WORKSHOP D

SPENT FUEL AS A WASTE FORM*

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INTRODUCTION

The recent policy decision to defer reprocessing of spent fuel has made it necessary to consider spent power-reactor fuel as a solid-waste form to be placed for an indefinite period in a surface-storage facility or in a geologic repository. Since the characteristics of spent fuel are different from those of solidified high-level waste, it is reasonable to expect that the problems associated with the long-term storage and disposal of spent-fuel assemblies may be substantially different from those of solidified high-level waste. This paper describes the properties and quantities of spent fuel projected to be discharged from LWRs in the United States over the next several decades,and briefly considers the potential problems associated with the surface storage and geologic emplacement of this fuel. It is intended to serve as a basis for discussion at the Waste Management '78 Workshop on "Spent Fuel Disposal."

DESCRIPTION OF LWR FUEL ASSEMBLIES

LWR fuel assemblies are composite units of fuel pins in a geometric cluster held together by end pieces and a number of pin spacers. Although boiling-water reactor (BWR) and pressurized-water reactor (PWR) fuel assemblies differ significantly, the basic components of each are the fuel pins which are long sections of metal tubing filled with ceramic pellets of uranium dioxide or mixed uranium-plutonium dioxide. Physical characteristics of typical fuel assemblies are given in Table I. When considering spent-fuel assemblies as a waste form, two relevant characteristics are overall size and weight. A typical BWR assembly has a 13.9 x 13.9 cm cross section, an overall length of 447 cm, and a weight of 275 kg. Approximately 175 of these assemblies are discharged each year by a 1000-MW(e) BWR. A typical PWR fuel

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assembly has a 21.4 x 21.4 cm cross section, an overall length of 406 cm, and a weight of 658 kg. Approximately 60 of these fuel assemblies are discharged each year by a 1000-MW(e) PWR.

Table I. Physical characteristics of typical unirradiated LWR fuel assemblies[1,2]

	BWR	PWR
Overall assembly length, m	4.470	4.059
Cross section, cm	13.9 x 13.9	21.4 x 21.4
Fuel pin length, m	4.4064	3.851
Active fuel height, m	3.759	3.658
Fuel pin O.D., cm	1.252	0.950
Fuel pin array	8 x 8	17 x 17
Fuel pins/assembly	63	264
Assembly total weight, kg	275.7	657.9
Uranium/assembly, kg	183.3	461.4
Uranium dioxide/assembly, kg	208.0	523.4
Zircaloy/assembly, kg	56.9[a]	108.4[b]
Hardware/assembly, kg	9.77[c]	26.1[d]

[a]Includes Zircaloy fuel-pin spacers.

[b]Includes Zircaloy control-rod guide thimbles.

[c]Includes stainless steel tie-plates and Inconel springs.

[d]Includes stainless steel nozzles and Inconel-718 grids.

Pertinent irradiation parameters of enriched uranium LWR fuels are summarized in Table II. An assembly is irradiated in a BWR (PWR) producing an average of 4.75 (17.3) MW of power. After the equivalent of 1062 (880) full-power days of irradiation, it is discharged. At this time, it contains uranium with a ^{235}U enrichment of 0.68 (0.84) wt % and 1.57 (4.32) kg of plutonium. The spent fuel also contains fission products and neptunium, americium, and curium isotopes.

Table II. Typical irradiation parameters of LWR fuels

Parameter	BWR	PWR
Uranium per assembly, kg		
Initial	183.3	461.4
Discharge	176.3	440.7
Enrichment, wt % ^{235}U		
Initial	2.75	3.20
Discharge	0.69	0.84
Plutonium per assembly at discharge, kg	1.57	4.32
Average power, MW/assembly	4.75	17.3
Average specific power, kW/kg initial uranium	25.9	37.5
Average discharge burnup, MWd/metric ton initial uranium	27,500	33,000
Irradiation duration, full-power days	1062	880

Calculations to predict the relevant characteristics of spent BWR and PWR fuel assemblies were performed with the ORIGEN computer code[3] using the input data of Tables I and II. Three relevant characteristics of spent fuels are the thermal power, radioactivity, and "ingestion toxicity"[a] as a function of decay time; and the three major groups of fuel constituents are the structural materials (cladding, grid spacers, etc.), the actinides, and the fission products.

[a]The "ingestion toxicity" is defined as the total volume of water that would be needed to dilute all of the radioactive constituents to concentrations specified in 10CFR20 as being the maximum acceptable for unrestricted use.

The variations of the thermal power and the radioactivity of both spent BWR and PWR fuel assemblies are shown in Figs. 1 and 2. The fuel-assembly structural materials are negligible contributors to the thermal power, activity, and toxicity of the assemblies at all decay times. The fission products dominate all three characteristics at decay times of less than 100 years, while the actinides dominate at decay times greater than 300 years. At decay times between 100 and 300 years, both the fission products and actinides contribute substantially to the totals.

In Fig. 3, the characteristics of a spent PWR fuel assembly are compared to those of the high-level, plus cladding, wastes that would result from reprocessing this assembly. (The ratios for BWR spent fuel are similar to those shown in Fig. 3 for the PWR.) The differences are small at decay times less than 100 years because the dominant fission products are present in equal amounts in both spent-fuel and high-level waste. However, at longer times the characteristics of spent fuel-assemblies are greater than those of the wastes by factors ranging from 10 to more than 30. Of particular interest is the greater long-term thermal power, which is the principal criterion in determining the spacing of solid-waste containers in a geologic repository.

Changes in the physiochemical characteristics of the fuel pellets with irradiation have been well characterized,[4] and consist of structural and dimensional changes, release of a significant fraction of the fission-product gases, and migration of other fission products (e.g., iodine and cesium) within the fuel pins. One-third to one-half of the fission-product tritium is associated with the Zircaloy cladding. Tests with irradiated pellets indicate that the leachability of important isotopes at room temperature in the absence of oxygen is similar to that observed for borosilicate glass containing radioactive waste.[5]

PROJECTIONS OF SPENT FUEL TO BE DISCHARGED

Projections were made recently of spent fuels to be discharged from LWRs in the United States through the year 2030 A.D.[6] They were based on installed nuclear capacities of 194, 380, 494, 553, and 540 GW(e) in the years 1990, 2000, 2010, 2020, and 2030, respectively, and allowance was made for 2342 metric tons of uranium reported by DOE to be in storage as commercial spent fuel at the end of 1976.[7] The projected quantities and characteristics of these fuels are given in Figs. 4 and 5.

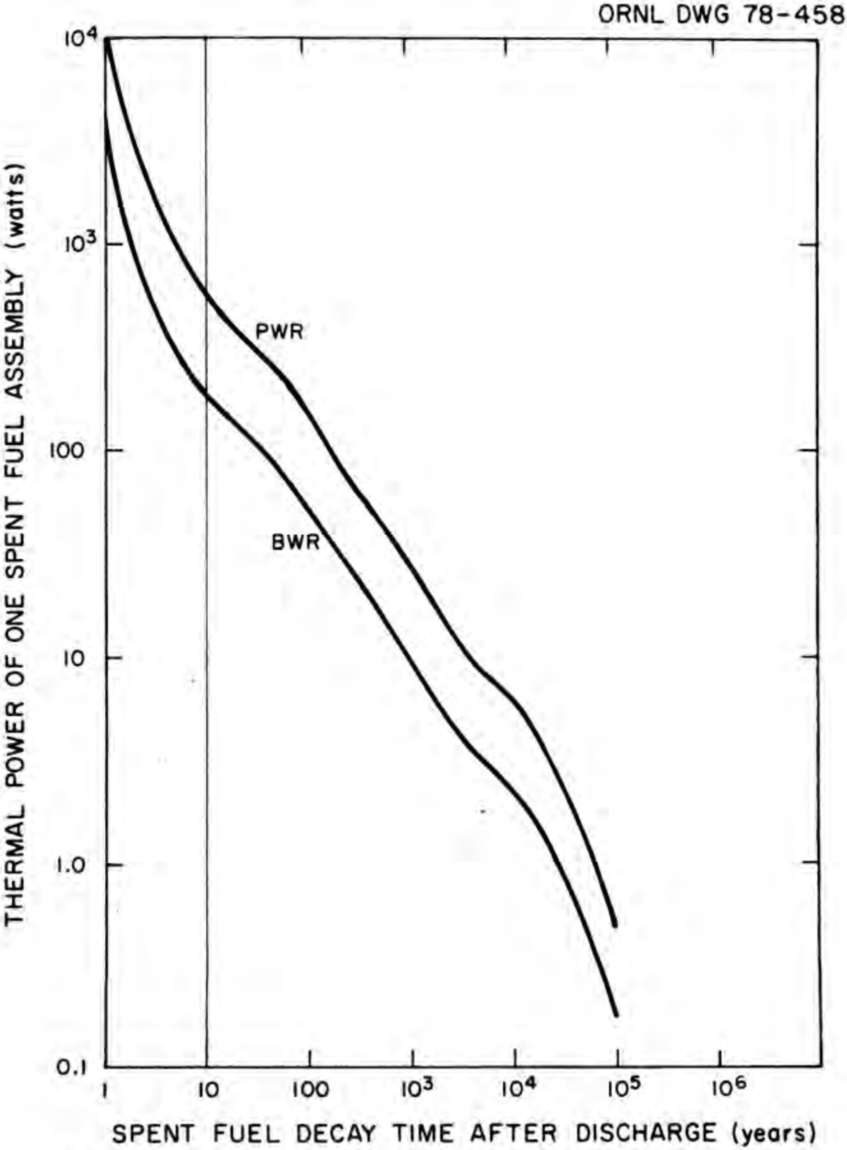

Fig. 1. Thermal power of spent BWR and PWR fuel assemblies.

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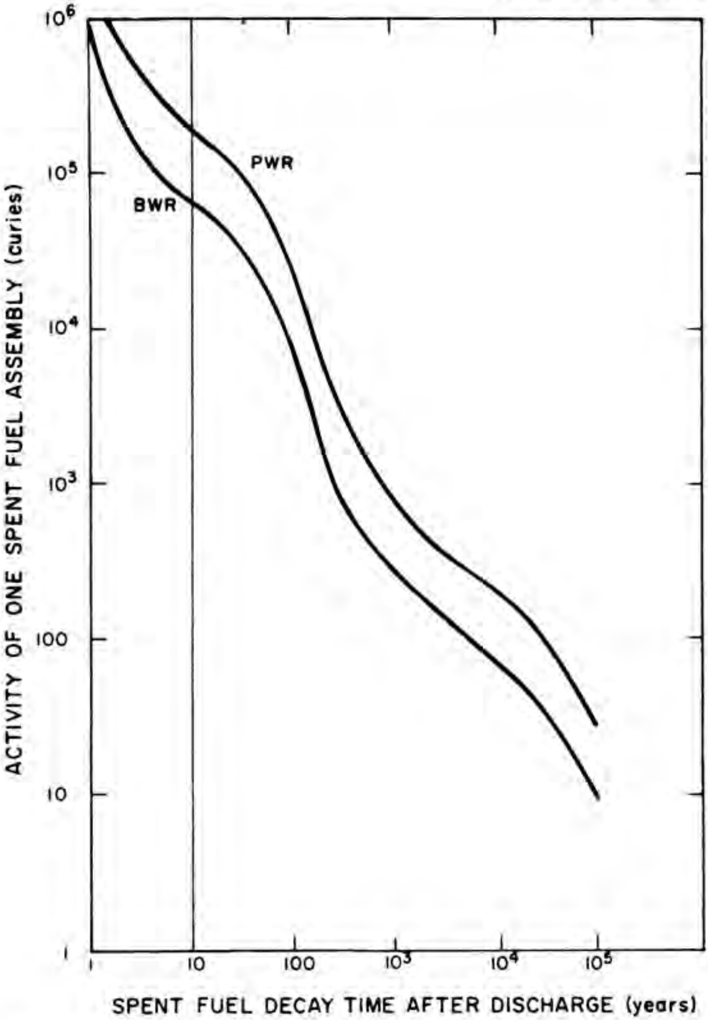

Fig. 2. Activities of spent BWR and PWR fuel assemblies.

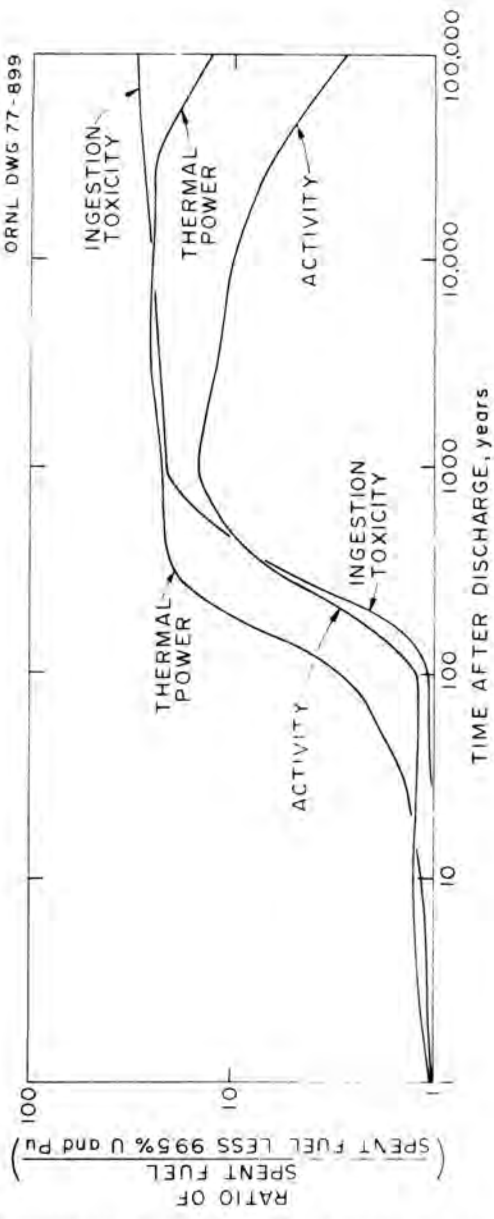

Fig. 3. Comparison of the characteristics of spent PWR fuel and the high-level plus cladding wastes from reprocessing this fuel.

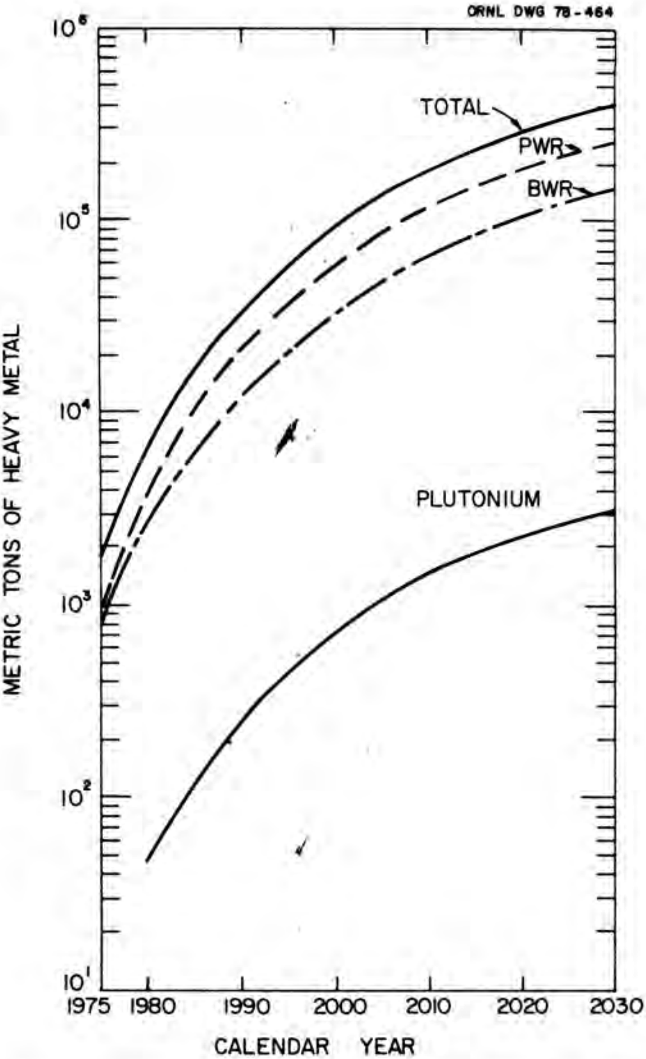

Fig. 4. Accumulated weight of heavy metal projected to be discharged in spent fuels.

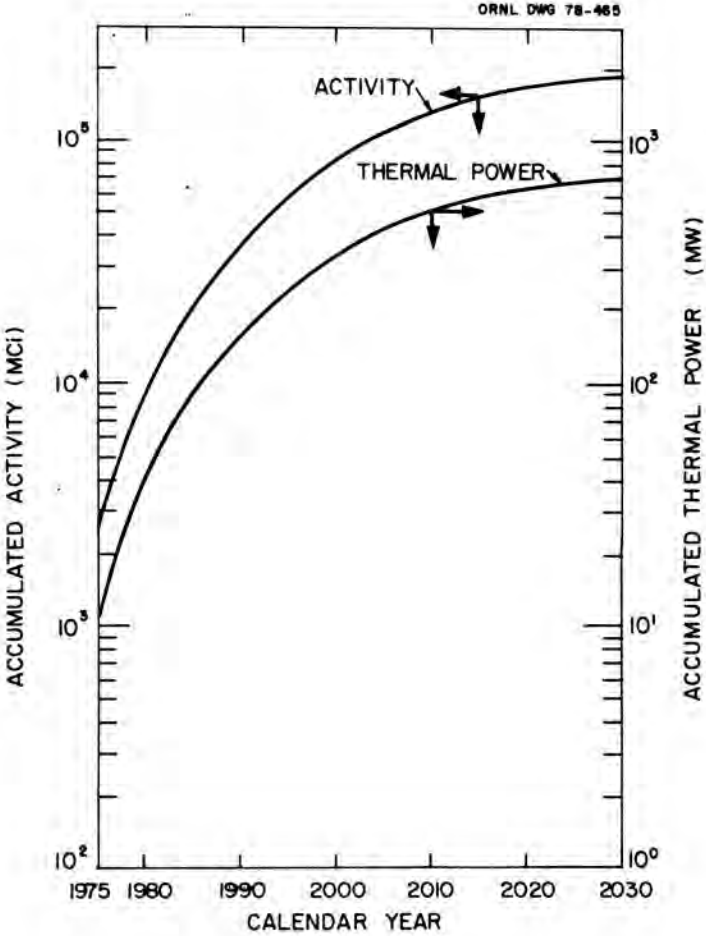

Fig. 5. Activity and thermal power in accumulated spent fuels projected to be discharged.

CONSIDERATIONS OF SPENT FUEL AS A WASTE FORM

There are three general options available for handling the spent-fuel assemblies after an initial period of interim storage. The first is to continue storage in water-filled basins until a decision is made either to recover the uranium and plutonium by reprocessing or to undertake final disposal. Studies indicate that the Zircaloy cladding should maintain its integrity under water for at least several decades.[8] The second is to build and operate surface-storage facilities designed for a somewhat longer term, perhaps 50 to 100-or-more years. The last option is to place the assemblies in a deep-geological formation after interim storage in water basins. This geological repository could be designed for retrievable storage for an indefinite period and would permit a later decision to be made on reprocessing or permanent disposal.

The use of spent-fuel assemblies as a solid-waste form poses several problems that would not be encountered if solidified high-level waste were used.

1. To facilitate handling and to provide a barrier to the spread of contamination in the event of an accident at the repository, the assemblies should probably be encapsulated in a canister.

2. The fuel pins contain radioactive gases under pressure which might have to be vented for safety considerations prior to encapsulation.

3. The spent fuel contains about 100 times more plutonium than would the high-level waste from reprocessing. This greatly increases the long-term waste toxicity and heat-generation rate.

4. The presence of plutonium and enriched uranium makes the possibility of nuclear criticality a concern if the repository were breached, water entered, and the fissile materials were somehow arranged into a suitable configuration.

There are currently three major programs that are underway to analyze spent-fuel assemblies as a waste form: (1) geologic isolation at the Office of Waste Isolation (OWI); (2) surface storage in a Spent Unreprocessed Fuel Facility (SURFF) at Rockwell Hanford Operations, and (3) geologic disposal in Sweden.

The OWI effort is investigating both permanent and retrievable storage of spent-fuel assemblies in salt formations. Preliminary results indicate that the maximum heat loading of a repository for 10-year-old spent fuel must be reduced from the 150 kW/acre recommended for high-level waste to 60 kW/acre. This reduction is necessary because of the greater amount of heat released by the larger amounts of plutonium in the spent fuel as compared to that in the high-level waste (Fig. 3). If the spent-fuel assemblies are to be stored retrievably, the maximum heat loading must be further reduced to 30 to 36 kW per acre to avoid the need for massive structural support in the repository. Other preliminary results of OWI studies are: (1) disassembly of the spent fuel does not appear to be necessary or desirable; (2) increasing the interim storage time from 1 year to 10 years increases the allowable assembly-emplacement density by about 20 percent; (3) standard fourteen-inch pipe, holding one PWR assembly or two BWR assemblies, with sand as a filler material, is a potentially attractive package for spent-fuel disposal, and (4) a 2,000-acre salt repository should be able to contain all of the spent-fuel assemblies produced through the year 2000.

The SURFF program has the objective of providing a surface-storage facility by 1985. The approach is to use only passive cooling and an early concept is to use shallow wells spaced 25 feet apart. The wells would be cased with a corrosion-resistant material and sealed after the spent-fuel assembly or assemblies had been emplaced. One PWR or three BWR assemblies would be stored in each hole.

The Swedish company, ASEA AB, has developed a process in which the spent-fuel elements are canned in steel containers, wound into a spring configuration, and placed in a shaped aluminum-oxide container about 50 cm in diameter and 3 m long. The full container is then sealed with an aluminum-oxide cover which becomes an integral part of the container itself. It is proposed that these units be emplaced in caverns excavated in granite and filled with a mixture of bentonite and quartz.

CONCLUSIONS

Based on rather preliminary analyses, spent-fuel assemblies are an acceptable form for waste disposal. However, further studies and experimental work are necessary to firmly establish feasibility and define the best method of preparing the assemblies for retrievable storage or ultimate disposal.

The following studies appear necessary, as a minimum, to bring our knowledge of spent fuel as a final disposal form to a level comparable with that of the solidified wastes from reprocessing:

1. A complete systems analysis is needed of spent-fuel disposition from reactor discharge to final isolation in a repository.

2. Since it appears desirable to encase the spent-fuel assembly in a metal canister to facilitate handling and increase safety at the repository, candidate materials for this container need to be enumerated and studied.

3. It is highly likely that some "filler" material will be used between the fuel elements and the can. The studies of promising materials should be started.

4. Leachability, stability, and waste-rock interaction studies, analogous to the ongoing studies on other waste forms, should be carried out on the fuels.

The major disadvantages of spent fuel as a disposal form are: the lower maximum heat loading (60 kW/acre versus 150 kW/acre for high-level waste from a reprocessing plant); the greater long-term potential hazard due to the larger quantities of plutonium and uranium introduced into a repository, and the possibility of criticality in case the repository is breached.

The major advantages are: lower cost; increased near-term safety resulting from eliminating reprocessing, and the treatment and handling of the wastes therefrom.

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