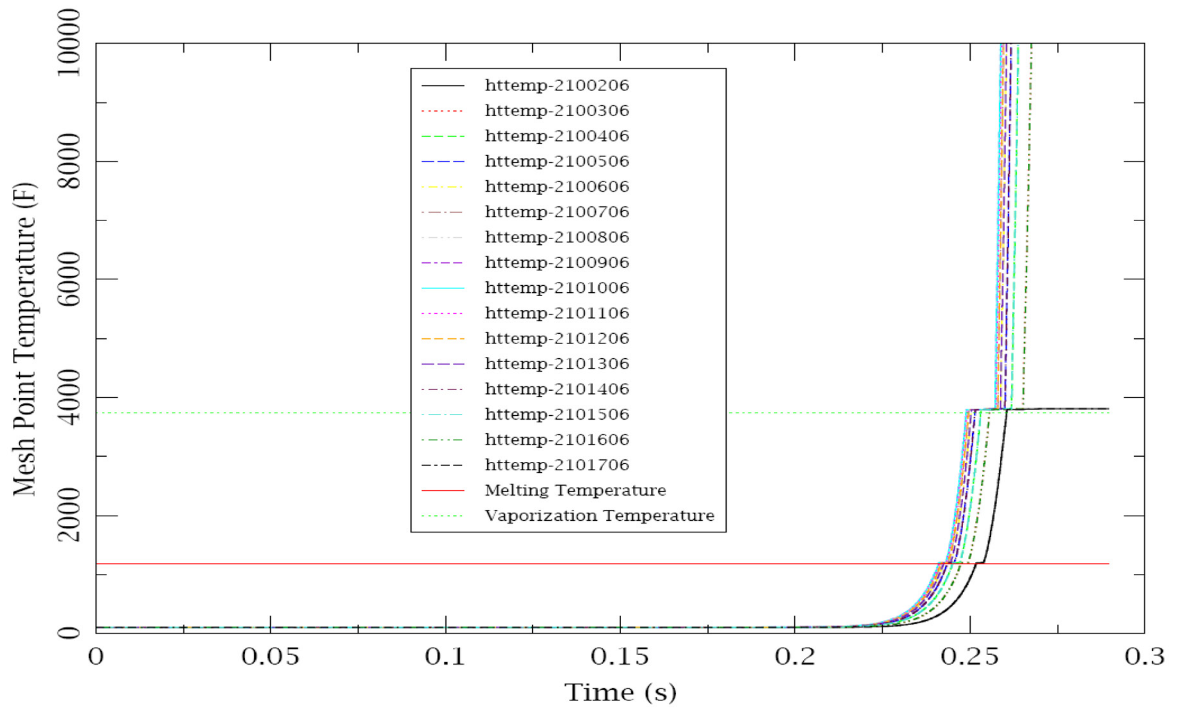

Figure 17. SL-1 - Cold Element Surface Temperature