[redacted]

MASTER

Astronuclear

WANL-TME-569
OCTOBER 15, 1963

(35)

SPECIAL REREVIEW
FINAL
DETERMINATION
Class: U

Reviewers KAW
Class. U
Date 5-4-82

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

SUBMITTED BY:

Westinghouse Electric Corporation
Astronuclear Laboratory
Pittsburgh 36, Pennsylvania

~~NOTICE~~

~~This [illegible] contains information of a preliminary nature and was prepared primarily for internal use at the originating installation. It is [illegible] revision or correction and therefore does not re[illegible] final report. It is passed to the recipient in confidence and should not be abstracted or further disclosed without the approval [illegible] originating installation or USERDA Technical Information Center, Oak Ridge, TN 37830.~~

~~INFORMATION CA[illegible]ORY~~
~~CR[illegible]~~
~~10/18/63~~
~~Authorized Classifier Date~~

PREPARED BY:

A.M. Poindexter

Z.R. Kanaan

Classification cancelled (~~or changed to~~ ________)
by authority of ________
by H.7.C. TIC, date SEP 11 1973

TASK 3.8

SPENT FUEL STORAGE & COOLING REQUIREMENTS

(Title Unclassified)

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

APPROVED BY:

A.M. Poindexter, Mgr.
Ground Support Engineering

[redacted]

~~[illegible]ROUP - 1~~
~~EXCLUDED FROM A[illegible]ING~~
~~[illegible]CLASSIFICATION~~

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

[redacted]

TABLE OF CONTENTS

[redacted]

[redacted]

I. ABSTRACT

This memo deals with storage of NERVA reactor fuel after test, disassembly and post operative examination of an engine. The conditions that are assumed to exist during storage and the limitations on fuel storage are stated. Calculations of fuel temperature in storage and WANL recommendations to insure that storage conditions are met are also presented.

[redacted]

II. INTRODUCTION

The spent fuel will be stored in aluminum containers which will retain fuel particles, but which will not retain gaseous fission products. Each container will hold one hundred fuel elements. These containers will be designed to suit the requirements for storage of fuel from reactors used in engine testing. They will conform approximately to the outside dimensions of the fuel element cask liners used for KIWI and intended for use with NRX. This container is shown on ACF drawing no. 3-508006-00 and also in Figure #1 of this memo. The means of handling these containers may differ from that used with KIWI. The containers will incorporate neutron absorbing material which will maintain adequate subcriticality even with a very large array of containers closely spaced.

The irradiation history of the stored fuel has been assumed to be as follows:

1. Total run duration - sixty minutes at full power. This is divided into three-twenty minute runs
2. Interval between runs - five days
3. Time elapsed between shutdown of last run and start of storage - ten days.

The hottest element is assumed to have generated power at 1.6 times the average power generation for the core. The hottest fuel container is assumed to be filled with 100 of these elements.

The containers will be stored on rail cars designed to the requirements for storage of engine fuel as described in AGC Report #2592. The containers will be stored with their long dimension vertical. Figure #2 shows the general arrangement of containers on a flat car. Suitable racks must be provided which will position the fuel with free air space around, above and below the container to permit unrestricted air convection over the container surfaces.

The cars are assumed to incorporate covers over and around the fuel storage space. These covers should be completely removable to allow unrestricted visual and mechanical access above the bed of the flat cars.

III. STORAGE LIMITATIONS

There are three basic limitations on NERVA fuel stored in air. The first of these limitations has to do with the fuel temperature. In order to prevent excessive oxidation of the graphite, it is desirable to keep the exposed surface of the fuel below approximately 300°C. At this temperature, the oxidation rate of graphite in air is below 1% by weight per year.

The second limitation on fuel storage pertains to the containers in which the fuel is stored. They will be constructed of aluminum. It is desirable to maintain the temperature of the internal structure of the containers below 600° F to maintain good mechanical properties.

The third limitation pertains to containment of fission products. Most of the gaseous fission products are released during the test, however, some are retained in the fuel and probably will be released slowly. The release rates of these fission products is very low. In addition, the fuel will be stored away from human occupancy in a monitored area. The released products will be diluted by convected air to a very low radioactive concentration. The combination of these factors makes it unnecessary to contain gaseous fission products released from the fuel in storage. They will not constitute a hazard to operating personnel.

Particulate matter in varying sizes will probably exist inside the containers. The fuel is somewhat suspeptible to fracture and chipping. It therefore seems proper to provide for containment of these particles. The breather openings in the fuel containers should therefore be fitted with filtering or other necessary arrangements for retaining fuel particles inside the containers.

IV. SUMMARY AND CONCLUSIONS

From the calculation of temperature differences for the various parts of the storage containers and car, the temperature summary of Table 3 has been established.

Table 3 - Fuel Storage Temperature Breakdown

Ambient air temperature	100°F
Air outlet temperature	150°F
Fuel container surface temperature	209°F
Maximum container structure temperature	262°F
Maximum fuel surface temperature	265°F

These temperatures along with the allowable temperature limitations (given in Section III) are indicated in Figure 6 on a temperature scale chart. It is apparent from Figure 6 that there is a large margin between the calculated temperatures and the maximum allowable temperature.

The following paragraphs summarize the conclusions and recommendations made in the various sections of this memo.

1. It is not necessary to use forced convection to cool the fuel.

2. The fuel containers should be stored in a vertical position with one foot horizontal spacing between adjacent containers (See Figure 2). Eighteen inches clear space between the storage car bed and the bottoms of the containers should be allowed. Also two feet clearance should be provided between the tops of the containers and the security cover roof.

3. The security covers should be provided with ventilation inlet openings near the bottom and outlet openings in the roof. The outlet openings should have free air flow area equivalent to $10 ft^2$ per core. Outlet opening area should be the same. The openings should be louvered to make the storage space weatherproof.

V. SUMMARY OF CALCULATIONS

A. Heat Loads

1. Decay Heat Generation Rate

The decay heat generation is based on accumulation of fission products from three full power, twenty minute runs spaced five days apart. It is assumed that ten days elapse between shutdown of the last run and the storage of fuel in containers.

Data on decay heat are taken from Reference 3. The conservative assumption is made that no burnup of fission products from any run occurs in the succeeding runs.

Adding the fission product decay heat generation from each of the tests, the total heat generation per core is 2.21 Btu/sec.

The maximum heat generation in the reactor is assumed to be 1.6 times the average. For purposes of this calculation it is assumed that each fuel container encloses 100 elements generating heat at the maximum rate. The heat generation per container on the above basis is calculated to be 771 Btu/hr.

2. Solar Radiant Heating

The aluminum security cover will be subjected to solar radiation. Part of this radiation will be absorbed in the cover, thus elevating its temperature. The net solar heat load will be dissipated primarily by convection to the outside air and the air inside the car.

The amount of the net solar radiation load varies with orientation of the car, time of day, and other variables.

Estimates of solar radiation heat load were made using the method outlined in Reference 1 on Pages 66 to 73. The calculated net solar heat flux to the aluminum cover was 160 Btu/hr, ft^2.

The equilibrium temperature of the cover was calculated by assuming that this net solar heat load is dissipated by air convection from the inner and outer surfaces. It was assumed that the convection was equally divided between these surfaces. The calculated equilibrium temperature (assuming 100°F ambient air temperature) was 200°F.

The possibility exists that there will be net heat radiation from the security cover to the fuel containers inside. Investigation revealed that this heat radiation is insignificant. In the first place, the tops of the fuel containers are the surface most exposed to radiation and they have been found to be at nearly the same temperature as the security cover. As a check, the net radiation heat load to the containers was calculated assuming a 100°F temperature difference between the cover and the containers. This calculated heat load amounted to only five per cent of the fission product decay heat load.

3. Total Heat Load in the Car

The total heat load is composed of two parts; fission product decay heat generation and solar heat load transmitted to the inside of the security cover. This total load has been calculated for a part of the car large enough to contain fuel from one core.

The fuel containers are assumed to be spaced as shown in Figure 2. With this spacing, the area of the security cover associated with one core is approximately 150 square feet. It is assumed that one half of the net solar radiation load estimated

[redacted]

in Section V-A2 (i .e., 80 Btu/hr, ft^2) is convected to the inside of the cover. This is conservative since two or more of the vertical sides will be receiving less solar radiation than the amount calculated for the flat roof. Based on the above assumption, the total net solar head load to the inside of the cover (per core) is approximately 12,000 Btu/hr. The decay heat generation per core estimated in Section V-A1 is 12,800 Btu/hr.

Therefore, the total heat load inside the cover is 24,800 Btu/hr.

B. Air Circulation

The total heat load as given in Section V-A3 is dissipated by natural convection of air in a manner described as follows: inward through openings of the lower edge of the security cover; through the open space beneath the fuel containers, upward through the spaces between the fuel containers; through the space above the fuel containers, and finally out through the openings in the top of the security cover.

Air entering the heated space expands decreasing its density (relative to the outside air) and creating a driving head fornatural circulation. Using the ideal gas laws to represent the density of air,

[redacted]

the driving head for natural circulation flow can be expressed in terms of the height of heated air column, the air temperature increase, the inlet air temperature, pressure and gas constant.

The resistance to turbulent flow can be expressed as

$$\Delta p = M \frac{\rho v^2}{2g} \tag{1}$$

where

Δp = total pressure loss due to flow, (#/ft^2)

ρ = air density, (#/ft^3)

v = air velocity through ventilation openings in covers, (ft/hr)

g = acceleration of gravity, (ft/hr^2)

m = total flow resistance coefficient (See Table 1)

A breakdown of the total flow resistance coefficient is given in Table 1.

Table 1 - Flow Resistance Coefficient

Item	Resistance Coefficient
Security Cover Inlet Opening	
Flow Contraction Loss	0.44
Flow Expansion Loss	1.00
Flow Channel Between Fuel Containers	

Item	Resistance Coefficient
Flow Contraction Loss	0.056*
Friction Loss	0.082*
Flow Expansion Loss	0.084*
Security Cover Outlet Opening	
Flow Contraction Loss	0.44
Flow Expansion Loss	1.00
Total	3.102

By equating the available flow driving head (for a selected air temperature) to the head required to overcome the resistance to flow, the flow velocity through the ventilation openings of the security cover can be determined.

From this velocity and the chosen air temperature rise, the volumetric air flow and required flow area of the inlet (and outlet) ventilation openings can be determined.

In the calculation of air circulation in this study, an air temperature rise (in the security cover) of 50°F was selected

---

*These loss coefficients have been reduced to take into account the fact that the velocity through this channel is lower than that through the security cover openings.

and a corresponding ventilation opening area of 2.9ft^2/ core was determined. This is the total inlet opening area per core. The outlet opening area should be the same. Since it is easy to provide more area, it is recommended that the above calculated requirement be increased to 10ft^2 per core.

C. Fuel and Container Temperatures

1. Outer Surface Temperature of Container

The decay heat generated in each container must be dissipated by convection to the air flowing over its outer surfaces. Several methods exist for calculation of heat flow through a natual convection boundary layer or film, all of them giving approximately the same result. The particular method used in this study is the one presented in Reference 2 on page 101. The natural convection film coefficient of heat transfer calculated by the above method is 0.78 Btu/hr,ft^2.

The outer surface area of the vertical sides of the container is 16.8 ft^2. No credit was taken for heat transfer through the ends of the container. The actual film temperature difference should therefore be somewhat less than the calculated value.

The temperature of the fuel container outer surface was calculated on the basis given above. It was found to be 59°F above the temperature of the surrounding air.

2. Temperature of Container Structure

The fuel storage containers are aluminum boxes filled with aluminum tubes arranged in a square pattern. Each tube holds one fuel element. This arrangement is shown on Figure 1. The array of tubes and fuel can be considered as a large number of identical repeating units. The typical repeating unit or cell is shown in Figure 3.

Heat will flow from each fuel element into its surrounding tube. It must then be tranmitted from this tube through the tube structure and air that intervenes between it and the outside surface of the container.

This section deals with evaluation of this outward heat flow to the container surface.

The repeating unit of Figure 3 is shown schematically in Figure 4. Heat flow paths through the cell are shown alongwith their corresponding thermal resistances. The subscripts used to designate the individual resistance indicate the beginning and end of its heat flow path as shown on Figure 3. For example, R_{ab} (Figure 3) is the thermal resistance of the aluminum tube for heat flow from point "a" to point "b".

Referring to Figure 4, heat will flow from the adjacent cell into the cell in question at points "a" and "e". Heat will flow in series through the fuel element and the stagnant air gap between it and the tube (R_{ef} and R_{fb} respectively).

Heat flow through the tube wall (R_{ab}) is in parallel with the above flow path. These two parallel flow paths join at "b"and all the heat flows across the air gap between the two tubes (R_{bc}). The remainder of the path is identical to the parts discussed above. Heat leaves the cell through points "h" and "d". It then flows into the next cell.

The basis for evaluation of the various thermal resistances will now be discussed.

a. Tube Wall Resistance

This can be expressed as follows:

$$R_{ab} = \frac{\ell}{AK} = \frac{\ell}{2\ wk} \qquad (2)$$

where ℓ = Path length from a to b, (ft)

w = Tube wall thickness (ft)

K = Tube wall thermal conductivity, (Btu/hr, ft,°F)

A = Cross sectional area for heat flow (ft^2)

Note that this and the following calculations of resistance are based on a one foot length along the axis of the tube.

b. Fuel Resistance

The unit cell filled with the homogeneous material is shown in Figure 5. This conduction resistance is calculated in the same general fashion as R_{ab}. The cross sectional area for heat flow is based on the diameter of an equivalent cylinder to represent the hexagonal shape. The heat flow path length is taken as the radius of this equivalent cylinder.

c. Fuel to Tube Air Gap (R_{fb})

The cross sectional area for heat flow is based on the perimeter of the equivalent fuel cylinder. The heat flow path length is taken as the air gap between the cylinder and tube.

d. Tube to Tube Air Gap (R_{bc})

Heat flows from one tube to the other across a stagnant air gap of varying thickness. The derivation and calculation of the heat flow across this air gap is given in Appendix 1.

A summary of the calculated thermal resistances is given in Table 2.

Table 2 - Thermal Resistances of Elements of the Unit Cell

R_{ab} = 0.0935 ($\frac{^{o}F, Hr.}{Btu}$)

R_{ef} = 0.0071 (")

R_{fb} = 2.90 (")

R_{bc} = 3.05 (")

Comparison of the sum of resistances R_{ef} and R_{fb} with R_{ab} (See Figure 4) shows that the heat flow through the R_{ef} and R_{fb} is negligible due to its much higher thermal resistance. Thus the total resistance of the cell is approximately:

$$R = R_{ab} + R_{bc} = R_{cd}$$

$$R = 2R_{ab} + R_{bc} \qquad (3)$$

The problem is one of determining the two dimensional temperature distribution in a rectangle that is filled with a large number of the unit cells described previously and having heat generation uniformly distributed in the gross sense.

Simple methods are available for calculation of one dimensional temperature distribution in solid, uniformly heat generating, homogeneous bodies such as an infinite cylinder or an infinite slab of finite thickness. These methods will yield entirely satisfactory results in the present problem if we do the following two things:

1. Replace the rectangular cross section of the fuel container with a one dimensional configuration which will conservatively represent the actual one. The configuration selected

was a cylinder having the same cross sectional area as the rectangle. This gives a temperature rise higher than actual since the radius of the cylinder is greater than the half thickness of the rectangle. The temperature rise was also calculated for an infinite slab having thickness equal to the short dimension of the rectangle. This temperature rise was lower than the one for the cylinder above. The higher of the two values was used.

2. Replace the actual repeating unit cell with a hypothetical homogeneous material having the same thermal properties as the actual cell. Since the steady state temperature distribution is desired, the pertinent thermal properties are the volumetric heat generation rate and the equivalent thermal conductivity of this hypothetical material. The unit cell filler with the homogeneous material is shown in Figure 5.

The volumetric heat generation rate of the hypothetical material is simply the total heat generation per container divided by the total volume of the container.

The equivalent thermal conductivity is found by equating the heat flow through the unit cell of homogeneous material to the heat flow through the actual cell, assuming the same temperature differences exists across each. The equivalent thermal properties of the hypothetical material calculated on the above basis are:

$$q'''_{eq} = 250 \text{ Btu/hr, ft}^3$$

$$K_{eq} = 0.309 \text{ Btu/hr, ft, }^{\circ}\text{F}$$

The difference in temperature between the center and the periphery of a homogeneous infinite cylinder having spatially uniform heat generation is:

$$\Delta t = \frac{q''' r^2}{4 K} \qquad (4)$$

where q''' = Volumetric heat generation rate, (Btu/hr, ft^3)

r = Radius of cylinder, (ft)

K = Thermal conductivity of cylinder, (Btu/hr, ft, °F)

When we apply the equivalent radius, thermal conductivity, and heat generation to the above expression, the temperature rise is 53°F. This is a somewhat higher than actual value for the temperature elevation of the hottest structure tube above the container surface temperature.

3. Fuel Surface Temperature

Heat flows from the individual fuel element to the structure tube through the air gap thermal resistance, R_{fb}. On this basis, the fuel was calculated to be 3°F above the surrounding tube.

[redacted]

VI. APPENDIX I - DERIVATION AND CALCULATION OF TUBE TO TUBE AIR GAP RESISTANCE

This derivation is based on the assumption that all parts of a tube wall are at the same temperature. Since the resistance of the tube wall is less than 3% of the resistance of the air gap, the temperature difference in the tube wall is less than 3% of that across the air gap and can therefore be neglected.

Figure A shows the two tubes and the air gap between them. With uniform tube wall temperature, the temperature difference across the air gap is constant with varying α. The heat flow path length, however varies with α. This path length can be expressed as:

$$\Delta \ell = 2r\,(1 + e/r - \cos\alpha) \qquad (6)$$

The cross sectional area of the differential heat flow path is the product of its width and the unit length (1 ft.) in the direction of the tube axis.

$$dA = r\cos\alpha\, d\alpha \qquad (7)$$

The heat flow through the differential path is

$$dq = -K\,dA\,\frac{\Delta t}{\Delta \ell} \qquad (8)$$

$$dq = \frac{-K\,r\cos\alpha\, d\alpha\,\Delta t}{2r\,(1 + e/r - \cos\alpha)}$$

$$q = \int_{-\beta}^{+\beta} dq = -\int_{-\beta}^{+\beta} \frac{K\ r\cos\alpha\,\Delta t\, d\alpha}{2r\,(1 + e/r - \cos\alpha)}$$

$$= -K\Delta \text{[redacted]} \int^{+\beta} \frac{\cos\alpha\, d\alpha}{1 + e/r - \cos\alpha}$$

[redacted]

$$q = -k\Delta t \quad -\beta + \frac{2(1+e/r)}{\sqrt{(1+e/r)^2-1}} \tan^{-1} \frac{\sqrt{(1+e/r)^2-1}}{(1+e/r)-1} \quad \tan \beta/2 \tag{9}$$

The thermal resistance of a heat flow path is defined as

$$R = -\frac{\Delta t}{q} \tag{10}$$

Substituting equation (9) in (10),

$$R = \frac{1}{K\left\{-\beta + \frac{2(1+e/r)}{\sqrt{(1+e/r)^2-1}} \tan^{-1} \left[\frac{\sqrt{(1+e/r)^2-1}}{(1+e/r)-1} \quad \tan \beta/2\right]\right\}} \tag{11}$$

For the fuel container in question the tube diameter is one inch and the tube to tube clearance is 0.01 inch. Thus, $e/r = 0.01$. Note from Figure A that for $e/r = .01$ and α greater than 30°, the path length is much longer than for $\alpha = 0$. This means that the differential heat flow is much reduced at higher values of α and the decrease in air gap resistance is small with further increase in α. It was decided for the sake of conservatism to take no credit for the heat passing through flow paths associated with angles larger than 30°. Thus β, the limit of integration was chosen as 30° or $\pi/12$ radians.

Substituting the following values in equation (11),

$e/r = 0.01$

$\beta = \pi/12$

The resulting resistance is:

$$R = 3.05 \ \frac{^\circ F, \text{Hr}}{\text{Btu}}$$

[redacted]

VII. REFERENCES

1. "Introduction to Heat Transfer", Brown and Marco, Second Edition, McGraw Hill

2. "Applied Heat Transmission" H. J. Stoever, First Edition, McGraw Hill

3. WANL-TME-072, "Test Engine Disassembly Cooling Requirements", W. Knecht, dated 6/25/62

[redacted]

[redacted]

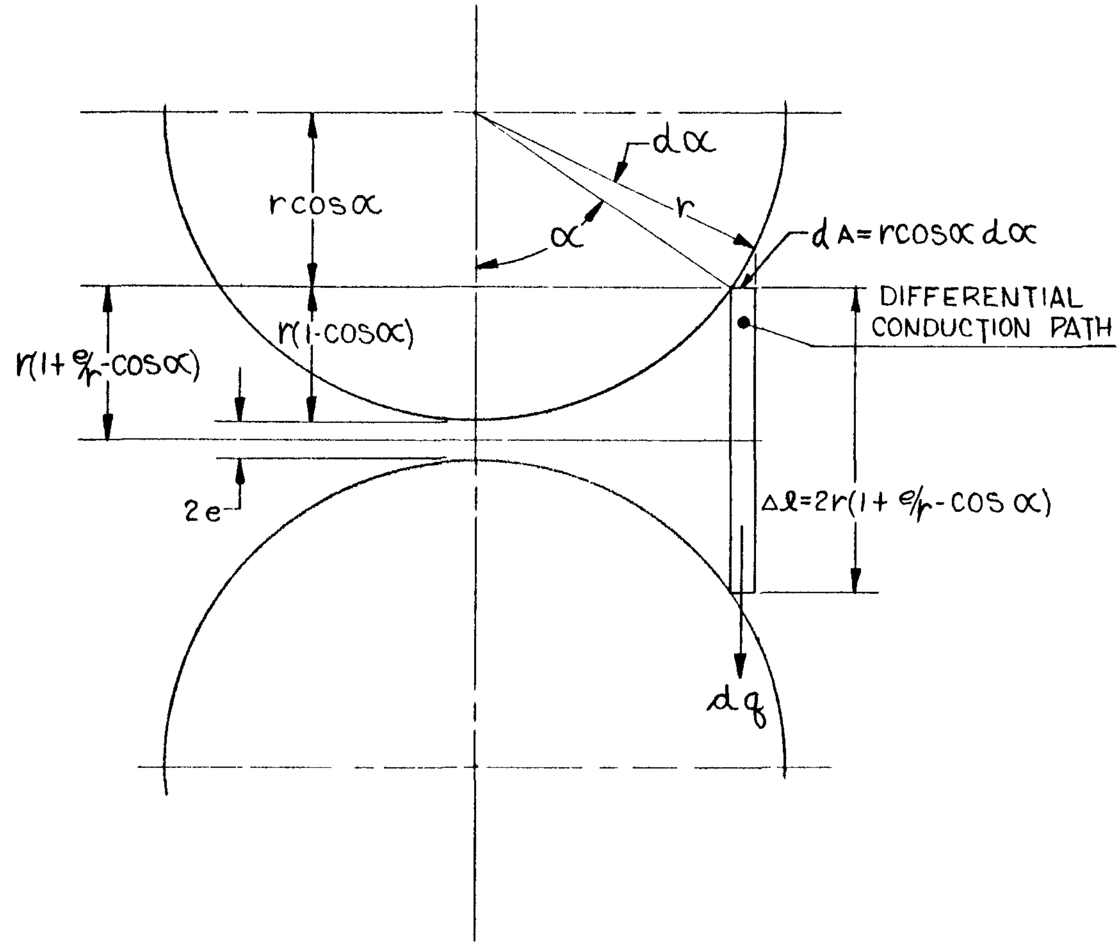
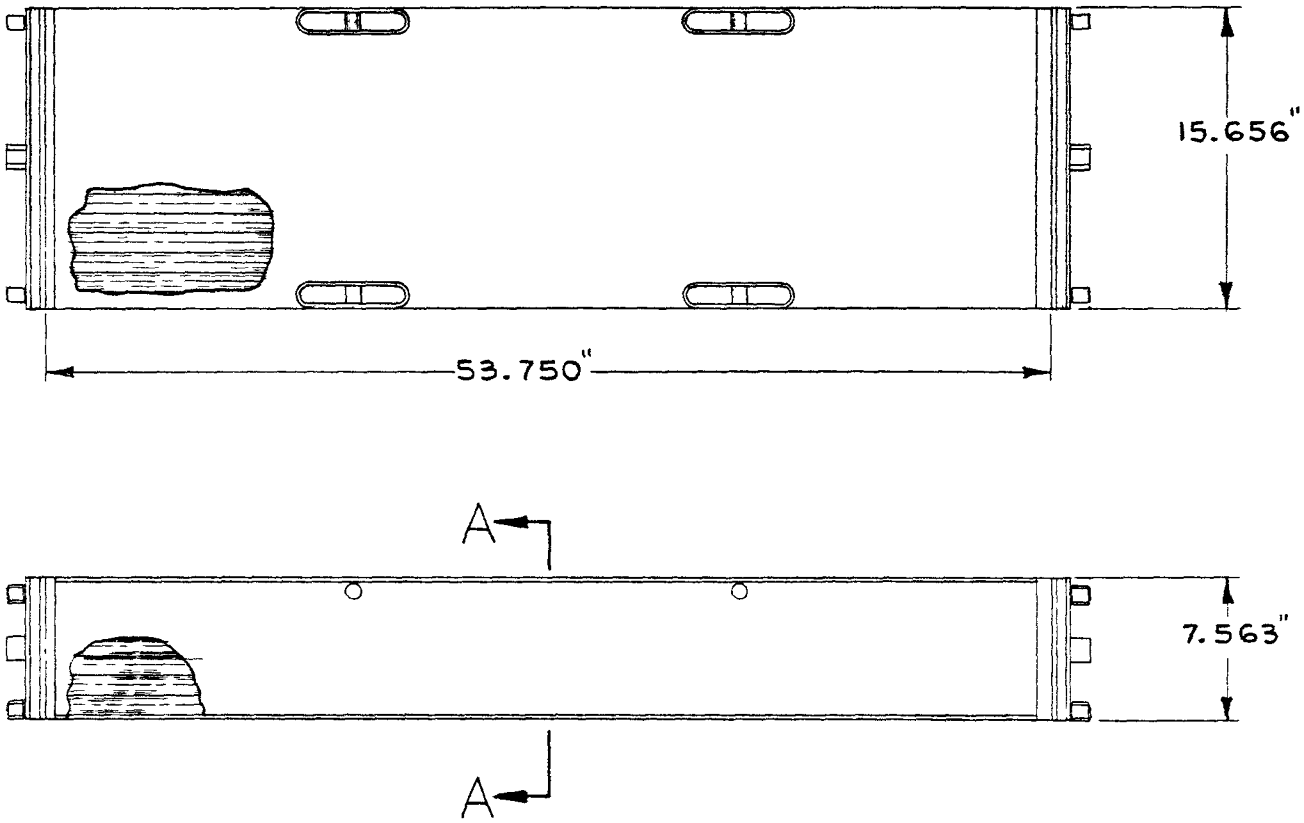


DIAGRAM OF AIR CONDUCTION PATH BETWEEN CONTAINER TUBES

FIG. A

[redacted]

[redacted]



[redacted]

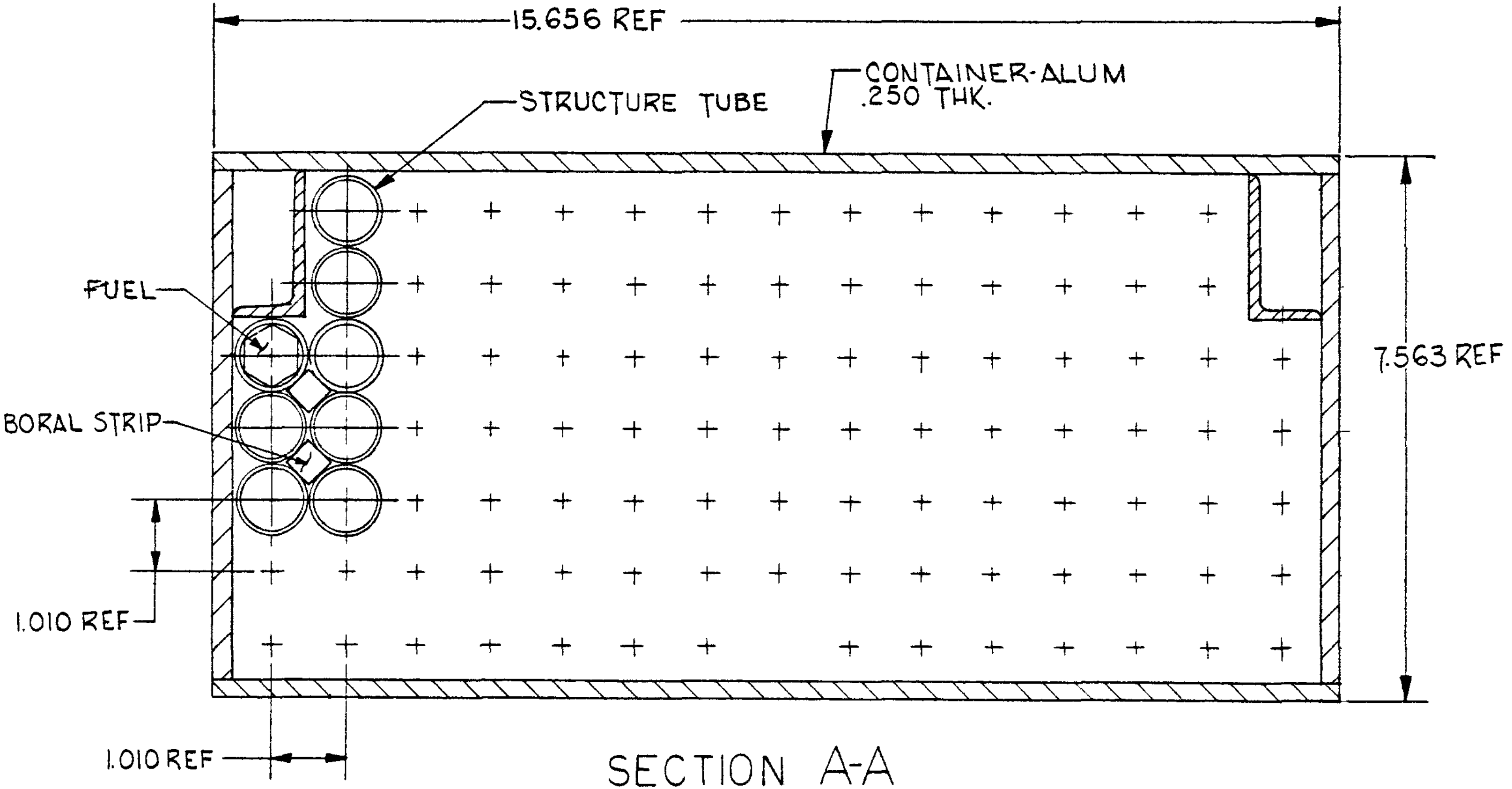
ELEMENT CASK INSERT
ARRANGEMENT DRAWING

FIG. I-SHEET 1

Astronuclear

[redacted]

[redacted]



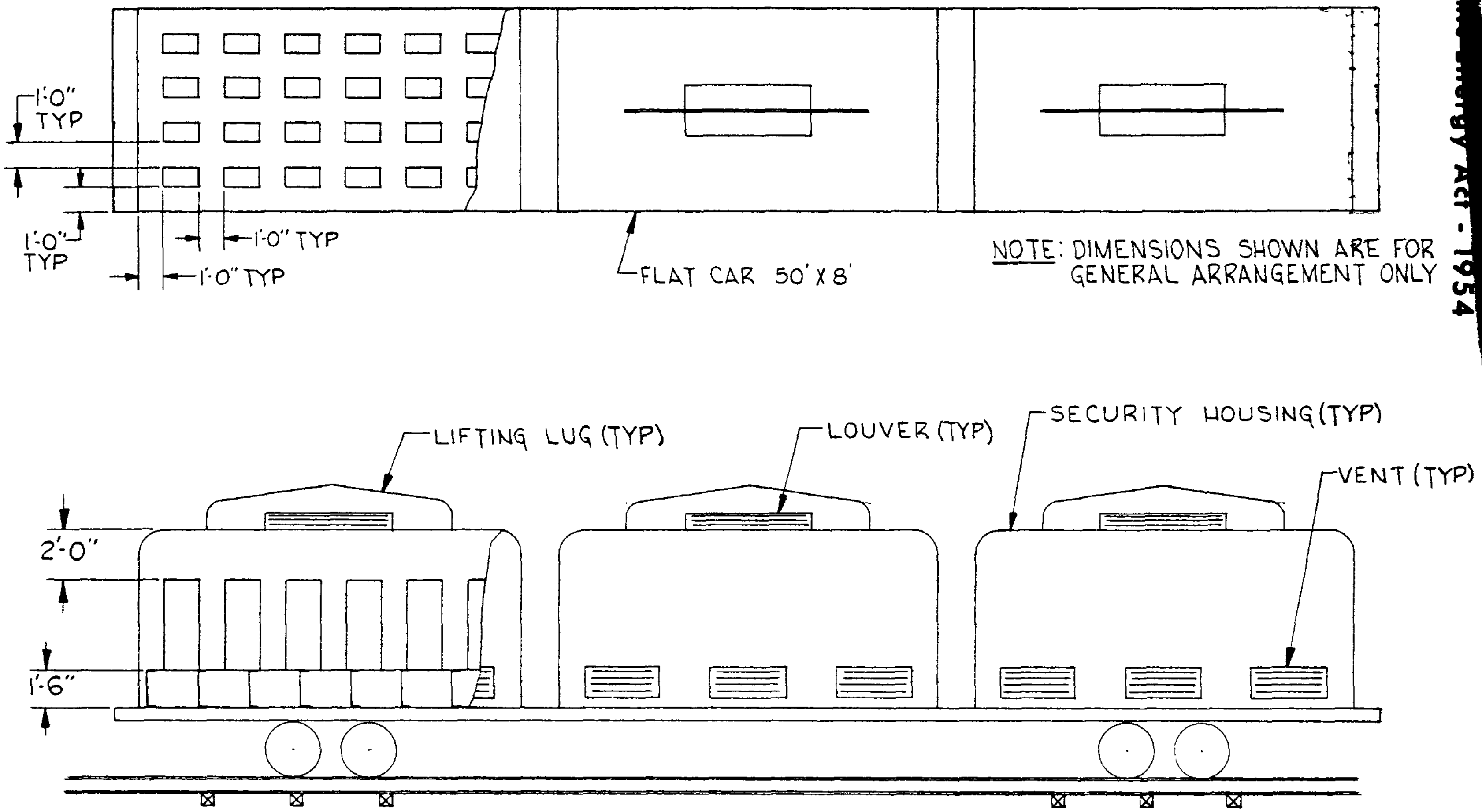
SECTION A-A

ELEMENT CASK INSERT
ARRANGEMENT DRAWING

FIG. I - SHEET 2

Astronuclear

~~CONFIDENTIAL~~
~~RESTRICTED DATA~~
~~Atomic Energy Act - 1954~~



NOTE: DIMENSIONS SHOWN ARE FOR GENERAL ARRANGEMENT ONLY

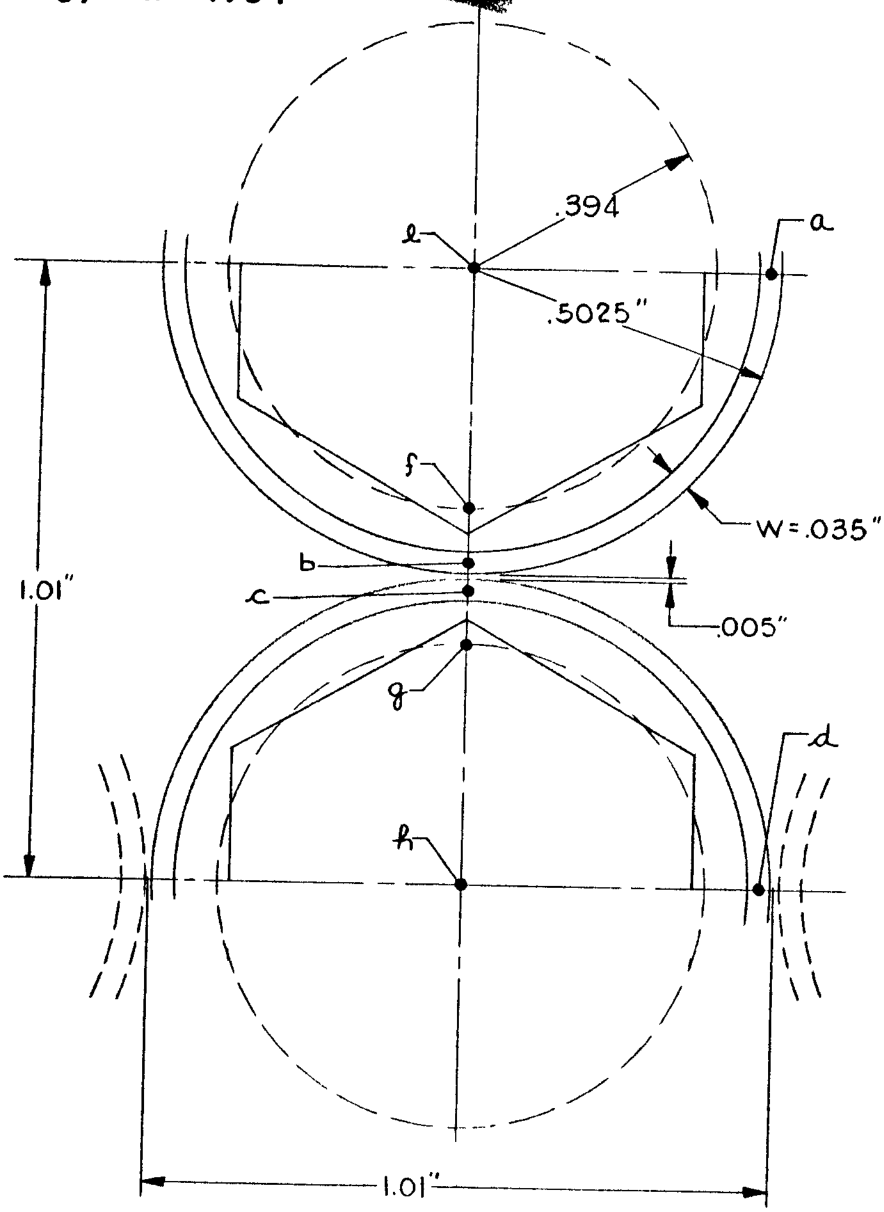
SPENT FUEL STORAGE ARRANGEMENT

FIG. 2

~~CONFIDENTIAL~~
~~RESTRICTED DATA~~
~~Atomic Energy Act - 1954~~

Astronuclear

[redacted]

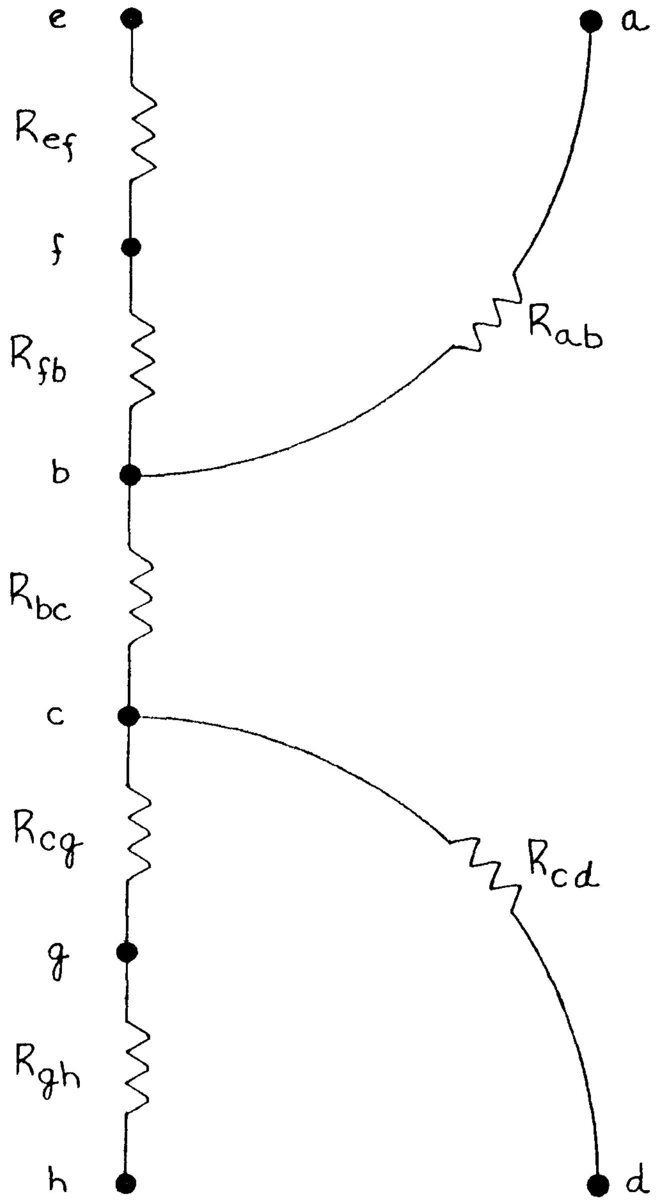


REPEATING MACROSCOPIC UNIT CELL INSIDE THE FUEL CONTAINER

FIG. 3

[redacted]

[redacted]

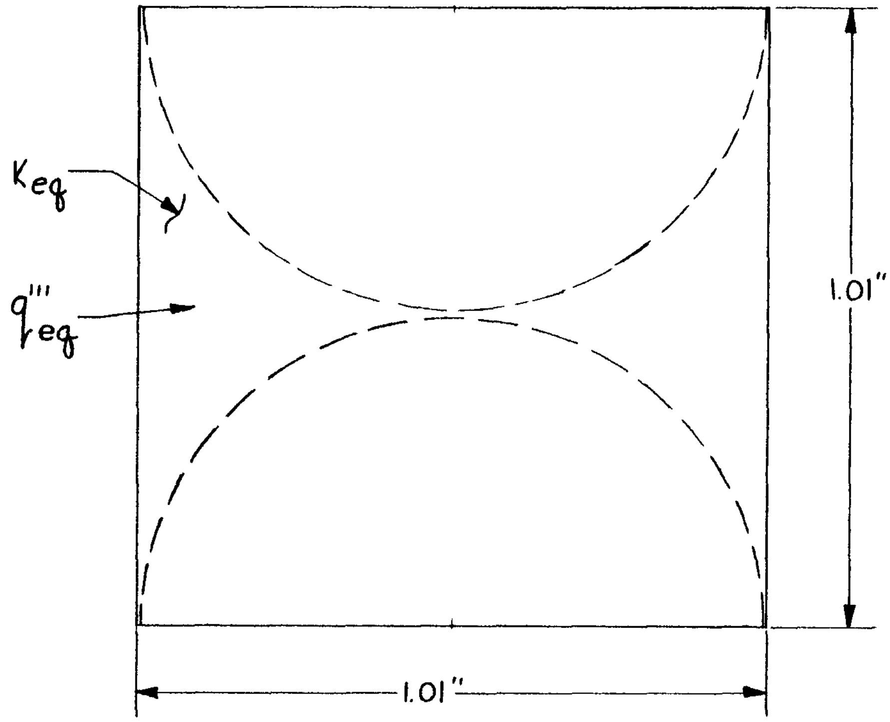


THERMAL RESISTANCE DIAGRAM FOR REPEATING UNIT CELL

FIG. 4

[redacted]

[redacted]

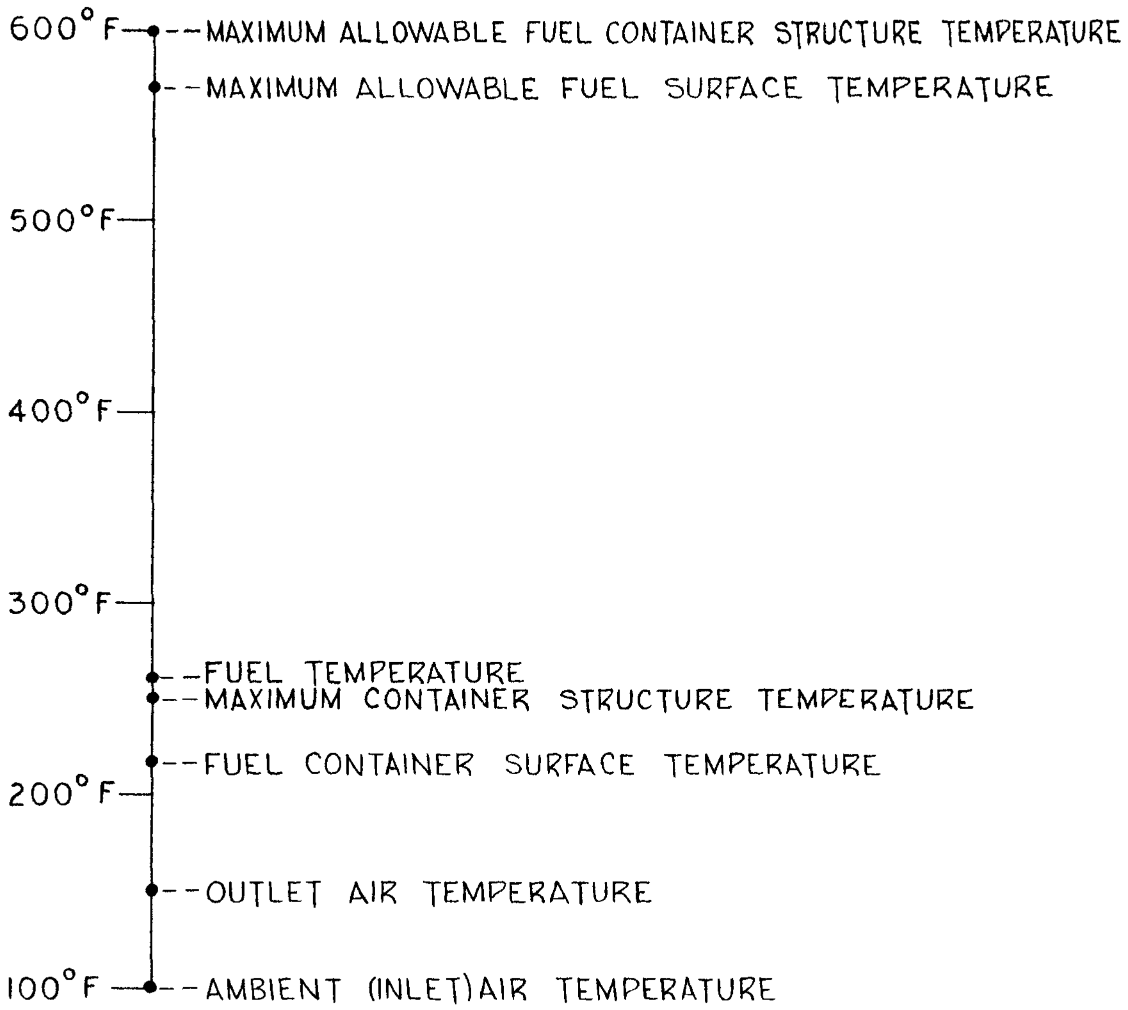


EQUIVALENT HOMOGENEOUS MATERIAL IN UNIT CELL

FIG. 5

[redacted]

[redacted]



TEMPERATURE DIAGRAM
FOR STORED FUEL

FIG. 6

[redacted]