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TEMPERATURE OF N.S. SAVANNAH IRRADIATED FUEL
FOLLOWING A POSTULATED LOSS OF COOLANT
FROM THE TRANSFER CASK

O. H. Klepper

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H.C. \$ 0.11; MN 65

ORNL-TM-1845

Contract No. W-7405-eng-26

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Reactor Division

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TEMPERATURE OF N.S. SAVANNAH IRRADIATED FUEL
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FROM THE TRANSFER CASK

O. H. Klepper

ABSTRACT

The objective of this study was to estimate the temperature of N.S. SAVANNAH spent fuel following a postulated loss of coolant from the spent fuel transfer cask. Hand and digital computer calculations were employed to determine the cask temperature distribution as a function of time after reactor shutdown. Peak cladding temperatures were estimated to remain well below the melting point.

INTRODUCTION

Refueling of the N.S. SAVANNAH reactor will require transferring the spent fuel from the ship to the shore fuel handling facility. This transfer is to be made in a transfer cask with a capacity of one fuel element. During normal cask operation the spent fuel element will be immersed in primary water that transports the fission product decay energy by natural convection to a secondary water-cooling system. Should the water be lost from the cask during the transfer, the fuel would become hotter, since the decay heat would be transported mainly by radiation and air convection from the fuel to the cask wall and on to the atmosphere. Under these circumstances it becomes of interest to know the temperature distribution within the cask, since this may affect the integrity of the cask and of the fuel. Should the fuel cladding fail, knowledge of the fuel temperature will be needed to assess the release of fission products from the fuel. In view of these considerations an estimate of transfer cask temperatures following simultaneous loss of primary and secondary coolant from the cask was made.

A number of factors that affect the heat removal process from the cask are not well known at the present time. These factors include the

emissivity of the cask internals and of the fuel, the extent to which the lead in the cask is bonded, and the external environment that the cask might be exposed to. Where convenient, these uncertainties were treated as variable parameters, permitting direct application of the results once a specific value of the parameter is known.

Steady state equilibrium conditions were assumed throughout the analysis. This neglects the time required for the cask structure to heat up following a loss of coolant, and it therefore ignores the concurrent decrease in the rate of decay energy release.

HEAT FLOW PATH FOLLOWING LOSS OF COOLANT

The spent fuel consists of sintered UO_2 pellets contained in 0.5-in.-OD stainless steel tubes. The fuel pins have an active length of 66 in. Each fuel element contains 164 fuel pins spaced 0.663 in. center-to-center in a rectangular array, which form a fuel element approximately 8.5 in. by 8.5 in. and 66 in. long. Inside the cask the fuel element is enclosed by a central box-shaped stainless steel liner about 1/4 in. thick, as shown in Fig. 1. Approximately 1/4-in. clearance is provided between the fuel element and the liner. Following a loss of coolant from the cask, heat must be transferred from the fuel to the surrounding liner. The energy absorbed by the liner in turn must be transferred to the stainless steel guide tube; this guide tube, which is about 14 in. ID and 15 in. OD, surrounds the liner. Average clearance between the liner and the guide tube is about 1.65 in. The next step in the outward heat flow is from the guide tube to the mild steel wall of the cask cavity, across an additional air gap about 1.5 in. in thickness. The cask wall consists of an inner cylindrical mild steel shell about 2 in. thick and 42 in. OD. The 10-in. void space between the shells contains lead shielding. The cask height is approximately 9.4 ft. The heat flow through the wall to the cask exterior surface is primarily by conduction except at the interfaces between lead and steel. Heat reaching the cask surface is then finally absorbed by the environmental heat sink.

Fig. 1. Cask Configuration

DECAY HEAT GENERATION

The fuel element heat generation from the decay of fission products was computed according to the Way-Wigner prescription.¹ This prescription should apply well for the shutdown times of 10 days and longer which are considered here. The following assumptions were made:

1. Reactor operation at 63.5 Mw(th) for 100 days preceding shutdown.
2. A radial power-peaking factor of 2.0 and an axial power-peaking factor of 1.5 for the central, hottest fuel element.²

The peak heat generation rate for the central fuel element is shown in Fig. 2 for 10 to 100 days after shutdown. The 10-day limit was selected as a reasonable time lapse between plant shutdown and removal of fuel from the core.

An estimate was made to determine the importance of the decay energy transported from the fuel by gamma radiation. Employing data by K. Shure,³ it was found that at 10 days after shutdown, approximately 15% of the decay heat would be carried by gamma radiation from the fuel to the cask wall inner surface and beyond. This refinement was not incorporated in the calculation, since the additional complexities seemed to outweigh the potential gain in precision. The error introduced by this neglect is, of course, in the direction of overestimating fuel temperatures.

HEAT TRANSFER FROM THE CASK TO THE ENVIRONMENT

The main heat exchange mechanisms for removing heat from the cask surface are convection and radiation. Conduction transfer to the ground may remove some energy; however, the amount of contact with the ground under accident conditions is difficult to predict, and this transfer mechanism

¹S. Glasstone, Principles of Nuclear Reactor Engineering, Van Nostrand, Princeton, p. 119, 1st ed., 1955.

²Babcock and Wilcox Company, Nuclear Merchant Ship Reactor, Final Safeguards Report, Vol. I, USAEC Report BAW-1164, p. 69, June 1960.

³K. Shure, Fission Product Decay Energy, Bettis Technical Review, Reactor Technology, USAEC Report WAPD-BT-24, p. 14, Westinghouse Electric Corporation, December 1961.

Fig. 2. Peak Decay Heat Generation for Central Fuel Element

was therefore ignored. Thermal radiation transfer from the cask to the environment depends upon the configuration, temperature, and emissivity of the surroundings. These factors are not well known at the present time, and, consequently, this heat transfer was also ignored. This was also true of external mechanisms such as fire, spray cooling, and solar heat. Of these, the first two may have a significant effect on cask surface temperature, and, accordingly, they should be evaluated once sufficient information becomes available. It was estimated that solar heating might increase surface temperatures by as much as 50°F if the cask exterior has moderate solar absorptivity such as rough or oxidized metals.⁴ The corresponding fuel element temperature rise would be somewhat smaller. Ignoring thermal radiation and conduction heat transfer leaves convection as the remaining mechanism. Natural convection in still air at 100°F was assumed. The convection heat transfer coefficient for vertical cylinders as given by McAdams⁵ is

$$\frac{h_c L}{k_f} = 0.13 \left(N_{Gr} N_{Pr} \right)_f^{1/3} \quad (1)$$

where

h_c = surface coefficient of natural convection heat transfer,
B/(hr)(ft²)(°F),

k_f = thermal conductivity of air, Btu/(hr)(ft)(°F),

L = height of vertical surface, feet,

N_{Gr_f} = Grashof number of air, dimensionless,

N_{Pr_f} = Prandtl number of air, dimensionless.

Equation (1) was used to calculate the cask surface temperature with the cask in a vertical position. Only the sides of the cylindrical cask

⁴D. K. Rider, Temperature Rise in Structures Due to Solar Heating, ASTM Special Technical Publication No. 270, pp. 43-60, 1959.

⁵W. H. McAdams, Heat Transmission, Eq. (7-4a), p. 172, McGraw-Hill, New York, 3rd ed., 1954.

were considered effective, providing 103.5 ft² of surface area. In view of the good conduction properties of the cask wall, a uniform temperature of the cask surfaces was assumed.

For the condition with the cask horizontal, convection data from McAdams⁶ were used. In order to allow for the interference of the ground with natural convection, it was arbitrarily assumed that only 2/3 of the actual cask surface area is effective, resulting in a heat transfer area of 82 ft². Under these conditions natural convection heat transfer from a horizontal cylinder is slightly poorer than from a vertical cylinder. However, subsequent investigation of convection within the cask showed that a vertical cask position will result in a higher fuel temperature, and this case was therefore treated. Cask surface temperatures ranged from 250°F at 10 days after shutdown to 150°F at 100 days.

HEAT TRANSFER THROUGH THE CASK WALL

As shown in Fig. 1, the cask wall consists of a mild steel shell about 2 in. thick and about 42 in. OD, a concentric inner mild steel shell 1 in. thick and about 18 in. OD, and about 10 in. of lead in the intervening void. The lead was cast in place and no special effort was made to bond the two materials together. How much surface contact exists between the lead and the cask walls is uncertain. L. S. Marks⁷ reports a linear shrinkage of 1/92 for lead castings. This shrinkage amounts to about 0.1 in. for the 10-in.-thick cask lead. Assuming, for simplicity's sake, that the entire gap is located at the outer interface and that the only heat transfer mechanism across the air gap is conduction, the temperature drop across the cask wall was estimated to be about 120°F at 10 days after shutdown and about 25°F at 100 days after shutdown. The corresponding temperature drops, assuming full contact between the lead and steel, are 15°F and 3°F, respectively. While a 0.1-in. air gap would increase the cask wall temperature drop by about 105°F at 10 days after shutdown, the resulting

⁶Ibid., Fig. 7-10, p. 176.

⁷L. S. Marks, Mechanical Engineer's Handbook, McGraw-Hill, New York, p. 298, 4th ed., 1941.

fuel temperature increase is considerably smaller - not exceeding 25°F. It appears, therefore, that air gaps of the magnitude considered here between the lead and the cask structure will not have a major impact on peak fuel temperature. The maximum wall temperature, if the air gap is considered, would be 370°F. This is well below the lead melting temperature of about 620°F.

HEAT TRANSFER FROM LINER TO CASK WALL

The liner is shaped like a hollow rectangular box that surrounds the spent fuel (see Fig. 1). The sides of the liner are of stainless steel, about 1/4 in. thick and 9.5 in. wide, extending the length of the fuel element. The stainless steel guide tube surrounding the liner has an inside diameter of about 14 in. and a wall thickness of 1/2 in. Heat flowing from the liner must therefore flow through the guide tube wall before reaching the cask wall that surrounds the guide tube.

The most important heat transfer mechanisms across the air gap between the liner and the guide tube are thermal radiation and natural convection. To simplify the calculations, the liner was treated as a cylindrical surface. The equivalent diameter for convection heat transfer was selected to produce the same flow area as the actual configuration. This resulted in an average clearance of 1.65 in. between the liner and the guide tube. The equivalent diameter for radiant heat transfer, on the other hand, was based on maintaining the same surface area as the liner actually possessed. The radial temperature gradient of the guide tube was neglected, since it would be quite small. Axial conduction in the liner and the guide tube were also neglected, and this is expected to result in a slight overestimate of the peak fuel temperature. Axial radiant heat transfer was neglected, and instead the surfaces were treated as infinitely long concentric cylinders for which radiant transfer is given by⁸

⁸W. H. Giedt, Principles of Engineering Heat Transfer, Van Nostrand, Princeton, p. 259, 1st ed., 1957.

$$q_{1 \rightarrow 2} = \frac{A_1 \sigma (T_1^4 - T_2^4)}{\frac{1}{\epsilon_1} + \frac{A_1}{A_2} \left(\frac{1}{\epsilon_2} - 1 \right)} \quad (2)$$

where

A_1 = area of inner surface, ft²,

A_2 = area of outer surface, ft²,

$q_{1 \rightarrow 2}$ = net rate of heat transfer from inner surface to outer surface, B/hr.

T_1 = temperature of inner surface, °R,

T_2 = temperature of outer surface, °R,

ϵ_1 = emissivity of inner surface, dimensionless,

ϵ_2 = emissivity of outer surface, dimensionless.

The assumption of infinitely long surfaces should be realistic for points near the midheight of the cask. The clearance between the concentric cylindrical surfaces is rather small, so that only a small fraction of the radiant energy released near the cask midheight can stream toward the cask extremities.

The convection heat transfer between the liner and the guide tube was calculated by the following expression:⁹

$$\frac{h'_c X}{k_f} = \frac{C}{(L/X)^{1/9}} \left[\frac{X^3 \rho_f g \beta_f \Delta t}{\mu_f^2} \left(\frac{C_P \mu}{k} \right)_f \right]^n \quad (3)$$

where $C = 0.20$ and $n = 0.25$ for the range of N_{Gr} from 2100 to 20,000.

C_{P_f} = specific heat of air, B/(lb)(°F),

g = acceleration due to gravity, ft/hr²,

h'_c = surface coefficient of natural convection heat transfer in an enclosed space, B/(hr)(ft²)(°F),

k_f = thermal conductivity of air, B/(hr)(ft)(°F),

⁹W. H. McAdams, Heat Transmission, Eq. (7-9b), p. 181, McGraw-Hill, New York, 3rd ed., 1954.

- L = height of vertical cask or diameter of annulus for horizontal cask, ft,
 x = clearance in enclosed space, ft,
 β_f = coefficient of volumetric expansion of air, $1/^\circ\text{F}$,
 Δt = temperature potential, $^\circ\text{F}$,
 μ_f = viscosity of air, $\text{lb}/(\text{hr})(\text{ft})$,
 ρ_f = density of air, lb/ft^3 .

The Grashof number in this case was based on the clearance between the cylindrical surfaces. In the case of enclosed gas spaces Eq. (3) is applicable to vertical enclosed air spaces as well as to horizontal enclosed annular air spaces. In the latter case the diameter of the annulus would replace L in the above expression. The diameter of this annulus is approximately $1/5$ of its length, so that the convective heat transfer coefficient will be greatest with the cask in the horizontal position.

The Grashof numbers for the $1/2$ -in. air gap between the guide tube and the cask wall are greater than 2000 for the temperature gradients expected, so that natural convection will still play a role in the heat transfer.¹⁰ Equations (2) and (3) were also used to compute the heat transfer in this region.

The following method was employed to calculate the liner temperature as a function of time after shutdown. The radiant heat flux between the cask wall and the guide tube was combined with the convective heat flux to give the total heat flux as a function of cask wall temperature and temperature gradient between the guide tube and the cask wall. This procedure was then repeated to compute the total heat flux between the liner and the guide tube. Then, by matching the heat flux from the guide tube to the wall with the corresponding heat flux from the liner to the guide tube, it was possible to compute the liner temperature as a function of heat flux and wall temperature. Knowing the heat flux as a function of time after shutdown and by considering the corresponding cask wall temperature as described in a preceding section (Heat Transfer Through the

¹⁰Ibid., p. 181.

Cask Wall), the liner temperature was determined as a function of time after shutdown.

Several conditions were investigated. A comparison of the cask upright versus cask horizontal showed that while the cask wall temperatures were somewhat lower in the first mentioned attitude, the liner temperatures were higher. This is the result of the poorer heat transfer between the liner and the wall when the cask is vertical, as mentioned before. Another uncertainty investigated was the emissivity of the stainless-steel liner and guide tube. McAdams¹¹ lists a range of 0.51 to 0.54 for stainless steels cleaned with abrasive soap, water, toluene and methanol. These values would be expected to increase somewhat during service as the surfaces become oxidized and soiled. In order to assess the effect of a possible increase in emissivity, temperatures were calculated for guide tube and liner emissivities of 0.5 and also 0.7. These emissivities apply only to the liner surface facing the fuel bundle. Because of a peculiarity of the computer program used to determine the radiant interchange factors between the fuel and the liner, both were assumed to have identical emissivities. The emissivity of the carbon steel cask wall is a further uncertainty, since it has not been measured. However, it appeared reasonable to assume an oxidized surface in view of the inaccessibility of the cask wall for cleaning and painting. Several references^{12,13,14} suggested a range of from 0.6 to 0.9 for oxidized steel, and the value of 0.7 was arbitrarily chosen. At this time it did not appear worth the additional effort to investigate the effect of other emissivities, since the calculations on fuel temperature changes due to varying the lead-steel contact in the cask wall indicated that the peak fuel temperature is only moderately sensitive to changes in cask wall temperature.

¹¹Ibid., p. 475.

¹²J. Kenneth Salisbury, Kent's Mechanical Engineer's Handbook - Power, John Wiley and Sons, New York, pp. 3-21, 12th ed., 1950.

¹³W. H. McAdams, Heat Transmission, McGraw-Hill, New York, p. 474, 3rd ed., 1954.

¹⁴W. H. Giedt, Principles of Engineering Heat Transfer, Van Nostrand, Princeton, p. 249, 1st ed., 1957.

HEAT TRANSFER FROM FUEL TO LINER

Because of the small clearance between the fuel pins and between the fuel pins and the liner, natural convection should be minor in these regions. Conductive heat transfer through the air also should not be significant at the elevated fuel temperatures that are of concern. This leaves thermal radiation as the main mechanism for transferring heat from the fuel element to the liner. Axial radiant heat transfer from the hottest point of the fuel element to the ends of the element should be small, since the fuel pins are closely packed.

The significance of axial conduction in the fuel pins was assessed by considering a single fuel pin with a cosine-shaped axial power distribution radiating at a rate corresponding to 10 days after shutdown in an environment arbitrarily selected at 1000°F. Axial conduction heat transfer in the fuel rod and radiant heat transfer to the environment were considered. The peak fuel temperature was calculated and compared with the temperature obtained similarly for a fuel rod sustaining the peak heat generation rate throughout its length. Results showed that the rod with uniform heat generation developed a surface temperature only 2°F hotter than the peak temperature of the rod with the cosine-shaped axial power distribution. This indicates that axial conduction heat transfer within the fuel rod has little influence on the peak surface temperatures, and this effect was therefore not considered further.

Of considerable importance to radiant heat transfer is the emissivity of the radiating surfaces, i.e., the fuel cladding and the cask liner. The emissivity of the cladding is the more important one, since most of the temperature gradient will be within the fuel bundle. Watson¹⁵ gives a value of 0.55 at 392°F for type 304 stainless steel tubing in the "as received" condition. Since the emissivity of metallic surfaces generally increases with temperature, one would expect an effective value somewhat above 0.55 at the higher cask temperatures. A further increase in cladding

¹⁵J. S. Watson, Heat Transfer from Spent Reactor Fuels During Shipping: A Proposed Method for Predicting Temperature Distribution in Fuel Bundles and Comparison with Experimental Data, USAEC Report ORNL-3439, Oak Ridge National Laboratory, May 27, 1963.

emissivity may result from exposure to the reactor environment. Fuel specimens irradiated in the ORR pressurized-water loop under "N.S. SAVANNAH" conditions generally acquired a somewhat dark crud deposit covering a major portion of the cladding surface. One would expect such a surface to have a higher emissivity than the initially bright stainless steel. The magnitude of the increase is uncertain, and therefore the calculations were performed over a range of emissivities varying from a low of 0.5 to a high of 0.9. The emissivity of the stainless steel liner facing the fuel bundle was taken to have the same emissivity as the fuel cladding, as mentioned before.

The radiant heat transfer from within the fuel bundle to the liner was computed with a program devised by J. S. Watson.¹⁵ This computer program, written for the IBM 7090, considers the fuel pins to be infinitely long compared to their radii and spacing. In addition, each pin is assumed to have a uniform temperature distribution. The first assumption is considered reasonable; since, as pointed out previously, axial heat transfer is not expected to be significant. The second assumption also is appropriate, since the temperature gradients in the fuel pins will be small compared to the temperature differences between pins. The computer program considers the following equation for each fuel pin:

$$Q_i = A \sigma \sum_{j=1}^N F_{ij} (T_i^4 - T_j^4), \quad (4)$$

where

Q_i = Net heat radiated from pin i ,

A = surface area of tube i ,

σ = Stephan-Boltzmann constant,

F_{ij} = interchange factor for net radiant heat transfer from pin i to pin j ,

T_i = absolute temperature of pin i ,

T_j = absolute temperature of pin j .

If a temperature is assumed for the enclosure surrounding the bundle, Eq. (4) can be solved simultaneously for all the pins in the bundle and

the temperature of each pin determined. This operation is performed iteratively by the computer program mentioned above. It will be noted from Eq. (4) that the interchange factor F_{ij} must be known before the temperature calculation can be performed. These values were obtained using the IBM 7090 computer code RAVE.¹⁶ Interchange factors for the pins near the enclosure walls were obtained by a suitable modification of the values for pins in the interior of pin arrays.

TEMPERATURE DISTRIBUTION

Cladding temperatures for the center pin of the central fuel element are shown in Fig. 3. Depending upon what assumptions are made concerning lead bonding and emissivities of various components, peak cladding temperatures range from 1220°F to 1540°F at 10 days after shutdown. The corresponding temperatures at 100 days after shutdown are 730°F to 880°F. It is noted that the degree of contact between the lead and the steel in the cask wall has a rather small effect on cladding temperature, increasing it no more than 25°F at 10 days after shutdown. The emissivity of the guide tube end of the liner surface facing it has a somewhat greater effect, increasing the cladding temperatures 10 days after shutdown by as much as 60°F for a decrease in emissivity from 0.7 to 0.5. The corresponding cladding temperature rise at 100 days after shutdown is only about 30°F. The emissivity of the fuel has a greater effect on the peak cladding temperature. A decrease in cladding emissivity from 0.9 to 0.7 results in a temperature rise of about 80°F at 10 days after shutdown. A further reduction in emissivity from 0.7 to 0.5 causes a peak temperature rise of about 170°F, again at 10 days after shutdown. For increasingly longer times after shutdown the temperature effect of the above mentioned factors, of course, becomes less.

Some typical cask temperature profiles shown in Fig. 4 were calculated for 10 days after shutdown, assuming full contact between the cask lead and its supporting structure. The guide tube and liner emissivity considered

¹⁶O. H. Klepper, Radiant Interchange Factors for Heat Transfer in Parallel Rod Arrays, USAEC Report ORNL-TM-583, Oak Ridge National Laboratory, December 26, 1963.

Fig. 3. Peak Cladding Temperature of Central Fuel Element

Fig. 4. Typical Temperature Profiles

for this case was 0.5. It will be noted that the temperature gradient between the cask inner shell and the atmosphere is rather modest compared to the temperature rise of over 700°F from the cask inner shell to the cask liner. The temperature rise from the liner to the center of the fuel bundle is also significant in this instance, amounting to over 500°F when the cladding emissivity is 0.5.

It is felt that these fuel cladding temperature estimates were made by fairly conservative calculational methods. Several minor factors not accounted for in the calculations will tend to reduce the actual temperatures. Among these are (1) the heat transport by gamma radiation that will transfer about 15% of the decay heat from the fuel to beyond the inner cask wall surface, (2) axial heat transfer in the fuel-liner-guide tube region, and (3) convection heat transfer inside the fuel bundle and between the fuel and the liner. The following factors would tend to increase the fuel temperatures beyond the estimated values:

1. If following the loss of coolant the cask cavity is filled with water vapor instead of with air as assumed here, radiant heat transfer would be impeded slightly. This does not appear to be a major factor.
2. Solar heating may increase the cask exterior surface temperature by as much as 50°F; the corresponding fuel temperature rise would be less.
3. An accidental fire following the loss of coolant accident might raise the cask temperatures.

DISCUSSION

The present investigation has indicated a range of fuel temperatures that might be expected following loss of coolant from the transfer cask. From this investigation it appears that the cask lead temperature will remain below its melting temperature of about 620°F. The fuel also should remain well below the cladding melting temperature of 2550°F. Fuel failure resulting in the release of fission products may, of course, take place at lower temperatures, and it may be necessary to estimate the expected temperatures more accurately. Better knowledge of the emissivities of the fuel cladding and of the cask internals would remove a major uncertainty in the calculation. In addition, the heat transfer from the cask liner to

the atmosphere might be verified experimentally using a heat source in the cask cavity.

It is emphasized again that this analysis considered only a normal environment external to the cask. The possibilities of explosion, fire, or other unusual circumstances that may precede or follow a loss of coolant accident should be examined closely, since cask temperatures may be altered drastically under those conditions.

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