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Fire Protection Device for LMFB Spent Fuel Shipping Casks

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FIRE PROTECTION DEVICE FOR LMFBR SPENT FUEL SHIPPING CASKS

M. Moss
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ABSTRACT

This report describes the analysis and experimental evaluation of a device to provide fire protection for a shipping cask used to transport liquid metal fast breeder reactor (LMFBR) fuel rods. Thermal analyses of various fire protection schemes were conducted by means of the finite difference code, CINDA. The choice of materials for the cask body was determined to be less important than the dimensions and number of cooling fins attached to the cask. Of several protection methods considered, radiation/convection shields between the cooling fins looked most attractive; these were tested on a quarter-scale cask model. The shields consisted of bi-metallic bands which expanded when heated, blocking the fire, and retracted when cooled. This automatic reversibility would allow the fins to dissipate internally generated heat of a full-size cask once the fire was out. Tests showed that, even in an asymmetric fire exposure, the bands expanded to provide protection to the cask. The directly exposed surface of the cask model, protected this way, reached a temperature of only 180°C compared with 295°C in the unprotected state, when subjected to a butane flame for 0.5 h at a distance of 15 cm. Greater relative effectiveness could be expected in an engulfing fire in which the bands would expand more symmetrically.

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INTRODUCTION

Before use, all spent fuel shipping casks (SFSC's) must be evaluated to determine their response to fire. Federal regulations require that a SFSC survive exposure to an 802°C fire for 0.5 hour, after which radioactivity release from the cask must not exceed specified limits.¹ It is noteworthy that most liquid fuel fires are significantly hotter than 802°C. The regulatory requirement apparently accounts for situations in which the fire is some distance from the SFSC. Also, designers must assume that a SFSC has experienced deformation or puncture prior to the fire.

During and following exposure, the temperature of the SFSC and its contents must not exceed certain values which depend upon the type of fuel being transported, the coolant, and the other materials of the cask. Many SFSC's are designed with cooling fins encircling their surfaces. These fins, which may be steel, aluminum or copper, dissipate heat generated by the spent fuel during transport. However, the fins provide an increased area through which heat can be added during a fire. Different methods of limiting the energy input include extinguishment, cooling, and isolation.

Extinguishment by liquids, gases, or foams appears impractical since the cask might be separated from its carrier, and the extinguishing agent would have to be contained within the SFSC itself. Fluid dispersal, particularly over a potentially large area, presents problems.

The cooling of the cask by liquids or transpiration materials implies large quantities of these substances for the kind of fire postulated. Ablation or intumescent materials applied to the cask surface, while slowing the transport of heat inward, would interfere with normal fin heat rejection in any configurations presently visualized.

Thermal isolation of the cask can readily be accomplished by a device which irreversibly decouples the fins, e.g., by the melting of the fin substructure, or the formation of cavities near the cask surface which would decrease radial thermal conductance. In these cases, human intervention would be required soon after the fire wanes in order to prevent excessive temperature rise from the internally generated heat. Such intervention might be in the form of reattachment of the fins, or forced cooling of the cask surface. Depending upon accident conditions, such an option may or may not be straightforward. Isolation may also be accomplished, with the fins intact, by heat resistant foams or blankets. Here, as in the case of extinguishing and cooling agents, quantity and deployment become difficult problems.

More promising are devices, integral with the structure, which thermally isolate the cask upon exposure to heat, and allow cooling by the fins to be reestablished once the fire is out--an automatic, reversible, thermal switch. Such devices were computer simulated, and then tested on a quarter-scale cask model.

The most promising was a set of bimetallic bands, nested between the cooling fins, which expanded in response to a fire, blocking radiative and convective heat transfer to a considerable extent. Upon cooling, the bands retracted to their original positions. Another test was of radially oriented baffles attached to the cask body; this device was not reversible.

The purpose of this study has been to explore fire protection concepts and not to optimize a device for a particular cask. While the study has made use of a specific cask design, the protection devices examined should be generally applicable to others. Cask size, shape, mass and fin configuration are not likely to differ sufficiently from that used here to alter the conclusions of this report.

ANALYSIS

A schematic drawing of a SFSC is shown in Fig. 1. The cask is shipped as shown, with the axis horizontal, to enhance convective cooling from the copper fins which encircle it. Figure 2 depicts a possible cross-section perpendicular to the axis of such a cask.

Thermal analyses of various fire protection schemes were conducted. The purpose of these calculations was to determine the general form of the problem, not to develop final design data. The model used (Fig. 2) was sized largely by NRC requirements on surface radiation dose levels. The selection of metal hydrides (MH_x) for neutron shielding is speculative.¹ Lithium hydride was selected as being representative of a class of materials which may prove useful. While the thermal conductivity of LiH is low, the impact on fire protection was found to be small. Uranium is used for gamma shielding; the stainless steel was selected largely for its strength and corrosion resistance.

On the other hand, factors of substantial importance in fire protection are the dimensions and number of fins attached to the cask. These parameters were estimated on the assumption that 100 kW was to be rejected from the 3-m long cask, and that the outer cask surface was to be no warmer than 82°C. The surrounding temperature was taken as 57°C. Estimates based on convective heat transfer theory led to a fin-to-cask area ratio of 15.²

The assumed fire was at 802°C and lasted 0.5 h;³ it was treated as a surface of unit emittance. It was further assumed that all the heat was transferred by radiation.⁴ Following the fire, the ambient conditions were taken to be identical to those preceding the fire, i.e., 57°C.

The computer calculations were done by means of the finite difference code, CINDA,⁵ with 40 or more nodes in the cask, depending on the particular calculation. Both radial and longitudinal components of heat flow were considered. In non-fire conditions, it was assumed that the outer surface of the cask was at 82°C; that is, the fins accomplished their intended purpose.

Material thermal properties used in the calculations were taken largely from published data.⁶ The material properties of the metal hydride were estimated from unpublished information.^{7,8}

The significant results of the calculations are shown in Fig. 3:

- a. Curve 1 shows the steady state temperature (non-fire conditions) with 100 kW generated internally, and the surface temperature fixed at 82°C.
- b. Curve 2 shows the maximum temperatures resulting from a fire at each point in a cask with no protection device. Note that the times at which these maximum temperatures are reached are different for each position, and that most occur after termination of the half-hour fire.
- c. Curve 3 shows the maximum temperatures achieved in a protected cask. The protection system is one that blocks the hot gas from the region between the fins, and restricts it to their outer radius. Following the fire, the protection device retracts and permits the fins to regain their normal heat removal function. The details of the protection system design are immaterial from the viewpoint of these analyses. In effect, by forcing the fire outside the fin region, the effective area through which the fire and cask exchange heat is that of a cylinder of radius equal to the outer fin radius. If the fire were not blocked from the fin region, the relevant area would be that of the fins and the cask surface, an area fifteen times larger than that of the protected cask. The analysis clearly points to the effectiveness of such an area-limiting fire protection system.

Curve 3 shows that no interior point of the cask reaches a temperature at which the material at that point melts, decomposes, or seriously loses strength. An elaboration of the simple calculations leading to curve 3 was done in which it was assumed that a metal shield closed off the region between the fins forming a cavity between fins, cask, and shield. The radiation from the fire impinged on the shield which re-radiated to the other surfaces. Emissivities of these surfaces were assumed to be characteristic of metals in an unpolished, "off-the-shelf" condition.⁶ As expected, the shield acted like a conventional radiation barrier, reducing the heat flux into the cask.

d. Curves 4 and 5 show the effect of introducing a variable thermal conductance just under the cask surface which effectively reduces the conductance in a short region by 70% and 90%, respectively. Again, temperature maxima are shown. The change in conductance might be accomplished by ejecting a low-melting point metal from cavities near the surface leaving behind only an assembly of struts. Since it is difficult to imagine how such a device can be made reversible, calculations were done of the steady states achieved after the devices were activated and the fire had ceased. These are shown in curves 6 and 7.

EXPERIMENT

Fuel Cask Model

A model, one quarter the size of the cask, for experimental convenience, was constructed. To facilitate assembly and instrumentation, the structure was laminated. The cask itself was simulated by circular steel plates, 0.635 cm thick and 36.8 cm in diameter. These plates, in pairs, alternated with copper plates 0.163 cm thick and 45.4 cm in diameter, the assembly being bolted together with four rods. The extension of the copper beyond the edges of the steel, by 4.3 cm, simulated cooling fins. Thirty-four steel plates and 17 copper plates were used to make a model 24 cm long (Fig. 4). Holes (2.54-cm dia.) at the centers of the plates produced a cylindrical cavity running the length of the cask. The small length-to-diameter ratio, compared with a full-size SFSC, was not considered a serious drawback in this type of experiment.

Chromel-alumel thermocouples in stainless steel sheaths were placed in grooves in one of the steel plates located at the middle of the cask. Three thermocouple junctions were positioned 90° apart around the center hole, and another three were placed within a few millimeters of the edge of the steel plate (cask surface), also 90° apart (Fig. 5). The leads were brought through the center hole. This arrangement permitted measurement of radial and circumferential temperature gradients within the cask.

Fire Protection Devices

The premise behind the devices tested was that the flames were to be prevented from entering the spaces between the fins as much as possible in order to reduce radiative and convective transport of heat to the fin surfaces. An effective device would be one which would form a snugly fitting circular band between each pair of fins at their perimeter (band device). This would constitute a cylindrical shell over the entire cask, blocking off the entry of hot gas and direct radiation (cf Fig. 3, curve 3).

Another, but less effective, approach would be a radial deployment of flaps extending from the cask surface between the fins (baffle device). These baffles, while not completely preventing the entry of gas, would reduce circulation between the fins. Radiation would not be as effectively blocked as with the band device.

1. Band Device

The band device evaluated in this program was made reversible with bands made from bimetals. Under normal ambient conditions, a band, with ends overlapping, fits snugly around the cask (Fig. 6a). When heated uniformly, it expands to the full fin diameter (Fig. 6b) where it is constrained from traveling further by pins at the fin perimeter; the band is long enough to completely enclose the fin space when expanded. Upon cooling, the band contracts to its original position, allowing the fins to dissipate the heat from the fuel rods again.

The choice of materials for the bands was dictated by the need for good response to a moderate rise in temperature, and refractoriness. Both requirements were met with 304 stainless steel (SS) and Kovar (29 Ni, 17 Co, bal. Fe). A bimetal strip of two dissimilar materials of equal thickness, t , will, if at an initial radius of curvature R_1 , expand (or contract) to R_2 in the temperature interval⁶

$$T_2 - T_1 = \frac{kt}{(\alpha_a - \alpha_b)} \left(\frac{1}{R_2} - \frac{1}{R_1} \right), \quad (2)$$

where

$$k = \frac{12E_a E_b + (E_a + E_b)^2}{12E_a E_b} \quad (3)$$

The α 's and E 's are the respective expansivities and elastic moduli of the component materials. For 304 SS-Kovar, $\alpha_a - \alpha_b = 11 \times 10^{-6}/^\circ\text{C}$, and $k = 1.34$. It was decided, arbitrarily, that the bimetal band should expand from the model cask to fin radius (18.4 to 22.7 cm) in a temperature interval of approximately 100°C . This condition was closely met for $t = 0.076$ cm, a stock thickness for these alloys.

Sample bimetals were made by spotwelding curved lengths of the 304 SS and Kovar strips together at 1.8-cm intervals. The higher expansivity 304 SS was on the inside. Test exposure up to 800°C in air confirmed Eq. 2, and also the refractory capability of the materials. Upon cooling, the samples recovered their original curvature.

Bands for the cask model were similarly fabricated from strips 150 cm long and 1.22 cm wide. The width is somewhat smaller than the combined thickness of two steel plates, which constitutes the spacing between fins, to prevent binding. A band was placed around each pair of steel plates as the cask was assembled.

2. Baffle Device

This device was constructed and tested for effectiveness, but no provision for automatic deployment and retraction was made. It was felt that this would be addressed later if the concept appeared attractive.

The ends of eighteen strips of steel, 5 cm long, were attached to the cask at 20° intervals around the perimeter. The free ends could be bent outward to assume an angle with the cask surface. Three configurations, shown in Fig. 7, were tested; the 45° and 90° orientations were compared with the one at 0°.

Testing and Results

Testing was done outdoors with the cask model standing on its end. In this preliminary evaluation, an asymmetric thermal load was applied by means of a pair of butane torches, with 7-cm throats, directed at one side of the cask. This configuration is rotated 90° from the supposed orientation of a full-size cask lying on its side with flames directed upward, the most likely accident situation. However, the flame was parallel to the cask plates.

The torches were played upon the cask at a distance of 15 cm. Reproducibility of the flame conditions from test to test was difficult, particularly if the wind varied. Readings from the six thermocouples were recorded for the half hour that the flame was on. Attempts to accurately record flame temperature were not successful; temperatures over 820°C were noted. Since the heat source did not model the regulatory fire environment, temperatures were only a qualitative measure of the actual benefits to be derived from the protection devices. The asymmetric exposure did permit an evaluation of the protection devices under non-standard conditions which could exist in an accident.

1. Band Device Test.

The bimetal bands responded to the heat in less than a minute. The expansion on heating and the contraction on cooling were not always smooth, as the bands sometimes stuck on irregularities on the plates. The most obvious visible effect was that the bands did not expand symmetrically. Heating from one side left those parts of the bands on the opposite side relatively cool. The hotter sections increased more in curvature radius as illustrated in Fig. 8. In an engulfing fire, this probably would not occur, i.e., the bands would expand uniformly. A solution to the asymmetrical expansion is not evident. However, depending upon the particular accident conditions, e.g., position of the cask and direction and intensity of the fire, such asymmetry may or may not be important.

TABLE I

Band device test. Temperatures ($^{\circ}\text{C}$) in cask model
subjected to butane flame for 0.5 h.

Thermocouple Position (see Fig. 5)	No bands, unprotected	With bands, protected
T1	295	180
T2	145	115
T3	-	100
T4	-	105
T5	80	85
T6	-	100

TABLE II

Baffle device test. Temperatures ($^{\circ}\text{C}$) in cask model
subjected to butane flame for 0.5 h.

Thermocouple Position (see Fig. 5)	Baffle Angle		
	0 $^{\circ}$ unprotected	45 $^{\circ}$ protected	90 $^{\circ}$ protected
T1	215	175	180
T2	140	110	110
T3	145	110	110
T4	130	105	100
T5	105	80	80
T6	125	100	100

Typical data for a cask with and without bimetal bands are given in Table I. Temperatures at the surface and interior on the side facing the flame show the maximum effect of the band device after 30 min; cask surface temperature was reduced by 115 $^{\circ}\text{C}$, and the interior by 30 $^{\circ}\text{C}$. Substantial gradients existed around the cask.

2. Baffle Device Test

The baffle configurations shown in Fig. 7 were tested with the flame moving over a broader area of the cask than in the band test. This simulated a real fire more closely. Overall heat inputs should have been about equal. The 0°-configuration represents a SFSC in the unprotected state. The results are given in Table II. The 0°-configuration temperature of the surface on the flame side was not as high as in the band device test because now the flame was not concentrated in one area. The 45° and 90° arrangements performed about the same in reducing temperatures to values approximately equal to those reached with the bands expanded. With the exception of the surface temperature on the flame side, the temperature profiles in the band and baffle tests were similar.

FUTURE WORK

Further tests of such protection devices for SFSC's in different fire environments, including regulatory fires, should be conducted. A cask lying on its side in a pool of burning liquid fuel, for example, would be a closer approximation to the kind of accident normally envisioned.

Tests should be conducted on casks with structural damage. Severely damaged fins could constitute an irreversible heat barrier themselves.

Cask models smaller than those used in this study should also be tested. They would permit the use of a laboratory furnace as a heat source under more controlled conditions.

CONCLUSIONS

Of the various protection methods considered, a heat barrier appears most promising. A radiation shield was modeled on the computer, and the analysis indicated that substantial protection from an 802°C fire for 0.5 h would be afforded the cask.

Radiation/convection barriers in the form of bimetallic bands (band device), which are automatic and reversible, and metal strips (baffle device) between the fins were tested on a quarter-scale cask model exposed to a butane flame on one side. Surface temperature reductions of 115°C were recorded with the band device; interior temperatures were lowered by 30°C. The direction and extent of the fire affects the operation of this device. From the tests, it may be inferred that the band device would be most effective in an engulfing fire. The baffle device achieved similar interior temperature reductions; this device was not automatic and reversible.

Figure 1. Schematic of a LMFBF spent fuel shipping cask showing cask body and cooling fins which are approximately 6 mm thick.

Figure 2. Possible cross section of a shipping cask for LMFBR spent fuel showing uranium (or uranium alloy) and metal hydride for gamma and neutron attenuation sandwiched between stainless steel.

Figure 3. Temperature within LMFBR cask (see Fig. 2):

1. Steady state temperatures with cask surface fixed at 82°C and 100 kW generated internally.
2. Maximum internal temperatures due to fire exposure without fire protection.
3. Maximum internal temperatures due to fire exposure with fire protection (see text).
- 4,5. Maximum internal temperatures due to fire exposure with 70% and 90%. Variable conductances activated.
- 6,7. Steady state temperatures following fire with 70% and 90%. Variable conductances activated.

Figure 4. Quarter-scale shipping cask model consisting of steel (cask body) and copper (fins) laminae.

Figure 5. Positions of thermocouples, in longitudinal center of cask model, relative to flame.

Figure 6. Band device with bimetal in (a) cold, contracted position, and (b) hot, expanded position where it blocks the entry of radiation and hot gas to the space between the fins.

Figure 7. Baffle device with baffles at 0, 45, and 90° to the cask surface.

Figure 8. Bimetallic band expanding asymmetrically from exposure to flame from one side only.

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