Spent Fuel Storage Alternatives

by John P. Colton

The nuclear fuel cycle is composed of a number of discrete operations before and after irradiation of fuel in the reactor. Those operations before insertion and irradiation of the fuel elements in a reactor are generally referred to as process steps in the *front end* of the fuel cycle, and those after irradiation as the *back end* of the fuel cycle.

Uranium ore mining and milling, uranium enrichment and uranium fuel fabrication are process steps at the front end of the nuclear fuel cycle. Spent fuel storage, reprocessing, refabrication of uranium-plutonium oxide fuel, and waste management are process steps at the back end of the fuel cycle. The front end of the fuel cycle is well-developed and is providing fuel for various light-water reactors (LWRs), heavy-water reactors (HWRs), and gas-cooled reactors (GCRs). The back end of the fuel cycle is not yet fully developed. Due to various economic (i.e. large cost of facilities), political (i.e. non-proliferation) and technical considerations, a clear, unanimous decision on the ultimate disposition of spent nuclear fuel in the nuclear power States has not yet been made.

As with many such delayed decisions the pressure of the inventory is reflected in additional "warehousing" requirements. In the instance of the nuclear cycle, this is reflected in the storage of spent nuclear fuel from the reactor. Spent fuel is presently being stored under water in basins until facilities become available either to reprocess and recycle uranium and plutonium or to permanently store the spent fuel. If spent fuel is not reprocessed, the back end of the fuel cycle becomes permanent storage of spent fuel.

The main types of reactors that will be discussed in this paper are the current generation of LWRs and briefly the CANDU-type HWRs. The LWR fuel cycle had always been based on the assumption that the spent fuel would stay for a short time in storage basins located at the reactor and then after an appropriate time, approximately one year, be sent to a reprocessing facility. The HWR spent fuel of the CANDU-type was intended originally for permanent storage and not for reprocessing. The technologies, economics of the nuclear industry, the fuel cycle and the political non-proliferation question will determine when or if these basic policies will be implemented.

According to the recent Regional Fuel Cycle Center Study estimates, the cumulative quantity of spent-oxide fuel expected to be in storage by 1985 could be as high as 26 000 tonnes. While the cumulative quantity in storage would reduce proportionately with any reductions in projected nuclear generating capacity, the storage requirements could not be altered significantly before 1985 by an immediate decision to build additional reprocessing plants because of the 8–10 year lead-time required to bring such plants on line.

Recently, environmental and political considerations have placed the future availability of reprocessing in question, prompting increased emphasis on the review of current storage programmes in light of technologies available for interim fuel storage alternatives.

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Characteristics of Nuclear Fuel

The total length of an LWR fuel element is 4–6 metres, whereas the HWR fuel element is one-half metre in length. The weight of each LWR assembly is about 700–800 kg for pressurized-water reactors (PWRs), 200-300 kg for boiling-water reactors (BWRs), and about 25 kg for HWRs. The current large reactor design foresees PWRs being exposed to 33 000 megawatt days thermal per metric tonne (MWd/t) at a specific power of 36 MW/t, BWRs at 27 500 MWd/t at a specific power of 22 MW/t, and HWRs at 7500 MWd/t with a specific power of 15.2 MW/t.

Radioactive decay with the ejection of alpha and beta particles from the nucleus, and the release of energy in the form of gamma rays, is the source of heat generation of the spent fuel assemblies. As an example, the heat generation in spent fuel exposed to 25 000 MWd/t of reactor operation at a specific power of 35 MW/t decays from a thermal power of 100 kW/t at ten days cooling to less than 1 kW/t as the fuel nears 100 days of cooling. The entrapped fission gases within the cladding tube presents a potential hazard should the cladding develop a hole through which the gas can escape. The heat generation, potential gas and water contamination, and criticality and safety measures are the primary design considerations that must be used in the design and construction of any type of storage facilities.

Current Practices for LWR Fuel Storage

Water-filled pools are being used both for short-term as well as for extended storage of spent fuel and are basically considered to be technologically fully developed. The choice of storage in water has been made primarily because of the convenience and effectiveness that it provides. Water is an effective radioactive shield and coolant, it is readily available and inexpensive, it is easily processed, and it provides a transparent medium that allows visual control in fuel handling.

Most fuel storage water basins are of the same design: rectangular in horizontal cross-section, and 12–13 metres deep. Fuel assemblies are placed in storage racks on the bottom of the pool. The racks provide support as well as protection against accidental criticality. Insertion or removal of the assemblies is accomplished vertically from above the racks using safety-designed mechanical handling systems. The fuel elements must remain submerged by about 3 metres during all fuel handling operations for radiological protection of the operator. The BWR pools are filled with demineralized water while PWR pools are filled with borated water. The reason for this difference is that PWRs use borated water in the primary system for reactivity control, which mixes with the pool water during the refuelling operation. BWRs use the demineralized water for coolant. The pools are constructed of reinforced concrete with sufficient thickness to meet the shielding and structural requirements. Each pool is designed to assure leak-tightness. The present pools at reactors are 10–20 metres long and 7 to 15 metres wide. The storage area varies with the amount of fuel to be stored, which in turn depends on the type and size of reactor being supported.

The design practices were initially based on the assumption that the spent fuel would be shipped to a reprocessing plant within one year following discharge from the reactor. Therefore, space is normally provided for one full core discharge plus one to two annual reload charges (a reload is normally one third of a full core requirement). Similarly, storage

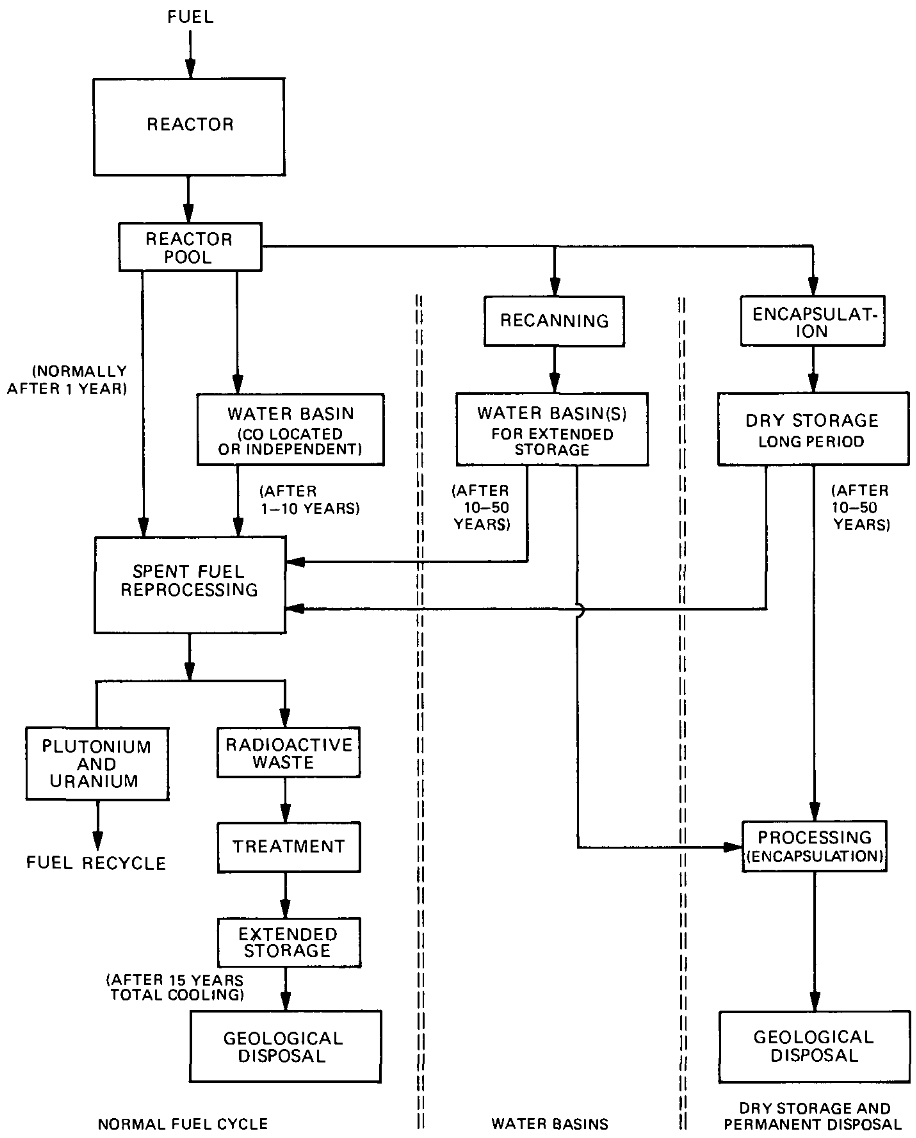

Figure 1. Possible Options for Spent Fuel Management.

basins at spent fuel reprocessing plants have been designed on the assumption that spent fuel would be reprocessed shortly after receipt. Space provided was sufficient for storage of fuel equivalent to three to four months of reprocessing plant throughput.

Because of delays in reprocessing, the initial complement of storage space provided for early reactors has not been adequate and alternative solutions to provide additional storage capability have been considered by the modifications of, or addition to, existing facilities:

1. Storage densification (compaction) — More storage capability is added to existing storage pools by providing for closer spacing of assemblies through utilization of neutron absorbing material.

2. Expansion of pool volumes — This alternative provides greater capability by increasing the physical dimensions of existing basins.

3. Additional wet storage facilities — This would include an additional storage at a reactor site, or at another location.

These considerations would be only for increasing immediate capacity and new design concepts must be considered if the fuel is to be stored for a longer, or indefinite, period of time in a retrievable mode.

Figure 1 shows what might be considered as a normal fuel cycle with several alternative options including a geological permanent disposal.

Long-term LWR Fuel Storage in Water Basins

The storage of spent fuel elements in water basins for periods greater than the short-term appears to be technically feasible. It can be anticipated that the operational storage considerations will be similar to the short-term. The new considerations which might possibly arise when anticipating storage of fuel elements for several decades is increased or aggravated fuel leakage, accelerated corrosion, thermal and radiation stability. In case any of these considerations do arise it is expected that the conditions would arrive in an incremental fashion and slowly enough so that time exists for dealing with the problems, for example, by encapsulation or canning. Arrangements would have to be made for corrosion test samples both from fuel-element materials and storage-pool related equipment to be monitored.

Alternative Storage Technologies for LWRs

Three basic techniques are currently being evaluated by various Member States.

- Sealed Cask: a near-surface vault containing one or more assemblies that are sealed from air using an individual shield;
- Caisson: one or more assemblies sealed from air and buried near surface in the ground to use ground as shielding;
- Air-cooled vault: a collection of several assemblies within a large shielded area (building) and cooled directly by air.

Figures 2, 3 and 4 portray the three concepts mentioned above These technologies for air cooling of spent fuel appear to require fuel elements being cooled in water pools for at least 5 years (longer cooling times are preferred and will occur in most programmes). Usually, the fuel will be encapsulated prior to air storage with considerations being given to the use of heat transfer media in spaces between fuel pins for better conduction of heat and subsequent cooling of elements. Should dry storage be considered as an interim storage of fuel prior to reprocessing, the encapsulation and filter materials must be compatible with the shearing and dissolution steps in the reprocessing plant.

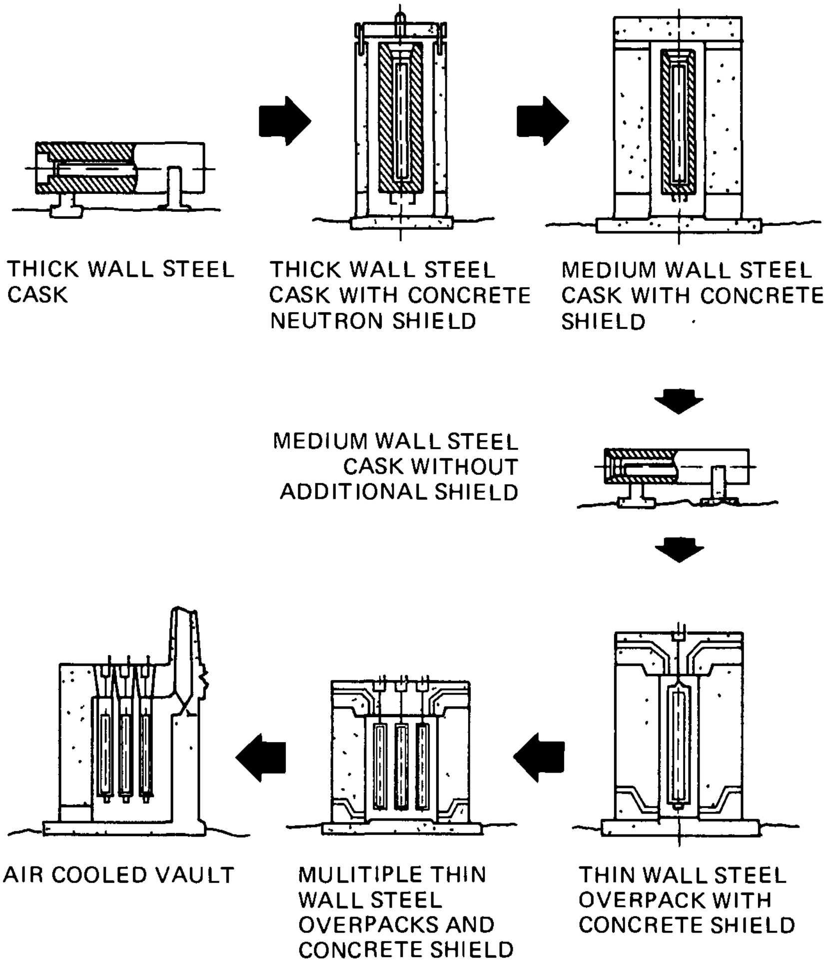

Figure 2. Sealed Cask Concept.

Air-cooled vaults are currently operating for high-temperature gas-cooled, graphite-moderated reactor (HTGR) fuel and they have demonstrated the construction, fuel handling and heat removal technologies. The French have operated an air-cooled vault (PIVER) for high-level waste (HLW) with forced circulation and high-efficiency filters. Adaptation of these technologies to LWR fuel storage would appear possible. Sealed-cask concepts have been demonstrated with electrical heating and with CANDU HWR fuel in Canada. The same concept for solidified HLW has been tested using electrical heating in the USA. In each case the conservative application of individual technologies (heat transfer, shielding, etc.) was applied. The third concept using a caisson has been utilized for storage of experimental reactor fuel in several countries.

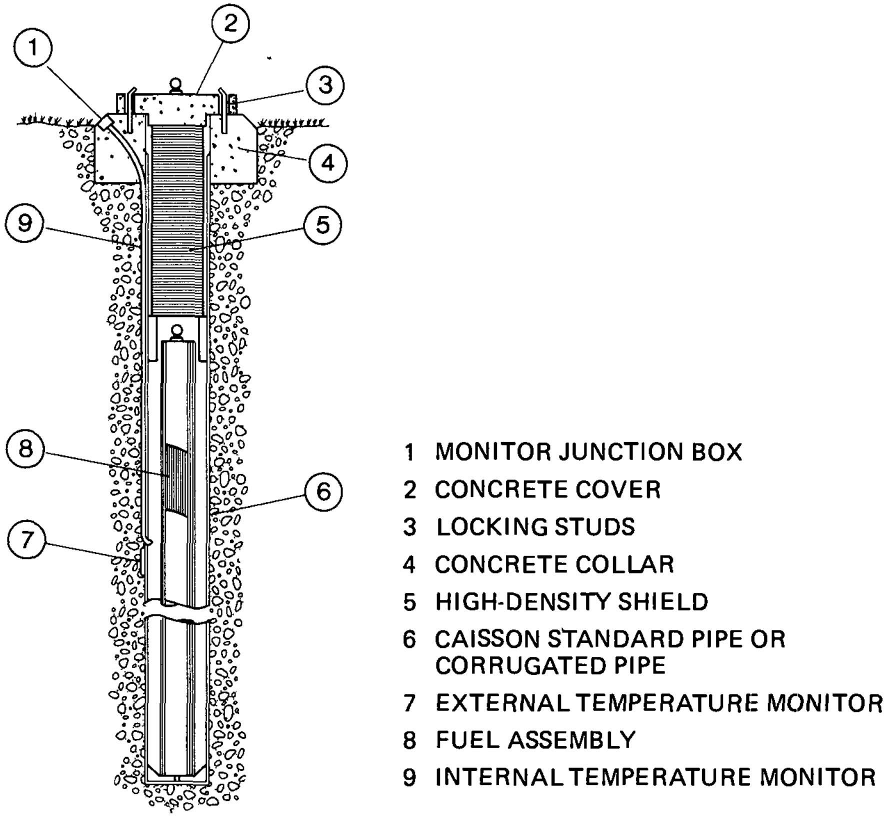

Figure 3. Caisson Concept.

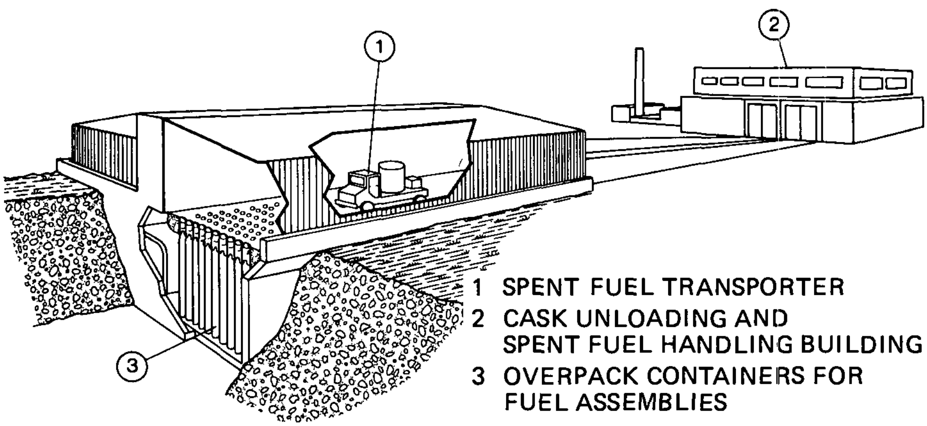

Figure 4. Air-Cooled Vault Concept.

Spent Fuel Storage and Disposal Option for HWRs

The main difference between HWR fuel and LWR fuel is that the HWR fuel is short (0.5 metre) and has lower burn-up (7600 MWd/t). Since the fuel is natural uranium, there is no criticality considerations in storage using light water as coolant.

The normal HWR fuel storage at CANDU reactor sites is in water-filled basins. The interim storage options of HWR fuel are similar to the LWR spent fuel alternatives. Water storage both at and away from the reactor sites, as well as dry-storage concepts, are being considered. The dry-storage alternatives include air-convection vaults, air-conduction vaults, concrete canisters and underground salt beds. It is felt that the use of water-storage basins is an established technology. Dry storage in vaults is considered in the HWR case to be available but not demonstrated. Dry storage in concrete canisters is an available option and is currently being demonstrated with a programme in Canada.

Summary

There is considerable experience with the storage of spent fuel in water basins. However, this storage has been on a short-term basis and little experience exists on requirements for cladding or encapsulation of spent fuels for long-term storage under water. Nevertheless, with very little additional development work, storage of spent fuel in water basins can be regarded as a suitable interim storage option.

A number of near-ground-surface, dry-storage concepts for long-term storage are under development. These include air-convection vaults, air-conduction vaults, use of concrete canisters, and use of caissons. The dry-storage concepts are considered to be potential options, although practical demonstration of technology must be made prior to acceptance as solutions.

Dry-storage deep underground in rock on a retrievable basis is under consideration. This method would be accomplished on lines similar to the work being done for long-term storage of highly radioactive solidified wastes. After sufficient experience has been gained, the facility could be converted into a permanent geologic disposal, if so desired, by backfilling and sealing. Further development and demonstration of this concept is likely to be initiated in the near future. Dry storage in salt mines is also under development on a similar basis.

In the world nuclear community, the ultimate disposition (reprocessing or waste treatment) of spent nuclear fuel is not clear. Some Member States have decided to go fully to reprocessing while others have decided to delay the final decision until additional evaluations can be made. All projections show that the need for additional short-term and intermediate-term storage capacity will be required. The brief discussion in this paper shows that there are various alternatives as how the problem can be solved. It must be stated that the storage on an interim basis is not the solution — an ultimate decision whether to reprocess or to store on a permanent, non-retrievable basis still must be made.