GA–A25644

KEEPING THE CRYOGENIC TARGETS LAYERED UNTIL SHOT TIME IN A Z-PINCH IFE POWER PLANT

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NOVEMBER 2006

GENERAL ATOMICS

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This is a preprint of a paper to be presented at the 17th ANS Topical Meeting on the Technology of Fusion Energy, Albuquerque, New Mexico, November 13-15, 2006 and to be published in the Proceedings.

Work performed for
Sandia National Laboratories
under Contract No. 453163.

GENERAL ATOMICS PROJECT 39214
NOVEMBER 2006

In a central building of a Z-pinch based IFE power plant, the DT fuel is formed into a very smooth and uniform layer of ice at ~18 K inside a beryllium shell; placed in a cryogenic target assembly that provides support, cooling, and thermal insulation; and put into an evacuated replaceable transfer line (RTL) at room temperature (RT) [1]. The RTL is transported and inserted into one of the reactor chambers at 923 K and shot, releasing 3 GJ of nuclear fusion energy. The DT ice layer must stay below ~19.7 K to keep its geometric integrity until shot time.

Detailed transient thermal analyses of the cryogenic target assembly in the RTL were performed. They showed that, with the original design, the DT ice would reach 24.6 K by shot time. With an improved design providing better thermal insulation of the target, the ice temperature would reach only 19.1 K, meeting the requirement for successful shots.

This paper compares the thermal analysis results for both designs, which included conduction and radiation effects with temperature-dependent material properties.

I. INTRODUCTION

Figures 1 and 2 show a concept for a 1000 MW(e) Z-Pinch IFE Power Plant. A central facility produces RTLs, wire arrays, and cryogenic targets, and feeds them to ten operating reactors, each shooting 3 GJ targets at 0.1 Hz. At time zero, a Z-Pinch load, composed of a wire array at RT and a cryogenic target at ~18 K, is inserted into an RTL under vacuum at RT. During the first 6 s the RTL is transported and inserted, still at RT, into one of the reactor chambers. There it is exposed to the chamber environment at 923 K for 4 s until shot time.

Tests have shown that a very smooth and uniform DT ice layer can be formed naturally by beta layering inside a spherical shell [2]. But if the temperature of the ice layer in the Z-IFE target were to exceed ~19.7 K, its geometry would become degraded and it could not produce a successful 3 GJ shot.

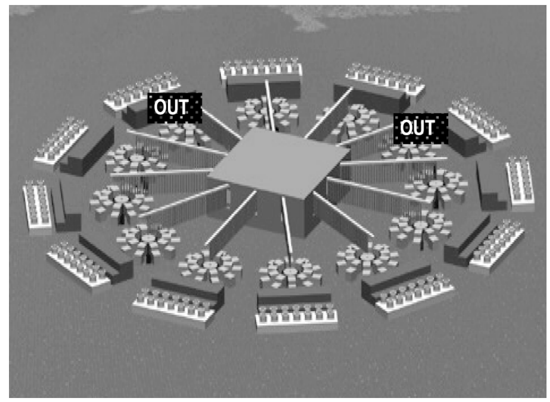

Fig. 1. Z-IFE Power Plant.

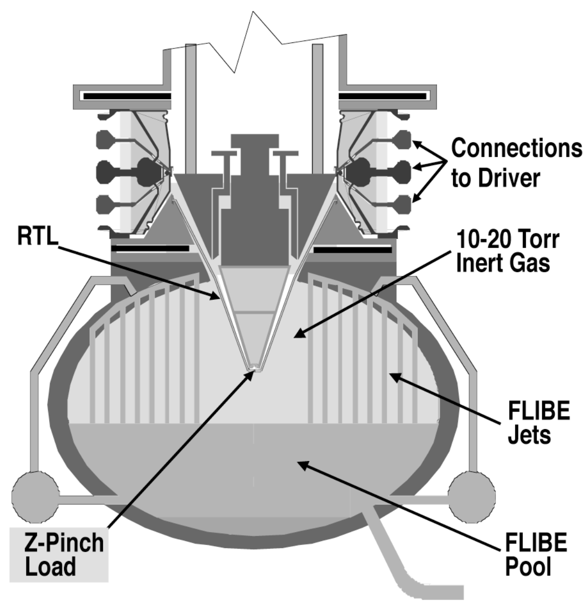

Fig. 2. Z-IFE Reactor Chamber.

Figure 3 shows a Z-Pinch load in the tip of an RTL. The cryogenic target assembly is composed of layered DT ice inside a beryllium capsule that is embedded in a cylinder of low-density foam capped at each end by a reservoir of LH_2. The foam cylinder is sealed and filled with 3 Torr of helium to conduct beta-decay heat from the DT ice to the LH_2. The space between the two RTL electrodes is evacuated.

The original design of the target assembly is shown on the left side of Fig. 3. Its analysis showed that by shot time, the DT ice temperature would exceed the specified 19.7 K limit. The right side of Fig. 3 shows the improved design, with the sealed, helium-filled, inner foam cylinder reduced in diameter and surrounded by an insulating outer cylinder of the same foam in vacuum. Its analysis showed that the DT ice temperature would stay below 19.7 K.

II. THERMAL MODELING

The axisymmetric finite element model shown in Fig. 4 was generated and used with the ANSYS code to calculate the temperature rise in the capsule during the 10 s until shot time.

The model included the following components: a spherical shell of beryllium containing 6%-wt copper; an inner cylinder of 10 mg/cm^3 polymer foam filled with 3 Torr of helium gas surrounding the shell; an outer, taller foam cylinder (containing 3 Torr of helium gas in the original design, but vacuum in the improved design); a reflective (0.066 emissivity) tungsten coating on the outer surface of the outer foam cylinder; above and below the foam cylinder: two 0.030-mm thick tungsten disks and two reservoirs with polished (0.02 emissivity), 0.1-mm thick walls made of the same 1004 carbon steel as the RTL electrodes and filled with LH_2; a pedestal of 10 mg/cm^3 polymer foam in vacuum, with a conservatively assumed emissivity of 1.0 and with recessed top and bottom surfaces to minimize conduction; the top and bottom RTL electrodes (with seal plate) and the top and bottom ring plates of the wire array, all made of 0.63-mm thick, type 1004 carbon steel, and conservatively assumed to be unpolished, with 1.0 emissivity.

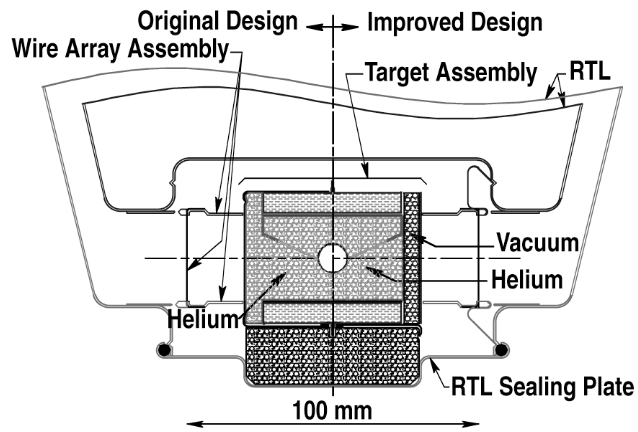

Fig. 3. Z-Pinch load in the tip of an RTL.

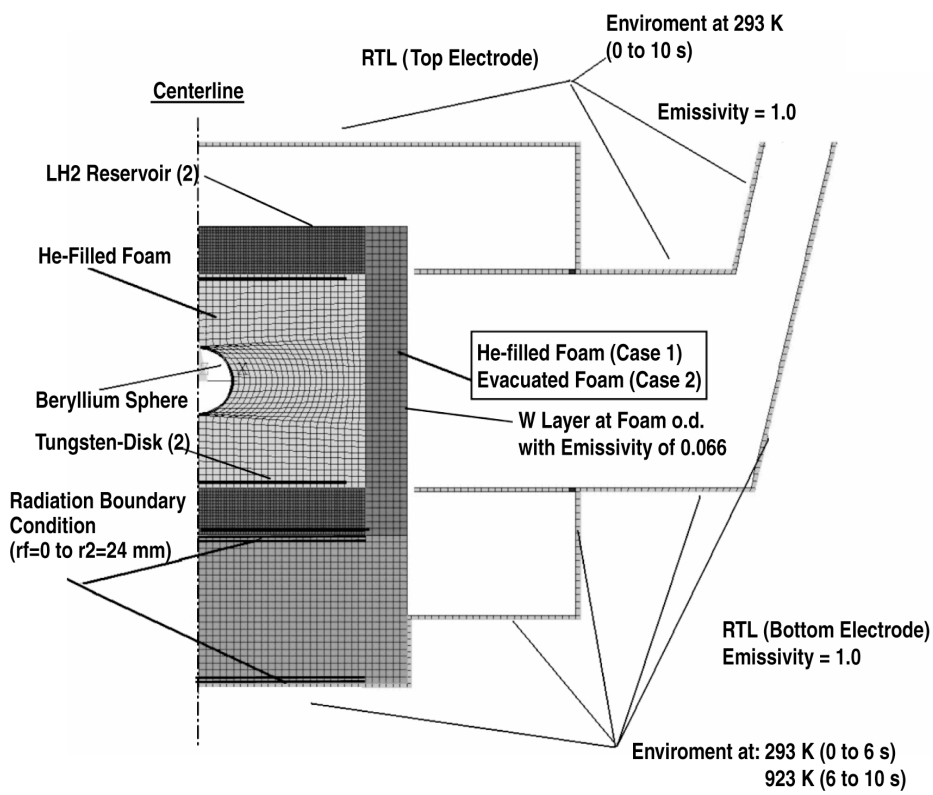

Fig. 4. Axisymmetric finite element model.

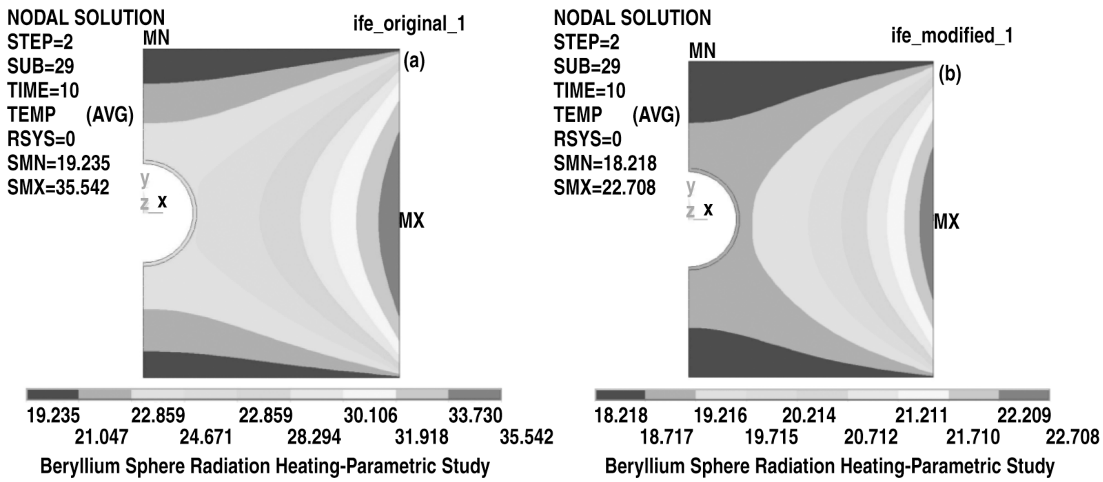

Fig. 5. Temperatures (K) in the inner foam cylinder at 10 s. (a) Original design: 19.2 K < T < 35.5 K. (b) Improved design: 18.2 K < T < 22.7 K.

Thermal conductivities, heat capacities, and densities were treated as temperature-dependent where warranted, but the emissivities were assumed constant. Thermal contact resistances between components were conservatively neglected. The thermal conductivity of helium-filled foam was conservatively taken as that of the helium alone.

At time zero, the temperature of all cryogenic target assembly components was set at 18 K, while the RTL, seal plate, and foam pedestal were set at RT (293 K). For the entire 10 s, the top surface of the top RTL electrode was exposed to thermal radiation from its RT environment at 293 K. The bottom surfaces of the bottom RTL electrode and the seal plate were exposed to radiation from their RT environment at 293 K for 6 s, followed by 4 s of exposure to radiation from the inside of the reactor chamber at 923 K. As a result, during 10 s the cryogenic target assembly was heated on the bottom by radiation and conduction from the seal plate through the foam pedestal, and on the side and top by radiation from both RTL electrodes. Additional heat transfer to the RTL electrodes by conduction and convection from their external environment was neglected.

By itself, the small amount of heat generated by beta-decay in the DT ice layer would raise the ice temperature from 18.0 to ~18.1 K, be conducted across the helium-filled foam to the two reservoirs, and absorbed by the LH_2 at 18 K, raising its temperature by a negligible amount (~15 mK in 10 s) because of its large sensible heat capacity. This separate steady-state heat transfer mechanism was not included in the present analysis. The DT ice layer was also not included in the model: its temperature rise can be conservatively taken as that calculated in the surrounding beryllium shell.

III. ANALYSIS RESULTS

The LH_2 reservoirs kept the top and the bottom of the helium-filled inner foam cylinder cold until shot time: its minimum temperature (on axis at the top) was 19.2 K in the original design and 18.2 K in the improved design, as shown in Fig. 5.

As expected, in the improved design, the side of the inner cylinder was better insulated from the heat radiated by the RTL electrodes than in the original design (Figs. 5 and 6). As a result, the temperature of the beryllium shell

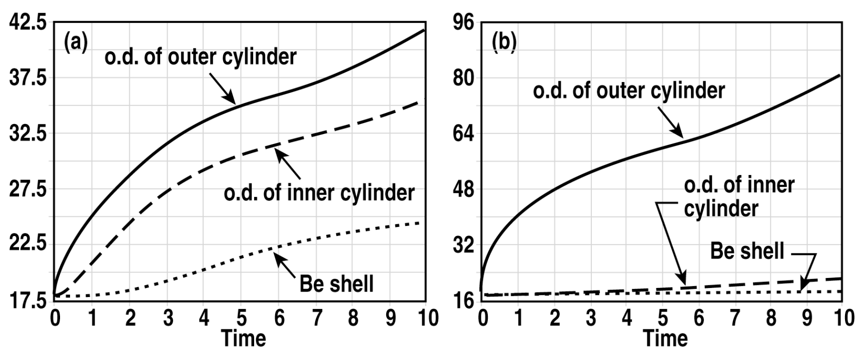

Fig. 6. Temperatures (K) from 0 to 10 s at the equator. (a) Original design. (b) Improved design.

at shot time rose to 24.6 K in the original design, but only to 19.1 K in the improved design.

Due to the good thermal conductivity of beryllium, the maximum temperature difference in the shell at shot time was small: the equator was 25 mK warmer than the north pole in the original design and only 6 mK warmer in the improved design.

Figure 6 shows, at different scales, the temperatures rising from 0 to 10 s at three points on the equator: at the outer diameter of the outer foam cylinder, at the outer diameter of the inner foam cylinder, and at the beryllium shell. In the improved design, these temperatures were higher at the outer cylinder, but lower at the inner cylinder and the beryllium shell, compared with the original design.

IV. CONCLUSIONS

These conservative transient analyses show that the improved design would limit the maximum temperature and temperature range in the beryllium shell after 10 s to, respectively, ~19.1 K and 3 mK. Therefore, the maximum temperature in the DT ice layer should remain below the 19.7 K limit needed for successful shots.

A similar thermal model could also be used to further optimize the cryogenic target design for mass production while maintaining or improving its thermal performance.

ACKNOWLEDGMENT

This work was performed for Sandia National Laboratories under Contract No. 453163.

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