COOLING MULTIPURPOSE SNF CASKS WITH REMOVABLE LIQUID–FILLED FINS

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Abstract—*Dry cask storage of spent nuclear fuel (SNF) offers very significant advantages: enhanced security (compared with traditional SNF pools) and the ability to add cask storage capacity incrementally. However, storage temperatures must be limited to avoid SNF degradation. With current cask designs, cask capacity for short-cooled SNF is limited by the ability to remove the decay heat (control temperature), not physical capacity. Large economic storage casks can not be fully loaded with short-cooled high-decay-heat SNF. Better methods to cool casks are required to avoid these limitations. The decay-heat-removal capability of dry storage casks can be improved by the use of liquid-filled hollow fins. Natural circulation of the liquid within each fin efficiently moves heat from the cask body to the fin surface, where the heat is removed by natural air circulation. This can reduce the temperature drop needed to transfer heat from the cask body to air by a factor of 3 or more. The approach is similar to that used in cooling electrical transformers and many other types of industrial equipment. This paper describes the performance and characteristics of liquid-cooled fins.*

I. INTRODUCTION

Spent nuclear fuel (SNF) produces decay heat. Because excessive temperatures will cause the SNF to degrade, methods for heat removal are required for SNF storage. SNF stored in casks has traditionally been cooled by conduction of the heat through the cask with natural-circulation air cooling of the casks. Solid fins on the casks have been used to improve heat transfer. Recently, however, a need has become more urgent for improved cooling methods during cask storage of SNF at reactors and off-site storage locations.

- *Terrorism*. SNF storage casks provide a more secure method of storing SNF than traditional pool storage in the United States: (1) the casks have thick walls that provide a high degree of physical security, (2) the large cask mass reduces the potential for theft, and (3) a means of passive cooling is ensured that is not dependent upon maintaining the SNF in water. Because of these considerations, there are increased incentives to store SNF—including short-cooled SNF—in dry casks. However, the decay heat from short-cooled fuel is higher than that from long-cooled fuel. If shorter-cooled fuel is to be stored in large casks without exceeding accepted limits on storage temperatures, better cask cooling methods are required.

- *Economics*. The cost of SNF storage decreases as the cask capacity increases. Better cask designs, new cask materials, and new technologies may enable the development of higher-capacity casks that contain more SNF elements within the same cask weight and size constraints. For example, work is ongoing[1–3] to develop depleted uranium dioxide (DUO_2)–steel cermet casks (DUO_2 embedded in steel). This cermet may be the highest-performance shielding material than meets all the requirements for a multipurpose cask—as part of a system in which the SNF is loaded into the cask at the reactor, the SNF is transported in the cask, and the cask is later used for disposal at the repository.

An SNF cask with a greater physical capacity is only of value if there is better cask cooling to remove the additional decay heat from the additional SNF put into the cask. Cask cooling is a limiting factor.

The typical maximum temperature for SNF in storage is 350EC. The heat transfer path is from the SNF to the cask body via the basket structure, through the cask body, and from the cask surface to the atmosphere. The first and third components are the primary resistences to heat transfer. A series of studies are being undertaken to find methods to reduce resistance to heat transfer from SNF to the atmosphere and thus allow for higher decay-heat loads within the cask. This paper addresses improved methods for heat rejection from the cask body to the atmosphere. Parallel studies are underway to examine improved heat transfer in the basket structure and in the cask body.

The use of passive liquid-cooled fins (Fig. 1) is proposed to improve heat transfer. This is the same approach that is used in most utility electrical transformers. Solid fins can improve this heat transfer by increasing the effective cask surface area; however, the effectiveness of the solid fins decreases with fin depth[3]. The total temperature drop to remove a given quantity of heat can be drastically reduced by the use of liquid-filled fins that allow efficient transfer of heat from the cask wall to high-surface-area fins. The liquid absorbs the heat at the cask body wall and by natural circulation transfers the heat to the fin surface. Although several coolants are candidates, for the analysis herein, the coolant considered is water (with antifreeze, appropriate corrosion inhibitors, and neutron absorbers). Water is inexpensive and a large experience base exists regarding its use.

Liquid-cooled fins are a viable option because the need for enhanced SNF cask cooling capabilities exists for only a relatively short period of storage time after the SNF is discharged from the reactor. SNF decay heat decreases with time; thus, the enhanced cooling capability is not required by the time the SNF is transported and will not be required by the time the SNF is disposed of. The effectiveness of many cooling options (including liquid-cooled fins) depends upon the orientation of the SNF cask. Cooling may be efficient if the cask is vertical but less efficient if the cask is horizontally mounted. In many cases, the casks are positioned vertically in storage; but are mounted horizontally for long-distance transport. This change in cooling performance is not important if the SNF is stored for several years, which provides sufficient time for a large decrease in the decay heat generated by the SNF and elimination of the need for enhanced cooling.

II. PERFORMANCE OF LIQUID-COOLED FINS

Figure 2 shows the performance of three different vertical liquid-cooled fins, each of which cools 15 cm of the external circumference of the cask. The fin dimensions are shown in Fig. 1. The fins differ only in depth (15, 75, and 120 cm). With a 120-cm fin, about 800 W per fin can be rejected with a temperature drop of 30EC between the cask body and the air. For a cask with 21 pressurized-water-reactor SNF assemblies and a diameter of 1.8 m, the total heat rejection is 30 kW (1.44 kW per SNF assembly).

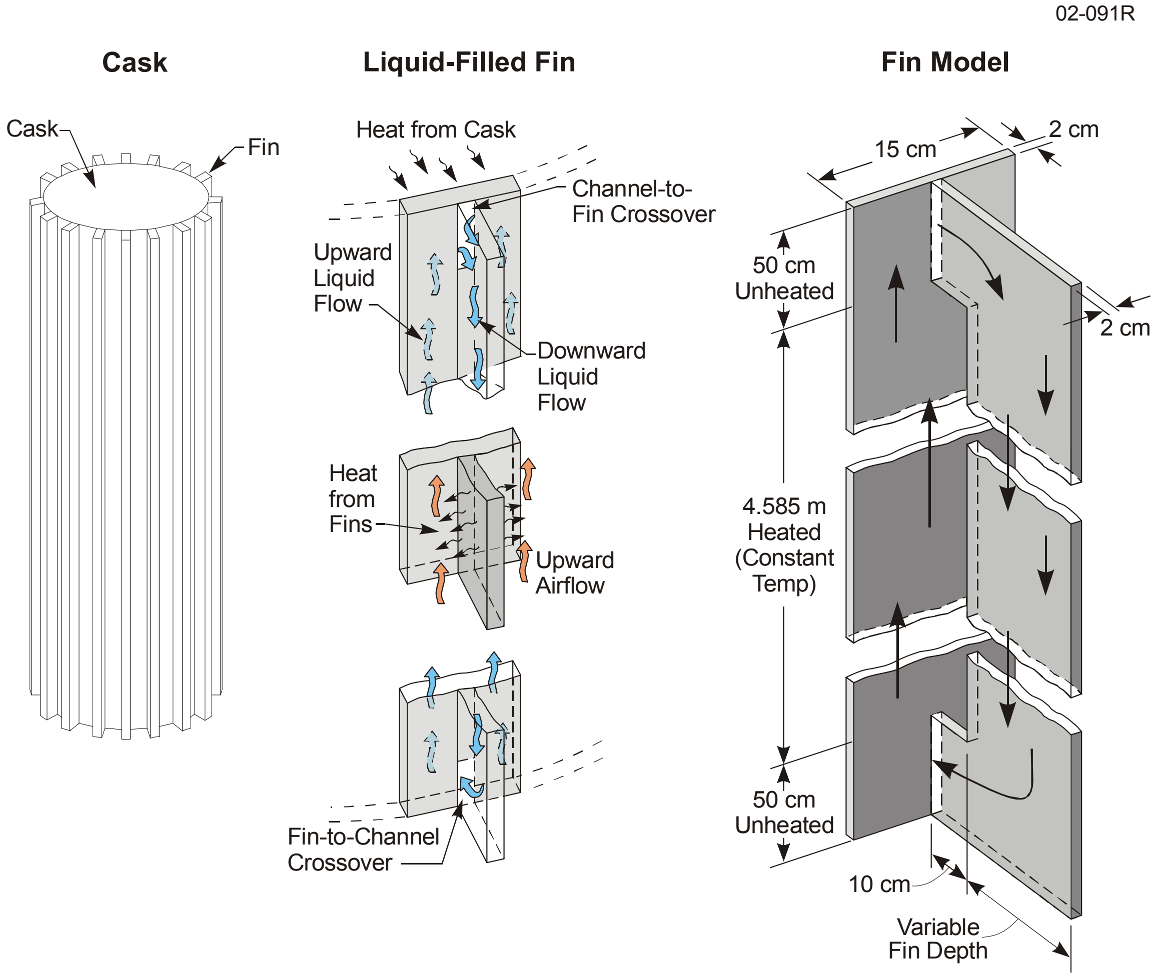

Fig. 1. Liquid-filled cooling fins.

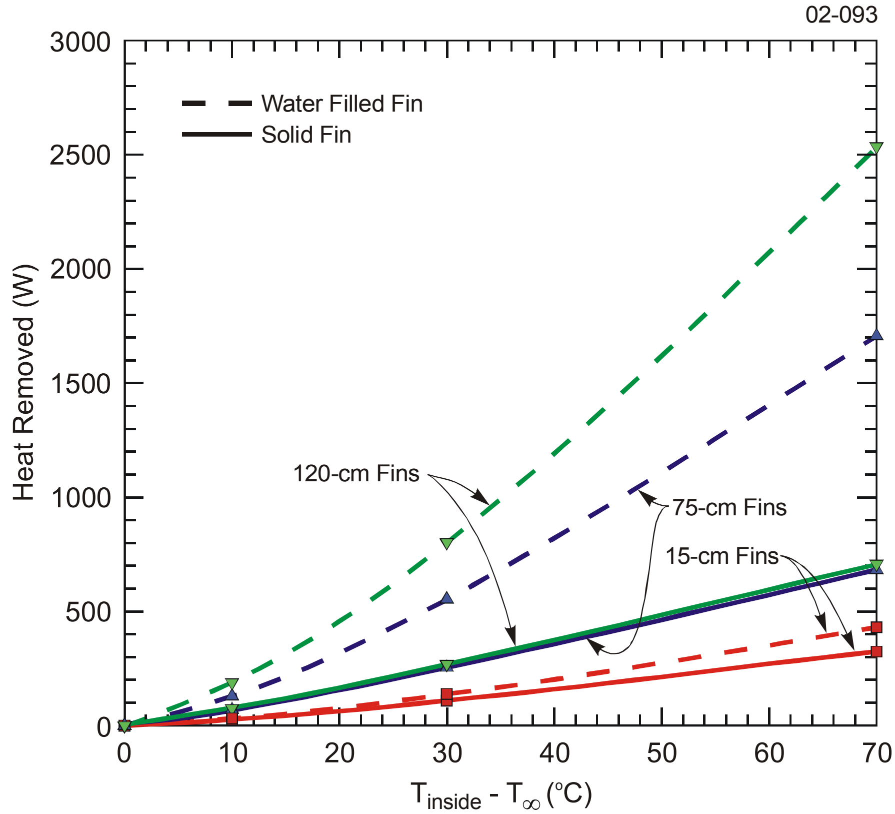

Fig. 2. Heat rejection per fin vs temperature drop for different fin depths.

For comparison, the heat rejection of solid fins with the same dimensions is also shown. The solid fins are in contact with the cask over their entire height (i.e., they do not have the cutout that the liquid-filled fins have). The first 10 cm at the base of each solid fin is insulated (equivalent to the cutout in the liquid-filled fins), and the exposed surface area is the same as that of the liquid-filled fin. In many metal cask designs, neutron absorbers are placed between fins. Consequently, the base of the fin is effectively insulated by the low-thermal-conductivity neutron absorber. An equivalent 120-cm solid fin will reject 270 W for a delta T of 30EC—less than one third as much heat. The solid-fin performance is dramatically lower because the temperature drop required to move heat through a solid fin by conduction is significantly greater than that required to circulate liquid in a liquid-filled fin. Almost no improvement in heat transfer is observed if the solid fin exceeds a few tens of centimeters in depth.[4]

The highly efficient heat transfer in a liquid-filled fin is a consequence of the very small temperature difference required to move heat by natural circulation of water vs conduction of heat through a solid. Table 1 shows the change in the bulk water temperature between the entrance and exit of the heated channel next to the cask for three fin depths and three total temperature differences between the cask and the air. A temperature difference of only a few degrees Celsius (EC) is required to move the heat from the cask body to the outer fins. The heat transfer coefficient from fin to air is low and represents the primary resistance to efficient heat transfer. An extremely large experience base exists for the application of liquid-cooled fins, which are used by many electrical transformers to enhance cooling (Fig. 3).

Table 1. Difference in Water Circulation Temperature (EC) for Three Fin Depths and Three Temperature Differences Between the Cask and the Ambient Air

Cask–Air Temperature Difference (EC)	Water Circulation Temperature Difference (EC) by Fin Depth		
	15 cm	75 cm	120 cm
10	0.79	1.87	2.41
30	2.47	6.11	7.63
70	6.13	14.11	18.97

In practice, a more compact fin design than the one shown Fig. 1 would be used to minimize space requirements. Such a fin design uses water cooling to transfer heat from the cask to the liquid-cooled fin, with smaller solid fins attached to the liquid-cooled fin. The optimum fin configuration (liquid filled or solid) changes with the required maximum heat rejection capability.

III. COMPUTATIONAL METHODOLOGY

The solid fins and natural convection loop in the water-filled fin were modeled with the commercial computational fluid dynamics code CFX[5]. The water flow was modeled as laminar and the metal encasing the water volume (not a significant resistance to heat transfer) was not included in the model. The inner surface of the water jacket adjacent to the cask is assumed to be isothermal, and the surfaces of the fin exposed to air are assumed to dissipate heat to the environment by means of free convection. Free convection from a heated surface to air is turbulent for $Gr_f Pr_f > 10^9$, where Gr and Pr are the Grashof and Prandtl numbers, respectively. The subscript “f” indicates that the Grashof and Prandtl numbers are calculated at the film temperature (average of the surface and air temperature). By this criterion all of the cases examined have turbulent flow on the fin surface. For turbulent free convection of air on a vertical plate Holman[6] suggests the empirical correlation

$$h = 0.95(\Delta T)^{1/3}$$

Fig. 3. Electrical transformers with liquid-filled fin cooling system. (Courtesy of ABB Corp.)

where *h* is the average heat transfer coefficient on the surface (in W/m^2-°C) and ÎT is the temperature difference between the surface of the fin and the ambient air (in °C). Since the heat transfer coefficient on the outer surface is a function of the surface–air temperature difference, the solution was obtained in an iterative manner. A surface temperature was assumed, and a tentative solution obtained from CFX. The average temperature on the surface of the fin was obtained from the initial CFX solution, and a new heat transfer coefficient was then calculated. This was repeated until the heat transfer coefficient was in agreement with the surface–air temperature difference. Eighteen cases were modeled with three surface–air temperature differences and three fin lengths for solid and liquid-cooled fins.

IV. OTHER PERFORMANCE CONSIDERATIONS

In fires, casks with liquid-cooled fins would be expected to have superior performance compared with casks that have solid fins. High-performance cooling fins lower the average surface temperature, and thus the average temperature of the cask body. This provides more heat capacity within the cask body to slow the effects of external fires. Liquid-cooled fins also provide improved fire resistance because of the large quantities of heat required to boil off the liquids before the cask body heats up. Each fin would have a pressure-relief and fill point at the highest location in the circulating loop (similar to the radiator cap in a car).

Liquid-cooled fins change the temperature distribution within the cask body and within the SNF. In a vertical-mounted solid-fin cask, the cask body temperatures peak toward the top of the cask because of two factors. First, helium gas circulation within the cask cavity increases the temperatures near the top of the cavity. Second, natural air circulation over the external fins results in colder air near the bottom of the cask and the hottest air at the top of the cask. With liquid-cooled fins, nearly isothermal conditions exist over the entire cask body because of the small differences in temperature from the hottest to the coldest locations in the liquid (Table 1). This reduces the temperature gradients in the cask and the SNF. This may have long-term storage benefits in reducing degradation of SNF over time.[7] One of the SNF degradation modes is the diffusion of hydrogen in zircaloy clad toward colder regions in the SNF. As the hydrogen concentrates, the clad becomes more brittle with the formation of zirconium hydride. Reducing the temperature gradients should improve SNF storage conditions.

If coolant is lost, the fin operates as a hollow solid fin with higher temperatures required to reject the same heat load from the cask. The heat-rejection capability of such a fin depends upon thickness of the steel in the liquid-cooled fin and other factors. SNF integrity can be ensured even if higher SNF temperatures occur for limited periods of time. The traditional SNF storage temperature limit of 350EC is not absolute but is imposed to limit long-term SNF clad degradation. Because it is the combination of time and temperature that must be controlled to avoid SNF degradation, the higher-than-desirable short-term SNF temperatures caused by loss of coolant due to fin failure would not be a major concern. Short-term operation at higher temperatures is not a safety issue. Furthermore, infrared cameras provide a low-cost method to verify the operation of each fin as a heat transfer system.

The cooling system provides added radiation shielding. SNF radiation levels, like decay heat, decrease with time. Thus the option exists to use the cooling system for added incremental shielding for short-cooled SNF. After the decay heat and radiation levels decrease, the cooling fins can be removed before cask transport or use as a disposal package.

V. DESIGN CONSIDERATIONS

Each fin is separate from the others; thus, damage to any individual fin does not significantly degrade the total system performance. If coolant is lost from a liquid-filled fin, that fin then operates as a solid fin, with higher temperatures required to reject the same heat load from the cask. In this context, the optimum design of the fin for an SNF cask may be different than in other applications, such as use in electrical transformers. Additional metal can be added to the fin structure to provide additional cooling capability in the event of a loss of coolant.

For many applications, strap-on fins may be preferred. If the cask is a multipurpose cask used for (1) storage and transport or (2) storage, transport, and disposal, removal of the fins after the SNF has cooled reduces the weight and size of the cask for transport and disposal operations. Strap-on fins also allow for easy fin repair. Various technologies[8] have been developed to ensure good thermal contact between multiple layers in SNF casks and in many types of electrical equipment. The required period for the operation of fins is less than a decade, which is short compared with the typical lifetimes of liquid-cooled fins in traditional industrial applications. Furthermore, radiation degradation is not a significant consideration because the fins are on the outside of the cask and thus are exposed to only very low radiation levels.

IV. CONCLUSIONS

There are large incentives to improve SNF cask cooling. Placing short-cooled SNF in storage casks improves security, and larger-capacity casks have lower costs. A major constraint is controlling the temperature of the SNF. The use of liquid-cooled fins, a technology supported by massive industrial experience, is a potentially attractive option to increase the allowable decay heat in an SNF cask.

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