POWER GENERATION TECHNOLOGY

THE INTERNATIONAL REVIEW OF PRIMARY POWER PRODUCTION

1990/91

Spent fuel storage options: a critical appraisal

K P Singh, Holtec International, USA
M G Bale, AAR Brooks & Perkins, USA

The delayed decisions on nuclear fuel reprocessing strategies in the USA and other countries have forced the development of new long-term irradiated fuel storage techniques, to allow a larger volume of fuel to be held on the nuclear station site after removal from the reactor.

In the early days of commercial nuclear power, when the power utilities looked upon reprocessing as an immutable certainty, fuel pools were a low priority item. Storage racks in the fuel pool were intended to house a few batches of normal discharge until they could be shipped away to the reprocessing site. The racks were of the so-called *open lattice* construction. The pitch (centre-to-centre distance between the storage locations) was large enough to preclude the need for any neutron absorber material.

The racks were mounted on floor embedments. The anchors were solidly welded to embedment plates positioned deep inside the pool floor slab. A gridwork of leak chase paths underneath the liner seam welds and embedment bolts provided the ability to indicate any leakage through the pool liner at an early stage. The pool had plenty of floor space for the projected storage requirements. The United States Nuclear Regulatory Commission (NRC) had no regulations for design manufacturing or operation of fuel storage racks. Utilities stored, in addition to spent fuel assemblies, a wide variety of miscellaneous hardware in the pool. Some even kept their nuclear waste containers on the pool floor. The fuel storage technology was in equilibrium with the industry needs.

The moratorium on fuel reprocessing in the US, and the Government's rapidly receding date for an operational offsite fuel repository (most recent date: the year 2010) changed this situation entirely. Long-term storage of spent fuel became a critical issue for many nuclear plants. The existing storage capacity in several operating plants will be exhausted long before the year 2010, and many more will have lost their prudent operation reserve (POR = 4/3 cores).

The nuclear power industry has responded to the challenge by developing several viable options for long-term onsite storage, which can be employed individually or in tandem. They are:

- Densification of storage in the existing spent fuel pool
- Building another fuel pool facility at the plant site
- Onsite cask park, and
- On site vault clusters.

Desirable attributes of a storage option are:

- Safety: minimise the number of fuel handling steps
- Economy: minimise total installed, and O&M cost
- Security: protection from anti-nuclear protesters
- Site adaptability: available site space, earthquake characteristics of the region and so on
- Non-intrusiveness: minimise required modifications to existing plant systems
- Modularisation: afford the option to adapt a modular approach for staged capital outlays, and
- Maturity: extent of industry experience with the technology.

We will now make a critical appraisal of each of the four aforementioned storage options in light of the criteria described above.

Increasing the storage capacity in the existing pool floor space can obviously be realised by reducing the centre-to-centre spacing between the stored fuel assemblies. Even further densification is possible by compacting two assemblies into one equivalent assembly (fuel consolidation), and thus, in principle, doubling the storage capacity. Therefore, in-pool storage increase can be viewed as a two step process: cell densification; fuel consolidation. A third concept, *double tiering*, will be explained at the end of this section.

Storage cell densification is usually accomplished by reracking. The old (existing) racks are removed from the pool, and are replaced by new high density racks. These high density racks are able to store nuclear fuel at a close spacing (pitch) by interposing a neutron absorber material between contiguous assemblies. Boral, a roller formed sandwich of aluminium and boron carbide (Figure 1) is a widely used neutron absorber in this application, and has garnered over 150 reactor years of satisfactory in-pool experience.[1] Other materials used in the rack construction are austenitic stainless steel and precipitation hardened stainless (17:4 ph) steel, both of which have well established histories of trouble-free use in nuclear applications.

Considerable increase in storage capacity can be attained by utilising the latest technologies in storage rack design. Some of the recent advances are detailed here.

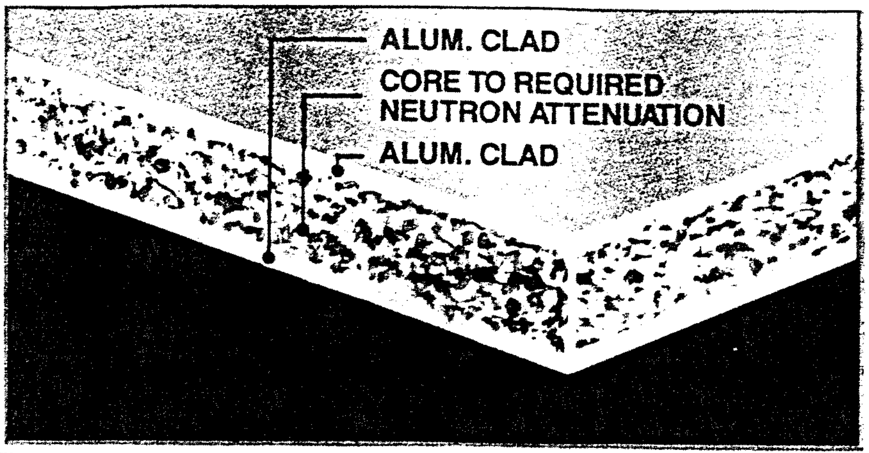

Figure 1. *Boral composite neutron absorber used to increase spent fuel racking density.*

Smaller cell pitch: the number of storage cells which can be accommodated in a certain pool floor space is inversely proportional to the square of the cell pitch. Thus, reducing the cell pitch from 13.5in (typical of mid-seventies design) to the state-of-the-art pitch of 9in results in $(13.5/9)^2 =$ 2.25 times increase in the number of storage cavities. Actual increases are even greater, because much of previously wasted pool space, occupied by unnecessary hardware such as sparger lines, work tables, and so on are removed in the reracking process.

Seismic simulation

Closely positioned racks: the replacement racks are designed to be free standing to minimise installation men-rem exposure and project cost. They have to be qualified for stability and structural integrity under seismic conditions which, until recently, meant leaving 3in to 4in spacing between racks to avoid rack-to-rack, or rack-to-pool wall collisions during postulated earthquake scenarios. However, certain major strides in the field of seismic simulation of racks have eliminated the deficiencies in this area. The most significant development has been the ability of the dynamicists to model mathematically all racks in the pool in one seismic model and thus predict the kinematic interaction between the rack modules in a precise manner. Industry's inability to simulate the three dimensional motion of the entire aggregate of racks in the fuel pool was a major plank in the intervenors' claim of *insufficient fuel rack technology* (vide Sierra Club vs Pacific Gas & Electric Co, Atomic Safety Licensing Board Hearings, 1987). The elimination of this technical deficiency has weakened the position of nuclear power's opponents in the US, and there has been no new initiative for intervention in a rerack project in the US in the past year.

The successful development of the so-called whole pool multi-rack seismic analysis technology was aided in no small measure by the experimental study of motions of rack underwater sponsored by the Northeast Utilities (NUSCO) of Berlin, Connecticut. NUSCO's experiments enabled experimental benchmarking of the fluid coupling theory of Dr Burton Paul[2] and paved the way for the articulation of a comprehensive dynamic model of rack modules in a fuel pool.

The ability to simulate the motion of all rack modules in a pool by an all-inclusive computer model enabled the rack designers to make quantum improvements in the quality of rack designs. Now, the structural characteristics of the rack modules could be fine tuned so that the rack arrays dissipate the seismic input. Therefore it has now become possible to produce detuned rack designs. These detuned racks could be placed closer to each other without the danger of impacts during seismic events. The difference in the physical appearance of a detuned rack from a standard design is hardly discernible. The photograph of fuel racks for PWRs built by Holtec International clearly show the attachment welds between the boxes (Figure 2). The extent of positioning of these longitudinal connector welds are carefully varied by the rack designer as their effect on the equipment seismic response is computed. An experienced designer can develop the detuned design in tow to three iterations.

Pool storage densification technology is now fully matured, well developed, and well established. It will continue to be the first preference for storage increase because of its many other desirable attributes. For example, it involves no increase in the number of fuel handling steps (safety), does not present a new visible target for sabotage (security), seldom requires any modification of existing plant systems, and is readily modularised. As shown in a later section, it is also by far the most economical option.

Its adaptability to the plant conditions cannot always be guaranteed, *a priori*. Many plants, particularly BWRs, have elevated fuel pools. The ability of these elevated pool slabs to withstand increased deadweight of stored fuel cannot be presupposed. However, extremely conservative reinforced concrete analysis methods[3] utilised in the initial design of the pool slabs led to large margins of safety inherent in the full pool structures. Reanalysis of these struc-

Figure 2. *PWR fuel racks, courtesy of Holtec International, showing the attachment welds between boxes to detune the rack for improved seismic performance.*

tures using present day finite element methods have demonstrated the presence of considerably greater design strengths than was envisaged by the original architect engineers of the nuclear plant. The result has been a rare break for the nuclear power industry: to date no fuel pool has been found to be too weak to withstand densified fuel storage. Many, including Oyster Creek (GPU Nuclear), Grand Gulf Unit 1 (SERI) — both BWRs, are considering licence application for consolidated storage, after having maximised cell locations in their pools.

Consolidated storage

Rod consolidation has been shown to be feasible technology. Rod consolidation involves disassembly of spent fuel, followed by the storage of the fuel rods from two assemblies into the volume of one and the disposal of the fuel assembly skeleton outside of the pool (this is considered a 2:1 compaction ratio). The rods are stored in a stainless steel can that has the outer dimensions of a fuel assembly. The can is stored in the spent fuel racks. The top of the can has an end fixture that matches up with the spent fuel handling tool. This permits moving the cans in an easy fashion.

Rod consolidation pilot project campaigns in the past have consisted of underwater tooling that is manipulated by an overhead crane and operated by a maintenance worker. This is a very slow and repetitive process that lends itself to mistakes caused by boredom. One company has applied robotics to the repetitive tasks and has increased the speed and eliminated much of the risk involved with such tasks. To date the robot has only done dry demonstrations on mockup fuel and will not be commercially available for large projects for one to two years.

Fuel rod consolidation can virtually double the pool capacity provided the existing spent fuel racks have adequate margin to contend with the live and dead loads. Along with this, the fuel pool cooling capacity and structural analysis will have to be updated.

There are three major drawbacks to fuel rod consolidation. The disassembling of the spent fuel will release large quantities of crud and hot particles. The consolidation equipment has filtration equipment but it will not capture everything that is released. In order to preserve the 2:1 compaction ratio the fuel assembly skeletons and the spent filters mentioned above must be stored outside the pool. This is an added cost for storage casks that is typically overlooked.

The most important drawback is regulatory in nature. The United States Department of Energy (DOE) considers consolidated fuel as a non-standard fuel form. The DOE gives non-standard fuel the lowest priority for disposal because it is considered more labour intensive to handle. This would cause, for the holder of such spent fuel, unnecessarily longer storage times prior to final turnover for disposal.

Fuel rod consolidation equipment would normally be rented as part of a contract to consolidate spent fuel. Some types of consolidated equipment require mounting to floors and semi permanent power sources. This is because typical consolidation campaigns would last six to eight months due to the inherently slow process.

Casks have to be purchased to store the skeleton remains of the consolidated fuel and the spent filters used to help control crud.

In double-tiering, if the pool structure is sufficiently strong, then it is possible to erect additional modules above the existing ones. A typical rack is approximately 14ft high. Therefore, the column of stacked racks would project less than 30ft from the pool liner. Since most pools have about 40ft of water, double tiering would still have a minimum of 10ft of shielding.

However, for this option to be feasible, one must consider the scenario of accidental pool drain down, permanent inaccessibility to the fuel stored in the lower deck, and redesign of the fuel handling bridge. So far, no pool has been double-decked with high density racks.

Dry cast storage

Dry cask storage is a method of storing spent nuclear fuel in a high capacity container. The cask provides radiation shielding and passive heat dissipation. Typical capacities for PWR fuel range from 21 to 37 assemblies that have been removed from the reactor for at least five years. The casks, once loaded, are then stored outdoors on a seismic concrete pad. The pad is normally located away from the secured boundary of the site because of space limitations. The storage location is required to have a high level of security which includes frequent tours, reliable lighting, intruder detection (E-Field) and continuous visual monitoring. The pad and security area required is approximately 120ft by 250ft.

The casks, as presently licensed, are limited to 20 year service life and for storage only. Once the 20 years has expired the cask manufacturer or the utility must recertify the cask or the utility must remove the spent fuel from the container. Work is also continuing on providing a dual purpose cask that will be capable of long storage and then transport. These casks would tend to have a reduced capacity thus requiring more containers in order to provide the same amount of storage space.

The plant must provide for a decontamination facility where the outgoing cask can be decontaminated for release.

Plant modifications

There are several plant modifications required to support cask use. Tap-ins must be made to the gaseous waste system and chilled water to support vacuum drying of the spent fuel and piping must be installed to return cask water back to the spent fuel pool/cask pit. A seismic concrete pad must be made to store the loaded casks. This pad must have a security fence, surveillance protection, a diesel generator for emergency power and video surveillance.

Finally, the cask park must have facilities to vacuum dry the cask, back fill it with helium, make leak checks, remachine the gasket surfaces if leaks persist, and assemble the cask onsite. The space between the inner and outer lid must be continuously monitored to check for inner seal failure.

Presently no cask has dual certification, it is only good for either storage or transportation. Dual purpose casks, if and when certified, will have reduced capacity thus increasing the quantity required. As a result, utilities consider dual purpose casks to be inferior overall to present day casks.

Vault storage consists of storing spent fuel in shielded stainless steel cylinders in a horizontal configuration in a reinforced concrete vault. Duke Power Company has opted for vault storage for adding storage capacity at its Oconee Nuclear Power Station. Duke's vault storage system, supplied by Nutech Inc under the tradename NUHOMS, consists of cylinders which can house up to 24 fuel assemblies. The concrete vault provides radiation shielding and missile protection. It must be designed to withstand the postulated seismic loadings for the site. Nutech's system uses a passive air cooling system, and has no installed air samplers or radiation monitors. Shift radiation technicians monitor the vault system on a weekly basis.

A transfer cask is needed to fetch the storage canisters from the fuel pool. The plant must provide for a decontamination bay to decontaminate the transfer cask, and connection to its gaseous waste system and chilled water systems. A collection and delivery system must be installed to return the pool water entrained in the canisters back to the fuel pool. Provisions for canister drying, helium injection, handling and automatic welding are also necessary.

The storage area must be designed to have a high level of security similar to that of the nuclear plant itself. Due to the required space, approximately 200ft × 300ft for a NUHOMS system, the vault secured area must be located outside the secured perimeter of most nuclear plants. Consideration of safety and security requires it to have its own video surveillance system, intrusion detection, and an autonomous backup diesel generator power source.

The merits and drawbacks of the various storge options are summarised in Table 1.

Constructing a new fuel pool may be an attractive concept for a multi-reactor plant site where the new pool could serve as the repository of fuel from several reactors. This approach has been taken by TVO of Finland. However, local opposition to build up of fuel inventory, and high cost of building and licensing a self-sufficient fuel pool facility has dampened the appeal of this option as a viable alternative. ☐

Acknowledgement
This paper draws extensively from an unpublished report by Mr Neil Morrison.^{4} The authors are grateful for his permission to use his material, and for his critique of this manuscript.

	Storage option			
Criteria	In-pool	Cask	Additional Vault	Pool
1Safety: Minimise the number of fuel handling steps	excellent	fair	fair	good
2Economy: (Total cost of cells)*	$7.37 million	$18.05 million	$11.22 million	not available
3Security consideration:	no added burden	added burden	added burden	added burden
4Site adoptability:	excellent	usually acceptable	usually acceptable	usually acceptable
5Modifications to plant systems:	none	some	some	some
6Modularisation characteristics:	good	excellent	excellent	good
7Maturity level of technology:	most matured and developed	well developed	developed	well developed

*See reference 3.

Table 1. *Comparison of storage options.*

References

1. Turner, S *Evaluation of the Acceptability of Boral for use in Spent Fuel Pools*, GPU Nuclear, Inc, T Richter, Parsippany, New Jersey (1990).
2. Paul, B, *Fluid Coupling in Fuel Racks: A Correlation of Theory and Experiment*, Northeast Utilities Co, R B Roy, Berlin, Connecticut (1989).
3. Aron, *Building Code Requirements for Reinforced Concrete, ACI-318*, American Concrete Institute, Chicago, Illinois (1977).
4. Morrison, N, *Spent Fuel Storage Study at Beaver Valley Power Station, Unit I*, Duquesne Light Co, internal report (1990).

serving as TEMA technical subcommittee chairman, pressure vessel and piping committee to the ASME and others. Dr Singh is a fellow of the ASME, and an adjunct professor of mechanical engineering at the University of Pennsylvania.

Dr M G Bale is nuclear sales and programme manager of AAR Brooks & Perkins of Livonia, Michigan. He received PhD and BSc (Honours Metallurgy) degrees from University College, Cardiff. Over the years he has been actively involved in various research and development programmes with fast and thermal reactor fuels, cladding materials, burnable poisons, control and shielding materials. He is subcommittee chairman of ASTM C26.03, on neutron absorber materials and member of ANS and A Cer Soc.