NOTICE
PORTIONS OF THIS REPORT ARE ILLEGIBLE.
It has been reproduced from the best
available copy to permit the broadest
possible availability.

LA-10022-MS

UC-85

Issued: September 1984

LA--10022-MS

DE85 002345

A Compact Approach to Monitored Retrievable Storage of Spent Fuel

D. W. Muir

MASTER

Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

A COMPACT APPROACH TO MONITORED RETRIEVABLE STORAGE OF SPENT FUEL

by

D. W. Muir

ABSTRACT

Recent federal waste-management legislation has raised national interest in monitored retrievable storage (MRS) of unprocessed spent fuel from civilian nuclear power plants. We have reviewed the current MRS design approaches, and we have examined an alternative concept that is extremely compact in terms of total land use. This approach may offer substantial advantages in the areas of monitoring and in safeguards against theft, as well as in reducing the chances of groundwater contamination. Total facility costs are roughly estimated and found to be generally competitive with other MRS concepts.

I. INTRODUCTION

As discussed in Ref. 1, the US Congress has directed the Department of Energy to develop concepts and identify sites for monitored retrievable storage (MRS) of spent fuel (and possibly high-level wastes) from civilian nuclear power plants. In general terms, MRS refers to passively cooled dry storage, either at the Earth's surface or in open tunnels. By June 1985, work should be completed on both (1) a detailed study of the need for such facilities and (2) a proposal containing at least five alternative site-specific designs at a minimum of three different sites.

Regarding the need for such facilities, MRS is not viewed as a replacement for geologic disposal, but as a valuable supplement that would provide increased flexibility in future fuel-cycle decisions (Ref. 2). Although there is some discussion of the possibility of storing high-level waste (HLW) in MRS, it seems likely that HLW will be sent to a geologic disposal facility as soon as

space can be made available. However, the appropriate strategy for handling unprocessed spent fuel, which is now accumulating in large quantities, is less clear. Whether this spent fuel is "waste" or "resource" will depend on future developments in the commercialization of plutonium-recycle and breeder technologies. MRS facilities would provide a more secure method of spent-fuel storage than cooling ponds or shipping casks, while at the same time holding open the reprocessing option. If future developments in energy technology (for example, development of a truly practical solar-electric or fusion technology) render the spent fuel valueless, then permanent geologic disposal of spent fuel could move forward at that time. This interaction between MRS and other energy systems deserves further study. The second item requested is the actual design of several MRS facilities. This design work also presents some new and interesting questions, and some of these questions are addressed in Sections II-IV.

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, will generate very substantial sums of money for waste-related activities in the future. As discussed in Section III, a very well engineered MRS spent-fuel storage facility would 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 interesting to note that the cost of constructing MRS facilities would be at least partially offset by the reduced demands on geologic disposal. To consider an example, suppose that 10-year-old spent fuel is stored in MRS for 60 years before being sent to a geologic repository. During the 60 years 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.

II. 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 over 100 years, depending on future needs. Because of the long storage times envisioned, water cannot be used as the 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 in the table) is necessary because, even after 10 years, typical spent-fuel assemblies would still be generating decay heat at the rate of about 4 w/t. Approximate values for various properties of spent fuel, 10 years after removal from the reactor, are summarized in Table II.^{2,3,4} 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 ²⁴⁴Cm 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. Probably the most practical 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 holes, called "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,

TABLE II

TYPICAL PROPERTIES OF SPENT FUEL FROM 1 GWy(e)

Fuel-assembly volume	$1.0 \times 10^7 \text{ cm}^3$
Heavy-metal mass	$3.2 \times 10^7 \text{ g}$
Heat generation	$3.8 \times 10^4 \text{ W}$
0.662-MeV gamma rays	$8.7 \times 10^{16} \text{ s}^{-1} (t_{1/2} = 30 \text{ y})$
Hard (>1 MeV) gammas	$3.4 \times 10^{15} \text{ s}^{-1} (t_{1/2} = 5.3 \text{ y})$
Spontaneous fission neutrons	$3.5 \times 10^9 \text{ s}^{-1} (t_{1/2} = 18 \text{ y})$
Waste-fund revenue	$8.8 \times 10^6 \text{ dollars}$

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.

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 less than 15 acres for a 10 000-MTHM facility, only a few per cent of that required for the dry-well approach. This compactness may have substantial benefits in the areas of monitoring and safeguards against theft, as well as reducing the chances of groundwater contamination.

III. COMPACT MRS CONCEPT

The basic approach we have considered is to place the spent-fuel assemblies horizontally at the bottom of large, rectangular, sealed, stainless steel containers, as shown (end view) in Fig. 1. These containers, with approximate dimensions 1 m x 2.6 m x 6.4 m, would be 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 thick (~1.4-m), 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 50 cm by packing aluminum powder and solid shims around the various components before sealing.

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).

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. 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.

TABLE III

PRELIMINARY COMPACT MRS DESIGN^a

Radiation dose (n+γ) at top surface	~1 mR/hr
Copper region thickness	55.5 cm
Radiation shield thickness	140 cm
Fuel region thickness	65 cm
Volumetric power density in fuel region	3.8 W/l
Areal power density	0.247 W/cm 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

^aSee 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 SiO₂ and B₄C 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 1.13 W cm⁻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 0.9 W cm⁻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 135 GW(e) (reactors now operating, under

construction or on order). During 3 years of operation of these reactors at just over 77% 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 m² 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.)

As a general illustration of facility layout and size, Fig. 3 provides a sketch of a possible 10 000-MTHM compact MRS facility. The 4800 m² of total top surface is divided into 3 identical arrays of 250 containers each. Thus each array holds about a 1-year national output of spent fuel. Arranging the containers in a 10 x 25 (y, x, z) array yields a convenient 10-m x 160-m size. It would appear practical to span the 10-m width with a simple crane arrangement, such as that shown in Fig. 2, and this crane could be used to position individual fuel containers. In addition to the three fuel arrays and their covering structures, a large service building would be required to process arriving spent fuel into the sealed storage containers. (This same building could be used for the reverse procedure when the time comes to begin retrieving the fuel from MRS storage.) The land area occupied by the total facility (see Fig. 3) is about 53 000 m², or 13 acres. Clearly this type of facility layout would permit the addition of storage capacity by simply adding more fuel-container arrays at the back of the facility (C-D).

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.

Fig. 3. Possible site layout for a 10 000-MTHM compact MRS facility.

IV. SUMMARY AND PROGNOSIS

After a brief examination, it appears that a compact MRS approach in which stored fuel rods are embedded in large blocks of solid aluminum is technically feasible. Although many details remain to be studied, 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 dry-well 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. Although we have made only rough estimates of costs, the facility cost for the compact approach considered here appears to be generally competitive with other concepts.

In several areas, the compact MRS design considered here would be clearly superior to the alternatives. The sheer mass of the fuel containers (approximately 48-metric tonnes each) would essentially rule out the possibility of clandestine removal of containerized spent fuel from the site. The energy-absorption characteristics of the copper honeycomb and the thickness of the aluminum shield below it would likewise provide superior protection against sabotage with high explosives.

REFERENCES

1. The Nuclear Waste Policy Act of 1982. Public Law 97-425, January 7, 1983. See also, Michael J. Lawrence, "Overview of DOE's Commercial Nuclear Waste Management Program," presentation at the Seminar on the Nuclear Waste Policy Act of 1982, Institute of Nuclear Material Management, Crystal City, Virginia, May 4, 1983.
2. "The Monitored Retrievable Storage Concept, A Review of Its Status and Analysis of Its Impact on the Waste Management System," US Department of Energy report DOE/NE-0019 (1981).
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," Los Alamos Scientific Laboratory report LA-8041-MS (1980). (See especially Table D-XI, p. 189.)
4. B. L. Cohen, "High-Level Waste from Nuclear Reactors," Rev. Mod. Phys. 49, 1 (1977).

APPENDIX

TIME DEPENDENCE OF SPENT-FUEL DECAY HEAT

The decay-heat calculations of Ref. 3 (Table D-XI, page 189) were fit with an exponential series, and the results are listed in Table A-I. The total heat generation, in units of W/cm^2 , for the reference design discussed in Section III of this report is listed in Column 3. In the first two columns, this total is broken down into fission-product and actinide contributions. Column 4 lists the resulting fuel-container top-surface temperature, calculated with an assumed ambient temperature of 90°C , as discussed in Section III. Because of the T^4 dependence of thermal radiation and because of the substantial contribution of the long-lived actinides such as ^{241}Am , the container temperature varies extremely slowly with time, changing by only a few degrees per year.

TABLE A-I

HEAT GENERATION AND TEMPERATURE FOR VARIOUS COOLING TIMES

Cooling Time (yr)	Heat Loss (W/cm ²)			Surface Temperature (°C)
	Fiss. Prod.	Actinides	Total	
2	7.940E-01	6.925E-02	8.633E-01	3.688E+02
4	4.728E-01	5.161E-02	5.244E-01	3.027E+02
6	3.157E-01	5.125E-02	3.669E-01	2.622E+02
8	2.368E-01	5.155E-02	2.883E-01	2.381E+02
10	1.952E-01	5.179E-02	2.470E-01	2.238E+02
12	1.716E-01	5.195E-02	2.235E-01	2.152E+02
14	1.567E-01	5.204E-02	2.087E-01	2.094E+02
16	1.461E-01	5.206E-02	1.981E-01	2.052E+02
18	1.377E-01	5.203E-02	1.897E-01	2.018E+02
20	1.305E-01	5.195E-02	1.824E-01	1.988E+02
22	1.240E-01	5.183E-02	1.758E-01	1.960E+02
24	1.180E-01	5.168E-02	1.697E-01	1.933E+02
26	1.124E-01	5.149E-02	1.639E-01	1.908E+02
28	1.071E-01	5.128E-02	1.584E-01	1.883E+02
30	1.021E-01	5.104E-02	1.531E-01	1.859E+02
32	9.728E-02	5.079E-02	1.481E-01	1.836E+02
34	9.272E-02	5.052E-02	1.432E-01	1.814E+02
36	8.837E-02	5.024E-02	1.386E-01	1.792E+02
38	8.423E-02	4.995E-02	1.342E-01	1.771E+02
40	8.028E-02	4.965E-02	1.299E-01	1.750E+02
44	7.293E-02	4.903E-02	1.220E-01	1.710E+02
48	6.625E-02	4.840E-02	1.147E-01	1.673E+02
52	6.019E-02	4.777E-02	1.080E-01	1.638E+02
56	5.468E-02	4.714E-02	1.018E-01	1.605E+02
60	4.968E-02	4.652E-02	9.620E-02	1.574E+02
64	4.513E-02	4.592E-02	9.104E-02	1.546E+02
68	4.100E-02	4.532E-02	8.632E-02	1.519E+02
72	3.724E-02	4.474E-02	8.198E-02	1.494E+02
76	3.384E-02	4.418E-02	7.801E-02	1.470E+02
80	3.074E-02	4.363E-02	7.437E-02	1.448E+02
84	2.792E-02	4.310E-02	7.102E-02	1.428E+02
88	2.537E-02	4.258E-02	6.795E-02	1.409E+02
92	2.305E-02	4.208E-02	6.513E-02	1.391E+02
96	2.094E-02	4.160E-02	6.253E-02	1.375E+02
100	1.902E-02	4.113E-02	6.015E-02	1.360E+02
104	1.728E-02	4.067E-02	5.795E-02	1.345E+02
108	1.570E-02	4.023E-02	5.593E-02	1.332E+02
112	1.426E-02	3.980E-02	5.406E-02	1.320E+02
116	1.296E-02	3.938E-02	5.233E-02	1.308E+02
120	1.177E-02	3.897E-02	5.074E-02	1.298E+02
124	1.069E-02	3.857E-02	4.926E-02	1.288E+02
128	9.713E-03	3.818E-02	4.789E-02	1.278E+02
132	8.824E-03	3.780E-02	4.663E-02	1.269E+02
136	8.017E-03	3.743E-02	4.545E-02	1.261E+02
140	7.283E-03	3.707E-02	4.435E-02	1.254E+02