A Multifunction Cask for At-Reactor Storage of Short-Cooled Spent Fuel, Transport, and Disposal

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Abstract—The spent nuclear fuel (SNF) system in the United States was designed with the assumptions that SNF would be stored for several years in an at-reactor pool and then transported to reprocessing plants for recovery of fissile materials, that security would not be a major issue, and that the SNF burnups would be low. The system has evolved into a once-through fuel cycle with high-burnup SNF, long-term storage at the reactor sites, and major requirements for safeguards and security. An alternative system is proposed to better meet these current requirements. The SNF is placed in multifunction casks with the casks used for at-reactor storage, transport, and repository disposal. The cask is the handling package, provides radiation shielding, and protects the SNF against accidents and assault. SNF assemblies are handled only once to minimize accident risks, maximize security and safeguards by minimizing access to SNF, and reduce costs. To maximize physical protection, the cask body is constructed of a cermet (oxide particles embedded in steel, the same class of materials used in tank armor) and contains no cooling channels or other penetrations that allow access to the SNF. To minimize pool storage of SNF, the cask is designed to accept short-cooled SNF. To maximize the capability of the cask to reject decay heat and to limit SNF temperatures from short-cooled SNF, the cask uses (1) natural circulation of inert gas mixtures inside the cask to transfer heat from the SNF to the cask body and (2) an overpack with external natural-circulation, liquid-cooled fins to transfer heat from the cask body to the atmosphere. This approach utilizes the entire cask body area for heat transfer to maximize heat removal rates—without any penetrations through the cask body that would reduce the physical protection capabilities of the cask body. After the SNF has cooled, the cooling overpack is removed. At the repository, the cask is placed in a corrosion-resistant overpack before disposal. This cask design approach can also be used for storage only and dual-purpose (storage and transport) SNF casks.

I. INTRODUCTION

The requirements for spent nuclear fuel (SNF) management have changed dramatically over time and continue to change. Because of these changes, alternative SNF management systems may offer superior economics and performance over existing systems. This paper is one in a series of papers[1–2] that describes one such alternative SNF management system. A general description of the system is provided followed by a more detailed description of recent work to develop a cask cooling system that allows cask storage of short-cooled SNF at the reactor. Security and economics provides large incentives to store short-cooled SNF in casks; but, it is a major design challenge because the high decay heat generated by such SNF. There are several major changes that strongly impact the requirements for management of SNF.

- *Goals.* Originally, SNF was to be reprocessed and plutonium and uranium were to be recycled. In such a system, the SNF is transported from the reactor SNF pool to the reprocessing plant pool before being chemically dissolved for recovery of fissile fuels. In such a system, SNF packaging should be limited because any packaging must be removed at the reprocessing plant. Today, direct disposal of SNF is preferred. In such a system, there is a need to handle fuel only once.

- *Burnup.* SNF burnup has more than doubled to -60 thousand MWd/ton. This significantly increases decay heat and radiation levels.

- *Storage.* The direct disposal of SNF requires interim storage of the SNF before disposal in a geological repository to reduce the SNF decay heat of each waste package (WP). If short-cooled SNF is disposed of, the disposal costs are higher and the repository capacity is significantly reduced. Higher-burnup SNF implies longer storage times. The planned Yucca Mountain (YM) repository will have aging pads for storage of SNF to provide time for the decay heat to be reduced. Because of delays in construction of the repository, SNF is stored at reactor sites. However, even if there had been an operating repository system, there would still be large-scale storage of SNF. The location might be different, but the requirement for storage would remain. There are significant incentives to store the SNF at the reactor for several years. This reduces the radioactivity and decay heat of the SNF before transport.

- *Security.* The events of 9/11 have placed greater emphasis on security and safeguards with corresponding additional physical and operational requirements.

The current SNF management system was designed with one set of requirements and then modified again and again to meet changing requirements. The result is a workable system but a system that is expensive, complicated, and not optimized to meet the current requirements. With changing requirements for SNF management and the potential for new utility reactor orders, it is time to ask whether a better SNF management could be designed.

II. SYSTEM DESIGN

The most rapidly changing requirements for the SNF management system are those associated with security and safeguards. While these risks were not major considerations in the development of the existing U.S. system, they were primary considerations in the development of the German SNF management system. Therefore, the German system, updated for newer technologies and changing conditions in the United States, may provide the best template for an economic high-security SNF management system.

Two major security considerations were the basis of the German SNF system: aircraft collisions into SNF storage facilities and highly competent terrorists. In the middle of the Cold War, more military flights took place over Germany than anywhere else in the world. For a period of time, on average, one military aircraft was lost during training and operations each week. Because of the small geographical area of West Germany and the large number of aircraft accidents, the safety design requirements for reactors and SNF included the ability to withstand aircraft collisions. At the same time, the German government was fighting a highly competent, efficient domestic terrorist groups such as the Baader Meinhof gang. This imposed additional security requirements for the SNF system.

In response to these requirements, Germany established a SNF management system that consisted of (1) storing short-cooled SNF inside reactor containment buildings and (2) then transferring the SNF to metal dual-purpose (storage and transport) casks. Both the reactor containments and casks are designed for resistance to aircraft collisions and terrorist attacks. The use of large casks (>70 tons) eliminates the risks of SNF theft by helicopter or truck. The casks have exterior cooling fins but have no internal air-cooling channels within or through the cask body that provide a potential access route for various explosives. Dual-purpose casks minimize SNF handling. Multiple handling of SNF or multipurpose canisters (containers with multiple SNF assemblies) is expensive because tough security requirements necessitate handling under conditions that will withstand the full range of assaults. In the context of nonproliferation, such a system provides easier tracking of SNF and an added barrier for diversion. Large casks can be designed to require significant time to open, are observable from earth orbit, and can have individual continuous monitors—something not viable with individual fuel assemblies.

We are proposing a modified German system (Fig. 1) applicable to the U.S. that can enhance the capabilities of such a system and potentially lower costs.

- *Multifunction cask.* A multifunction cask is used for SNF storage, transport, and disposal. The cask is loaded at the reactor with SNF. The cask is the handling package, the radiation shielding, the safeguards package, and the "vault" to protect the SNF against assault. Including SNF disposal further reduces risk and may significantly reduce total system costs by avoiding (1) separate SNF aging facilities at the repository, (2) SNF handling at the repository, and (3) the need for separate WPs. This was not an option when the German system was designed because (1) the original repository design had only hoist access and (2) the hoist technology was insufficient for such heavy casks. However, such a system is a viable option for the YM repository because a rail system is to be used to transport disposal casks from the surface facility to the underground disposal drifts.

- *Cermet cask.* New fabrication methods[2] may allow the low-cost fabrication of casks made of cermets (ceramics embedded in steel). Cermets are a traditional material used in tank armor and have the potential of superior performance in terms of resistance to assault. The same technology allows the fabrication of cermets containing depleted uranium dioxide (DUO_2). Such cermets have superior shielding capabilities that can increase cask SNF capacity for a given weight limit.

The enhanced system requires the use of overpacks to meet the conflicting requirements for storage and disposal of SNF. With storage of short-cooled SNF, the primary design constraint is the need to avoid high temperatures that would degrade the SNF. Storage casks require a high ratio of surface area to volume (small casks or fins) to dissipate heat from short-cooled SNF. For disposal, the primary design constraint is to ensure long-term WP integrity. Decay heat levels are lower. The WP should have a low ratio of surface area to volume to minimize both (1) the interactions between groundwater and the WP and (2) the cost of expensive corrosion-resistant materials in the repository overpack. This requirement implies a multifunction cask with smooth surfaces. The use of a removable overpack with heat removal features (fins) during storage can resolve these conflicting performance requirements. The overpack is used at the reactor but removed after the SNF decay heat has decreased. A corrosion-resistant overpack is placed over the multifunction cask at the repository to meet repository requirements.

III. SNF CASK COOLING SYSTEM DESIGN

Economics strongly favors the use of large casks with their lower cost per fuel assembly and the capability to store short-cooled SNF. Cask storage of short-cooled SNF minimizes reactor facility storage requirements. For new reactors, this minimizes the size and cost of the SNF pool. For operating reactors, it minimizes SNF pool storage and maximizes pool space available for maintenance operations. For reactors about to be shut down, emptying the pool at the earliest time reduces operational costs associated with the shutdown reactor. The primary technical challenge with large casks and storing short-cooled SNF in casks is that more decay heat must be removed from the cask to prevent SNF damage. SNF temperatures must be limited to typically 350EC. The need for enhanced cooling methods for casks is further increased by two developments.

- *Improved cask materials.* Improved cask materials (such as DUO_2 cermets) enable the construction of higher-capacity casks with lower costs per fuel assembly, provided that improved cask cooling systems are developed. Otherwise, cask capacity may be limited by decay heat rather than cask weight.

- *Security.* New cask body materials, such as cermets, have potentially superior capabilities to withstand assault. However, to gain the full benefits of such materials, no cooling channels or other penetrations of the cask body are acceptable.

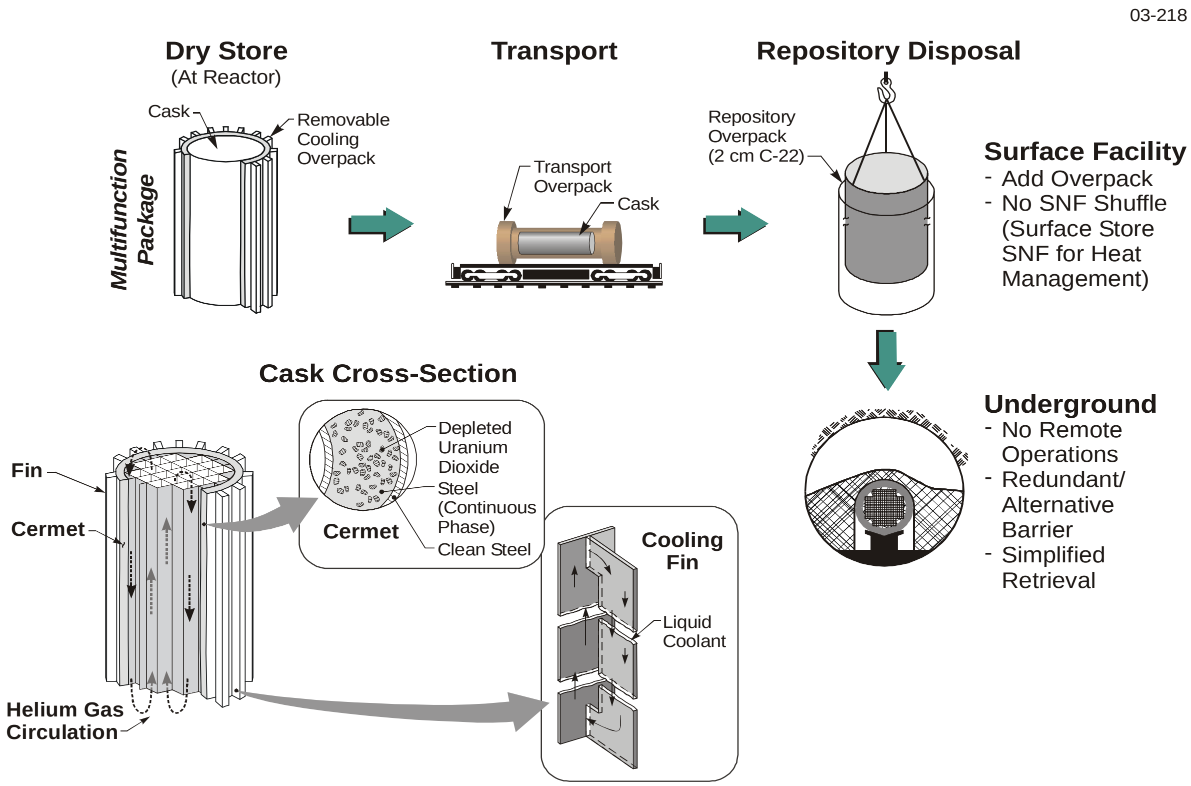

Fig. 1. DUO_2–steel cermet multifunction cask system.

A series of studies have been undertaken on methods to improve heat transfer from SNF in the cask to the environment. Cask vendors with near-term market considerations have emphasized evolutionary improvements in heat removal. Our strategy has been to examine larger changes in cask design. Although these changes have greater uncertainties, they have the potential for at least doubling heat rejection capabilities of casks given the same allowable peak SNF temperatures. The decay heat removal system of such a cask consists of three components.

- *SNF to cask body*. Decay heat is transferred from the SNF to the cask body by two mechanisms: conduction through the basket structure and circulation of inert gases from the SNF to the inner cask wall. Convective heat transfer is improved by use of a xenon-helium or argon-helium gas mixture rather than the traditional helium gas mixture.

- *Cask body*. Requirements for shielding and physical protection control the cask body design. No improvements have been identified for improving heat transfer.

- *Cask body to atmosphere*. On the outside cask wall, liquid-cooled, natural-circulation, bolt-on cooling fins replace solid fins to improve transfer of heat from the cask body to the air. The fins provide an almost uniform temperature over the entire surface of the cask body. The fins are similar to those used in electrical transformers and perform much better than the traditional solid fins typically used in cask storage. The use of circulating fluids inside and outside the cask maximizes the effective surface area of the cask body used for heat transfer (no cold zones with inefficient heat transfer) and minimizes the temperature drop across the cask body, thus maximizing cask heat rejection capabilities while protecting the SNF with the full thickness of the cask body. While heat pipes and other devices can further improve cooling, such systems reduce security by penetrating the cask body. Bolt-on fins, a design feature of some existing casks,[3] offer the advantage of being removable after the SNF decay heat has decreased.

To examine these options, initial analysis were conducted using simplifying assumptions. After an understanding of the key variables is obtained, more complex design tools will be used.

III.A. Heat Transfer from SNF to Cask Body

SNF decay heat in modern casks is transferred from the SNF to the cask body wall by (1) conduction of heat from the SNF to the basket structure and through the basket structure to the cask body and (2) heat-driven natural convection of helium up through the SNF assembly and down through the channels by the cask body. Helium is the traditional fill gas because it is inert, has excellent heat transfer capabilities—including the highest thermal conductivity of any inert gas, and allows the use of helium leak-detection methods to ensure cask sealing. We are investigating alternative gas fills. The requirement for an inert gas limits the choices to helium, neon, krypton, argon, krypton, and xenon. The choice of gas requires consideration of both heat transfer mechanisms.

- *Conduction*. Helium has a very high thermal conductivity compared to any other inert gas (Fig. 2).

- *Convection*. Xenon, the highest density gas, is the best gas to maximize natural circulation of the fill gas from the SNF to the cask body. Natural convection currents are driven by differences in the density of gases in the hot fuel channel versus the cooler walls of the cask body. The relative performance of different gases is determined by a figure of merit[4] that is $[\beta\rho^2 C_p/\mu]^{0.5}$ for laminar flow conditions and $[\beta\rho^2 C_p^{1.8}/\mu^{0.2}]^{0.36}$ for turbulent flow conditions. In these equations: β = thermal expansion coefficient, ρ = density, C_p = heat capacity, and μ = viscosity. Higher density gases improve natural circulation of gases. The relative densities of He, Ar, and Xe are 1, 10, and 33.

Helium is the preferred fill gas in SNF casks because of the low thermal conductivity of the other noble gases. However, measurements of the physical properties of gas mixtures containing helium and heaver gases indicate the potential for superior performance[5] of gas mixtures to transfer heat in a SNF cask compared to pure gases. The addition of helium to another inert gas greatly improves the thermal conductivity of the gas mixture. This is shown in Fig. 2 for a mixture of helium and xenon. If xenon and helium are mixed so the average molecular weight is equal to argon (-40), the natural circulation currents driven by density differences with this gas mixture are about equal to argon. However, the thermal conductivity of such a mixture is over three times that of argon. In effect, the gas mixture has some of the desirable properties of heavy gases (convective heat transfer) and some of the desirable properties of helium (conductive heat transfer). Such gas mixtures are being considered for closed Brayton power cycles in applications such as space craft. We are examining these gas mixtures to understand the optimum gas mixtures for maximizing cooling in SNF casks.

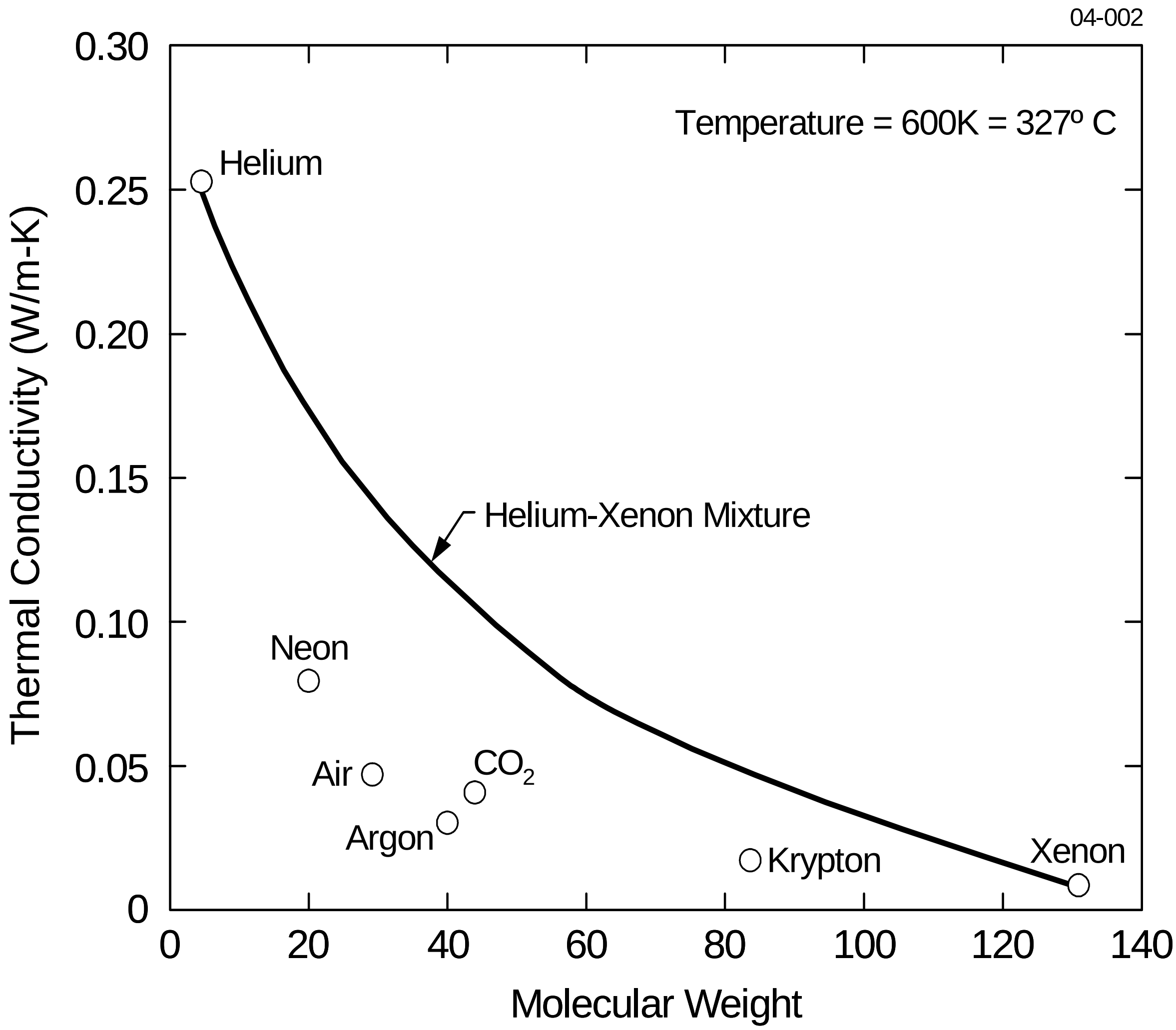

Fig. 2. Thermal conductivity of various gases and various gas mixtures.

III.B. Heat Transfer from Cask Body to Atmosphere

The temperature drop to remove a given quantity of heat from the cask body to the atmosphere can be reduced by the use of liquid-filled fins that allow efficient transfer of heat from all of the cask surface 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. Very small temperature drops are required to remove heat from the cask body to the fin surface. An analysis was completed using water (with antifreeze, appropriate corrosion inhibitors, and neutron absorbers) as the coolant. Water is inexpensive and a large experience base exists regarding its use.

Figure 3 shows the fin configuration, whereas Fig. 4 shows the performance of three different vertical liquid-cooled fins, each of which cools 15 cm of the external circumference of the cask. 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).

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 for the same temperature drop. The solid-fin performance is 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.

The 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 different fin depths and three total temperature differences between the cask and the air. A temperature difference of only a few degrees Celsius 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. Equally important, the system results in a nearly uniform low external cask body temperature. This maximizes heat removal by efficiently utilizing the entire cask body surface for efficient heat removal. In practice, a more compact fin design than the one shown in Fig. 3 would be used to minimize space requirements.

IV. CONCLUSIONS

The requirements for the SNF management system are changing. The cumulative consequences of these changes is sufficient that a new SNF system should be considered for future SNF. Multifunction casks using new technologies have the potential for major improvements in the total system performance and the potential for significant improvements in economics. Improvements in heat transfer may allow relatively short-cooled SNF to be stored in casks, reducing reactor facility storage requirements.

ACKNOWLEDGMENTS

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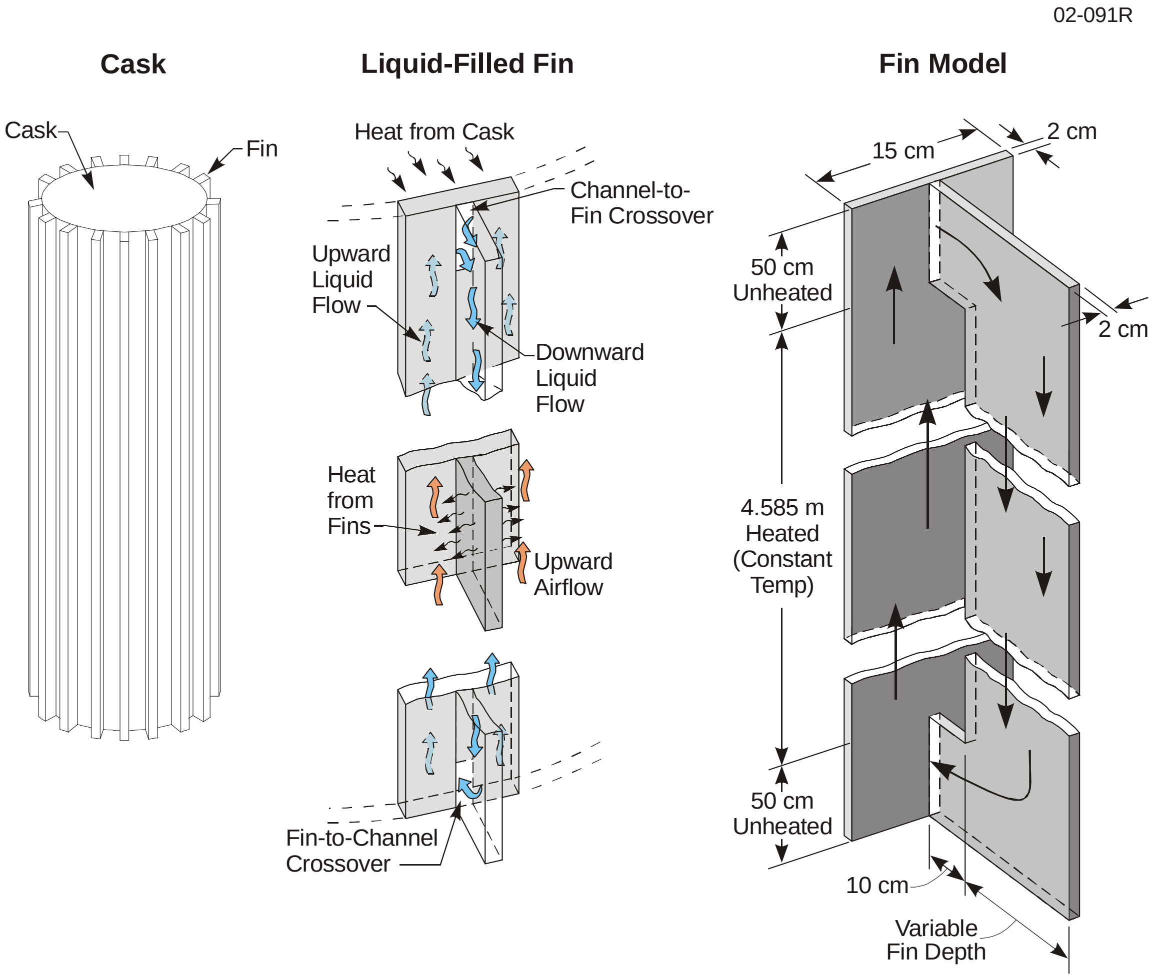

Fig. 3. Liquid-filled cooling fins.

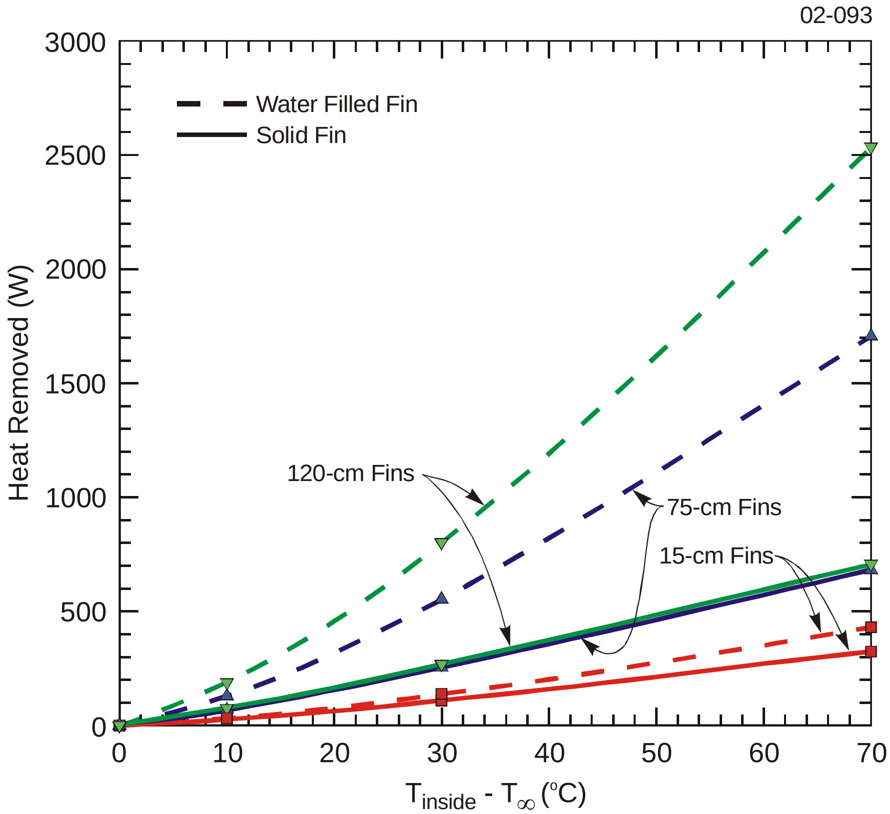

Fig. 4. Heat rejection per fin vs temperature drop for different fin depths.

Table 1. Temperature Difference (EC) in Water for Three Fin Depths and Three Cask-to-Air Temperature Differences

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

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