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CONF-790822--17

**Vitrification of High Level Wastes:
A Review of the
Computer Thermal Analyses
for Storage Canisters**

**R. I. Wescott
S. C. Slate**

August 1979

**Presented at the American Institute of
Chemical Engineers' 87th National Meeting
in Boston, Massachusetts
August, 1979**

**Work Supported by
the U.S. Department of Energy
under Contract EY-76-C-06-1830**

PNL-SA-7917

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VITRIFICATION OF HIGH LEVEL WASTES:
A REVIEW OF THE COMPUTER THERMAL
ANALYSES FOR STORAGE CANISTERS

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SUMMARY

CANIST, a two-dimensional (r and θ) computer program that solves the unsteady-state, heat conduction equation was used to model the thermal behavior of canisters filled with waste glass. CANIST has been found to be a valuable analytical tool for predicting the temperature profile of a waste storage canister as a function of several variables, including the diameter of the canister, the placement of internal fins, the heat generation rate of the waste glass, and the thermophysical properties of the canister and the waste glass. Thus, temperature dependent processes that may affect the integrity of the glass/canister unit, for example cracking, can be investigated using an analytical approach.

In the present study, the canister temperature profiles predicted by CANIST were compared to canister temperatures measured during full-scale non-radioactive waste immobilization tests conducted at Pacific Northwest Laboratory. The agreement between experimental and predicted temperatures was good, particularly considering the fact that the thermophysical properties of the waste glass modeled have not yet been accurately determined. Examination of some glass-filled canisters has revealed cracking to have occurred in the glass. However, the comparison between measured and CANIST predicted temperatures suggests that cracking does not significantly influence the heat-transfer process.

CANIST was also used to evaluate different ways of reducing the centerline temperature of a canister. Computer modeling indicated that reducing the diameter of the canister, adding internal fins, and increasing the cooldown rate are effective means of reducing the centerline temperature. Moreover, it was found that extending the fins toward the center of the canister was more effective than adding more fins or adding flanges to the ends of the fins. Finally, CANIST was used to predict the centerline temperature as a function of the heat generation rate of the waste glass and the type of interim storage, i.e., air or water. Lower heat generation rates resulted in lower centerline and canister wall temperatures. Water storage also resulted in both lower centerline and wall temperatures as compared to air storage.

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VITRIFICATION OF HIGH-LEVEL WASTES:
A REVIEW OF THE COMPUTER THERMAL ANALYSES
FOR STORAGE CANISTERS

INTRODUCTION

The Pacific Northwest Laboratory (PNL), operated by Battelle Memorial Institute for the United States Department of Energy is developing the technology to immobilize high-level liquid wastes. Substantial research and development have been directed towards solidifying the waste into a borosilicate glass. A detailed discussion of the storage and disposal of nuclear wastes as glass cast into large steel canisters is contained in a document by Mendel (1978).

The purpose of this report is to describe the computer analyses and the actual experiments that have been performed to determine the thermal behavior during cooldown of borosilicate glass stored in canisters. These analyses are part of a larger study which involves evaluation of the temperatures of the glass/canister unit through all phases of processing, from vitrification to disposal. This report focuses on the analytical techniques and compares the predictions of the computer analyses to actual experimental data from the full-scale vitrification demonstrations that have been conducted at PNL.

Two major full-scale vitrification processes have been under development at PNL for several years. The first is a batch melting process called in-can melting (ICM). In this process, dried waste and glass forming materials are melted together inside the storage canister. This process has been described in detail by Blair (1976). The second process is called continuous melting (CM). Dried or liquid waste is continuously fed to an electric ceramic-lined glass melter. The glass is then poured from the melter into the storage canister. Several documents describing this process have been written by Chapman (Chapman and Buelt 1978) and Buelt (Buelt and Chapman 1978; Buelt, Chapman, Barnes and Dierks 1979). The ICM and CM processes serve as the basis for the work discussed in this report.

Storage canisters are the subject of an extensive experimental program at PNL. They have the important role of preventing contact between the glass and the immediate environment, protecting the glass from damage, and providing a means of handling the glass. The canisters under study are similar to those illustrated in Figure 1. The standard design consists of a single-wall pipe with formed heads welded to each end. The top has a carefully designed opening that can be connected to the vitrification equipment and can be reliably sealed. The design of the canister and the processing operations that must be performed on it can significantly affect the temperature of the glass as well as the temperature of the canister. For example, the canister may or may not have internal fins. Fins may be used in canisters in either process to improve heat transfer from the center of the glass to the outside. In the case of the ICM process, fins are also desirable to maintain the high melting rates that are necessary for large-scale production.

It is important to be able to predict the temperatures of the glass and the canister during cooldown, because most phenomena that affect the glass/canister unit are temperature dependent. In the case of glass, one is concerned with cracking and devitrification. Cracking results largely from temperature gradients that occur during cooldown. In general, larger gradients mean more cracking. Devitrification, the formation of crystals within the glass matrix, is a function of both time and temperature.

In the case of the canister, one needs to know the surface temperature of the canister wall to evaluate the potential for corrosion and metallurgical changes. For stress analysis, one needs to know the temperature in order to select material properties and temperature gradients to predict strain levels. In addition, practical and efficient facility operation requires that handling temperatures and cooling time be known. The effects of temperature on the canister have been discussed in other reports. For the effect on corrosion, the reader should refer to the work by Slate and Maness (1978). The effects of temperature on the structural integrity of the canister are discussed by Simonen and Slate (1979).

FIGURE 1. Canister Designs

Analytic techniques are a valuable aid in addition to experimental data for two reasons. The first reason is that one can easily simulate the heat that would be generated by actual waste, which is not possible in full-scale, nonradioactive tests. Secondly, computer analyses allow one to model a wide range of design parameters that affect temperatures, before prototype canisters are actually built and tested.

Computer modeling complements the experimental efforts in waste immobilization studies being conducted at PNL. In the experimental program, full-scale canisters have been filled with simulated waste to evaluate the performance of the glass/canister unit during the immobilization process. Of particular concern is the amount of cracking that occurs as the glass cools, and the effect of the cracking on the temperature of the canister and the glass. The effect of the glass cracks on the transfer of heat can be accounted for in CANIST by modifying the thermal conductivity equation for the glass. By comparing the temperatures recorded from actual experiments with those predicted by CANIST, an estimate of the degree of modification necessary to account for cracking could be achieved.

COMPUTER MODEL

In the past, modeling radial cross-section configurations of storage canisters containing waste glass was done using HEAT4. HEAT4 was developed at PNL and is a modified version of the HEATING3 computer program (Turner 1971). However, the use of cylindrical coordinates in HEAT4 resulted in the approximation of rectangular internal fins as tapered fins. This approximation was determined to be inappropriate, especially for large diameter storage canisters. Therefore, a new computer program, called CANIST, was developed at PNL specifically to model waste canisters with internal fins.

CANIST, a two-dimensional program (r and θ), solves for the distribution of temperatures within the canister and glass under transient or steady-state conditions. It uses an ADI (Alternating Direction Implicit) method to solve the unsteady-state, heat-conduction equation. The ADI method involves solving the finite-difference equations for a single time-step in one direction (r) first, and using those results to solve the other direction (θ). As a two-dimensional program, CANIST accounts for the transfer of heat radially and circumferentially, but assumes heat is not transferred axially. Therefore, the process of filling a storage canister with glass, or determining temperatures near either end of a canister cannot be modeled properly using CANIST. In CANIST, conduction within the canister is assumed to be the dominant mode of heat transfer; any heat that may be transferred within the canister by convection or radiation is considered to be relatively small. CANIST is also set up so that several different boundary conditions outside the canister can be modeled. These include:

- natural convection and radiation in air
- convective heat transfer in water
- interaction between canister and enclosure
- time-temperature profile of canister wall.

By taking advantage of symmetry in the θ direction, the entire radial cross-section does not have to be modeled. To save computational time, CANIST is set up to model only a selected angular section of the canister. The

angular section is divided into control volumes. Figure 2 shows the relationship between the canister cross-section, an angular section, and a control volume.

CANIST was developed to model a variety of waste canisters. Thus, the input parameters include the diameter of the canister and the configuration and location of fins. The angle of the angular section determines the number of fins modeled. The rate at which the waste glass generates heat and the initial temperature distribution of the glass and canister are also input parameters. The thermophysical properties of the waste glass, canister, and fins are temperature dependent and are assigned to the control volumes on the basis of the particular waste glass, storage canister, and internal fins being modeled.

To ensure a reasonably precise computer model, the thermophysical properties of the waste glass must be known. Many different glass compositions have been developed over the years, but the thermophysical properties of relatively few glasses have been rigorously measured. The results presented in this report are based on waste glass properties determined several years ago and believed to be representative of today's glass compositions.

In this past summer, R. E. Taylor at Purdue University started to experimentally determine the density, specific heat and thermal conductivity for BNW-76-183 and SRL Composite 411. (The compositions of these two glasses, which are leading candidates for waste glass fixation, are presented in Table 1.) Shown in Figures 3 and 4 are comparisons between the values of the thermophysical properties presently used in CANIST and the preliminary data received from Taylor for SRL Composite 411. The properties are plotted as a function of temperature. The large change in the experimental data for heat capacity is due to approaching the melting point of glass during the experimental tests. Several typical canister situations will be modeled again once the final set of properties is received from Taylor, to determine the effect of the revised properties on the temperature of the glass. The thermal conductivity and volumetric heat capacity values used in CANIST for 304L stainless steel canisters and fins were obtained from Touloukian (1967).

FIGURE 2. Canister Cross Section

TABLE 1. Composition of Two Simulated Waste Glasses

Glass Formers	BW-76-183 (wt%)	SRL Composite 411 (wt%)
SiO ₂	35.3	44.5
B ₂ O ₃	9.3	3.3
Na ₂ O, K ₂ O	10.0	9.4
CaO	2.0	5.2
TiO ₂ , CuO, LiO ₂ , etc.	10.0	9.4
<u>Waste</u>		
Na ₂ O	3.5	--
Fe ₂ O ₃	2.4	8.0
Al ₂ O ₃	--	12.0
MuO ₂ , NiO	0.5	3.2
Rare Earth mix oxide	15.3	--
P ₂ O ₅ ZrO ₂ , etc.	11.7	--
TOTAL	100.0	100.0

FIGURE 3. Comparison of Computer and Experimental Thermal Conductivity of SRL Composite 411

FIGURE 4. Comparison of Computer and Experimental Volumetric Heat Capacity of SRL Composite 411

COMPARISON OF COMPUTER MODEL TO EXPERIMENTAL RESULTS

One purpose of comparing experimental and computer-generated canister temperatures is to determine the degree to which the estimated thermal conductivity and/or heat capacity of the glass must be changed to achieve agreement. It is possible that the computer model does not account for the various physical processes that could potentially affect the transfer of heat. A comparison between the computer predictions and experimental results will give an indication that some process is not being modeled, if significant discrepancies exist. Inferences can then be made about what processes, besides conduction, are influencing the transfer of heat. For example, if significant convection occurs while the glass is in a molten state, the actual centerline temperature should be lower than that predicted by CANIST. If cracking obstructs heat transfer, actual temperatures should be higher than predicted temperatures. With certain processes, for example cracking, the effect on heat transfer can possibly be taken into account by modifying the thermal conductivity equation. The thermophysical properties must be known as accurately as possible to lessen the likelihood of the properties causing the discrepancies rather than physical processes.

The thermal conductivity was selected as the thermophysical property to be allowed to vary in the attempt to improve the agreement between computer and experimental temperatures, if needed. The thermal conductivity was chosen in the belief that the data for density and specific heat were more reliable. The equations for thermal conductivity and heat capacity were based on data from older glass compositions believed to be typical of today's glasses. The older data was assumed to be the best estimate at the time, although a comparison between the older data and the newer values from Taylor (see Figures 3 and 4) shows that the older data is quite low for both thermal conductivity and heat capacity.

The experimental temperature results were obtained from thermocouples attached to the outside of the canister walls and positioned inside the canister to record temperatures during the filling and cooldown phases. The canister was 24 in. in dia, was filled using the CM process, and contained no

internal fins. The canister contained glass very similar in composition to SRL Composite 411. The thermocouples were radially positioned at 1 in., 4 in., and 9 in. from the centerline and were at different heights, such that both axial and radial temperature profiles could be determined. The temperatures measured by a set of thermocouples located halfway down the filled canister should be minimally affected by heat losses at the top and bottom of the canister, and so can be modeled by a two-dimensional computer program such as CANIST. The first part of the cooldown was in an insulated enclosure, then the thermocouples had to be disconnected from the strip chart to remove the canister from the enclosure to stand in air.

CANIST was used to model the experimental conditions described above. However, rather than trying to model the various boundary conditions outside the canister (about which little was known), the actual variation of the temperature of the canister wall with time was used for the boundary condition.

Shown in Figure 5 are experimental temperatures and temperatures predicted by the computer model using the original thermal conductivity equation. The temperatures 4 in. from the centerline were omitted from the figures for clarity; the temperatures at 4 in. followed the same trends as those recorded at 1 in. The agreement between the experimental and predicted temperature behavior of the glass during the experiment is encouraging. The figure shows that the glass, both at 1 and 9 in., cooled down in approximately the same manner as the canister wall. At lower temperatures this is particularly significant, as it indicates that cracking did not seriously obstruct the transfer of heat from the center of the canister.

The thermal conductivity equation in CANIST was modified to decrease the conductivity at lower temperatures (below 500^oK) and maintain similar values at higher temperatures (above 750^oK). The modified thermal conductivity equation improved the agreement between computer predicted temperatures and experimental temperatures as shown in Figure 6. Figure 7 shows a comparison between the original and the modified thermal conductivity equations. The idea was not to find one thermal conductivity equation to reconcile the temperature differences between experimental data and computer predictions,

FIGURE 5. Comparison Between Experimental and Predicted Temperatures Using the Original Thermal Conductivity Equation

FIGURE 6. Comparison Between Experimental and Predicted Temperatures Using the Modified Thermal Conductivity Equation

FIGURE 7. Comparison Between the Modified and Original Thermal Conductivity Equations

but to show that the analytical approach has merit. Now that more recent data is available for the thermophysical properties of the glass, the agreement between computer predicted and experimental temperatures will be reevaluated. Both heat capacity and thermal conductivity will be considered when transient data is examined for additional potential heat-transfer mechanisms.

DESIGN APPLICATIONS OF COMPUTER MODEL

Maintaining the integrity of the canister and waste glass during the cooldown phase is of prime importance to providing reliable waste immobilization. There are several phenomena that can be detrimental to the structure of the canister or glass. The canister wall and centerline temperatures can be used as common denominators to discuss the processes about which there is concern. The processes influenced by the centerline temperature are: devitrification, phase separation, and gravity settling. The temperature of the canister wall influences: sensitization of the stainless steel, thermal stresses in the canister wall which affects glass cracking and stress-corrosion cracking of the wall, and the processing time and handling considerations for the canister.

Devitrification, the formation of crystals in the glass, is a function of time and temperature. The temperature range in which rapid devitrification is most likely to occur is between 950°C and 500°C for most waste glasses. The leach rate of the glass modestly increases with the extent of devitrification. However, if the cooling rate is 50°C/h or more, the devitrification occurring during canister cooldown is negligible. Phase separation is another time-temperature dependent process that increases the leach rate of the glass. The addition of reducing agents to the glass can prevent phase separation to a large extent. Gravity settling of some crystals occurs, if the glass at the center of the canister stays partially melted for several or more days. By cooling the glass rapidly (greater than 50°C/h) and subsequently maintaining the glass at temperatures below approximately 500°C , these phenomena should not seriously affect the integrity of the glass.

Sensitization of the stainless steel canister walls is the precipitation of chromium carbides in the grain boundaries, which usually occurs between 500°C and 750°C . The walls are more susceptible to intergranular corrosion after sensitization, but the process is reversible at temperatures above 850°C . A cooldown rate of 50°C/h or greater, in the range of 850°C to 500°C , will reduce the sensitization experienced by the canister wall. Wall

stresses make the canisters more susceptible to chloride-induced, stress-corrosion cracking during water-basin storage. Maintaining proper water quality at the storage basin will minimize this potential problem. Wall stresses result from the glass shrinking less than the steel as it cools, especially below the transition temperature of the glass (the temperature at which glass changes from a plastic state to a brittle state, $525^{\circ} \pm 25^{\circ}\text{C}$ for most waste glasses). If the canister and glass are cooled too rapidly (100°C/h), thermal stresses cause fracturing of the glass. Excessive cracking of the glass is undesirable, because it increases the available surface area of the glass that is subject to leaching in an aqueous environment. For more information on the phenomena described above see Mendel (1978).

For large-scale processing of waste, the processing time for a canister from the start of filling to sealing and the handling temperatures for the canister wall are going to involve economic considerations. Faster processing times require less redundant equipment and cooler canister wall temperatures simplify handling requirements. However, a tradeoff exists between cooling rapidly to prevent devitrification and sensitization, etc. and cooling slowly to prevent significant cracking. By varying parameters such as the diameter of the canister, the number of internal fins, and the environment outside the canisters, the temperature profile of the canister can be modified for a given waste glass with a specific internal-heat generation rate.

As previously mentioned, cracks in the waste glass have also been a serious concern with respect to their effect on heat transfer. Examination of filled canisters has revealed that significant cracking does occur especially near the canister wall, shown in Figure 8. An earlier computer analysis of a 360° fracture in the glass, with only radiation heat transfer across the gap (a vacuum gap), resulted in a 120°C temperature drop across the gap and approximately the same temperature rise in the centerline temperature. Analytic evaluation showed that expressing the crack width in terms of an equivalent glass thickness was dependent only on the temperature of glass and not the width of the crack. For example, at 450°C the equivalent glass thickness is 1.4 cm, while at 50°C it was 15 cm. Since most cracks would not be 1.4 cm wide, the glass fractures would be less efficient than the glass at

FIGURE 8. Cracking Near Canister Wall

transferring heat; thus, cracks act as a barrier to heat transfer. If the gap contained helium, a comparison of thermal conductivities between the glass and the helium suggests a 1 mm wide crack would have a heat-transfer rate equivalent to 4 mm of glass.

Fortunately, such phenomena were not observed from the experimental data of filled canisters (refer to Figures 5 and 6). Two factors may be effectively nullifying the resistance to heat transfer by the cracks. The two factors are contact resistance and "bridging." Assuming the cracks are jagged with many points of contact, conduction should occur between the glass surfaces, thereby reducing the heat that must flow through the "void" of the crack. The fracture surfaces may also be kept in intimate contact because the glass is under compression (Simonen and Slate 1979). The "bridging" effect implies that the crack, with its high resistance, is bypassed in a large measure as the heat flows through the surrounding glass with the lower resistance.

LIMITING THE CENTERLINE TEMPERATURE DURING COOLDOWN

There are three basic approaches to limiting the centerline temperature of a waste glass with a fixed heat generation rate. The approaches are: 1) reduce the diameter of the canister, 2) add internal fins, or 3) increase the cooldown rate. CANIST was used to predict variations in the centerline temperature as a function of the size of the canister diameter, the cooldown rate, and the addition of internal fins. Moreover, it was used to determine optimal fin volume and placement.

As an example of the effect of changing the canister diameter, Figure 9 shows the predicted centerline temperature and the temperature of the canister wall for canisters varying in diameter. These canisters contained waste with (0.58 W/L-glass) and without (0.13 W/L-glass) salt cake separation. The canisters modeled had no internal fins, and the temperatures reflect a steady-state condition in 50°C ambient air. The centerline temperature dropped by a factor of two when going from a 36-in.-dia to a 12-in.-dia canister. In this particular case, the centerline temperature was not a serious problem for the 36-in.-dia canister, because it contained waste that does not generate

FIGURE 9. Temperatures as a Function of Reducing the Diameter of the Canister With No Fins

heat at a very high rate. However, the centerline temperature of a canister filled with waste that generates heat at a higher rate would also decrease as the diameter of the canister was reduced. Figure 10 shows the effect on the centerline temperature of both reducing the diameter of and adding internal fins to a canister filled with light-water reactor (LWR) waste that was 20 yr old (9.1 W/L-glass). The fins occupied 8% of the volume of the canister. The

FIGURE 10. Temperature as a Function of Reducing the Diameter and Adding Internal Fins

centerline temperature of the 24-in.-dia canister dropped 110°C when internal fins were added. Figure 10 also shows that the effect on the centerline temperature was about the same when the canister diameter was decreased from 36 in. to 24 in. (with no fins) and when fins were added to the 36-in.-dia canister.

Increasing the volume of the fins inside a canister can also produce dramatic reductions in the temperature profile of the canister. For a 12-in.-dia canister filled with waste that generates heat at a rate of 150 W/L (glass containing 1-yr-old waste) and that has fins that comprise 8% of the total volume, the predicted steady-state centerline temperature was 860°C at an ambient air-temperature of 50°C. The fin configuration in this instance consisted of eight 1/4-in.-thick fins, positioned 1 in. from the center of the canister and 1/2 in. from the interior of the canister wall. By increasing the fin volume to 22%, the predicted steady-state centerline temperature was reduced to 600°C. The fin configuration in this instance consisted of eight 3/8-in. fins with eight shorter 1/4-in. fins between the 3/8-in. fins. The 8% fin volume and 22% fin volume configurations are shown in Figure 11. The radial steady-state predicted temperature profiles for the two fin configurations are shown in Figure 12.

The volume of the canister occupied by the fins can be increased several different ways. These include widening the fin, lengthening the fin, adding more fins, and adding a flange to the fin near the canister wall. CANIST was used to evaluate the effect of the last three methods of increasing the fin volume on the centerline temperature of the canister. The computer representation of an ICM-filled canister started with an isothermal temperature profile of 1100°C in the canister and furnace. The heat generation rate of the glass was 150 W/L. The computer modeled a controlled cooldown of 100°C/h of the canister wall until the surface temperature of the wall was 700°C. The canister was then removed from the furnace to stand in air at 50°C until steady state was reached. Both 12- and 16-in.-dia canisters were modeled with various fin configurations. The time to reach steady state for the 12-in.-dia canister was 13 to 16 h, whereas it took 15 to 20 h to reach steady state for a 16-in.-dia canister.

In Figure 13, the effect of increasing the fin volume and decreasing the distance of the fins from the center on the centerline temperature is shown for 12- and 16-in.-dia canisters. The effect of fin volume was reasonably linear for a given distance from the canister center. (In this case, the fin volume was increased by adding more fins.) Figure 13 also shows that while

8% FIN VOLUME

22% FIN VOLUME

FIGURE 11. Fin Configurations

FIGURE 12. The Radial Steady-State Temperature Profile for Two Fin Configurations

FIGURE 13. Centerline Temperatures as a Function of Diameter Size, Fin Volume, Distance from Center, and Presence of Flanges

the centerline temperature decreased with increasing fin volume, the distance from the edge of the fin to the canister center had an even greater effect on the centerline temperature. For a 12-in.-dia canister, by including eight fins that came within 1 in. of the centerline instead of 1.75 in. the centerline temperature dropped from 1203⁰K (930⁰C) to 1093⁰K (820⁰C). The fin volume in this case was increased (7% to 8.4%) by lengthening the fins 0.75 in. Furthermore, the centerline temperature of a 12-in.-dia canister can be reduced to 1128⁰K (855⁰C) from 1203⁰K (930⁰C), keeping the same fin volume (7%) by reducing the number of fins, if the fins are positioned 1 in. from the center rather than 1.75 in. from the center.

In addition, the closer the fin is to the centerline to start with, the more the centerline temperature is effected by adding length to the fin. For example, for a 12-in.-dia canister, going from eight fins that are 2.5 in. from the center to eight fins that are 2.25 in. from the center, the centerline temperature dropped 20⁰C. In contrast, the centerline temperature of a 12-in.-dia canister dropped 50⁰C by decreasing the distance to the center from 1.75 in. to 1.5 in. for eight fins.

Adding flanges to the fins has the same effect on the centerline temperature as adding more fins to the canister. See Figure 11 for an illustration of a flange. Flanges on the end of the fins facing the canister wall did not affect the centerline temperature to a great extent, but did reduce circumferential temperature gradients in the canister wall and nearby glass. Thus, the flanges are useful because they reduce temperature gradients which can induce stress, affect the integrity of the canister walls, and cause additional cracking in the glass.

In summary, the computer predictions suggest that lengthening the fins is the most effective way of increasing the fin volume in a canister to reduce the canister centerline temperature. Increasing the number of fins or adding flanges has less of an impact on the centerline temperature.

Controlling the rate at which the canister wall is cooled is another approach to limiting the centerline temperature of glasses with high heat-generation rates. The situation modeled was the controlled cooldown of a

12-in.-dia canister containing waste glass that generates heat at a rate of 150 W/L. The canister was presumed to start with an isothermal temperature distribution of 1050°C, which is typical of ICM. The purpose of modeling this situation was to determine the rate at which the canister wall must cool to keep the centerline temperature below 1150°C. The two fin configurations modeled were the same as those shown in Figure 11. With the 16-fin configuration, a cooling rate of 100°C/h limited the centerline temperature to 1157°C. The 8-fin configuration required a 700°C/h cooling rate to keep the centerline temperature below 1156°C. When the heat generation rate of the waste glass was reduced to 100 W/L, and the cooling rate kept at 150°C/h, the maximum centerline temperature can be maintained at 1159°C. Cooling rates of 100°C to 150°C/h are: 1) rapid enough to minimize the effects of devitrification and sensitization, and 2) rates that will not fracture the glass from thermal stress any more than necessary.

OTHER DESIGN CONSIDERATIONS FOR STORAGE CANISTERS

The heat generation rate of the waste glass and the environment outside the canister during interim storage (i.e., air or water) are other important variables to consider in designing canisters. Both affect the centerline temperature as well as the temperature of the canister wall.

As would be expected, a lower heat generation rate results in lower centerline and canister wall temperatures. There are three approaches to dealing with high heat-generation rates, which might result in the glass in the canister not solidifying. One approach, which was mentioned earlier, is to decrease the diameter of the canister. The second approach is to reduce the heat generation rate by holding the waste in storage for a longer period of time, to allow decay of the heat-producing elements. For example, if 1-yr-old LWR waste is assumed to have a heat generation rate of 150 W/L, by waiting until the waste is five years old the heat generation rate will decrease to 22.5 W/L. A decay curve for heat generation of the LWR waste glass is shown in Figure 14. The third approach is to store the canister in water rather than in air.

FIGURE 14. Decay Curve for Heat Generation Rate of LWR Waste

CANIST was used to determine the centerline and canister wall temperatures in relation to different heat generation rates, air versus water storage, and variations in the diameter of the canister. The effect of different heat generation rates on the centerline and wall temperature of 12-in.-dia canisters is shown in Figure 15, for both air and water storage with an ambient temperature of 50°C . The canisters contain no fins and the temperatures are steady-state values. For a 12-in.-dia canister stored in air and containing waste glass generating heat at 100 W/L, the centerline temperature predicted by CANIST was 990°C . The wall temperature was 345°C . Under the same conditions, except that the glass was assumed to generate heat at 10 W/L, the centerline and canister wall temperatures were 165°C and 105°C , respectively. Water storage of the waste canister with glass generating heat at 100 W/L reduced the centerline temperature by 255°C , from 990° to

FIGURE 15. Centerline and Canister Wall Temperatures as a Function of Heat Generation Rates and Storage in Air and Water

735°C. Likewise, the wall temperature was reduced from 345°C to 65°C when storage was switched from air to water. A similar evaluation for 24-in.-dia canisters is shown in Figure 16; the 24-in.-dia canister was not evaluated for water storage. The canister wall temperature for a 24-in.-dia canister containing waste glass that generates heat at 10 W/L was 145°C, and a 12-in.-dia canister had a wall temperature of 105°C; thus, the diameter of

FIGURE 16. Centerline and Canister Wall Temperatures as a Function of Heat Generation Rates for a 24-in.-dia Canister Stored in Air

the canister does not have a significant effect on the wall temperature. However, the centerline temperature for the 24-in.-dia canister was 370°C compared to 165°C for the 12-in.-dia canister.

CONCLUSIONS

The analytical approach has been found to be a valuable aid in predicting the temperature profile of a canister filled with waste that generates its own heat, as a function of several design variables. The comparison of computer predicted temperatures with experimental temperatures indicated that the thermophysical properties may need to be modified to achieve agreement between the two. However, the fact that the thermal conductivity equation had to be modified slightly is not surprising since the thermophysical properties of most waste glasses have not been accurately determined.

The extent to which cracks in the glass act as a barrier to the transfer of heat is not as significant as previously thought. The experimental temperature response of the thermocouples near the center of the canister followed the cooldown of the canister wall. If cracks were a serious problem, the temperatures near the center of the canister would have started to cool at a slower rate due to the formation of cracks as the glass solidifies. That behavior was not observed in CM canisters, and therefore it can be assumed that cracks do not obstruct heat transfer.

Various techniques can be used to reduce the centerline temperature of a canister. A lower centerline temperature reduces the temperature gradients within the canister and the glass at the center solidifies sooner. A smaller diameter canister will have a lower centerline temperature. Adding to the volume of the fins usually reduces the centerline temperature. The most effective use of the extra fin volume is extending the fins toward the center of the canister. The further the fins are from the center, the less effect they have on the centerline temperature. A lower rate of heat generated by the waste glass certainly reduces the centerline temperature. The lower rate of generation is achieved by storing the waste longer before processing. The mode of storage affects the centerline temperature also. Water storage results in both lower centerline and wall temperatures as opposed to air storage.

Through analysis and experiments, waste canisters can be designed to maintain the integrity of stainless steel canisters and waste glass. Storage of waste canisters in an interim storage facility, utilizing either water or air, is possible and the centerline temperature can be maintained at a reasonable level with a judicious choice of canister design parameters.

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