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FINITE ELEMENT MODELLING OF AN EVACUATED CANISTER FOR REMOVAL OF MOLTEN RADIOACTIVE GLASS

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ABSTRACT

Pacific Northwest Laboratory (PNL) has prepared a preliminary design for the West Valley Demonstration Project[2] evacuated canister system. The function of the evacuated canister is to remove radioactive molten glass from a hot cell melter cavity during a planned melter shutdown. The proposed evacuated canister system consists of an L-shaped 4-in. 304L stainless steel (SS) schedule 40 pipe, sealed at one end with an aluminum plug and attached at the other end to a canister. While the canister is being filled, it is positioned and held above the melter at approximately 15° from horizontal by two turntable-mounted cranes. ANSYS finite element analyses were conducted to evaluate the heat transfer from the glass to the canister and establish a maximum canister temperature for material strength evaluation. Finite element structural analyses were conducted to identify areas that required reinforcement for high temperature use. Finite element results will be used to locate strain gauges at high stress locations during prototype testing.

INTRODUCTION

West Valley Nuclear Services Company (WVNS) has been charged with the responsibility of disposing of two million liters of high-level radioactive waste. This waste remains from the former commercial nuclear fuel processing plant at West Valley, New York. The waste will be combined with non-radioactive components to form a borosilicate glass waste form in a melter at the WVNS Vitrification Facility. The molten glass is removed by pouring the glass into a standard canister that serves as a mold until the glass solidifies. The function of the evacuated canister is to remove molten glass from the melter during a planned melter shutdown. The differential pressure between the evacuated canister and the atmosphere will cause the fluid waste form to flow into the evacuated canister. The evacuated canister design simplifies the glass extraction process, reduces personnel exposure in a hot cell environment, and can accommodate remote operation.

BACKGROUND

The design of the evacuated canister system relies heavily on testing experience at PNL and WVNS. In 1987, as part of work for the Hanford Waste Vitrification Project (HWVP), a glass simulant transfer was made at PNL from the liquid-fed ceramic melter through a transfer pipe, configured as an inverted "U", to an evacuated canister located beside the melter. A relatively low-temperature glass

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[1]Pacific Northwest Laboratory is operated by Battelle Memorial Institute for the U.S. Department of Energy under DE-AC06-76RLO 1830.

[2]West Valley Demonstration Project is operated by West Valley Nuclear Service Company.

transfer was conducted, with test glass at 1560°F. Glass was transferred at rates varying from 5 to 8.7 lb./min. The transfer pipe was extended 78-in. horizontally and 113-in. vertically. An aluminum plug was heat shrunk into the melter end of the pipe to allow preheating of the pipe. The canister bottom and the end of the melter transfer pipe were at approximately the same elevation.

Testing of this system was relatively unsuccessful, and resulted in only 200 lb. of glass being transferred. Approximately 170 lb. of glass filled the transfer pipe and only 30 lb. reached the canister. This was due to a relatively low glass temperature and the excessive length of the transfer tube. During the test, the maximum temperature of the transfer pipe was observed to be 610°F, well below the glass transition temperature (~910°F) where glass viscosity significantly increases. The temperature at the canister throat reached a maximum of 180°F during the test.

In contrast, an evacuated canister design at WVNS was quite successful. This design minimized the length of the transfer tube by placing the canister on top of the melter. The major restriction with this design is the height to which a glass of density 0.10 $lb./in.^3$ can be raised by one atmosphere vacuum. The glass was lifted approximately 12 ft. in the WVNS tests at temperatures above 1830°F. Canisters were filled in less than 10 minutes with up to 1500 lb. of glass.

Roller-expanded aluminum plugs (3/8-in. thick) were placed in the neck of the canister to maintain a vacuum prior to insertion in the melter. When the canister is inserted into the melter, the molten glass melts the plug and the vacuum draws the glass into the canister. This seal design maintained a vacuum that typically initiated at 0.5 psia and resulted in a vacuum of approximately 1.0 psia at the conclusion of glass transfer (the canister was not full at the conclusion of glass transfer). Plug melting times ranged from 3 to 10 minutes.

The important factors learned from these testing programs are as follows:

- The length of the transfer tube from the melter to the canister should be minimized to reduce the possibility of glass solidifying inside the pipe.
- The glass temperature should be as high as possible, to reduce the glass viscosity during transfer and increase the glass transfer rate.
- The design of the aluminum plug inside the transfer tube is critical. The plug must prevent leakage until the pipe is lowered into the glass and melt quickly and completely.
- The height of the canister above the melter must be minimized.

CANISTER SYSTEM DESIGN

An initial design concept was proposed that consisted of the canister standing upright on a turntable next to the melter, with the transfer pipe routed in an inverted "U" configuration (Figure 1). PNL evaluated the glass flow for such a design based on historical methods. The design was found to be marginal because of free convective and radiative cooling effects stemming from the long pipe length. Therefore, a design locating the canister above the melter was proposed (Figure 2). This design is discussed in detail in another publication (Ketner et al., 1993). Highlights of the design are provided below.

To minimize the viscosity of the molten glass and increase the glass transfer rate, it was desirable to design the canister to withstand molten glass at 2010°F. However, the limited strength of 304L SS at this elevated temperature necessitated lowering the temperature to 1650°F. Thermal analyses indicate that the canister temperature will be less than the glass temperature in the melter and should accommodate melter glass temperatures above 1830°F. This estimate will be further evaluated during prototype testing.

The exterior dimensions of the WVNS standard glass canister were unchanged to allow the evacuated canister to be handled like standard canisters for final disposal. This required that internal modifications be made to strengthen the standard canister design. The wall thickness of the cylindrical portion was increased to 0.375-in. to eliminate the possibility of buckling at high temperature and one atmosphere internal vacuum. The thickness of the top and bottom heads was increased to 0.25-in. and reinforcing ribs were added to the top and bottom heads as a result of the finite element stress analysis. A baffle was added to the neck of the canister to prevent glass from reentering the transfer pipe and canister seal after filling with glass to 80% of the canister volume at the 15° incline.

A cage structure was designed to support the canister above the melter during operation. The cage is constructed of 0.375-in. 304L SS plate with cut-outs to promote free convection cooling. The canister is supported inside the cage on ceramic insulating pads. Since these pads have a high thermal resistance, they keep the cage temperature substantially less than the canister temperature, resulting in greater cage structural capability.

The cage and canister are supported at a 15° angle from horizontal above the melter during operation. The transfer pipe end is at the high point. This configuration allows the glass to flow into the canister while minimizing the height required to lift the glass. The structure will not be supported on the melter due to geometric and melter load capability constraints. Rather, WVNS direction was given to support the canister from the two in-cell process cranes.

An O-ring design was used to limit maximum leak rate between the transfer pipe assembly and the canister to 6.1×10^{-6} $in.^3$/sec. The O-ring design is a nickel-coated Inconel 750 ringed tube (0.188-in. tall by 0.020-in. wall thickness). Under static conditions, this design can easily support a 6.1×10^{-10} $in.^3$/sec. helium leak rate at standard temperature and pressure. The advantages of this design include tolerance of high temperature (up to 2170°F), tolerance to variation in seal surface flatness, and 0.004-in. of springback. The function of the nickel coating is to fill any anomalies in the sealing surface. The disadvantages include the requirement for a surface finish of 16-μin rms, circumferential machining, and high load to compress the ring. The ring is not reusable once compressed.

The transfer pipe used for drawing the glass into the canister is made of 4-in. schedule 40 304L SS pipe with an explosively bonded aluminum plug welded to the melter end. The aluminum plug is machined from a block of explosively bonded plates of 304 SS and aluminum. The aluminum plug thickness was established at 0.5-in. to give the transfer pipe approximately 3 to 8 minutes to heat prior to glass flow. This preheating minimizes the amount of glass that solidifies on the tube wall, thus minimizing flow restriction.

The outer diameter of the canister is required to be 24.0 +0.6/-0.4-in. after glass fill and cooling. This requirement was established for placement in a secondary container for final disposition in the waste repository. This tolerance may be exceeded due to the unsymmetric configuration of the canister and support system during glass transfer and due to the high temperatures that the canister will experience. Analysis indicates that canister warpage should not exceed this limit, but analytical conditions were ideal. Evaluation of this potential problem will be made during prototype testing.

FINITE ELEMENT ANALYSES

Thermal Analysis

Finite element analyses were conducted to evaluate the heat transfer from the glass to the canister. The West Valley waste form will enter the evacuated canister at a maximum temperature of 1830°F. The glass will increase the temperature of the canister and cage rapidly and cool, due to radiation and convective heat losses. The strength of 304L SS at elevated temperatures is very limited, so there was a strong desire to defend the use of a lower temperature to maximize the material strength of the canister and cage. This justified the need for a thermal model that would apply conservative assumptions, and still allow the use of a lower temperature for structural components.

To predict the maximum canister and cage temperatures, transient thermal analyses were conducted with the ANSYS finite element computer code. An axial slice at a location removed from the ends of the canister was analyzed. Since the canister is quite long, this assumption is justified. The model consists of the molted glass, canister, alumina pads, and cage. An ideal bond was assumed at the glass-metal interface, which will achieve a maximum canister and cage temperature. Heat was transferred to the outside ambient by convection and radiation.

Overall model assumptions include: 1) No internal energy generation of the glass was included, 2) an ambient temperature of 100°F was assumed for the hot cell temperature, 3) the canister, initially at ambient, was assumed to be instantly filled with glass at 1830°F (as glass transfer will actually be achieved over several minutes, this is conservative).

Two models were used to analyze the system using different conservative assumptions. To determine the maximum cage temperature, it was assumed that the canister will be in intimate contact with the alumina pads (see Figure 3). Since the alumina and cage have thermal mass that will tend to cool the canister, and the pads are not present around the entire canister circumference, another model was used to determine the maximum canister temperature. This model (not shown) assumed that the surface of canister was fully insulated, except where it was directly exposed to ambient air.

The glass, metal, and alumina were assigned temperature dependent material properties for conductivity, specific heat, and density. Documented properties were used to evaluate the density and thermal diffusivity of the West Valley Waste Form (Cadoff et al. 1991). The specific heat of the waste form was unavailable, so the specific heat of the HWVP waste form was used as representative of borosilicate glass. The conductivity was calculated by the relationship between thermal diffusivity, density, and specific heat. The properties of the alumina pads were taken from manufacturer's data sheets for alumina insulating board. High temperature material properties of 304L were collected from two sources. Specific heat and density data were obtained from the material testing program at Purdue (Touloukian 1967), while the conductivity was obtained from design data for high-level waste canister materials (Simonen and Slate 1979).

Radiation from the canister and cage to the ambient was accounted for by including radiation elements from the surface nodes to a node held at a specified ambient temperature. The emissivity of 304L is approximately 0.8 for a polished surface, but to be conservative, an emissivity of 0.6 was used to account for any oxidation.

Convection elements were included from surface nodes to a node held at the ambient temperature. A temperature dependent heat transfer coefficient was calculated for a horizontal cylinder cooling in air (Holman 1974). To be conservative, the boundary layer between the surface and ambient air is assumed to be laminar. This heat transfer coefficient, as a function of surface temperature, was included in the ANSYS analyses. To account for the fact that 50% of the canister is covered by the cage, this heat transfer coefficient was degraded by 50%. On the surface of the cage, the full heat transfer coefficient was used.

Transient thermal analyses were conducted using the two models to bound the maximum canister and cage temperature profiles. The analyses were carried out for one hour to capture any long-term effects. Time step optimization procedures were used to increase the time step as the transient progressed. Figure 4 provides a time temperature history for selected nodes on the cage and canister for the maximum cage temperature model. A maximum cage temperature of 570°F occurred at approximately one hour after the initial glass pour. Using the second model, the maximum canister temperature of 1650°F occurred at approximately 0.3 hour after the initial glass pour. These temperatures were used to evaluated the material properties of the structural components during glass fill conditions.

Structural Analysis

Finite element analyses were conducted to identify internal structural reinforcement required for high-temperature canister use. The finite element model shown in Figure 5 was used to evaluate the canister stresses under various loading conditions. The most severe loading case occurs at the end of the fill, when the canister is still at a 15° angle and the vacuum seal is intact. Symmetry considerations allowed the use of a 180° model constructed of STIF63, four-noded shell elements. STIF52 gap elements were included on the surfaces where the canister initially contacted the supporting cage structure. This allowed the non-symmetric loading to cause a "banana" shaped deformation.

A pressure of 14.7 psi was applied to the outer surfaces of the canister to represent the vacuum. Pressures were also applied to the inner surfaces to represent the weight of the glass. Figure 6 shows the pressure gradient due to the increasing depth of the glass at the 15° inclination angle. A uniform temperature of 1650°F was applied to the canister.

The results indicated the need for increased wall thickness (minimum 0.25-in.) from the standard WVNS canister (0.188-in.) and for the addition of eight 0.25-in. reinforcing ribs on the inside of the top and bottom heads. The ribs must be in alignment with the supporting alumina pads on the cage structure to reduce the bending moment in the head. In addition, a baffle was added to the neck of the canister to keep glass away from the transfer pipe seal area. Figure 7 shows the von Mises equivalent stresses in the top head region. Maximum stress levels are below the estimated yield point of 8000 psi for 304L SS at 900°C, and are very localized. Most stress levels are below 2000 psi.

FUTURE WORK

To verify the design and remote handling, a test is planned at PNL in the summer of 1994. A prototype canister system is being constructed and will be tested using simulated WVNS glass prepared in the PNL pilot scale ceramic melter. Flow and temperature response of the transfer pipe and glass will be characterized. Temperature response will then be used to verify structural analysis assumptions. Finite element results will be used to locate strain gauges at high stress locations during prototype testing.

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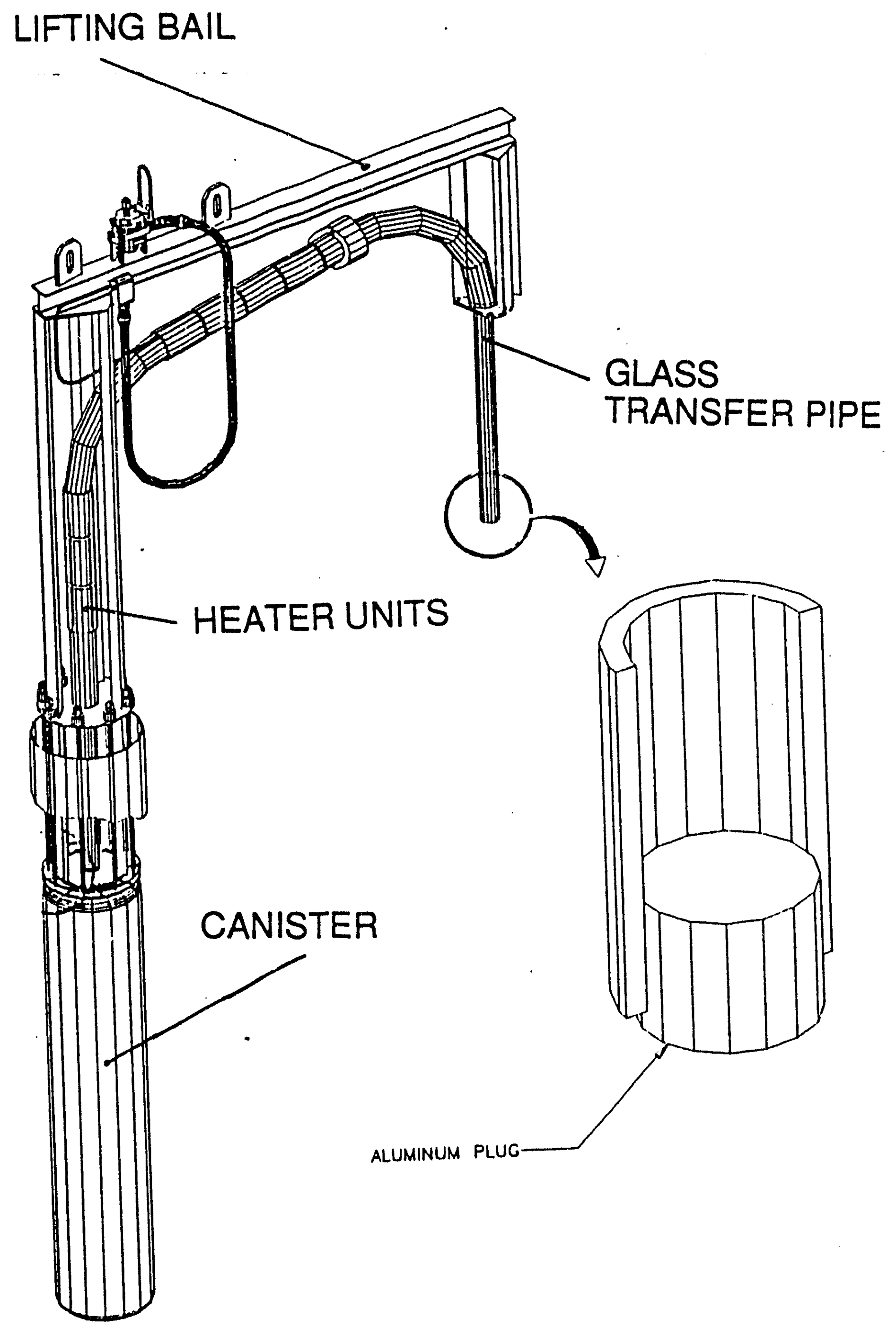


Figure 1. Initial Evacuated Canister Design

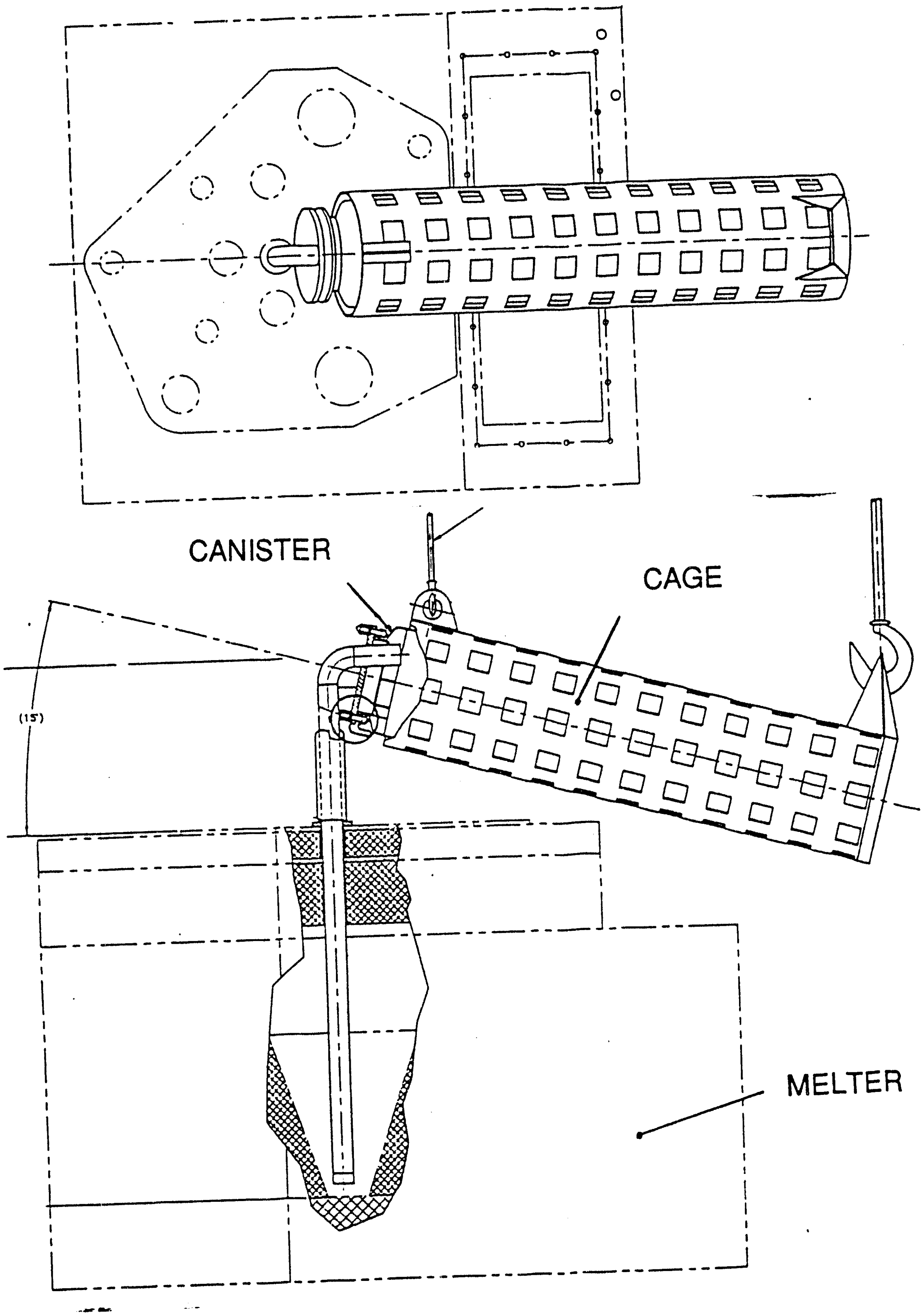


Figure 2. Final WVNS Evacuated Canister System Design

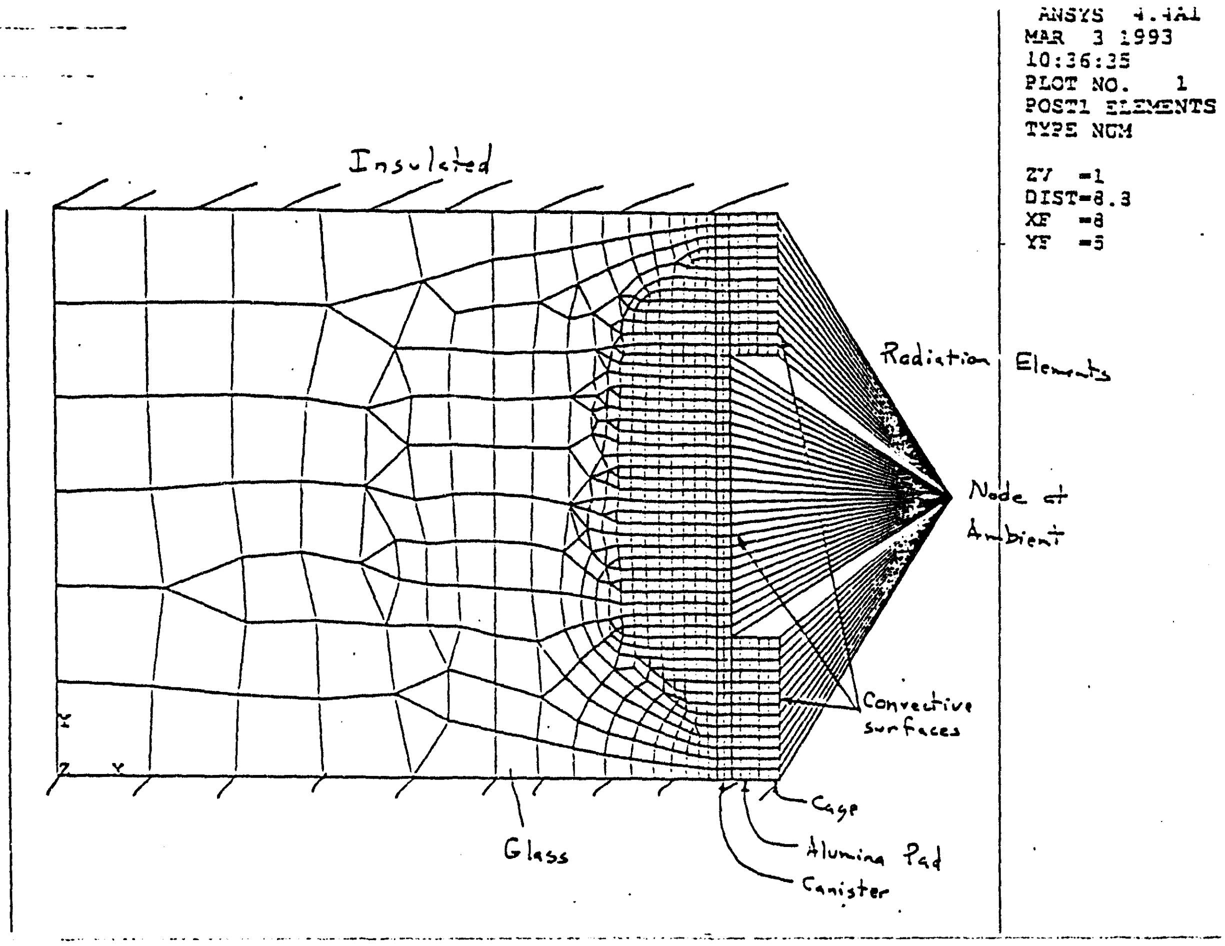


FIGURE 3. Thermal Model used to Determine Maximum Cage Temperature

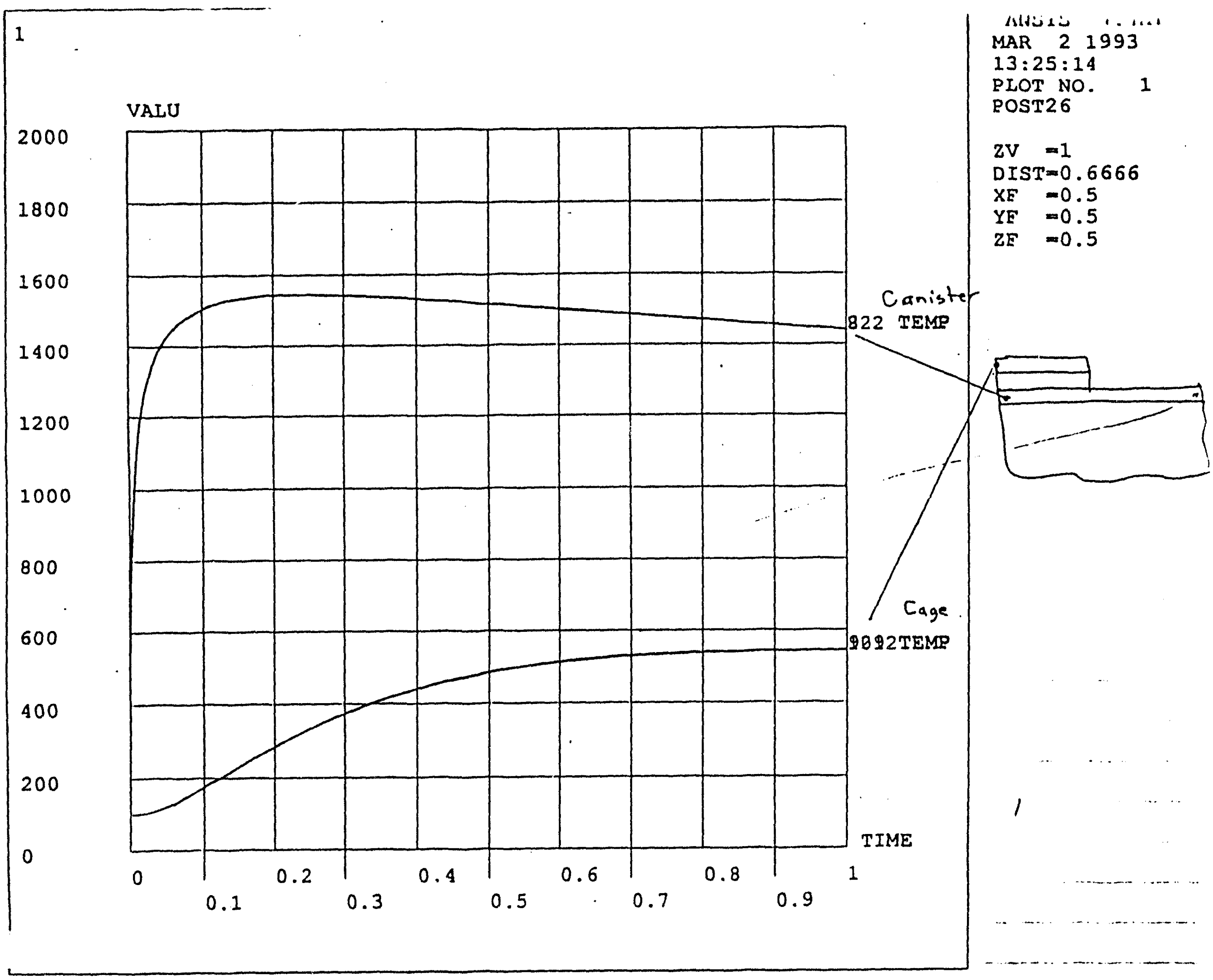


FIGURE 4. Temperature Histories for selected Nodes – Maximum Cage Temperature Run

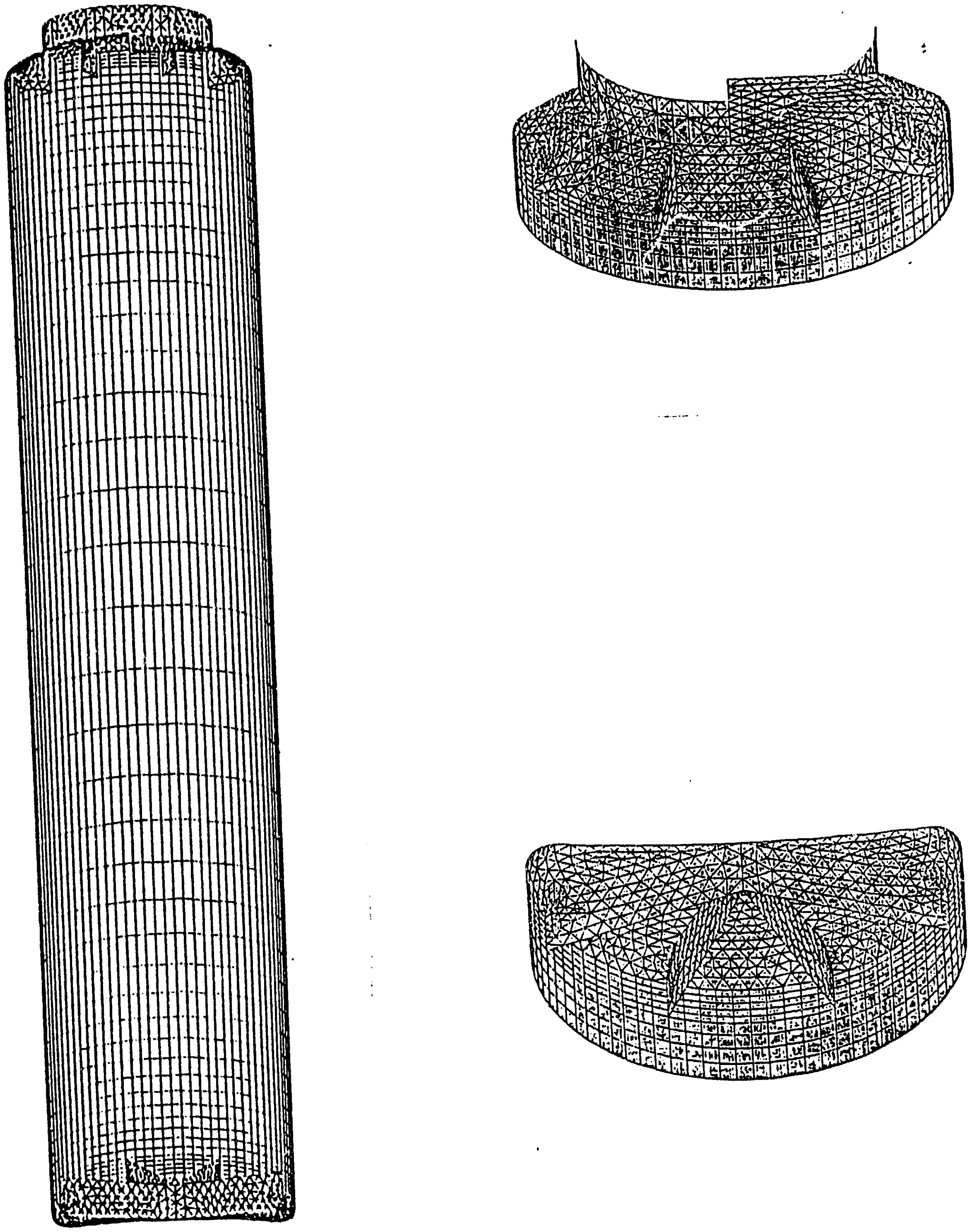
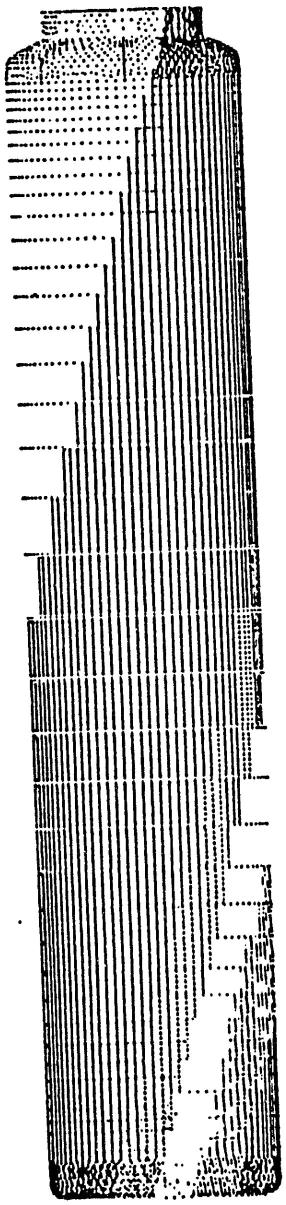


Figure 5 Finite Element Structural Model



(Color)

Figure 6 Internal Pressure Distribution

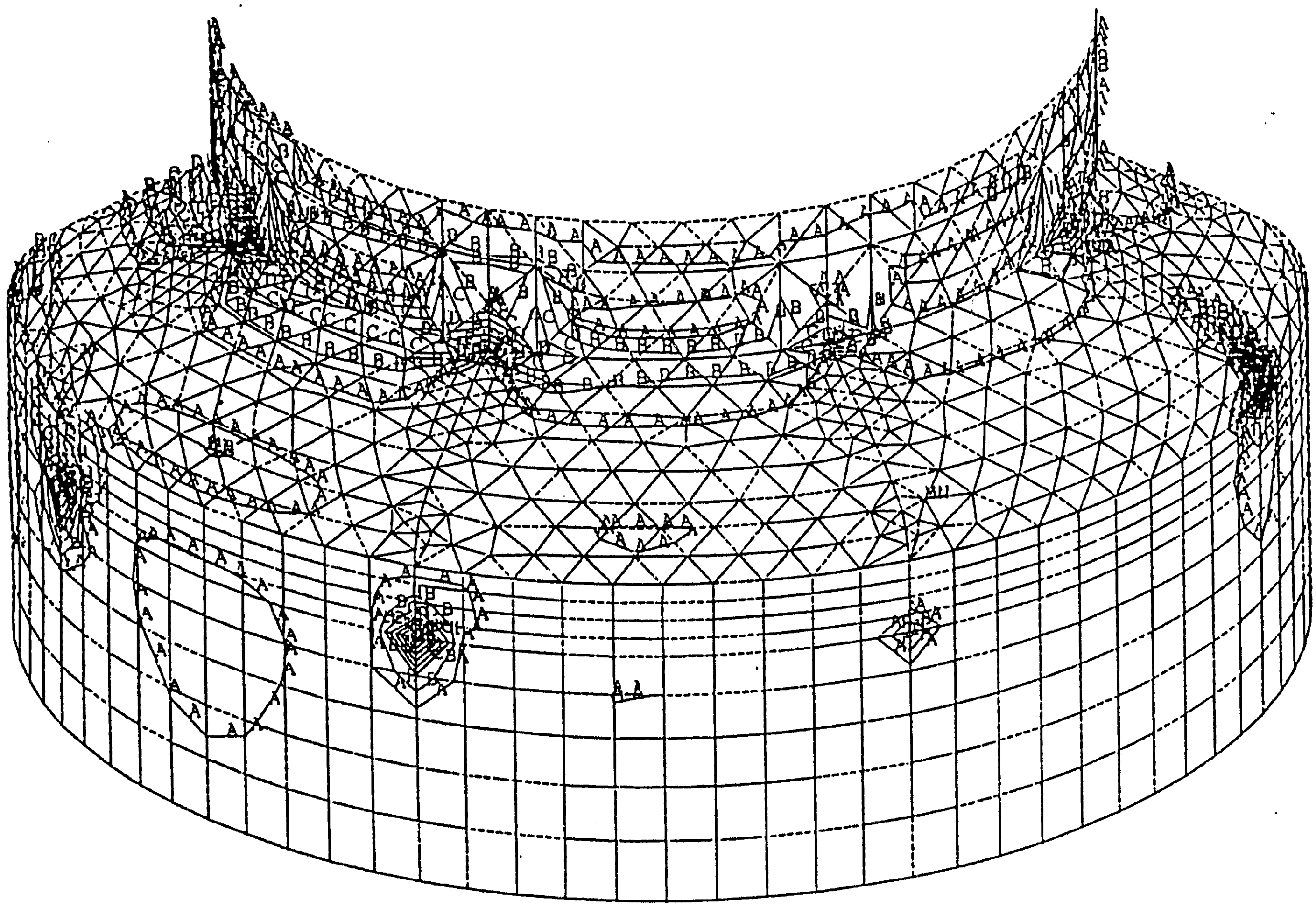


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Figure 7 Top Head Equivalent Stress

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