ANRCP-1999-6
February 1999

Amarillo National Resource Center for Plutonium

A Higher Education Consortium of The Texas A&M University System,
Texas Tech University, and The University of Texas System

Development of Characterization of Plutonium Storage Containers

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This report was prepared with the support of the U.S. Department of Energy (DOE), Cooperative Agreement No. DE-FC04-93AL83832. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the author(s) and do not necessarily reflect the views of DOE. This work was conducted through the Amarillo National Resource Center for Plutonium.

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AMARILLO NATIONAL RESOURCE CENTER FOR PLUTONIUM/
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A Report on

Development of Characterization of Plutonium Storage Containers

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Submitted for publication to

ANRC Nuclear Program

February 1999

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Abstract

As a result of the end of the Cold War, at least 11,000 (possibly 20,000 or more) plutonium pits are projected to be stored at Pantex for up to fifty years. The current pit (shipping) container, the ALR8 (a 30-gallon, mild-steel drum with an internal fixture for supporting the pit) was not designed for this length of storage duration. As a result, Pantex officials have searched for alternative container options.

The objective of this research is to develop and validate a model to predict the temperature distribution within the stored components and the internal structure of the proposed ALR8(SI) container, and to consider and analyze the safety features of the ALR8(SI) container as seen from the thermal performance view.

Figure 1 illustrates the components of the ALR8(SI) container. The plutonium pit (4) is placed in an internal supporting fixture (3) – referred to as the birdcage. The birdcage enters the sealed insert (2) up to the level of the upper disc of the birdcage, which is then gripped between the sealed insert and its cover (5). Celotex insulation (1) fills the volume between the sealed insert and the drum in which the whole assembly illustrated in the figure is placed. Due to the time scale involved with the current simulations, the radioactive decay of the plutonium may be assumed to provide a uniform rate of heat

generation. This heat is conducted to the surroundings through the solid structures of the assembly. In addition to conduction, the inert gas that fills the volume within the steel container convects a fraction of the generated heat from the plutonium to the colder steel surfaces. Radiation must also be accounted for as natural convection and limited conduction paths are present within the container.

The research efforts in this project have been directed into two paths, numerical and experimental. First, the temperature distribution within the stored components are being determined experimentally as a function of fill gases, energy generation rate, and boundary conditions. Second, a finite element model of the ALR8 container has been developed so that the temperature distribution can be predicted as a function of the same experimental parameters. The obtained experimental data will serve as a comparison and criteria for examining the validity of the numerical model.

This is a report on the progress that has been made during the year of 1998. This paper presents the experimental method and data that have been obtained thus far, as well as the finite element model created using SDRC I-DEAS. A plan of the future work is provided at the end of the report.

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1. EXPERIMENTAL METHOD

1.1 Objective

The objective of the experiment is to obtain temperature readings at various locations within the ALR8 container. For this purpose, an ALR8(SI) container has been supplied from the Amarillo National Resource Center for Plutonium (ANRC). Obviously, the plutonium pit was not provided; this component has to be simulated by other means, as well as the heat generated from it.

1.2 Experimental Setup

Figure 2 shows a cross-sectional view of the experimental setup. The pit simulator was arbitrarily sized to be the same as a standard bowling ball. It has been manufactured from stainless steel 316, and it consists of two hemispheres of diameter 215

mm and wall thickness of 15 mm that are joined together. In order to simulate heat generation, a resistive element has been placed in the center of the pit simulator. It is a $5\ \Omega$ porcelain resistor of hollow cylinder (position 1 in Figure 2). The resistor is attached with its leads to a Plexiglas rod (position 7). Since the rod has very low thermal conductivity, the heat generated in the resistor is mainly radiated to the inner surface of the pit simulator, creating a fairly uniform heat rate distribution on the inner surface of the sphere. The resistor is connected to a DC power supply (4) through electric lead wire (2). To achieve a connection with the resistor from outside, without losing the hermetic properties of the sealed insert, a multiconductive feedthrough (3) is used.

Figure 1: ALR8(SI) Container

It allows up to sixteen probes to be inserted inside the container through the 1/16" openings, and seals the passages with conic ferrules. Thermocouples (6) are placed at different positions and connected to the data acquisition system (5) through the same feedthrough. A computer process the signals collected at the thermocouples, and readings of the temperatures are available. For this purpose, a virtual instrument program file created in LabVIEW is used.

Before their use, the thermocouples were calibrated in a circulating oil bath from 20°C to 110°C. All the components were then assembled and the ALR8 was placed in a horizontal or vertical position. By adjusting the voltage of the DC supplied to the resistor, various heat generation rates were simulated, and corresponding temperatures measured. A

series of experiments have been performed during October and November 1998, using the supplies that were available at that time. The sealed insert was filled with air instead of argon or helium. An isothermal external boundary condition was not available yet; consequently, the external boundary condition was the ambient air temperature that was maintained in the laboratory -- approximately $25^{\circ}\text{C} \pm 1.5^{\circ}\text{C}$. The container was sitting in a vertical position as shown in Figure 3. Fifteen thermocouples were distributed throughout the container as shown in Figure 3. Four of the thermocouples were placed on the exterior of the pit simulator itself in order to find the location with maximum temperature. Three thermocouples measured the temperature on the upper and lower discs of the birdcage,

Figure 2: Cross-Sectional View of Experimental Setup

the primary conduction paths. The remaining thermocouples were located outside the sealed insert. Two thermocouples were placed on the outside drum surface. The experimental series started with 15 Watts generated within the pit. For that purpose, the voltage has been adjusted so that a current of 1.75 amps passed through the resistor. The power is then given by Joules law:

$$P = I^2 R \quad [W]$$

After approximately 2 days, steady state had been reached and data was collected from the thermocouples. The data collected for four different power values are shown in Table 1 (all temperatures are reported in degrees Celsius).

Figure 3: Thermocouple Position and Container Orientation

Table 1: Experimental Data

	DC	1.75A 10V		2A 11.6V		2.23A 13V		2.45A 17V
Power		15W		20W		25W		30W**
Position:	Outside	° C		° C		° C		° C
	1	27.14		25.97		25.73		26.54
	2	26.45		24.90		24.81		25.28
	Container							
	3	37.16		39.79		41.74		48.70
	4	40.30		43.63		47.03		55.35
	5	36.17		38.24		40.48		47.40
	6	33.48		34.97		36.43		41.67
	7	31.02		31.74		32.33		36.53
	8	38.15		41.18		44.15		51.52
	Cage							
	9	36.78		39.67		41.96		50.11
	10	35.65		38.05		40.04		48.22
	11	35.84		38.00		39.89		47.88
	Sphere							
	12	52.44		59.09		65.29		82.02
	13	47.63		53.43		58.47		73.22
	14	42.65		46.81		50.91		63.72
	15	49.13		55.09		60.78		75.86

**An exception is data collected for 30 W, where the additional power suddenly exceeded 30%, or additional 11W. This was a signal that a failure in the electric circuit, caused by an electrical short, had occurred.

It has to be acknowledged that beside the power that is generated in the pit simulator due to its resistance (the number given in Table 1), additional power was required as a result of the electric wire resistance and the resistance within the security fuse. The additional power can be calculated based on the voltage and current readings given in Table 1 as follows:

$$R_t = \frac{U}{I} = R_{pit} + R_{add}, \text{ which gives,}$$

$$R_{add} = \frac{U}{I} - R_{pit}$$

$$P_{add} = I^2 R_{add}$$

where:

R_t - total resistance;

$R_{pit} = 5[\Omega]$ - resistance of the resistor;

R_{add} - additional resistance due to the electric wire and fuse resistance;

P_{add} - additional power generated in the wire;

U - DC voltage reading, [V];

I - DC current reading, [A].

The values given in Table 1 show the power generated just in the pit simulator. The calculations give an additional power of approximately 20% of the values in Table 1. This heat is partly released in the ambient (from the part of the wire that lies outside of the assembly). The rest is released within the container and has to be taken into account.

1.3 Discussion of Results

It can be deduced from the results that the power within the experimental range values (15-30W) can be absorbed by the room temperature ambient without effect on the

outside drum temperature. The fluctuations (between 24 – 27 °C, positions 1 and 2) for different power values, happened mainly due to the changes of the room temperature. The reason for the minimal change in the outside container temperature is a result of the very low thermal conductivity of the Celotex packing material that effectively insulates the sealed insert from the surroundings. It should be noted that the temperature at all experimental locations was less than 60°C for the 15 and 20 W test cases.

The temperatures of the sealed steel container and its contents showed dependence on the heat generation rate. The highest temperatures were measured, as expected, on the plutonium pit surface. The maximum temperature appeared at position 12, on the top of the pit. There exists a 10 to 20°C temperature difference between points 12 and 14, that is due to natural convection heat transfer that occurs as a result of the temperature of the steel surfaces of the sealed insert, the birdcage and the pit causing the hotter air to move upwards. Virtually, we can consider three gas subvolumes within the steel container where convection takes place. The discs of the birdcage make the subvolumes. Most of the convection heat transfer occurs in the middle subvolume (between the two cage discs), where most of the surface area of the pit exists. Evidence of good convection in this subvolume is the small temperature difference between points 10 and 11. In the bottom subvolume only a small area of the pit surface is exposed, surrounded by large, relatively cold surfaces resulting in a much lower temperature at point 14. In contrast, point 12 belongs to the smallest subvolume, which is filled with relatively hot and stagnant air compared to the other two subvolumes. The buoyancy force coupled with the vertical

orientation that was tested setup a stable thermal stratification within the sealed insert such that for steady-state conditions, conduction through stagnant air is likely a significant mode of heat transfer. Generally a large temperature difference existed between the pit and the birdcage discs because rubber rings obstruct the conduction path between them. The conduction path will provide a critical role in establishing an unstable thermal stratification so as to decrease the temperature differences (provide a more uniform temperature distribution) within the sealed insert.

In Figure 4, a plot of the maximum temperature change for different power values can be seen. It should be noted, again, that for the 30 W case, there is a significant amount of additional power distributed, which contributes to deviation of the trendline.

1.4 Future Work

The following improvements have been made for continuation of the experiment:

1. The resistor from the first experiment was replaced with one that does not have exposed wires, in order to sustain higher power dissipated within the pit and the corresponding higher resistor temperatures.
2. Backfill gases will be used instead of air.
3. More thermocouples will be used to better determine the temperature distribution within the sealed container.
4. A system has been developed that will maintain an isothermal boundary condition at the outside drum surface. This will also make possible experimental simulations with higher ambient temperatures.

Figure 4: Experimental Data (Points 12 and 9)

2. NUMERICAL METHOD

2.1 Finite Element Model

A numerical model based on the Pro/E solid model geometry of the ALR8 assembly has been developed. For that purpose, one half of the assembly in the radial plane is removed due to the existing symmetry condition. Furthermore, the model has been simplified by removing minor parts, i.e. screws and other irrelevant details that do not significantly contribute to the heat transfer. The final geometry of the model is then exported to the SDRC I-DEAS Simulation Mode for meshing. It consists of the following components: sealed insert, birdcage, plutonium pit, and outside insulation that represent the Celotex insulation as well as the thin metal drum. This model of ALR8 can be seen in Figure 5.

Beside the models of the solid components, an additional solid volume is created that represents the gas volume that fills the space within the sealed insert. Also, Figure 6 shows the spherical surfaces of the plutonium pit are meshed with a multitude of conic surfaces with one-dimensional curvature. The reason for doing this is the inability of the I-DEAS grid generator to mesh spherical surfaces with triangular thin shell elements.

Further, finite element models are made from all the parts of the assembly, and merged together creating one finite element model of ALR8. As can be seen in figure 6, the FE Model consists of tetrahedral solid elements. The mesh is finer inside the container to allow higher accuracy in predicting the phenomena concerning the fluid (gas) flow. On the other hand, the dimensions of the outside insulation elements, where pure heat conduction occurs, are bigger. Other factors that influence the size of the elements is the complexity of the geometry.

Elements belonging to each part are assigned corresponding material properties. These include thermal conductivity, specific mass, and specific heat for the elements involving conduction. For the fluid elements, viscosity and other fluid properties are assigned. Buoyancy forces are included, as well as convection between the fluid elements and the elements in the flow blockage group. The flow blockage consists from elements of the plutonium pit, the birdcage, and the sealed insert. A smooth surface property is assigned to the areas of contact between solid and fluid elements where convection occurs.

2.2 Boundary Conditions

The boundary conditions used in this analysis can be seen in figure 7. The boundary condition elements used by I-DEAS and a brief description follow:

- (a) Heat load is applied on the inside surface of the plutonium pit. Since boundary conditions in I-DEAS ESC Mode can be applied only on a surface mesh, this surface is meshed with triangular thin shell elements (the thickness is zero). The heat load is applied to these shell elements.
- (b) Ambient temperature boundary condition is applied to the shell elements that envelop the Celotex insulation.
- (c) Fluid flow symmetry plane is applied to thin shell elements of the fluid volume that lie in the cutting plane.
- (d) Adiabatic symmetry boundary condition is applied to the rest of the shell elements in the cutting plane that belong to the solid components; their thickness is a small value greater than zero and their thermal conductivity is zero, so that heat cannot cross this section.

Solid Model used for I-DEAS Simulation

Figure 5: Solid Model

Figure 6: Numerical Mesh of the ALR8(SI)

2.3 Thermal Couplings

When the finite element models of the parts are merged together, there exists no thermal connection between elements belonging to different parts, even though they share same surfaces. In order to create heat flow path between these parts, thermal couplings are used. When these thermal couplings are made, they can also take into

account the thermal contact resistance at the contact surface. The procedure is as follows: Surfaces on both parts that come in contact are coated with thin shell elements. Then, a specific type of thermal coupling boundary condition is used. In this case, that is the Heat Transfer Coefficient Thermal Coupling. Here is a list of thermal couplings used in the model. Their locations can be seen in Figure 8.

Figure 7: Boundary Conditions

1. Thermal coupling between the plutonium pit and the birdcage discs. Since these two parts are not in a direct contact, but there are rubber inserts between them, the effective heat transfer coefficient depends on the rubber parameters. It can be calculated as follows:

$$h = \frac{k}{L} \quad [\text{W/m}^2]$$

where, k is the thermal conductivity of rubber and L is the effective thickness of the rubber insert.

2. Thermal coupling between the lower birdcage disc and the steel container. Due to the difference in the diameters of this

disc and the container, there is a fluid gap with heat transfer coefficient:

$$h = \frac{k(1+c)}{L} \quad [\text{W/m}^2]$$

where, k is thermal conductivity of the fluid, L is the length of the gap, and c is the coefficient that accounts for the convection between the surfaces. In this case, the coefficient may take values greater than 1, because the gap connects two fluid volumes with different temperatures, and conditions for convection are favorable.

Figure 8: Thermal Coupling

3. Thermal coupling between the upper cage disc and the steel container. The heat transfer coefficient is high because the steel surfaces are smooth and in good contact. This thermal coupling can be modeled also as a Thermal Contact Resistance type, with an appropriate value of the thermal contact resistance taken from literature.

4.-9: These are thermal couplings that represent the contact between the surfaces of the steel container and the ones from the Celotex insulation. The heat transfer coefficients associated with them can be calculated from the equation above, considering appropriate gap lengths and convection conditions.

3. FUTURE WORK

The model is to be solved simultaneously by a thermal and a flow solver. Due to the complexity of the model, relatively large processing abilities and memory are required from a system. Presently, efforts are being made to enable such conditions.

Results from the numerical simulations are expected in parallel with the experimental work. Experimental verification of the predicted steady-state temperature values will be used to refine the numerical model.

REFERENCES

There were no references cited for this report.