A COMPACT APPROACH TO LONG-TERM MONITORED RETRIEVABLE STORAGE OF SPENT FUEL

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ABSTRACT

We examine a new approach to monitored retrievable storage (MRS) that is extremely compact in terms of total land use and may offer increased security and reduced environmental impact, relative to current designs. This approach involves embedding the spent fuel assemblies in monolithic blocks of metallic aluminum. While this would clearly require increased effort in the spent-fuel packaging phase, it would offer in return the above-mentioned environmental advantages, plus the option of easily extending the surface-storage time scale from several years to several decades if a need for longer storage times should arise in the future.

INTRODUCTION

Recent federal legislation[1] has raised interest in new concepts for monitored retrievable storage of spent fuel from civilian nuclear power plants. MRS is generally viewed as a valuable supplement to geologic disposal that would provide increased flexibility in future fuel-cycle decisions.[2] In addition to mandating work on various waste-disposal systems, the Congress has also levied a fee of 1 mill/kWh(e) on nuclear power generation, the proceeds of which are to be used to fund the various governmental activities in nuclear waste management and disposal. This fee, which took effect on April 7, 1983, is already generating substantial sums of money for waste-related activities. As discussed below, a very well engineered MRS spent-fuel storage facility could cost less than 10% of the waste-fee revenues collected from the producers of the spent fuel. Furthermore, the cost of operating such a facility would be very low, especially if located at an installation where the cost of monitoring and security could be shared with other ongoing programs.

It is of interest to note that the modest cost of MRS would be at least partially offset by the reduced demands on geologic disposal if MRS storage times are long enough to permit substantial cooling. To consider an example, suppose that 10-year-old spent fuel were stored in MRS for 60 years before being sent to a geologic repository. During this period of storage, the decay heat would decrease by a factor of three.[2,3] Since the net heat load is the dominant factor in determining the size of a geologic disposal facility, it is clear that the cost of eventual geologic disposal would be substantially reduced. For further details on the time dependence of the decay heat, see the Appendix of Ref. 4.

MRS DESIGN CONCEPTS

In several respects, an MRS facility would resemble a scaled up and "ruggedized" version of the spent-fuel cooling ponds located at individual power plants. However, while cooling ponds are designed to hold spent fuel for a few (up to 10) years, storage in an MRS facility may last from 10 years to several decades, depending on future needs. Because of the long storage times that may be needed, water is not an appropriate storage medium.

The general functional requirements are listed in Table I. This table is adapted from Ref. 2, which also contains a good review of the recent history of surface-storage programs.

TABLE I

Functional Requirements of an MRS Facility

1. Provide storage of spent fuel and high-level waste for a minimum of 100 years.
2. Provide protection from extreme environmental events and accidental or deliberate intrusion.
3. Provide shielding and containment of radioactive material to protect the environment and the health and safety of the public and operating personnel.
4. Provide decay-heat removal systems using passive cooling methods.
5. Provide retrieval capability throughout the entire storage period.
6. Provide warning of potential and actual release of radioactive material.

Cooling (Item 4) is necessary because, even after 10 years, typical spent-fuel assemblies would still be generating decay heat at the rate of about 4 kW/m^3. Approximate values for various properties of spent fuel, 10 years after removal from the reactor, are summarized in Table II.[2,3,5] These figures are based on a once-through cycle and a burnup of 34 000 MWD(t)/tonne uranium, which is typical of current practice. It should be noted that a shift toward higher burnup values would result in substantially higher ^{244}Cm production and, hence, a higher neutron generation rate than is shown in the table.

Several concepts for passively cooled dry storage are described in Ref. 2. For example, one scheme discussed there involves placing the spent fuel in hermetically sealed canisters, placing the canisters in 8-m-deep holes in the ground, and plugging the holes with sand. These "dry wells" would be drilled into the ground in an open field, with about a 6-m spacing between the holes. Each canister would contain 0.48 metric tonnes, heavy metal, (MTHM) of spent fuel. A patrolled security fence surrounding the facility would be required both to protect the public and to safeguard the large quantities of nuclear materials (especially plutonium) contained in the spent fuel.

TABLE II

Typical Properties of Spent Fuel from 1 GWy(e)

Fuel-assembly volume	1.0×10^{1} m^{3}
Heavy-metal mass	3.2×10^{4} kg
Heat generation	3.8×10^{1} kW
0.662-MeV gamma rays	8.7×10^{16} s^{-1} ($t_{1/2}$ = 30 y)
Hard (>1 MeV) gammas	3.4×10^{15} s^{-1} ($t_{1/2}$ = 5.3 y)
Spontaneous-fission neutrons	3.5×10^{9} s^{-1} ($t_{1/2}$ = 18 y)
Waste-fund revenue	8.8×10^{6} dollars

COMPACT MRS CONCEPT

We have briefly examined a different concept for MRS, one that would be far more compact than the open-field dry-well approach. Land use for the concept we have examined would be only a few per cent of that required for the dry-well approach. This approach may also have advantages in the areas of monitoring and safeguards against theft, as well as reducing the chances of groundwater contamination.

The basic approach we have considered is to place the spent-fuel assemblies horizontally at the bottom of large, rectangular, stainless steel containers, as shown (end view) in Fig. 1. These containers, with nominal dimensions of 1.0 m x 6.4 m in the horizontal plane and 2.6 m deep, would be sealed, heat treated, and then assembled into a tightly fitting array, with perhaps 250 containers in an array. The top surface of the containers (A-B) would be located approximately at ground level, and this surface would be separated from the atmosphere by only a low-mass vented structure, included mainly to shield the container surfaces from precipitation.

Within each container, just above the spent fuel, would be a 1.4-m-thick, largely aluminum, neutron and gamma-ray shield. Above the shield would be a copper "honeycomb" region. At the time of container sealing (probably by welding), the cells of the copper honeycomb would contain full-density aluminum, with an aluminum-to-copper volume ratio of 9:1 in this region. After sealing, the entire container would be raised above the aluminum melting point (659°C) by applying external heat. Aluminum from the honeycomb would flow downward, exchanging positions with small voids in the shield and spent-fuel regions below. The initial effective total void thickness in the lower regions probably can be reduced to less than 0.50 m by packing aluminum powder and solid shims around the various components before sealing.

The flowing aluminum would establish good thermal contact between the spent-fuel rods and other components. After resolidification, the aluminum would provide great mechanical strength and additional fission-product containment. After placement in the storage array, the residual decay heat, instead of being conducted into the earth, would be conducted up through the shield and through the copper region. At surface temperatures in the 200-250°C range, thermal radiation from the top surface of the container would provide very adequate heat-removal rates. Various parameters of a preliminary design are listed in Table III. No portion of the sealed containers would have a temperature below 100°C, even after 100 years of storage.[4] This means that, even if a container were to rupture, there would be no pathway for the transport of non-volatile fission products to the groundwater.

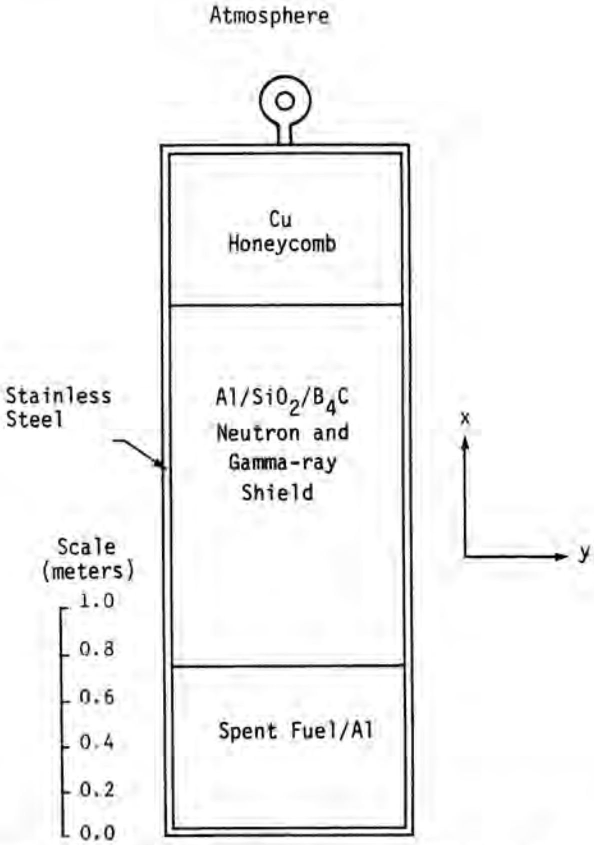

Fig. 1. Vertical section of radiatively cooled compact MRS fuel container. Geometry shown would be repeated in the y- and z-directions. For analysis, complete symmetry is assumed in the y- and z- directions (one-dimensional slab geometry).

TABLE III

Preliminary Compact MRS Design[a]

Radiation dose (n+γ) at top surface	~1 mR/hr
Copper honeycomb region thickness	0.555 m
Radiation shield thickness	1.40 m
Fuel region thickness	0.65 m
Volumetric power density in fuel region	3.8 kW/m^3
Areal power density	2.47 kW/m^2
Structure temperature (see text)	90°C
Temperature at container top surface	224°C
Temperature at copper/shield boundary	260°C
Temperature at shield/fuel boundary	291°C
Temperature at bottom of fuel	300°C

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[a] See also Fig. 1.

In obtaining the numerical values given in Table III, a number of simplifying assumptions are made. Presumably, the neutron/gamma shield would incorporate materials such as SiO_2 and B_4C in some form, to help moderate and absorb spontaneous-fission neutrons from the fuel. The presence of these materials is assumed to degrade the thermal conductivity of the shield to 113 W m^{-1} °C^{-1}, or about 0.48 times that for pure aluminum at 275°C. In the fuel region, the solid fuel rods (as opposed to assemblies) are assumed to occupy 33% of the available volume; the remaining volume is assumed to be occupied by full-density aluminum. Multidimensional heat-transfer calculations have not been performed to estimate the heat-flow rates in the vertical direction (perpendicular to the fuel-rod axes). Instead, a hand calculation of the heat flow around the fuel rods was performed, and this calculation suggests the use of an effective average thermal conductivity of 90 W m^{-1} °C^{-1}, or 0.38 times that for pure aluminum, to estimate vertical heat-flow rates.

The previously mentioned low-mass structure (see Fig. 2) would help maintain container integrity by avoiding the thermal stress and corrosion associated with precipitation falling directly on the container surfaces. Large air vents in the walls and roof would allow reasonably rapid air flow through the space above the spent-fuel containers. The structure itself would be cooled by both radiation and convection. We have assumed that the structure equilibrates at about 90°C (194°F), and this figure is used as the "ambient" temperature in calculating the radiative cooling of the fuel containers. To obtain an exact temperature profile for the structure would require rather detailed calculations, and these have not yet been done. Fortunately, the overall system size and cost do not depend strongly on the assumed ambient temperature.

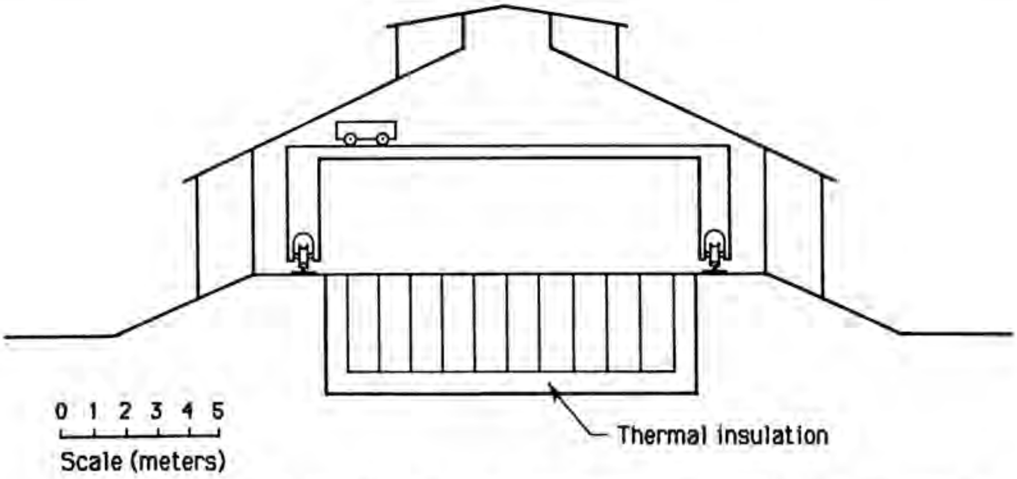

Fig. 2. End view of 10 x 25 fuel-container array, showing the low-mass vented structure and crane for placing and retrieving containers.

Although the *covering* structure itself would be somewhat vulnerable to damage, by violent winds for example, even its complete removal would not seriously compromise the protection and isolation of the stored fuel. Presumably the structure would be repaired, or replaced, on a nonemergency basis, after such an event. Insurance against such damage would contribute very little to the facility operating expenses.

The numerical values given in Table III are applicable over a wide range of facility sizes. However, it is of interest to apply these figures to a facility of some particular size. In the mid 1990s, the installed nuclear capacity in the US will be at least 120 GW(e) (reactors now operating, under construction or on order). During 4 years of operation of these reactors at just over 65% capacity, some 312.5 GWy(e) of electricity, and according to the figures in Table II, exactly 10 000 MTHM of spent fuel will be produced. An MRS facility of the kind described here, with a capacity of 10 000 MTHM, would have a total top-surface area of 4800 m^2 and an initial thermal output of 11.9 MW. (This total area and the corresponding areal power density in Table III refer to the surface area directly overlying the stored fuel and, hence, do not include the thickness of the stainless steel side walls nor the small air gaps between containers.)

The general features of a possible 10 000-MTHM compact MRS facility are discussed in Ref. 4. In that layout, the 4800 m^2 of total top surface is divided into 3 identical arrays of 250 containers each. Arranging the containers in a 10 x 25 (y,z) array yields a convenient 10-m x 160-m size for each of the 3 container arrays. It would appear convenient to span the 10-m width with a simple crane arrangement such as that shown in Fig. 2. The total land area occupied by the facility (including a large containerization building) is 53 000 m^2 or 13 acres.

The amount of aluminum required for a 10 000-MTHM facility would be 23 800 metric tonnes, and the required amount of copper would be 2400 metric tonnes. Based on a cost of $0.82 per pound for (99.7%-purity) aluminum and $2.24 per pound for copper (99.9% purity), the cost of (unfabricated) construction materials for the fuel containers would be around 65 million dollars. Construction of the service building and other site-preparation expenses, plus the actual fabrication and processing of the fuel containers, could easily raise the final facility cost to 150-250 million dollars. Even so, this is quite modest in comparison with the 2.7 billion dollars that would be raised by the 1 mill/kWh(e) waste fee collected from the producers of the stored fuel. It is of interest to note that the cost of the compact MRS facility considered here is generally competitive with the cost of other MRS concepts, such as those discussed in Ref. 2.

SUMMARY AND PROGNOSIS

After a brief examination, a compact MRS approach where stored fuel rods are embedded in large blocks of solid aluminum appears to be technically and economically feasible. Moreover, it appears that this approach would combine the best features of several alternatives. For example, the protection offered by this approach against extreme environmental events, such as tornadoes and earthquakes, would be about as good as the protection offered by the open-field drywell approach, which is the best of the alternatives in this regard. At the same time, this approach would be about as good as the compact alternatives, such as vault storage, in the areas of land use, ease of monitoring, and protection of the groundwater. In several areas, the compact MRS design considered here would be clearly superior. For example, the sheer mass of the fuel-containing blocks (approximately 48-metric tonnes each) would eliminate the possibility of clandestine removal of containerized spent fuel from the site. The thickness and strength of the aluminum radiation shield would likewise provide superior protection against sabotage with high explosives.

REFERENCES

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3. T. R. ENGLAND and W. B. WILSON, "TMI-2 Decay Power: LASL Fission-Product and Actinide Decay Power Calculations for the President's Commission on the Accident at Three-Mile Island," LA-8041-MS, Los Alamos Scientific Laboratory (1980). (See especially Table D-XI, p. 189.)

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