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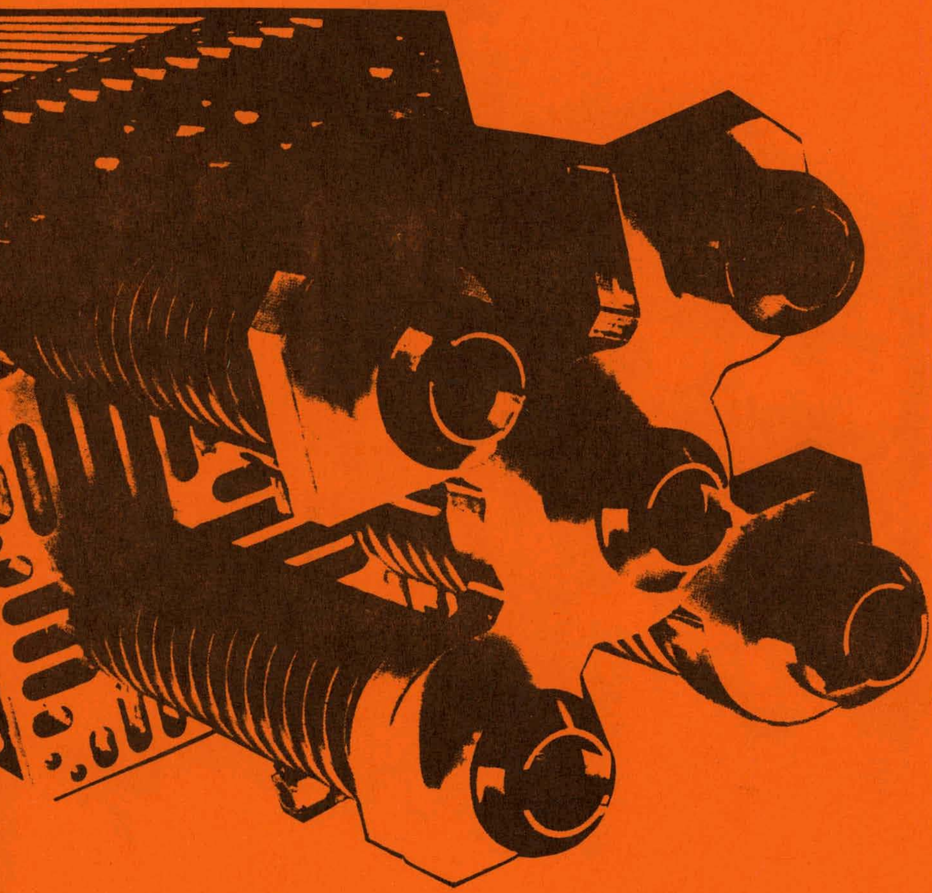
SPENT FUEL STORAGE FACT BOOK

DOE/NE-0005
(UC-85)

MASTER



DEPARTMENT OF ENERGY
UNITED STATES OF AMERICA

DISCLAIMER

FOREWORD

In October 1977, the Department of Energy (DOE) announced a spent nuclear fuel policy where the Government would, under certain conditions, take title to and store spent nuclear fuel from commercial power reactors. The policy is intended to provide spent fuel storage until final disposition is available. DOE has programs for providing safe, long term disposal of nuclear waste. The spent fuel storage program is one element of waste management and compliments the disposal program. The costs for spent fuel services are to be fully recovered by the Government from the utilities. This will allow the utilities to confidently consider the costs for disposition of spent fuel in their rate structure. The United States would also store limited amounts of foreign spent fuel to meet nonproliferation objectives. This booklet summarizes information on many aspects of spent fuel storage.

Cover: Fuel assembly from a pressurized water reactor
(Combustion Engineering Corp.)

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SPENT FUEL STORAGE FACTS BOOKLET

April 1980

DEPARTMENT OF ENERGY UNITED STATES OF AMERICA

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CONTENTS

LIGHT WATER REACTORS FOR NUCLEAR POWER IN THE U.S.

There are 68 commercial nuclear reactors in the U.S. today producing from 50 megawatts* (MW) (LaCrosse Reactor) to 1,130 MW (Trojan Reactor) of electrical power. The heat from nuclear fission converts water to steam which in turn drives turbines to produce electricity.

The latest generation of reactor (Table 1) typically:

- generates 1,000 MW of electricity
- contains about 100 metric tonnes** of uranium fuel in its nuclear core
- shuts down once each year to discharge (replace) part of the uranium fuel.

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* Megawatt -- a million watts of electrical power.

** Metric tonne -- 1,000 kg or about 2,200 lb compared to a standard ton of 2,000 lb.

TABLE 1
CHARACTERISTICS OF TYPICAL LIGHT WATER REACTORS

	Pressurized Water Reactor	Boiling Water Reactor
Thermal power (MWT)	3,300	3,300
Electric power (MWe)	1,000	1,000
Megawatt day per metric tonne of fuel (MWD/MT)[a]	31,000	23,000
Capacity factor (CF)[b]	0.70	0.70
No. of assemblies in reactor core	190	760
Assemblies discharged per year	59	176
MTU per reactor core	87	142
MTU discharge per year	27	37

[a] A measure of the fuel burnup or consumption.
[b] Fraction of time reactor is operating at rated power.

The commercial power reactors in this country use ordinary water as a coolant and, thus, are called light water reactors (LWR). There are two types of reactors whose names are derived from the condition of the water coolant within the reactor. They are:

- Pressurized water reactors (PWR)
- Boiling water reactors (BWR).

LWR FUEL ASSEMBLIES

DESCRIPTION

The power source in a light water power reactor is a number of bundles of uranium-filled rods called fuel assemblies. The fission process within the uranium produces heat from which electric power is derived. Each of the fuel assemblies:

- consists of many small metal tubes* (cladding) filled with uranium dioxide (UO_2) pellets
- has the fissionable mass 235 isotope of uranium (^{235}U) increased to 2 to 4% of the total uranium weight
- is designed for either a PWR or BWR reactor (Figure 1)
- is 5 to 8 inches square and 13 to 15 feet long (Table 2).

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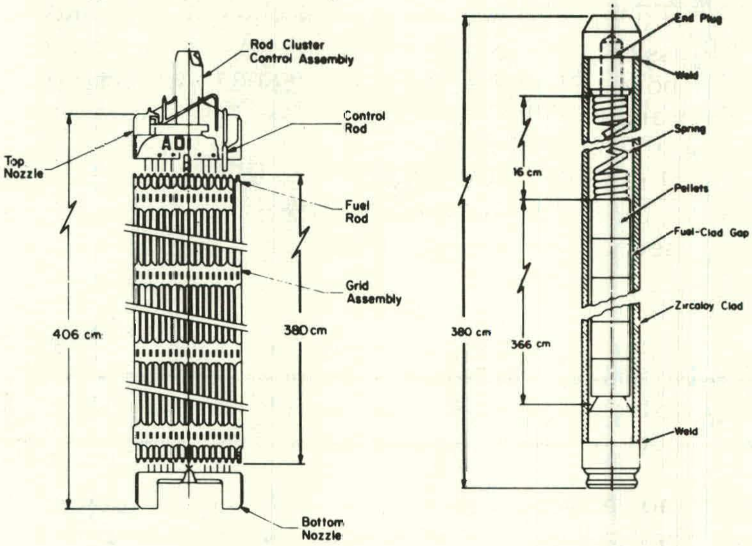
* Each tube is called a fuel rod.



A. Typical PWR Fuel Assembly **B. Typical Fuel Rod**

C. Typical BWR Fuel Assembly

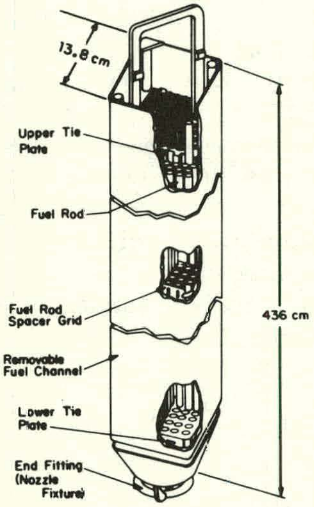


FIGURE 1. Typical Light Water Reactor (LWR) Fuel Assemblies

TABLE 2

CHARACTERISTICS OF TYPICAL LWR FUEL ASSEMBLIES[1]

	PWR	BWR
Assembly length, ft	13.5	14.3
Assembly width, in.	8.4	5.5
No. of fuel rods	264 (17x17 array)[a]	64 (8x8 array)
Fuel rod diameter, in.	0.37	0.49
Weight of uranium Metric ton (lb)	 0.52 (1,146)	 0.21 (462)
Total assembly weight, Metric ton (lb)	 0.66 (1,443)	 0.28 (605)

[a] Array -- the regular arrangement.

IRRADIATION PROPERTIES

When certain conditions are reached, the reactor is shut down and new fuel assemblies are put in place of partially burned out assemblies. The no-longer-usable fuel assemblies are called spent fuel. Only one-fourth to one-third of the assemblies are discharged each year. Reasons for discharge may be the fuel has accumulated maximum licensed burnup [2], or the fuel does not economically sustain the reactor. Some of the fuel may be discharged prematurely because the utilities must consider peak electrical demands, scheduled inspections, and maintenance requirements before shutting down the reactor again. Discharged assemblies:

- have a total UO_2 weight of about 30 metric tonnes
- produce ionizing radiation and heat
- contain a total weight of about 290 kg of ^{235}U that was not burned and 220 kg of fissionable plutonium (Pu) that was produced in the reactor (PWR assemblies). [3]

The irradiation process produces radioactive isotopes within the uranium and the metal parts of the assemblies. Isotopes also cling to the surface in a layer called crud. This radioactivity requires care in handling fuel to:

- shield people from radiation which remains for hundreds of years (Figure 2)
- remove heat which continues to be produced by the radioactive decay after irradiation (Figure 3)
- remove and contain loose particles on the cladding surface or from small penetrations of the fuel cladding.

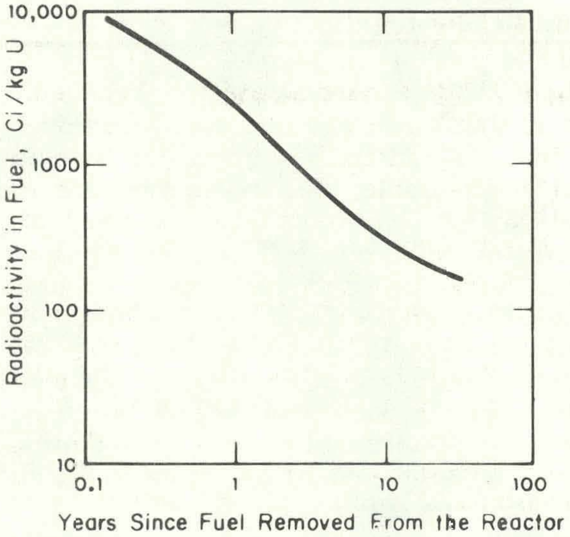


FIGURE 2. Radioactivity Due to Fission Products in Spent Fuel[4]

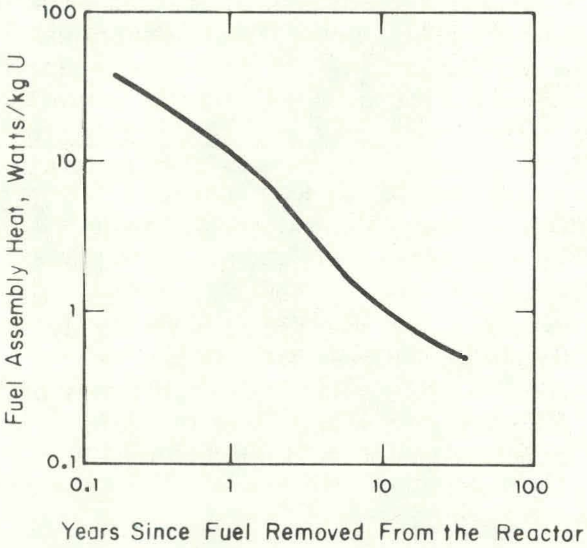


FIGURE 3. Heat Produced by LWR Fuel Assemblies[4]

The irradiation process can cause failures in the fuel cladding which allow a small portion of the radioactivity to escape. The defective assemblies:

- have decreased in number in recent years [4] due to improved fabrication and design (Figure 4)
- do not constrain storage pool design other than requiring water cleanup.

The large number of fuel rods in an assembly account for the large percent of assemblies with at least one failed rod. Actually, less than 0.3% of the fuel rods have leaked radioactivity in the reactor [5] and investigation indicates [6] that these do not continue to deteriorate or release fission products while stored underwater in a storage pool.

FUEL MANUFACTURERS

Fuel assemblies are made by five commercial companies in the U.S. (Table 3). All companies except Exxon also manufacture power reactors.

REACTOR OUANTITIES

The number of nuclear reactors that will be operating in the U.S. has been estimated from announced plans. Commitments and plans show about 180 GWe* of nuclear power will be available by the year 1993 (Figure 5). With this estimate, the number of reactors beginning operation each year will peak at about 23 in 1986 (Figure 6). It is expected that actual growth in the 1990's will be higher (Figure 5, Low Growth Projection) because utility plans for this period are not yet completed.

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* 1 GWe -- 1,000 MWe which is about the size of the latest generation of power reactors.

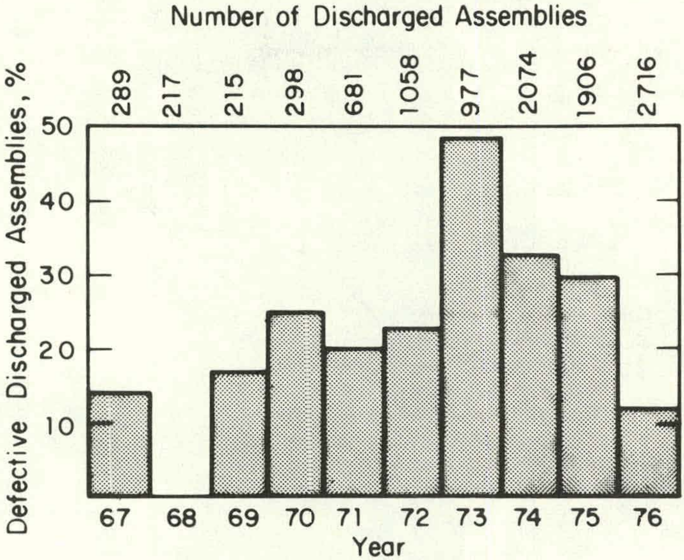

FIGURE 4. Trend of Defective LWR Fuel Assemblies[5]

TABLE 3
MANUFACTURERS OF LWR
FUEL ASSEMBLIES IN THE U.S.

Name	PWR	BWR
Exxon	x	x
Westinghouse	x	–
General Electric	–	x
Babcock & Wilcox	x	–
Combustion Engineering	x	–

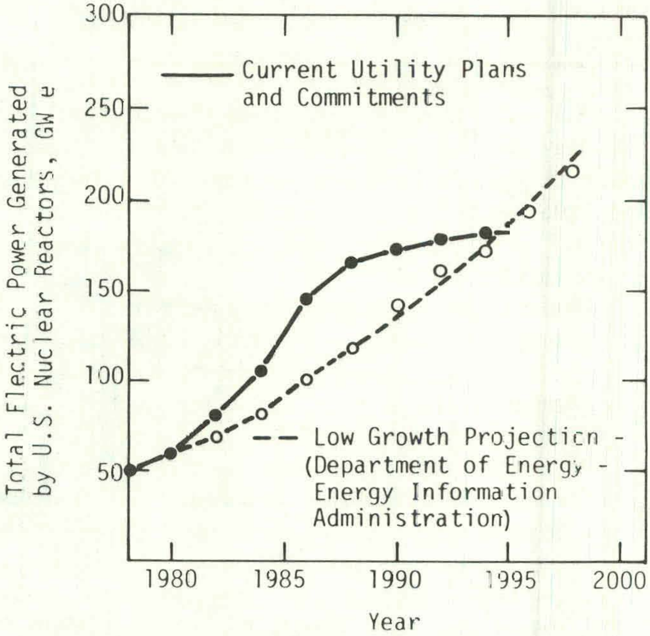

FIGURE 5. Planned and Projected Cumulative Nuclear Power Generation in the U.S.

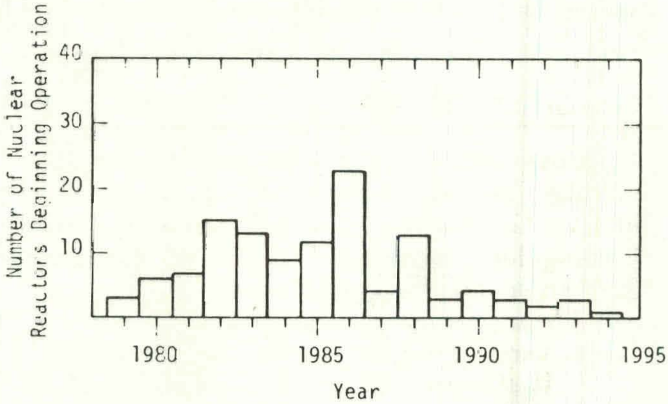

FIGURE 6. Planned Number of Nuclear Reactors Starting Up Each Year in the U.S.

UNDERWATER STORAGE OF IRRADIATED FUEL

All of the spent fuel discharged from commercial LWR power reactors is stored in water pools. Underwater storage of spent fuel is also planned for all future reactors and for existing or currently planned away-from-reactor (AFR) facilities.

Underwater storage of spent fuel:

- has been used successfully for 30 years [6]
- has not harmed Zr-clad, U.S. fuel assemblies that have been stored continuously for up to 20 years [6]
- provides an efficient method of removing residual heat from the fuel
- allows easy movement and inspection of fuel while shielding people from radiation
- retains most of the radioactivity released from the fuel so that it can be collected and safely packaged for disposal.

The pools are designed to stay watertight for all credible accidents (including design basis tornadoes and earthquakes). Systems are provided to remove heat and impurities from the water. A typical underwater storage pool is shown in Figure 7.

STORAGE AT THE REACTOR

Fuel assemblies discharged from reactors are initially stored underwater in reactor storage pools. Generally reactor storage pools are rectangular, made of reinforced concrete, and lined with stainless steel.

These reactor storage pools:

- vary from as small as 11 ft by 11 ft (LaCrosse Reactor) to as large as 40 ft by 60 ft (Donald C. Cook Reactor)
- are 26 ft (Humboldt Bay Reactor) to 45 ft (Donald C. Cook Reactor) deep with at least 12 ft of water above the fuel

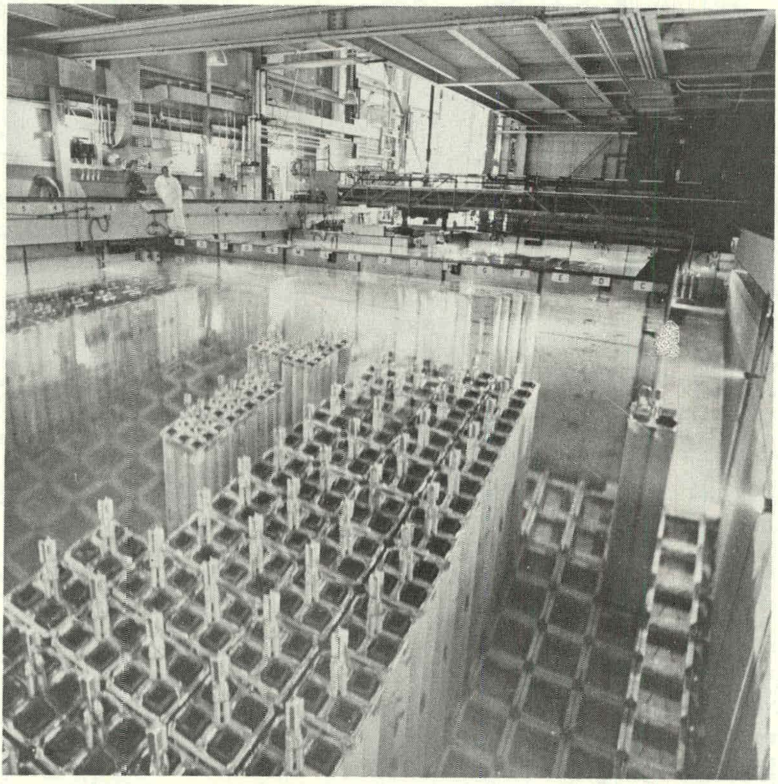

FIGURE 7. Fuel Storage Pool - G. E. Morris - Water Depth, 28.5 ft

- are maintained below 50°C with less than 5×10^{-4} curies* of radioactivity in each cubic meter (m^3) of water.

Originally, the pools at the reactors were expected to store only a few years of discharges before the spent fuel would be removed to be chemically reprocessed. Additionally, there was enough empty space reserved in the pool so that all of the assemblies in the core could be fully discharged at one time if required.** The space is not mandatory but is highly desired for operational flexibility and potentially lower power costs. In the past, reactors have had to make a full core discharge 50 times. [7] Recent studies show consumer rates may be higher from a utility without FCR space. That utility must buy replacement power if an outage occurs and pay for additional transportation charges to move the necessary spent fuel to another pool.

INCREASED STORAGE CAPACITY

As reactors discharge spent fuel assemblies, many storage pools are gradually filling. Additional storage capability for these assemblies is being obtained by:

- replacing their old fuel storage racks with new, more efficient racks that allow the fuel to be stored closer together
- shipping fuel to an existing AFR storage pool at inactive reprocessing plants
- shipping fuel to newer reactors that have not yet filled their pools (this practice is called "fuel transshipment")
- limited use of FCR space.

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* Curie - A basic unit to describe intensity of radioactivity.

** This space is defined as full-core reserve (FCR).

The total amount of fuel stored in reactor pools at the end of 1979 was 5,900 MTU (23,000 assemblies). An additional 160 tons was stored at the NFS site, West Valley, NY and 350 tons at the GE site, Morris, IL. As the number of nuclear reactors increase, the amount of fuel in storage will increase to 19,000 MTU in 1985 and to 39,000 MTU in 1990 (Figure 8).

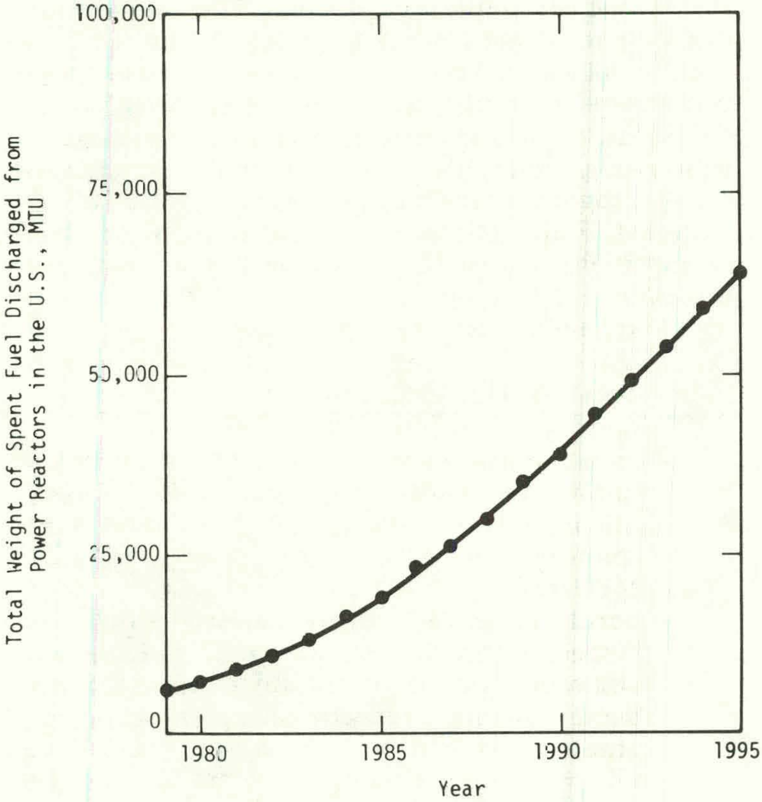

FIGURE 8. Accumulation of Amount of Spent Fuel Discharged from U.S. LWR Power Reactors*

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*Based on firm utility plans[8]

CURRENT METHODS OF INCREASING STORAGE CAPACITY AT THE REACTOR

The original racks used in water pools to store spent fuel were designed with open frames of steel or aluminum. Racks kept the BWR assemblies 10 to 13 inches and PWR assemblies 18 to 22 inches between centers. This separation distance resulted in a fuel storage density of less than 0.25 MTU/ft^2. Distance prevented criticality* even if unirradiated fuel in which no ^{235}U had been burned were put into the rack. It was recognized that the fuel could be stored closer together if storage racks contained a material that absorbed neutrons (a "neutron poison"). Three types of racks were developed and licensed:

- stainless steel racks which store the assemblies 8 (BWR) to 13 (PWR) inches between centers to achieve a fuel storage density of up to 0.39 MTU/ft^2
- racks, made from stainless steel, to which boron (a neutron poison) was added, allowing 6.5 (BWR) to 10.5 (PWR) inch fuel spacing with storage densities up to 0.58 MTU/ft^2
- boral racks in which boron carbide is dispersed in aluminum and sandwiched between aluminum plates, allowing the same spacing as with borated stainless steel.

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* Criticality - The state of balance between production and loss of neutrons.

FUTURE METHODS OF INCREASING STORAGE AT THE REACTOR AND AWAY FROM THE REACTOR

Methods currently used for safely storing fuel assemblies close together (high storage density) depend on adding neutron poisons to storage racks. Methods for closer spacing of fuel (higher storage density) are being investigated. [9] Closer spacing in similar racks is allowed if water around the fuel is decreased (storage densities up to 1.1 MTU/ft^2 -- Figure 9).

The higher densities can be obtained by:

- Placing spent fuel assemblies inside cans and filling all spaces between rods with small metal beads (shot filling). This allows assemblies to be stored with a density of 0.75 MTU/ft^2.
- Uniformly compacting assemblies (crushing the fuel spacers) until rods are nearly touching. This allows a storage density of about 0.95 MTU/ft^2.
- Removing individual fuel rods from an assembly and storing more than one assembly in a can with rods touching. This allows a storage density of about 1.1 MTU/ft^2 in a can about the same size as the original fuel assembly.

Of these, individual rod storage is being studied further because it appears to be the most feasible. Rod storage could double or triple the amount of fuel stored at a reactor, greatly decrease the need for AFR storage, and decrease the cost of fuel disposal by reducing the fuel volume transported. The limiting factor for advanced storage methods is the load carrying capacity of existing pool walls.

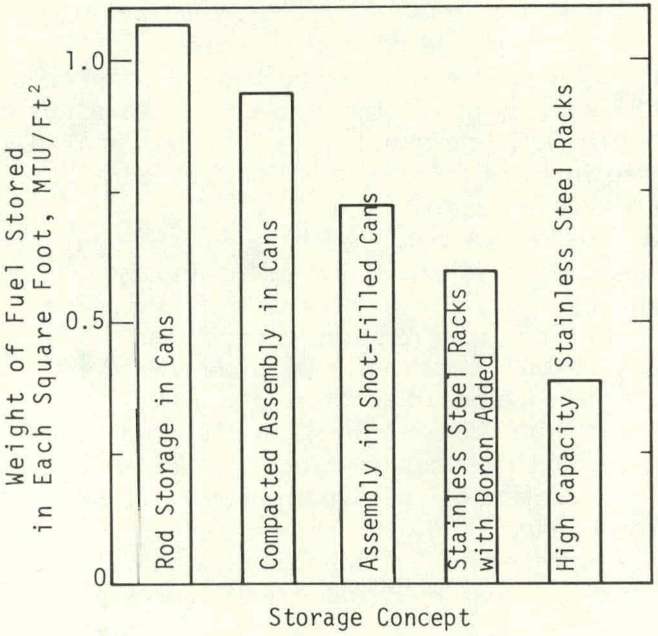

FIGURE 9. Comparison of Fuel Storage Density for Alternative Methods of Storing Spent Fuel in Water Basin[9]

STORAGE AWAY FROM REACTORS

Some U.S. reactors are storing fuel in their FCR space. If the utilities took no action, the number of reactors in this position would increase each year. Even after the planned expansion by the utilities, the number of reactors with fuel stored in the FCR space will increase rapidly in the 1980's (Figure 10).

Thus, even with greatly expanded spent fuel storage at reactors, it will be necessary to store some fuel away from reactors. The quantity of AFR storage space required depends on:

- extent of utility rerack efforts
- the number of reactors operating
- the amount of transshipment* that occurs.
- the time each reactor can run on a given quantity of fuel (fuel exposure and reactor capacity factor)
- whether FCR is maintained at the reactors

Utilities without FCR space will probably charge consumers higher rates to replace power lost during reactor outage and to pay for spent fuel transport to another pool.

Existing Away-from-Reactor Storage

Although most U.S. spent fuel is stored at reactors, there are three AFR locations that may be suitable for storing LWR fuel. These are:

- Allied-General Nuclear Service (AGNS) at Barnwell, South Carolina (designed for 400 MTU)
- General Electric (GE) at Morris, Illinois, (current capacity of 700 MTU)
- Nuclear Fuel Services (NFS) at West Valley, New York (current capacity of 250 MTU).

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* Transshipment - Moving spent fuel from a full pool to another reactor basin with available space.

All three pools were designed to provide inventory storage for spent fuel chemical reprocessing plants. The AGNS pool has never been used or licensed. The NFS pool has unused space but is not receiving more fuel. The GE pool is actively receiving fuel. Each of these facilities can be expanded as shown in Table 4. Their current status is shown in Figure 11.

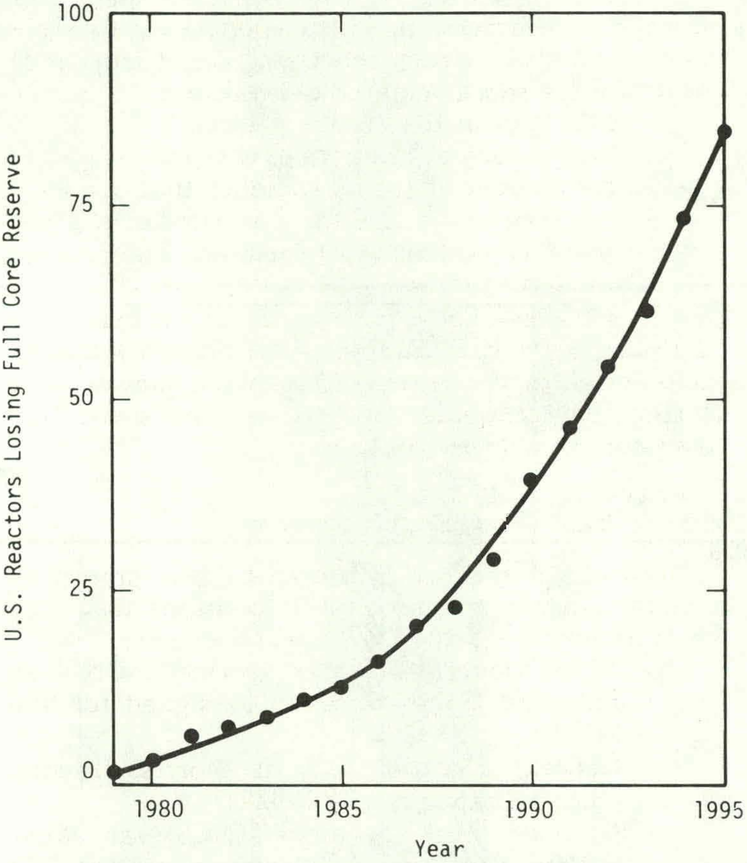


FIGURE 10. Cumulative Number of Reactors Losing Full Core Reserve[8]

TABLE 4

SOME STORAGE ALTERNATIVES FOR AFR FACILITIES

Facility	Cumulative Storage Space, MTU	Remarks
AGNS[10]	400	Needs license
(Barnwell)	1,750	New racks (proposed)
	5,000	New basins (proposed)
GE[11]	350	Remaining empty space
(Morris)	1,450	New basin (proposed)
	4,450	New facility (proposed)
NFS	85	Remaining empty space
(West Valley)		
New	5,000	Proposed

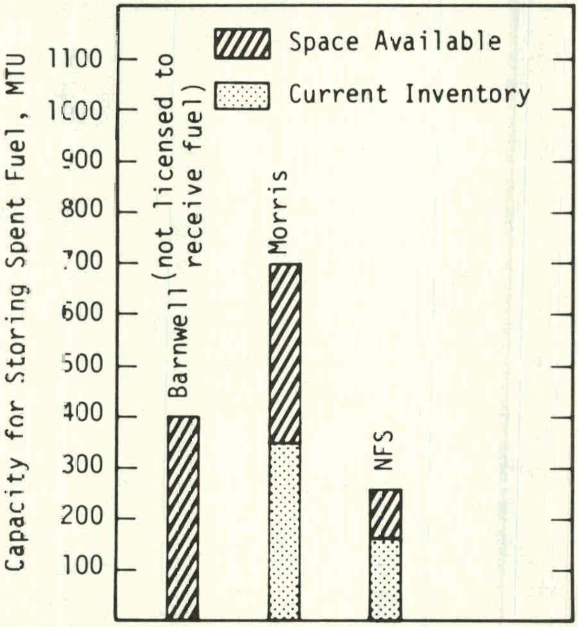


FIGURE 11. Status of Existing AFR Facilities

An AFR facility might also be established at sites other than those designed originally for commercial reprocessing. Several designs have been made of facilities designed specifically for interim storage of spent fuel and independent of reactor complexes. [12] These facilities (Figures 12 and 13) provide many functions.

A standalone facility should:

- receive, handle, decontaminate, and reship irradiated fuel casks
- remove the fuel from the casks, put it in storage baskets, and transfer the baskets to a storage pool (a typical pool is shown in Figure 7)
- remove fuel from the storage pools and reload fuel into shipping casks (when shipment to a geologic repository begins)
- cool and control the quality of the water in the pools
- treat and immobilize waste material
- provide a reservoir of water for emergency cooling
- provide support services such as a power plant for heat, sanitary and other nonradioactive waste treatment, electrical services, and administrative offices.

Basin facilities that depend on a nearby reactor complex for support are possible [13] and are being studied. They are called at-reactor-basins (ARB).

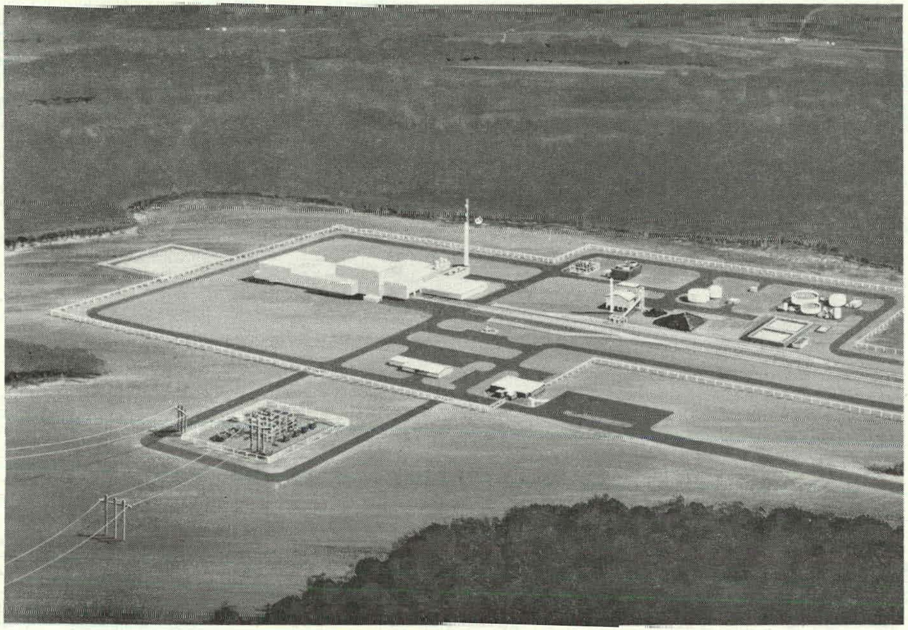


FIGURE 12. Artist's Conception of a New 5000-MTU Away-From-Reactor Storage Facility

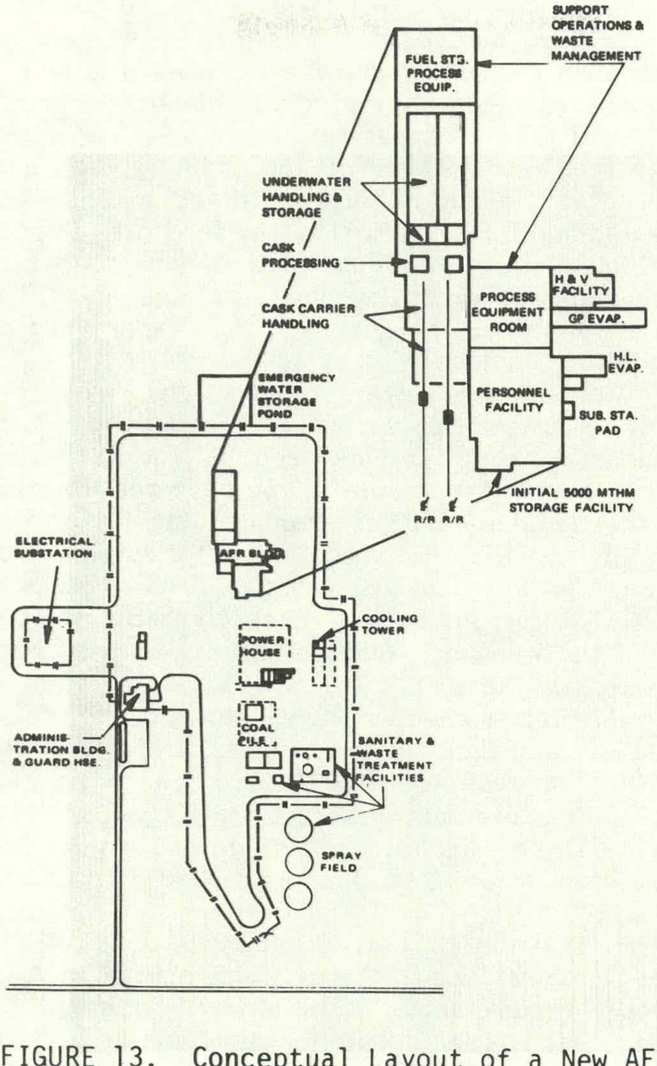


FIGURE 13. Conceptual Layout of a New AFR Storage Facility[15]

DOE encourages domestic utilities to provide their own spent fuel storage requirements and is conducting research and development programs for even greater capacities in existing facilities. But, the best efforts of the industry may not guarantee adequate storage will be available in the mid and late 1980's. [14] Any forecast of spent fuel quantities or timing of additional capacity will change with utility plans and the ability of these plans to be licensed and approved by regulatory bodies.

Most of the current reactors that increased their storage space will eventually require additional capacity. This need will occur before either permanent disposal or possible reprocessing of fuel is available. For example, Carolina Power and Light's (CPL) Robinson-2 reactor solved early storage problems by using higher density racks in 1976. Their spent fuel is currently being shipped to CPL's Brunswick reactor basin. However, both reactors will lose FCR around 1982.

Interim storage of spent fuel is one element of waste management and a necessary part of the present nuclear fuel cycle. Storage in reactor pools, in pools near reactors (ARB), or at AFR pools will be temporary. Ultimate disposal will be instituted by the Government, probably about the mid-1990's.

The availability of a geologic repository or fuel reprocessing has the greatest effect on AFR storage requirements. If either were available in 1988, AFR storage requirements to maintain FCR would be 2,000 MTU (Figure 14). As geologic storage is delayed, the AFR requirement increases to 7,000 MTU for a year 1993 availability. The number of new, large AFR facilities required is shown in Table 5; other combinations (Table 4) are also possible.

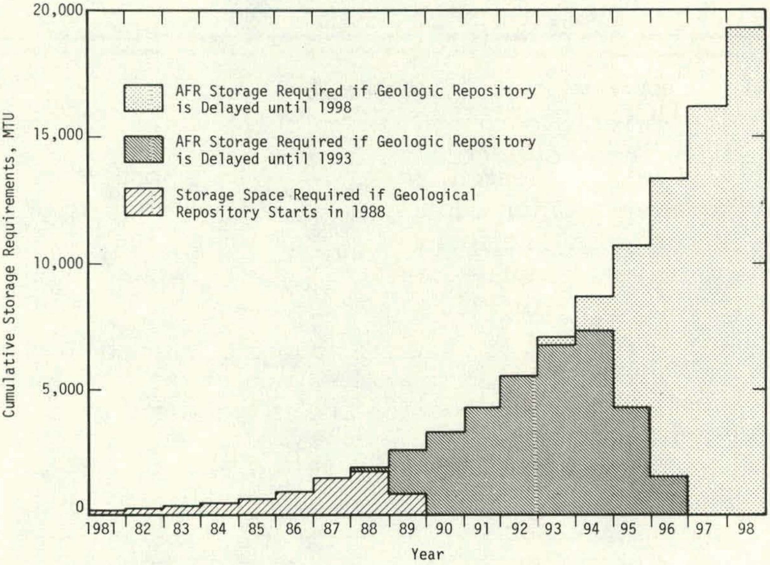


FIGURE 14. Effect of Geologic Repository Startup Date on AFR Storage Requirements

TABLE 5
NUMBER OF NEW AFR FACILITIES
REQUIRED FOR STORAGE OF SPENT FUEL

Year Geologic Storage Starts[16]	Number of 5,000 MTU AFR Storage Facilities Required
1988	1
1993	2

Several concepts other than water basins have been considered for interim storage of spent fuel. These dry storage concepts [17] include:

- Concrete Surface Silo - sealing fuel into steel cans inside concrete cylinders (tested in Canada for heavy water reactor fuel and in the U.S. for LWR fuel)
- Air-Cooled Vault - hanging canned fuel inside concrete vaults (used in the U.S. for gas-cooled reactor fuel from the Fort St. Vrain Reactor)
- Dry Caisson (Figure 15) - inserting canned fuel inside a steel-lined hole in the earth (tested for high temperature gas reactor, heavy water reactor, and LWR fuel)
- Transport Casks - placing fuel into spent fuel shipping casks (being considered in Germany and the U.S.).

Although none of these concepts have been used for LWR fuel, they are being considered because they could be less expensive, provide flexibility in site selection, require less precautions against loss of coolant and criticality, or produce less waste. Dry storage for LWR fuel can have the disadvantages [3] of:

- requiring wet storage for 3 to 5 years until air cooling is adequate
- requiring canning
- higher fuel temperature
- somewhat larger land requirements
- lack of experience and previous licensing.

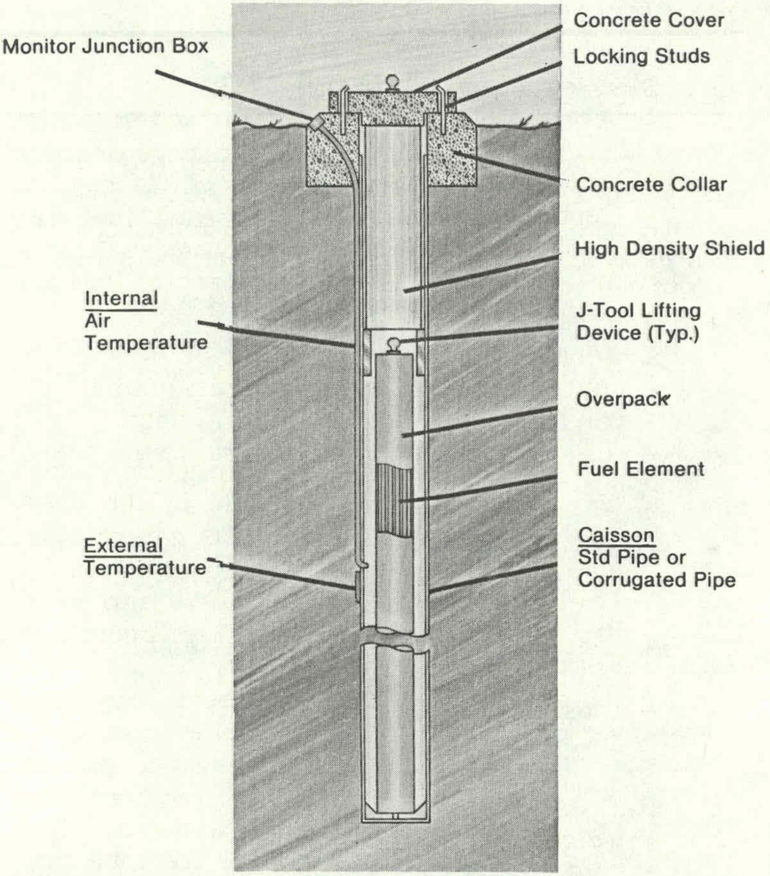


FIGURE 15. Spent Fuel Storage Caisson

DESCRIPTION OF SHIPPING CASKS

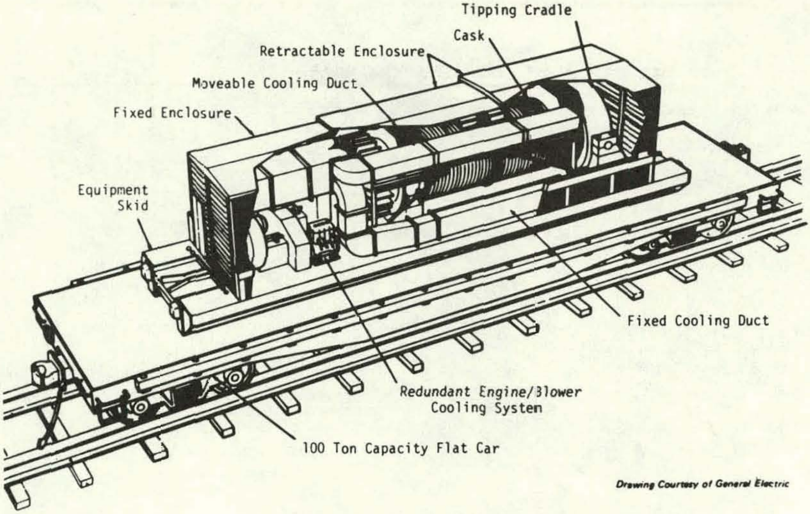
Irradiated fuel is moved between reactors or between a reactor and an AFR in heavy shielded containers called casks (Figures 16 through 18). Three types of casks [18] are used for spent fuel:

- Truck Casks (legal weight)
  - weigh less than 25 tons
  - contain only one or two fuel assemblies
  - can be unloaded in less than 12 hours
  - result in maximum exposure to personnel during unloading (about 194 mrem/MTU)

- Overweight Truck Casks
  - weigh up to 35 tons and are restricted in movement
  - contain three to seven fuel assemblies
  - can be unloaded in less than 16 hours
  - cause about 74 mrem/MTU of exposure during unloading

- Rail Casks
  - weigh up to 100 tons
  - contain between seven and 32 fuel assemblies
  - can be unloaded in 28 to 36 hours
  - minimize personnel exposure (about 54 mrem/MTU)

The names, capacities, and quantities of existing U.S. casks are summarized in Table 6 and shown in detail in Appendix B. These casks are designed to ship fuel that has been out of the reactor as few as 120 days.



Drawing Courtesy of General Electric

FIGURE 16. Spent Fuel Cask and Carrier (GE-IF)

TABLE 6

CURRENT U.S. SHIPPING CASKS FOR LWR SPENT FUEL

Transport Mode	Cask Name	Cask Weight, tons	Cask Capacity PWR Assemblies	Cask Capacity BWR Assemblies
Legal weight truck	NFS-4	22.4	1	2
	NAC-1	22.4	1	2
	NLI-1/2	22.0	1	2
Overweight truck	TN 8	34.3	3	
	TN 9	34.4		7
Rail	GE IF-300	63.3	7	18
	NLI 10/24	90.0	10	24
	TN 12	97.0	12	32

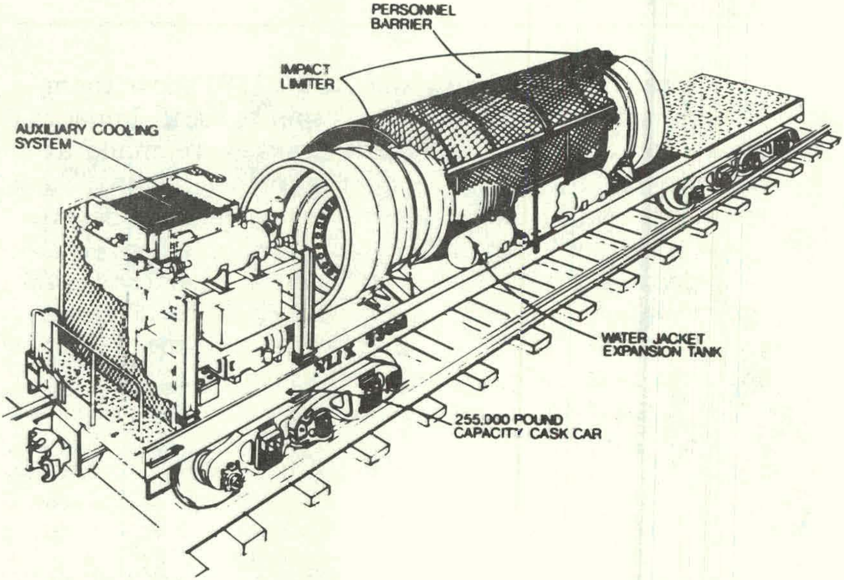


FIGURE 17. Details of NL-10/24 Cask

FIGURE 18. Truck Cask Loaded on a Special Trailer

CASK TESTING

Crash tests on full size casks [19] show them to be safe for transporting spent fuel. Impact tests for both rail and truck casks were made at speeds up to 135 km/hr (82 mi/hr) against a concrete wall. These severe tests were made to gain a better perspective on transportation risk, accident severity, and to reduce concerns of government, industry, and the public. Figures 19-22 show stages of one crash and the minor damage to an unirradiated fuel assembly.

CASK REQUIREMENTS

To use AFR space for spent fuel storage, the fuel must be transported from the reactor to the AFR facility. Figure 23 shows the calculated number of rail and truck casks required for shipments to AFR's. Both types of transportation are required because some reactors cannot handle rail casks. These cask requirements assume the AFR demand of Figure 14 and no shipments to a geologic repository (this is equivalent to assuming geologic repository startup after the year 1993).

Other assumptions were:

- domestic spent fuel only
- two AFR sites are available: Morris, IL prior to 1984; Barnwell, SC starting in 1984
- all reactors with rail access use a cask that accepts 10 PWR or 24 BWR assemblies
- others use legal weight trucks.

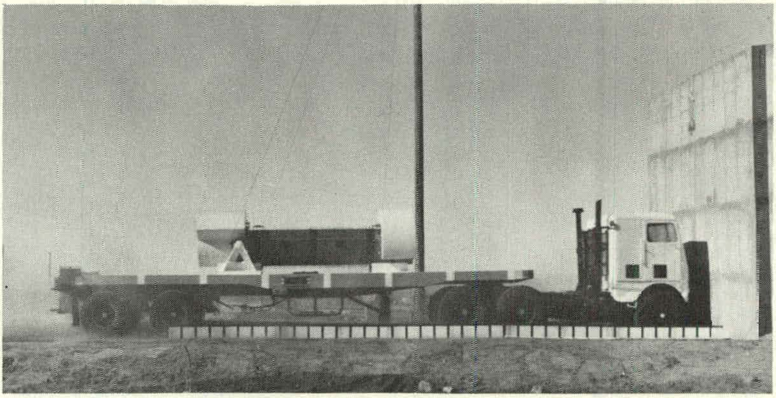


FIGURE 19. Truck Cask Just Before Hitting the 626 MT Concrete Wall

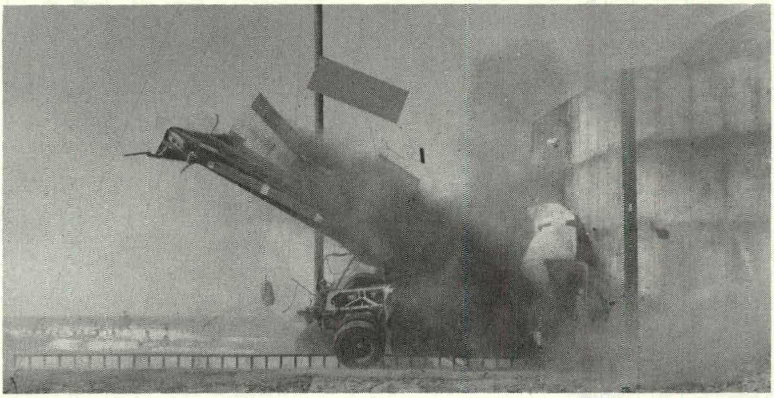


FIGURE 20. Cask and Truck Hitting the Wall at 135 Km/hr

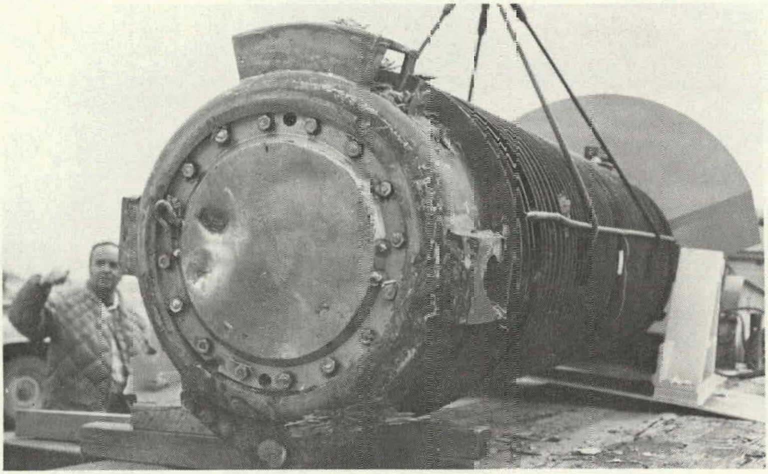


FIGURE 21. Minor Damage to Cask After Impact

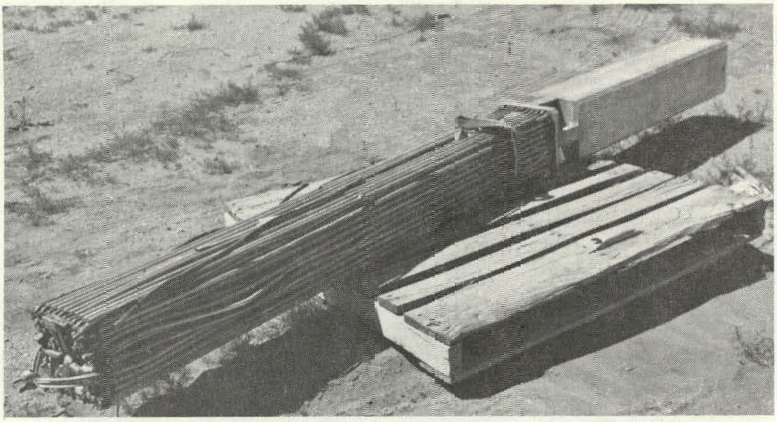


FIGURE 22. Unirradiated N. S. Savannah Fuel Assembly in Cask (Damaged but Unbroken)

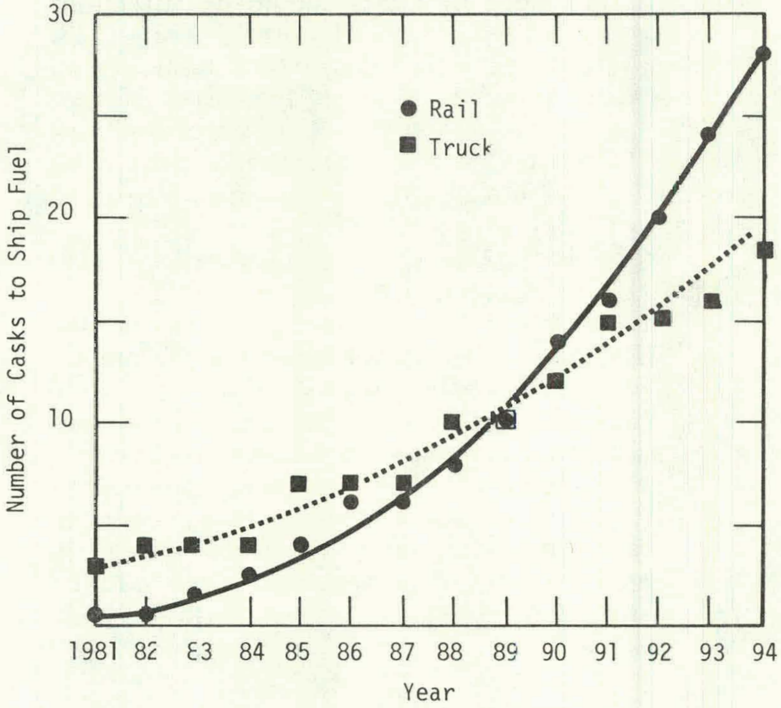


FIGURE 23. Spent Fuel Shipping Cask Requirements[20] to AFR

CASK AVAILABILITY

Currently, there are 11 truck casks and six rail casks in the U.S. If all were used for a single trip, their combined capacity would be 28 MTU. Up to eight additional truck casks have been ordered. This fleet of casks should be sufficient for the projected demand until 1986-1988. Because 1 to 4 years are required to duplicate an existing cask and 6 to 8 years for casks of new designs, a large lead time is needed on cask orders. Once production has started, it should be possible for industry to meet the projected demand.

Recently announced cask programs [18] include:

- Transnuclear - intends to fabricate six TN-8/9 and six TN-12 casks in Europe by 1981-1982.
- Nuclear Assurance Corporation - has applied for a license for a new rail cask.
- Some companies are studying designs to license a cask specifically for 5 year or older fuel. A truck cask of this design is expected to carry twice the fuel load of existing truck casks due to the lower heat and radiation levels in older fuel.

SPENT FUEL STORAGE OUTSIDE THE U.S.

The fuel assemblies irradiated in LWR reactors outside the U.S. look very similar (and are sometimes identical) to those in the U.S.

The design of spent fuel storage pools outside the U.S. differ from those in the U.S. Some countries require lower water temperatures, greater redundancy of the pool cooling system, and more protection against the possibility that an airplane or other missile might crash into the pool. There are five existing AFR's outside the U.S.; most are part of reprocessing plants.

OTHER REACTOR FUELS

The three major reactor types other than light water reactors are:

- Heavy Water* Reactor (HWR) with fuel consisting of short bundles of Zr-clad natural uranium (Figure 24)
- Gas-Cooled Reactor (GCR) with fuel consisting of enriched uranium and thorium carbide particles in a graphite matrix (Figure 25)
- Fast Breeder Reactor (FBR) with fuel consisting of hexagonal arrays of rods made up of stainless steel clad mixed uranium-plutonium oxide pellets (Figure 26).

Satisfactory methods of storing, transporting, and reprocessing each of these fuel types have been demonstrated on a relatively large scale. AFR's for GCR are in operation in the United Kingdom, France, and the U.S., and planned for the Federal Republic of Germany.

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* Water in which hydrogen atoms have been replaced with deuterium, a naturally occurring isotope.

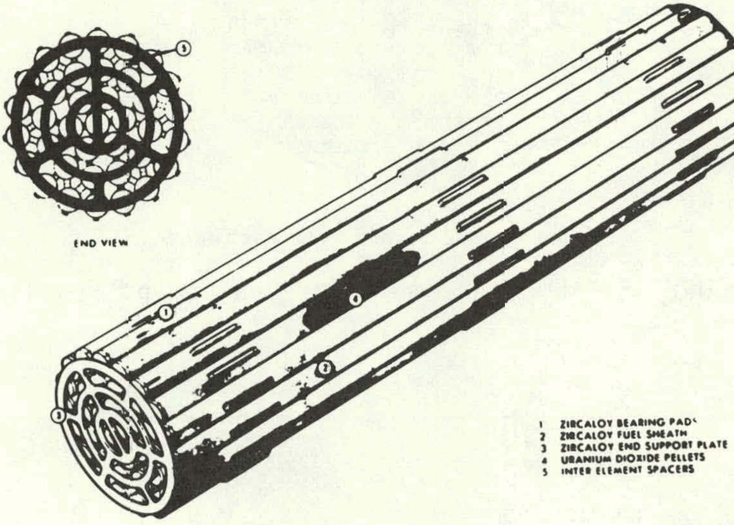

FIGURE 24. Thirty-Seven Rod HWR Fuel Bundle (CANDU)

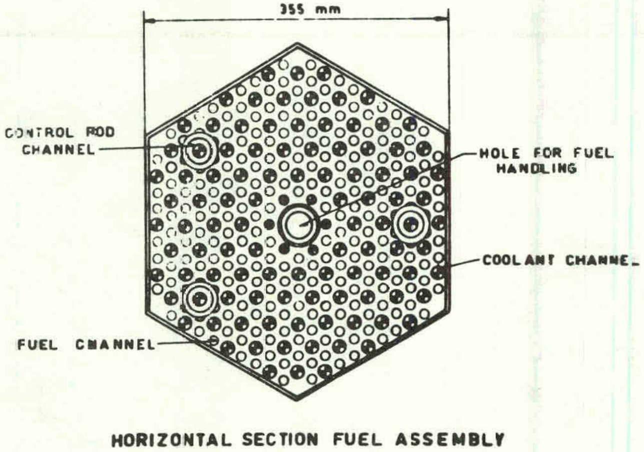

FIGURE 25. Fuel Assembly for Gas-Cooled Reactors

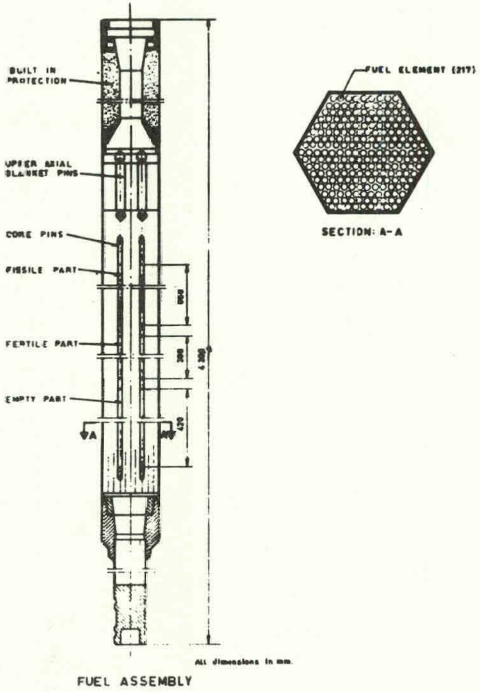

FIGURE 26 Fast Breeder Reactor Fuel Assembly

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APPENDIX A

STORAGE PARAMETERS FOR CURRENTLY OPERATING U.S. LIGHT WATER REACTORS (1979)

	Startup Date	Reactor Type	Electrical Power, MWe	Present Storage Capacity, MTU[b]	Annual Fuel Discharge, MTU	Weight of Fuel in Reactor	Year[d] When Reactors First Lose FCR	Year[e] When Reactors First Lose FCR
Region 1[a]								
Consumers Power Co.								
Big Rock Point	1962	BWR	72	25	5.5	25.5	1998	1993
Palisades	1971	PWR	740	324	26.8	82.8	1987	1983
Duquesne Light Co.								
Beaver Valley-1	1976	PWR	852	384	22.1	72.4	1993	1993
Indiana and Michigan Elec. Co.								
Donald C. Cook-1	1975	PWR	1,054	230	26.8	87.8	1995	1993
Donald C. Cook-2	1978	PWR	1,094	950	27.8	87.8	1995	1993
Toledo Edison Co.								
Davis-Besse-1	1977	PWR	906	348	22.7	83.7	1991	1991
Region 2[a]								
Commonwealth Edison								
Dresden-1	1960	BWR	200	76	7.6	48.7	1979	1979
Dresden-2	1972	BWR	794	711[f]	28.0	136.1	1996	1996
Dresden-3	1971	BWR	794	711[f]	28.0	136.1	1996	1996
Quad Cities-1	1973	BWR	809	274[c]	27.8	136.1	1995	1983
Quad Cities-2	1973	BWR	809		27.8	136.1	1995	1983
Zion-1	1973	PWR	1,050	961[c,f]	26.8	87.8	1992	1992
Zion-2	1974	PWR	1,050		26.8	87.8	1992	1992

[a] The utilities are categorized as being located in one of the nine regions defined by the National Electric Reliability Council, NERC.

[b] Capacity estimated using computer program DISFUL code.[21]

[c] Spent Fuel Pool or Pools shared by reactors.

[d] Assumes maximum utility plans for increasing storage capacity and no transshipment between reactor basins within each utility.

[e] Assumes current utility plans for increasing storage and no transshipment.

[f] Not yet licensed.

APPENDIX A (Contd)

	Startup Date	Reactor Type	Electrical Power, MWe	Present Storage Capacity, MTU[b]	Annual Fuel Discharge, MTU	Weight of Fuel in Reactor	Year[d] When Reactors First Lose FCR	Year[e] When Reactors First Lose FCR
Wisconsin Elec. Power Co. & Wisconsin Michigan Power Co.								
Point Beach-1	1970	PWR	497	281[c]	12.4	48.4	1998	1998
Point Beach-2	1972	PWR	497		12.4	48.4	1998	1998
Wisconsin Public Service Corp.								
Kewaunee	1974	PWR	540	142	13.8	47.7	2000	2000
Region 3[a]								
Baltimore Gas & Elec. Co.								
Calvert Cliffs-1	1975	PWR	860	202[c]	22.2	82.9	1989	1986
Calvert Cliffs-2	1977	PWR	860		22.2	82.9	1989	1986
Jersey Central P & L Co.								
Oyster Creek	1969	BWR	650	223	21.5	106.4	1984	1984
Metropolitan Edison								
Three-Mile Island-1	1974	PWR	837	230	20.9	82.1	1998	1998
Three-Mile Island-2	1978	PWR	926	210	22.7	82.1	2000(?)	1989
Philadelphia Electric Co.								
Peach Bottom-2	1974	BWR	1,053	205	38.3	141.3	1986	1985
Peach Bottom-3	1974	BWR	1,053	521	38.3	141.3	1986	1985

[a] The utilities are categorized as being located in one of the nine regions defined by the National Electric Reliability Council, NERC.

[b] Capacity estimated using computer program DISFUL code.[21]

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[d] Assumes maximum utility plans for increasing storage capacity and no transshipment between reactor basins within each utility.

[e] Assumes current utility plans for increasing storage and no transshipment.

APPENDIX A (Contd)

	Startup Date	Reactor Type	Electrical Power, MWe	Present Storage Capacity MTU[b]	Annual Fuel Discharge, MTU	Weight of Fuel in Reactor	Year[d] When Reactors First Lose FCR	Year[e] When Reactors First Lose FCR
Public Service Elec. & Gas Co.								
Salem-1	1977	PWR	1,090	122	27.6	88.8	1995	1995
Salem-2[f]	1979	PWR	1,115	122	28.1	88.8	1996	1996
Region 4[a]								
Dairyland Power Corporative								
LaCrosse	1969	BWR	48	58[f]	2.5	7.9	1990	1990
Iowa Electric Light & Power Co.								
Duane Arnold	1975	BWR	529	108	17.8	68.1	1994	1994
Nebraska Public Power District								
Cooper	1974	BWR	778	431	26.4	101.9	1990	1990
Northern States Power Co.								
Monticello	1971	BWR	545	414	18.5	89.5	1990	1990
Prairie Island-1	1973	PWR	520	272[c]	13.4	47.8	1993	1993
Prairie Island-2	1974	PWR	520		13.4	47.8	1993	1993
Omaha Public Power District								
Fort Calhoun-1	1973	PWR	457	176	13.1	48.4	1989	1985
Region 5[a]								
Boston Edison Co.								
Pilgrim-1	1972	BWR	670	229	22.1	112.5	1990	1990

[a] The utilities are categorized as being located in one of the nine regions defined by the National Electric Reliability Council, NERC.

[b] Capacity estimated using computer program DISFUL code.[21]

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APPENDIX A (Contd)

	Startup Date	Reactor Type	Electrical Power, MWe	Present Storage Capacity, MTU[b]	Annual Fuel Discharge, MTU	Weight of Fuel in Reactor	Year[d] When Reactors First Lose FCR	Year[e] When Reactors First Lose FCR
Connecticut Yankee Atomic Power Co.								
Connecticut Yankee	1967	PWR	575	277	23.5	64.7	1991	1991
Consolidated Edison								
Indian Point-2	1974	PWR	873	220	22.9	86.7	1989	1989
Main Yankee Atomic Power Co.								
Maine Yankee	1972	PWR	824	362	21.7	82.5	1988	1985
Niagara Mohawk Power								
Nine Mile Point-1	1969	BWR	625	304	20.6	103.2	1993	1995
Northeast Utilities								
Millstone-1	1970	BWR	652	385	22.4	102.1	1986	1986
Millstone-2	1975	PWR	828	260	21.0	84.4	1985	1985
Power Auth. of State of N.Y.								
Fitzpatrick	1975	BWR	821	424	27.0	105.8	1989	1989
Indian Point-3	1976	PWR	965	375	22.8	86.3	1989	1989
Rochester Gas & Electric Co.								
Ginna	1970	PWR	470	235	12.6	47.8	1994	1988
Vermont Yankee Nuclear Power Corp.								
Vermont Yankee	1972	BWR	517	257	19.5	67.0	1990	1987

[a] The utilities are categorized as being located in one of the nine regions defined by the National Electric Reliability Council, NERC.

[b] Capacity estimated using computer program DISFUL code.[21]

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[d] Assumes maximum utility plans for increasing storage capacity and no transshipment between reactor basins within each utility.

[e] Assumes current utility plans for increasing storage and no transshipment.

APPENDIX A (Contd)

	Startup Date	Reactor Type	Electrical Power, MWe	Present Storage Capacity, MTU[b]	Annual Fuel Discharge, MTU	Weight of Fuel in Reactor	Year[d] When Reactors First Lose FCR	Year[e] When Reactors First Lose FCR
Yankee Atomic Electric Co.								
Yankee-Rowe	1961	PWR	175	92	9.2	17.9	1991	1983
Region 6[a]								
Alabama Power Co.								
Farley-1	1977	PWR	829	310	22.0	72.1	2002	1989
Carolina Power & Light Co.								
Robinson-2	1971	PWR	740	124	20.2	70.5	1980	1980
Brunswick-2	1976	BWR	821	207	27.1	109.2	1982	1982
Brunswick-1	1977	BWR	821	200	27.1	109.2	1981	1981
Duke Power Co.								
Oconee-1	1973	PWR	886	348[c,f]	24.3	82.1	1987	1982
Oconee-2	1974	PWR	886		24.3	82.1	1987	1982
Oconee-3	1974	PWR	886	220	24.3	82.1	1979	1979
Florida Power Corp.								
Crystal River-3	1977	PWR	825	254[f]	25.0	82.0	1997	1997
Florida Power & Light Co.								
Turkey Point-3	1972	PWR	652	283	19.2	71.6	1990	1989
Turkey Point-4	1973	PWR	652	283	19.2	71.6	1981	1981
St. Lucie-1	1976	PWR	810	283	21.0	84.2	1987	1987
Georgia Power Co.								
Hatch-1	1975	BWR	786	207[c]	27.0	103.6	1997	1983
Hatch-2	1979	BWR	795		27.0	103.6	1997	1983

[a] The utilities are categorized as being located in one of the nine regions defined by the National Electric Reliability Council, NERC.

[b] Capacity estimated using computer program DISFUL code.[21]

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[e] Assumes current utility plans for increasing storage and no transshipment.

[f] Not yet licensed.

APPENDIX A (Contd)

	Startup Date	Reactor Type	Electrical Power, *MWe*	Present Storage Capacity, *MTU*[b]	Annual Fuel Discharge, *MTU*	Weight of Fuel in *Reactor*	Year[d] When Reactors First Lose *FCR*	Year[e] When Reactors First Lose *FCR*
Tennessee Valley Authority								
Browns Ferry-1	1974	BWR	1,067	632[c]	40.4	142.1	1992	1992
Browns Ferry-2	1975	BWR	1,067		40.4	142.1	1992	1992
Browns Ferry-3	1977	BWR	1,067		40.4	142.1	1990	1990
Virginia Electric & Power Co.								
Surry-1	1972	PWR	784	460[c]	20.2	71.9	1984	1984
Surry-2	1973	PWR	782		20.2	71.9	1984	1984
North Anna-1	1978	PWR	907	425[c]	23.0	72.2	1987	1987
North Anna-2[f]	1979	PWR	907			72.2	1987	1987
Region 7[a]								
Arkansas Power & Light Co.								
Arkansas Nuclear One-1	1974	PWR	850	274	21.3	82.1	1985	1985
Arkansas Nuclear One-2	1979	PWR	912	201	23.2	73.5	1993	1993
Region 9[a]								
Pacific Gas & Electric Co.								
Humboldt Bay	1963	BWR	63	35	3.1	13.2	1988	1984
Portland General Electric Co.								
Trojan	1976	PWR	1,130	300	28.1	89.0	1992	1986
Sacramento Municipal Utility District								
Rancho Seco-1	1975	PWR	913	268	22.7	82.0	1994	1985
Southern California Edison Co.								
San Onofre-1	1968	PWR	430	80	11.1	58.1	1981	1981

[a] The utilities are categorized as being located in one of the nine regions defined by the National Electric Reliability Council, NERC.

[b] *Capacity estimated using computer program DISFUL code.*[21]

[c] Spent Fuel Pool or Pools shared by reactors.

[d] Assumes maximum utility plans for increasing storage capacity and no transshipment between reactor basins within each utility.

[e] Assumes current utility plans for increasing storage and no transshipment.

[f] Not yet licensed.

APPENDIX B
CHARACTERISTICS OF LWR SPENT FUEL CASKS

	Nuclear Fuel Services, West Valley, N.Y.	Nuclear Assurance Corp., Atlanta, Georgia	General Electric Co., San Jose, California	Transnuclear, Inc., White Plains, N.Y.		NL Industries, Inc., Nuclear Division, Wilmington, Del.	
Cask name	NFS-4	NAC-1[a]	IF-300	TN-8/9	TN-12	NLI-1/2	NLI 10/24
Transport mode	LWT[b]	LWT[b]	OWT[b]/Rail	OWT[b]	Rail	LWT[b]	Rail
PWR/BWR assemblies per cask	1/2	1/2	7/18	3/7	12/32	1/2	10/24
Loaded weight, tons	22.5	22.5	63.5	34.5	97	22	90
Gamma shield material	Lead	Lead	Uranium	Lead	Steel	Lead/U	Lead
Neutron shield	Borated water	Borated water	Water	Organic	Organic	Water	Water
Cavity coolant	Water[c]	Water[c]	Water[c]	Air	Air	Helium[c]	Helium
Cask exterior surface	Smooth	Smooth	Corrugated	Copperas	Copperas	Smooth	Stainless steel fins
U.S. NRC license	Yes	Yes	Yes	Yes	Pending	Yes	Yes
Number of units (operational/under construction)	2/0	4/0	4/0	(0/1)	0/0	5/0	1/2

[a] NAC-1 and the NFS-4 cask designs are essentially identical.

[b] LWT - Legal Weight Truck; OWT - Overweight Truck.

[c] These casks may be shipped dry (air) under low heat loads.

APPENDIX C

GLOSSARY OF TERMS AND ABBREVIATIONS

activity

Radioactivity or radioactive materials. A measure of the rate at which a material is emitting radiations; usually given in terms of the number of nuclear disintegrations occurring in a given quantity of material over a unit of time. The standard unit of activity is the curie (Ci).

AFR

An acronym for Away-from-Reactor. Sometimes used as AFR basins or facility.

ARB

At-reactor basin. A facility constructed adjacent to reactors to provide interim storage of spent fuel to minimize risks to the public associated with transportation.

BWR

A boiling water reactor is a reactor in which boiling light water is used as the coolant.

cask

A container that provides shielding and containment for the shipment or storage of radioactive material.

cubic meter (m^3)

A volume measuring 1 meter in length, width, and depth.

cladding

The outer jacket of a nuclear fuel element.

compaction

Reduction in the spacing of racks that hold spent fuel in a water storage basin so that the basin can hold more fuel and still remain subcritical.

contamination

The deposition of radioactive material on a surface.

criticality

State of being critical; a self-sustaining neutron chain reaction in which there is an exact balance between the production and loss of neutrons.

curie

The basic unit used to describe the intensity of radioactivity in a sample of material. One curie (Ci) equals 37 billion disintegrations per second.

deuterium

A natural isotope of hydrogen with one neutron and one proton in its nucleus (atomic weight = 2).

disposal

The planned release of radioactive and other waste or its placement in a manner which is considered permanent so that recovery is not provided for.

DOE

Department of Energy (created October 1, 1977). Includes former Energy Research and Development Administration.

DOT

Department of Transportation.

enriched uranium

Uranium in which the percentage of the fissionable isotope ^{235}U has been increased above the 0.7% normally found in natural uranium.

federal repository

A U.S. government-controlled facility to be used for the disposal of nuclear waste.

fission (nuclear)

The spontaneous or neutron induced splitting of a heavy nucleus into two nuclei or more of different mass, with the emission of two or more neutrons and substantial energy.

fuel (nuclear reactor)

Fissionable material used as the source of energy when placed in a nuclear reactor.

fuel assembly

A grouping of fuel rods which is not taken apart during the charging and discharging of a reactor core.

fuel rod

The smallest structurally discrete part of a reactor assembly which has nuclear fuel as its principal constituent.

full-core reserve

Space in the reactor basin to accommodate all of the fuel contained in the reactor.

full-cost recovery

Includes charges to the user that compensate the government for budgetary spending, for capital and operating costs, for return on invested capital, and for costs to cover unusual hazards, e.g., insurance premiums, premium pay for hazardous work, workmen's compensation, etc.

geologic storage

Storage in a repository constructed in a geologic formation.

GWe

Gigawatts electric, i.e., 1 billion (10^9) watts or 1,000 megawatts.

heavy water

Deuterium oxide, D_2O. Water in which hydrogen atoms have been replaced with deuterium atoms.

isotope

Any of the two or more forms of the same element, containing the same number of protons but different number of neutrons. The isotopes are chemically similar but have different atomic weights.

kilo

A prefix indicating 1,000 (10^3) times the affixed unit, abbreviated (k).

kilogram

kg = 1,000 grams.

kWh

kilowatt-hour, a unit of energy generation or consumption in a given hour.

(LWR)

A light water reactor uses light water (H_2O) as coolant and as the moderator for slowing fast neutrons. Most common types are pressurized water reactors (PWR) or boiling water reactors (BWR).

metric ton (MT or tonne)

Unit of weight; 1 MT = 1,000 kilograms

millirem

one-thousanth of a rem.

ml

milliliters.

MW

Megawatt (1 MW = 1 million watts), a unit of the rate of energy production or consumption.

MWD/MTU

Megawatt days per metric ton of uranium. A unit of uranium consumption cr burnup.

mrem

millirems.

MTU

Metric tons of uranium (2,200 pounds or 1,000 kilograms).

neutron

An uncharged elementary particle with a mass nearly equal to that of the proton. Neutrons sustain the fission chain reaction in a nuclear reactor.

nonproliferation

Limits the number of nations capable of producing nuclear weapons without limiting worldwide use of nuclear power.

NRC

Nuclear Regulatory Commission (includes the regulatory branch of the former AEC).

nuclear reaction

Neutron reactions with materials that cause fission with the simultaneous release of energy.

nuclear safety

The application of technical knowledge and administration control to prevent an unplanned, uncontrolled nuclear chain reaction.

plutonium

A radioactive element with an atomic number of 94. Its most important isotope is fissionable $^{239}\mathrm{Pu}$, produced by neutron irradiation of $^{238}\mathrm{U}$.

pool

A concrete chamber filled with water to provide shielding for irradiated fuel elements.

radioactive

Unstable in a manner shown by spontaneous nuclear disintegration with accompanying emission of radiation and particles.

radioactive decay

The spontaneous decrease of a radioactive substance due to disintegration by the emission of particles and radiation.

radioactivity

The spontaneous decay of disintegration of unstable nuclei accompanied by the emission of radiation and particles.

reactor (nuclear)

A device in which a fission chain reaction can be initiated, maintained, and controlled.

rem

A unit used in radiation protection to express the effective dose equivalent for all forms of ionizing radiation.

repository

A facility or designated site for storage or disposal of high level wastes.

reprocessing

Dissolving spent reactor fuel to recover useful materials such as thorium, uranium, and plutonium. Other radioactive materials are usually separated and treated as waste.

risk

The product of an event's frequency and its consequence yielding an estimate of the expected damage rate (e.g., population dose per year) from a specified event.

shielding

The material interposed between a source of radiation and the environment for protection against the danger of radiation. Common shielding materials are concrete, water, and lead.

shipping cask

A specially designed container used for shipping radioactive materials (see cask).

spent fuel

Irradiated nuclear reactor fuel at the end of its useful life.

storage

Retention of waste in some type of man-made device.

storage basin

A water-filled, stainless steel lined pool for the interim storage of spent fuel.

ton

Unit of weight, 1 ton = 2,000 pounds (1 short ton).

tonne

Unit of weight, 1 tonne = 1,000 kg (1 metric ton).

transshipment

Shipping spent fuel from one reactor basin to another reactor within the utility system with available space.

tritium

A radioactive isotope of hydrogen containing two neutrons and one proton in the nucleus, with an atomic weight of 3. It is heavier than deuterium (heavy hydrogen) with an atomic weight of 2.

uranium

A naturally radioactive element with the atomic number 92 and an atomic weight of approximately 238. The two principal naturally occurring isotopes are the fissionable ^{235}U (0.7% of natural uranium) and the fertile ^{238}U (99.3% of natural uranium).

uranium dioxide (UO_2)

Stable chemical compound of uranium and oxygen which does not readily decompose in the reactor.

waste, radioactive

Equipment and materials (from nuclear operations) that are radioactive or have radioactive contamination and for which there is not recognized use or for which recovery is impractical.

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