How the pool storage industry keeps its head well above water

Designers have proved very ingenious at continuously squeezing more storage capacity from LWR spent fuel pools, through seemingly unending rerack cycles. How has the wet storage industry remained resilient against the marketing onslaught from the dry storage vendors and what are the sources of its continuing strength? What are the potential hazards which may sully the reputation of wet storage as a low risk, low cost fuel management option?

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Termination of spent fuel reprocessing in the USA in 1977 spawned a flurry of rerackings which continued unabated through the 1980s, reaching a peak in 1992. The pace of wet storage expansion has slowed noticeably since 1992, as dry storage vendors aggressively marketed their technologies and successfully pursued some utilities, getting them to opt for dry storage even though the technical logic pointed to wet capacity expansion as the optimal choice.

In view of the very well defined and finite size of the marketplace, the wet storage business was destined to slow down as more and more pools reracked. However, the designers of high-density storage equipment for LWR spent fuel pools have proved extremely resourceful and innovative: pools which were deemed to be reracked to their maximum capacity in 1985 were reassessed and found to have several fuel cycles worth of additional storage capacity available in them. This apparent elasticity in storage capacity was fuelled by several key technical breakthroughs.

The case of Prairie Island (Northern States Power Company, Minneapolis, Minnesota) is typical. The Prairie Island spent fuel pool was reracked in 1980 with a total storage capacity of 1386 cells (see Fig 1). Some years later, faced with the looming loss of its capacity to discharge a full core in its fuel pools, Northern States Power looked to the dry storage option. After a protracted and expensive process, NSP successfully established an IFSFI (Independent Fuel Storage Facility Installation) and loaded two 40-assembly metal casks in 1996. Meanwhile, a feasibility study by Holtec International in 1995 showed that the storage capacity in the Prairie Island pools could be increased by an enormous 50% if state-of-the-art fuel rack technology were to be employed.

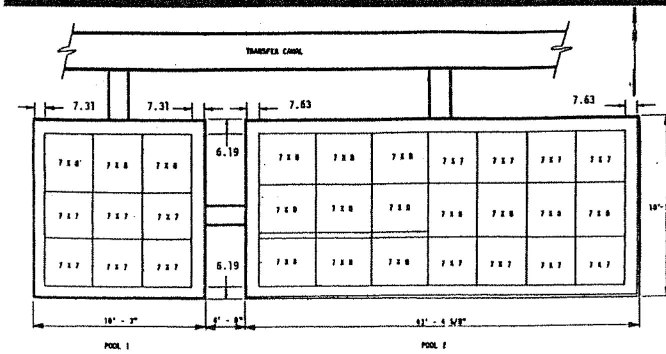
NSP is hard pressed to explain to State officials why the wet storage option, considered moribund in 1988, is now so bountiful. Similar examples abound.

Pools are, of course, circumscribed by their size, and there is a physical limit to which the storage capacity can be enlarged.

Table 1. Spent fuel storage capacity decisions

Plant	Utility	Year	Option chosen	Increase in capacity
Indian Point 2	Consolidated Edison	1990	Wet storage	38%
Indian Point 3	NYPA	1990	Wet storage	40%
Zion	ComEd	1993	Wet storage	23%
Sequoyah	TVA	1993	Wet storage	50%
Duane Arnold	Iowa Electric	1994	Wet storage	34%
ANO	Entergy	1994	Dry storage	(Potential increase if wet storage had been adopted = 67%)
Davis Besse	Toledo Edison	1993	Dry storage	(Potential increase if wet storage had been adopted = 130%)

Fig 1



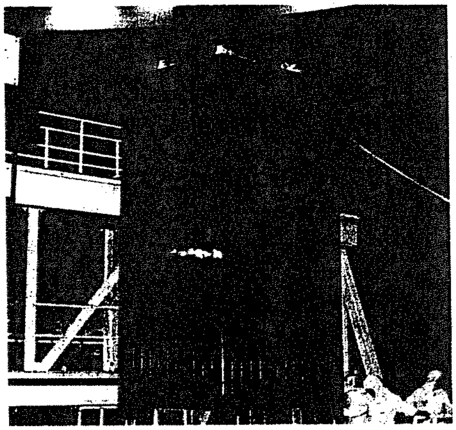
▲ *Existing fuel rack configuration at Prairie Island spent fuel pool. Gaps between racking and pool wall shown in inches.*

Nevertheless, it is most surprising that after 20 years of reracking technology, a sizeable minority of fuel pools remain equipped with sub-optimal capacity. Why is this?

DIFFERENT UTILITIES, DIFFERENT STRATEGIES

From the vantage point of wet storage, nuclear plants may be divided into two categories:

- Those who have aggressively sought to maximise their in-pool capacities. And
- Those who have embraced dry storage even when considerable capacity increase in their pools was possible.



▲ *High density fuel storage rack being prepared for installation in a spent fuel pool.*

The latter group, in most cases, viewed dry storage as eliminating the (needless) step of intermediate storage in the fuel pool. Presented with a similar set of facts, economists in the two camps came to diametrically opposite conclusions, which should not be surprising to those familiar with the handsome adaptability of economic models to suit the analyst's predilections. Table 1 shows a typical sampling: Zion (ComEd) and Indian Point 2 (Consolidated Edison) with a mere 23% and 38% capacity gains, respectively, reracked, while Davis Besse (Toledo Edison) and Arkansas Nuclear One (Entergy) with relatively hefty 67% and 130% potential capacity gains, respectively, chose dry storage.

An overwhelming majority of plants, however, have opted for wet storage expansion instead of dry storage, as is borne out by Tables 2 and 3, which list, respectively, units that have opted to rerack and to establish Independent Fuel Storage Facility Installations, over the past five years. (In this list the countries which did not permit their utilities to seek worldwide bids are excluded, because their decisions could not be considered to be guided by market forces. These countries, until very recently, included France, Germany, Japan, and the former Soviet bloc.)

We expect a majority of plants with more than ten years of remaining operating life to opt for rerackings, provided the additional capacity increase can be achieved at a cost of $15 000 per storage cell (or less).

DRY STORAGE WOES AND BORAFLEX

Cost, however, is not the only factor, perhaps not even the most dominant factor. The two most significant considerations likely to affect the pace of future rerackings are:

- Setbacks in the dry storage industry. And
- The prognosis for Boraflex.

Table 2. Plants opting for reracks (1986-97) – excluding projects not open to international bidding

Plant	Type	Contractor	Year
Beaver Valley	PWR	Holtec	1992
Nine Mile Unit 1	BWR	Holtec	1991
Fort Calhoun	PWR	Holtec	1992
Pilgrim	BWR	Holtec	1992
Duane Arnold	BWR	Holtec	1992
Salem 1 & 2	PWR	Holtec	1992
Limerick 1 & 2	BWR	Holtec	1993
Ulchin 1 & 2	PWR	Holtec	1994
Conn Yankee	PWR	Holtec	1994
Maine Yankee	PWR	Rust	1994
Kori-4	PWR	Holtec	1995
Yonggwang 1 & 2	PWR	Holtec	1995
Angra 1	PWR	Holtec	1995
Watts Bar	PWR	Holtec	1996
Shearon Harris	PWR/BWR	Holtec	1995
J A FitzPatrick	BWR	Holtec	1996
Waterford 3	PWR	Holtec	1996
Vogtle 1	PWR	To be determined	1997
Wolf Creek	PWR	Holtec	1997
Callaway	PWR	Holtec	1997
Koeberg 1 & 2	PWR	Siemens	1996
Fermi 2	BWR	To be determined	1997
Cofrentes	BWR	Sulzer	1995
Maanshan	PWR	Framatome	1994
Santa Maria de Garona	BWR	Siemens	1995
Ginna	PWR	Framatome	1996
Jose Cabrera	PWR	Siemens	1995
Chinshan	BWR	To be determined	1997
Sizewell B	PWR	Holtec	1997

Table 3. Plants opting for dry storage

Plant	Type	Contractor	Year
Susquehanna	BWR	Vectra	1994
North Anna	PWR	TN	1993
Point Beach	PWR	SNC	1992
Rancho Seco	PWR	Vectra	1993
ANO	PWR	SNC	1992
Oyster Creek	BWR	Vectra	1993
Davis Besse	PWR	Vectra	1993
Dresden 1	BWR	Holtec	1995
Yankee Rowe	PWR	NAC	1996
Trojan	PWR	SNC	1995
Peach Bottom	BWR	To be determined	1997
McGuire	PWR	To be determined	1997
Hatch	BWR	To be determined	1997
WNP-2	BWR	To be determined	1997
FitzPatrick	BWR	To be determined	1997

■ Dry storage woes

There is no question that the wet storage industry stands to be buoyed by the recent setbacks experienced in the dry storage industry. Out of five active suppliers of dry storage systems in the US – Holtec, NAC, SNC, Transnuclear, and Vectra – three have been served immediate and stern demands for quality rehabilitation by the US Nuclear Regulatory Commision within the past year (see panel below).

While it is widely believed that the dry storage vendor base will undergo a period of consolidation such that the number of suppliers (judged to be two to three) will be consistent with the industry size, the QA turmoil at three vendors has fostered unease among the prospective customers. Adding to the negatives is the on-again, off-again forays of the US DOE to involve itself in the design and licensing of the so-called Multi-Purpose Canister (MPC) technologies. There is widespread concern in the industry that DOE's attempts to play an active role in the MPC-system development will smother the ongoing active technology race among the cask vendors and subvert the Darwinian selection of the best and fittest via the workings of the market.

In fairness, we should add that the concept of the Multi-Purpose Canister introduced by the DOE in 1993 helped standardise packaging approaches for high level waste and usher in the era of technical innovation in dry storage. The utilities, always uncomfortable with storage-only systems, saw the new MPC-based technologies as the permanent solution to their spent fuel problems. A measure of focus and direction was established in the backend of the nuclear fuel cycle. However, by intervening in the evolution of the MPC technology itself, the DOE, in our opinion, may be overreaching beyond the realm of its effectiveness – a common tendency for publicly funded bodies.

Table 4. Storage density comparison among various PWRs

Plant	Storage density*
D C Cook (Westinghouse PWR)	84.3%
Sequoyah (Westinghouse PWR)	88.7%
Waterford (CE PWR)	91.6%
Arkansas Nuclear One (B&W PWR)	91.4%
Davis Besse (B&W PWR)	90.8%

Table 5. Storage density comparison among various BWRs

Plant	Storage density*
Duane Arnold	85.4%
Nine Mile Point 1	77.0%
Limerick	84.6%
Hatch	88.9%

*Ratio of storage cell area to pool space occupied by each storage location

There is little reason to doubt that the quality problems being faced by the dry storage industry will, over time, be rectified and the industry will once again restore its image of unimpeachable quality. The present turbulence has, however, forced several utilities to postpone dry storage procurement and secure limited wet storage capacity expansion to tide them over by meeting immediate storage needs. This should give a modest boost to the wet storage business.

Another fillip to wet storage is coming from the growing understanding among utility executives that their pool real estate is underutilised, which is the case in a vast majority of the plants. The disparity in the ways different utilities are utilising spent fuel pool floor space becomes apparent when we compare storage densities achieved by the industry leaders, see Tables 4 and 5.

The Boraflex problem

A further reason for the recent revival in reracking is the problem of degrading Boraflex (see *NEI*, March 1997, p29). Boraflex is a silicone-based polymer which was heavily marketed in the industry in the late 1970s by Chicago based Brand Inc. Over 30 nuclear plants in the US and overseas employed Boraflex in their racks (Table 6). Unfortunately, Boraflex has failed to live up to its manufacturer's assertions with respect to its gamma and neutron exposure resistance. Underwater blackness tests (neutron logging) by Holtec International to monitor the continued integrity of irradiated Boraflex in spent fuel pools have shown evidence of widespread rupture, gap formation, and edge degradation.

Utilities have responded to the Boraflex degradation problem in two ways: either rerack the pool using the proven neutron absorber, Boral; or carry out partial reracking by replacing those racks which are used to store freshly discharged fuel, in each outage, with Boral-equipped racks. The result has been a minor boomlet in rerackings.

RESILIENCE OF THE WET STORAGE INDUSTRY

Table 6. Plants using Boraflex for high density racks

Site	Plant type
Point Beach 1 & 2	PWR
Nine Mile Point 1 & 2	BWR
Oconee 1, 2, & 3	PWR
Prairie Island 1 & 2	PWR
Calvert Cliffs 1 & 2	BWR
Quad Cities 1 & 2	BWR
Fermi 2	BWR
H B Robinson 2	BWR
River Bend 1	BWR
Rancho Seco 1	PWR
Shearon Harris 1	PWR
Millstone 2 & 3	PWR
Grand Gulf 1	BWR
Oyster Creek	BWR
V C Summer	PWR
Diablo Canyon 1 & 2	PWR
Byron 1 & 2	PWR
St Lucie 1	PWR
Turkey Point 3 & 4	PWR
Indian Point 2	PWR
Ulchin 2 (Korea)	PWR
Farley 1	PWR
North Anna 1 & 2	PWR
Beaver Valley 2	PWR
Tihange 3 (Belgium)	PWR
Doel 4 (Belgium)	PWR
Seabrook 1 & 2	PWR
Comanche Peak 1 & 2	PWR
Caorso (Italy)	BWR
Pilgrim 1	BWR
Peach Bottom	BWR
Braidwood 1 & 2	PWR
La Salle 2	BWR

Problems with dry storage and Boraflex degradation are important factors affecting the demand for reracking, but the bulk of the wet storage implementation projects in the late 1990s have resulted from advances in wet storage technology.

Twenty years ago, most industry analysts predicted the demise of the wet storage industry by the mid-1980s, echoing the conventional wisdom that all that could be done with pool capacity expansion would have been done by then. Their prophecy turned out to be as misplaced as the proposal by a leading scientist at the turn of the century to close the US Patent Office "because everything that had to be discovered had already been discovered." Thanks to certain key technology breakthroughs, it has been possible to compress the storage to levels which correspond to the spacings in the reactor. The achievable storage densities (ratio of storage cell area to pool area occupied by each storage location) are:

- 91.6% in Westinghouse, Siemens, and Framatome pools.
- 88.9% in BWR pools.

If a plant has a lower density of storage than these figures, then it is a potential candidate for further in-pool capacity addition. Several plants in the USA have taken advantage of the continuous improvements in wet storage technology, eg James A Fitzpatrick and Millstone 1 (Fig 2).

There have been an array of innovations in the underlying technologies. We will limit ourselves to discussing the key developments.

Detuned rack designs

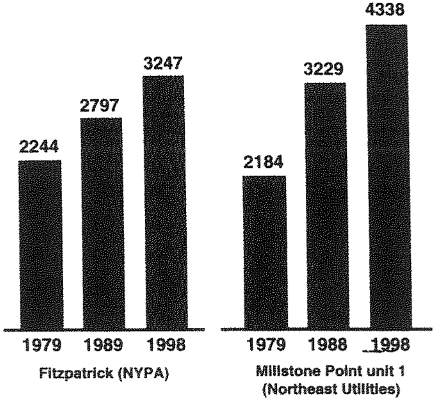
Rack-to-rack gaps, necessary to ensure that they will not impact each other during seismic events, are essentially wasted space in the fuel pool. To minimise this space, the designer must engineer the rack modules so they move less during a seismic event. Even though freestanding racks are not linear structures, Holtec's dynamicists discovered in the late 1980s that a rack custom designed for a nuclear plant can be "detuned" from the dominant excitation frequencies of the site. The detuned racks were found to sustain a fraction of the displacements and stresses experienced by the "prior art" racks. The detuning technology, which is the intellectual property of Holtec International, has been responsible for at least a 15% increase in storage capacity in the fuel pools where it has been deployed.

Manufacturing precision

From a structural standpoint, spent fuel racks are quintessential weldments. A typical spent fuel rack contains as much as a mile (or more) of weld. Such a large quantity of weld plays havoc with the dimensional stability of the rack. But some manufacturers, notably UST&D of Pittsburgh, have tamed the scourge of welding distortion successfully.

A typical high-density rack fabricated by UST&D is vertical and straight to within 1/16in, compared with 3/16in and 1/4in a decade ago. Such strides in manufacturing precision have been a great help to designers in compacting storage capacities.

Fig 2



▲ *Incremental pool capacity expansion at two typical plants.*

WPMR technology

Whole Pool Multi-Rack technology, developed in 1988, gave seismic analysts for the first time the ability to accurately simulate the dynamic behaviour of all racks in the pool under stipulated seismic events. The advent of WPMR technology, simulating the three-dimensional motion of the modules and the interplay of hydrodynamic coupling forces among them, gave the rack designers, for the first time, the ability to iterate on the rack aspect ratios, inter-rack spacings, and rack support pedestal locations to maximise the cell count. The underpinnings of WPMR technology were created by Dr Burton Paul of Holtec International, who devised the multi-body fluid coupling theory and conducted extensive experiments to corroborate the theory. The WPMR technology took the guesswork and empiricism out of rack dynamic analysis and gave the rack designers a powerful tool to optimise pool storage.

Computational fluid dynamics

Thermal-hydraulic concerns were a major impediment to increasing the storage capacity density of spent fuel pools. However in the past five years, implementation of three-dimensional computational fluid dynamics algorithms to spent fuel pools has helped articulate the temperature and flow field in the pools to unprecedented levels of accuracy. Spent fuel pools are therefore now optimised for thermal fields as well as stress fields (under seismic loadings).

Pool structure evaluation

Spent fuel pool structures were historically designed to meet the strength limits of ACI-349 or ACI-318. When equipped with freestanding racks, a governing loading condition arises from the dynamic action during seismic events. By developing and implementing a 3-D dynamic model of reinforced concrete pool structures, it has been possible to demonstrate the viability of densifying storage in elevated pools which were otherwise considered to have reached their structural limit.

Boral

Behind many technology advances, there is a breakthrough in materials technology. For wet storage, Boral epitomises the materials breakthrough. Commercially introduced in 1956, Boral has been the mainstay of the wet storage industry, even as other neutron absorbers have come and gone.

Boral is a metallic composite of a hot-rolled (sintered) aluminium matrix containing boron carbide sandwiched between and bonded to Type 1100 Al plates. Boron carbide (B_4C) is an extremely stable and inert chemical compound which does not react* with any materials found in spent fuel pools. Consequently, the corrosion properties are determined entirely by the Al, which is well known to have very good corrosion resistance in neutral or slightly acid water. In water (or boric acid solutions), metallic Al reacts (oxidises) to form a strong and impervious layer of hydrated Al oxide ($Al_2O_3 \cdot 3H_2O$) which passivates the Al and protects it from further reaction. Long-term resistance to corrosion is therefore excellent as indicated in numerous corrosion and engineering handbooks. The tightly-adhering impervious layer of oxide on the aluminium also blocks or inhibits any electrolytic (galvanic) corrosion in contact with steel in spite of the difference their oxidation potentials (emf). Occasional small pits have been observed in the surface of the Al cladding, although these small pits have no effect on the intended performance of the Boral. They are attributed to minor imperfections or occlusions in the metal that allow localised galvanic corrosion to occur before the defects are sealed in the passivation process.

The Al cladding on the Boral serves two principal purposes: as a lubricant in the hot-rolling process; and to facilitate handling of the long narrow panels during manufacture and assembly. Once installed in the racks and supported between stainless steel plates, the integrity of the Al cladding is no longer of major significance. Boral is a very rugged material, with properties akin to those of a carbide grinding wheel, and, like a grinding wheel, it is very difficult to machine or drill, but will break if bent excessively. The Al clad helps to prevent bending of the Boral during handling of panels and assembly of racks.

In 1988, following cases of swelling in non-Holtec-supplied racks, Holtec and AAR Advanced Structures developed and implemented an extensive testing campaign aimed at uncovering the cause and developing corrective actions.

As a consequence of the testing programme and implementation of the (proprietary) Holtec specifications and procedures Boral has performed extremely well in spent fuel pool applications and Holtec International has standardised on it as the preferred neutron absorber for fuel racks. There are now tens of thousands of storage cells in use and, after years of in-pool service, no operational problem has been experienced in any Holtec-supplied Boral rack, while attempts to find alternatives to Boral have generally been unsuccessful (see panel).

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*B_4C is stable against hot concentrated acids and is only slowly attacked by molten NaOH or $NaHCO_3$.