LWR SPENT FUEL STORAGE TECHNOLOGY: ADVANCES AND EXPERIENCE

E. R. Gilbert, W. J. Bailey, A. B. Johnson, Jr., and M. A. McKinnon
Pacific Northwest Laboratory
P. O. Box 999
Richland, Washington 99352 USA

ABSTRACT

By 2003, the year the U.S. Department of Energy (DOE) currently predicts a repository will be available, 58 domestic commercial nuclear-power plant units are expected to run out of wet storage space for LWR spent fuel. To alleviate this problem, utilities implemented advances in storage methods that increased storage capacity as well as reduced the rate of generating spent fuel. Those advances include 1) transshipping spent-fuel assemblies between pools within the same utility system, 2) reracking pools to accommodate additional spent-fuel assemblies, 3) taking credit for fuel burnup in pool storage rack designs, 4) extending fuel burnup, 5) rod consolidation, and 6) dry storage. The focus of this paper is on advances in rod consolidation and dry storage.

Wet storage continues to be the predominant U.S. spent-fuel management technology, but as a measure to enhance at-reactor storage capacity, the Nuclear Waste Policy Act of 1982 authorized DOE to assist utilities with licensing at-reactor dry storage. Information exchanges with other nations, laboratory testing and modeling, and cask tests cooperatively funded by U.S. utilities and DOE produced a strong technical basis to develop confidence that LWR spent fuel can be stored safely for several decades in both wet and dry modes. Licensed dry storage of spent fuel in an inert atmosphere was first achieved in the U.S. in 1986. Studies are underway in several countries to determine acceptable conditions for storing LWR spent fuel in air.

Rod-consolidation technology is being developed and demonstrated to enhance the capacity for both wet and dry storage. Large-scale commercial implementation is awaiting optimization of practical and economical mechanical systems.

INTRODUCTION

The fuel cycle for the U.S. commercial nuclear power industry initially included reprocessing spent fuel from light water reactors (LWRs) after a short cooling period in wet storage, i.e., in the water-filled spent-fuel storage pool at the reactor site. Commercial reprocessing, though, has not been available in the U.S. after 1971; therefore, spent fuel is not being removed from the storage pools for reprocessing as planned, so it continues to accumulate at reactor storage sites.

Without expanded storage capacity, 13 nuclear generating units out of the 108 units now operating, are predicted to reach the existing spent-fuel storage capacity by 1993, and 42 units will reach that point by the beginning of 1998. By 2003, the year the DOE draft Mission Plan Amendment currently predicts a repository to be available, existing wet-storage space at 58 domestic commercial nuclear power plant units now in operation (1) will be filled.

Several methods being employed by U.S. utilities to augment and extend the existing spent-fuel storage capacity are described in this paper. The methods include:

1) transshipping of spent fuel from one unit to another within the same reactor system,
2) reracking spent-fuel storage pools,
3) taking credit for burnup, and
4) extending fuel burnup.

Two other methods are being developed through cooperative activities between the U.S. utilities and the DOE in which the Pacific Northwest Laboratory (PNL) is participating. Included are testing and analysis of dry storage and rod consolidation.

SPENT-FUEL INVENTORY AND PROJECTIONS

The five fuel vendors that provide nuclear fuel for U.S. commercial plants indicate that as of the end of 1986 over 12 million fuel rods in over 109,000 fuel assemblies had been irradiated in commercial nuclear power reactors. Six fuel assemblies have reached unusually high burnups of 52,000 MWd/MTU or higher. Overall domestic fuel-operation experience continues to be excellent; current fuel-rod reliabilities are typically 99.99%, which corresponds to fuel rod failure rates of % (2). Average burnup levels have been increasing yearly; however, fuel-rod failure rates have not exhibited a similar trend. Evidence to date suggests that extending burnup has not been detrimental to fuel performance.

At the end of 1986, over 50,000 spent-fuel assemblies (60% BWR type and 40% PWR type) were stored in facilities at U.S. commercial nuclear power plants (1). Nearly all of the assemblies are still in wet storage. Among them are 101 assemblies that are involved in R&D programs some of which are in dry storage.

WET STORAGE

Irradiated fuel has been stored in water pools in the U.S. since the first reactors were built in 1943 (3). Its behavior in wet storage and experience with pool components have been the subjects of many reviews (3, 4, 5, 6, 7, 8, 9, 10). A guidebook on spent-fuel wet storage has been published by the International Atomic Energy Agency (11).

ENHANCING EXISTING STORAGE CAPACITY

U.S. utilities have moved aggressively to optimize wet-storage technology, assisted in some areas by federal programs. Since passage of the NWPA of 1982, DOE and utilities have been actively developing and evaluating candidate methods for expanding spent-fuel storage capacities at reactor sites. Studies indicate that one option, expanding the physical size of wet storage in reactor pools by enlarging an existing pool or by constructing another pool, is not a viable solution because it costs too much and takes too long (12). Therefore, several other methods have been and are being explored and developed, and some are now being used, including 1) rod consolidation, 2) transshipping spent fuel between pools operated by the same utility, 3) reracking pools, 4) taking credit for fuel burnup in pool storage-rack designs, and 5) extending fuel burnup. A promising method is rod consolidation.

ROD CONSOLIDATION

Rod consolidation provides more efficient use of existing space in spent-fuel storage pools and could also improve space use in dry-storage Interim Spent Fuel Storage Installations (ISFSI). Involved is mechanically removing all the fuel rods from the fuel assembly hardware that normally maintains rod-to-rod spacing and placing the fuel rods in a close-packed array in a canister. The objective is to combine the fuel rods from two spent-fuel assemblies into one canister that has the same exterior dimensions as a standard fuel assembly, to achieve a consolidation or compaction ratio of 2 to 1.

The nonfuel-bearing components (NFBC) of a fuel assembly, such as spacer grids, guide tubes, and end fittings, may be compacted to reduce their volume by a factor of 10 to 1 or 20 to 1. A 2 to 1 rod-consolidation ratio in conjunction with a 10 to 1 NFBC compaction ratio results in reducing the number of pool or dry-storage locations needed from the original 10 to 6 (5 for fuel, 1 for NFBC). The equivalent of 1.67 fuel assemblies can then be stored in the same space previously occupied by only one unconsolidated fuel assembly. In general, rod-consolidation operations do not appear to result in significant damage to the fuel cladding.

DRY STORAGE

Dry storage is an advancement in the storage of spent fuel that has been licensed in the U.S. and in several other countries as an alternative to extended wet storage of spent fuel. Two types of atmospheres are being developed: nonreactive gases such as nitrogen or inert gases [inert dry storage (IDS)] and air (oxidizing). Important factors in the licensing were tests and demonstrations conducted before regulatory requirements for dry storage were established. These began as early as 1964. These early experiences in the development of dry-storage technology involved numerous cold and hot demonstrations with vaults, concrete silos, dry wells, and metal casks. They were performed in the temperature range of ambient to approximately 800°C; some were extended to periods in excess of 5 years. This experience has been summarized in Johnson and Gilbert (13), and Johnson, Gilbert, and Oden (14) and later updated in Cunningham et al. (15).

STORAGE IN INERT GAS

The licensing of interim dry storage requires assurance that the release limits of radioactive materials are not exceeded. Because of the potential for degradation of spent fuel by UO_2 oxidation through reactor-produced cladding breaches, dry storage was first licensed for inert or nitrogen atmospheres. The extent to which Zircaloy cladding can be relied on as a barrier to the release of radioactive spent fuel and fission products depends on its integrity. The possible breach of the cladding by creep rupture is considered the most limiting phenomenon in IDS. Current experience, however, indicates that the incidence of fuel cladding failures during IDS will be low, though some cladding failures cannot be ruled out.

The principal potential Zircaloy cladding breach mechanisms during IDS were identified as creep rupture, stress corrosion cracking, and delayed hydride cracking. The dominant mechanism found was stress rupture. Cladding breach due to stress corrosion cracking and delayed hydride cracking is not expected the threshold stress intensity levels for these mechanisms are greater than those estimated to exist in spent-fuel cladding (15).

The internal pressure from helium and fission gases can be a source for stress rupture, if pressures and temperatures are sufficiently high. Consequently, the condition of spent-fuel cladding during up to 40 years of licensable interim dry storage must be predicted. To develop this prediction, theoretical deformation and fracture theory was used to develop cladding fracture maps. Where available, experimental deformation and fracture data for Zircaloy cladding materials were used to test the validity of the maps. Predictive equations were developed, and cumulative damage methodology was used to take credit for the declining temperature. This methodology was then applied to predict storage temperatures below which creep rupture would not to occur, except in fuel rods with pre-existing flaws. Because the pin-hole cracks tend to be small in diameter (typically, less than μ10 m) and because there are no strong convection currents of gas flowing.

CONSEQUENCES OF CLADDING FAILURE

Cladding temperature limits for IDS of spent-fuel were derived on the basis that cladding breach by stress rupture should involve less than 0.5% of the spent-fuel rods. The possibility of a few failures is considered acceptable because of the low consequence in IDS of a cladding breach. The mechanism of cladding breach by stress rupture leads to a pin-hole penetration through the cladding. Because the pin-hole cracks tend to be small in diameter, (typically, less than 10 μm) and because there are no strong convection currents of gas flowing through the cracks, confinement of the fuel by the cladding is not compromised. The driving force for continued cracking and enlargement of the breach would be the internal gas pressure. However, the internal gas pressure is reduced in response to gas leakage through the pin-hole breach until the mechanism for continued cracking is eventually deactivated. After the gas pressure is relieved, the remaining stresses are too low for continued cladding degradation.

RECOMMENDED STORAGE CONDITIONS

To accommodate the effects of variations in fuel design, burnup level, fuel age, and the geometry and makeup of IDS casks, a model was developed and used to predict temperature limits for IDS conditions (15). Database predictions regarding the time-to-breach at various storage temperatures were needed to evaluate the feasibility of dry storage. With the new model, predictions of cladding integrity can be made for specific storage periods and temperature conditions. A computer code was developed from the model to predict allowable temperature/stress limits for storage in inert gases and nitrogen and has been documented as DATING: Determination of Allowable Temperatures in Inert and Nitrogen Gases. The code is available through the National Energy Code Center at Argonne National Laboratory.

The methodology and model used in DATING is based on creep strain and breach of Zircaloy spent-fuel cladding during dry storage. The model

predictions are presented as a family of generic limit curves in Fig. 1 for fuel that has been out of reactor for 5, 6, 7, 10, and 15 years. The effect of the internal gas pressure is reflected in the initial cladding stress at dry-storage temperatures. Predictions using the model have been demonstrated to correlate reasonably well with published deformation and creep rupture data (16).

U.S. CASK TESTS

Tests and demonstrations with spent fuel in metal casks--BWR spent fuel in the MSF-IV (REA-2023) cask (18), and PWR spent fuel in the Castor V/21 (19), TN-24P (20), and MC-10 (21) casks--provided valuable thermal performance data and experience with handling and storing spent fuel. The tests and demonstrations on metal casks have also provided important information regarding spent-fuel behavior during dry storage (22). In a few cases, Krypton-85 monitoring of cover gases provided evidence of one or more leaking rods. The slow rate of Kr-85 release from cladding breaches that developed during dry storage and the difficulty of detecting these breaches during visual inspections of the fuel indicate that the breaches were very small pin-hole leaks that did not compromise confinement of spent UO_2 fuel. There are no known mechanisms for these breaches to grow during storage in an inert storage atmosphere. The major conclusion is that cladding behavior was satisfactory in the dry-storage tests and demonstrations.

A significant increase in the number of leaking fuel rods during dry storage in the TN-24P cask resulted from the rod-consolidation process in which approximately 9,800 spent-fuel rods were pulled from 48 PWR assemblies and

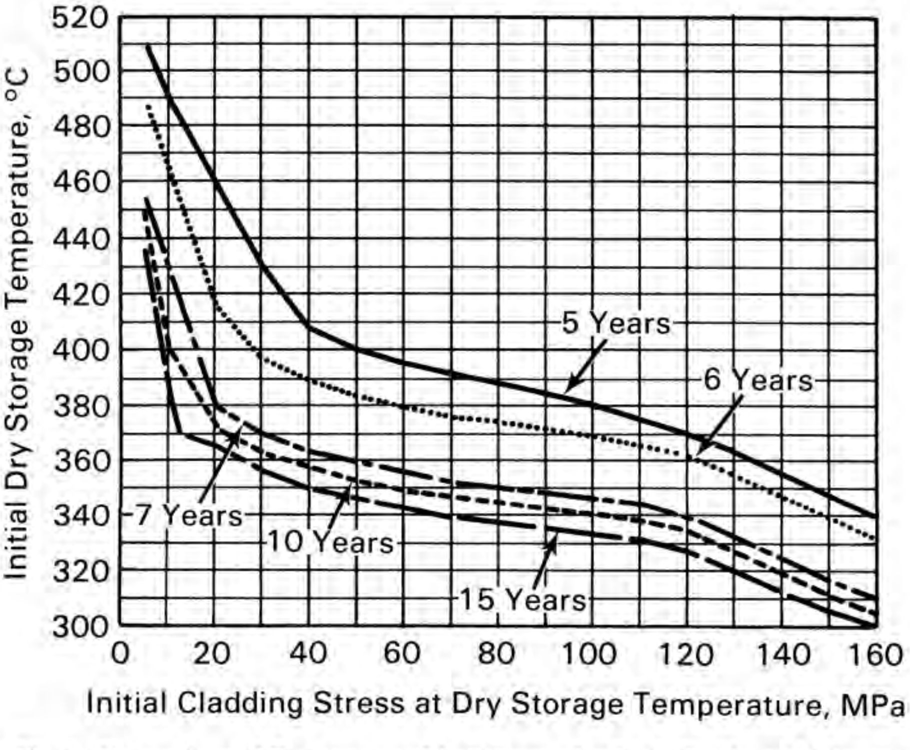

Fig. 1. Comparison of Temperature Limit Curves for 5-, 6-, 7-, 10-, and 15-year Fuel Age (17).

loaded into canisters. Visual observations and exhaust gas monitoring of the air in the vicinity of the consolidation equipment did not reveal fuel rods with cladding breaches during the consolidation process. During the process, breakaway forces ranged up to 35.8 kg (79.9 lb) and occasional bowing of rods resulted during attachment of the rod gripper.

Analyses of gas samples taken from the TN-24P cask containing the consolidated fuel revealed that up to seven out of 9,800 spent-fuel rods developed breaches during the first few months of dry storage (20). Another gas sample taken a few months later revealed an increased Krypton-85 concentration corresponding to release from an additional four spent-fuel rods. The implications are that the cladding breaches resulted from propagation of incipient cracks after the consolidated fuel heated up in the TN-24P cask. The stresses imposed on the cladding by the pulling and flexing operations during the consolidation process caused the cracks to extend. A few cracks apparently grew during the dry storage at elevated temperatures until they extended through to the surface of the cladding.

Peak fuel temperatures in helium during vertical tests of consolidated spent fuel in the TN-24P cask were, however, essentially the same as for intact fuel (211°C for consolidated fuel versus 214°C for intact fuel). Therefore, the higher fuel failure rate during storage of consolidated fuel cannot be attributed to differences in storage temperature. However, the major conclusion is that these small cracks did not compromise fuel handling and storage operations and the cladding behavior was satisfactory in the dry-storage tests and demonstrations.

STORAGE IN AIR

The main issue remaining for dry storage is prevention of gross degradation of the cladding while spent-fuel rods are stored in air prior to its final disposal. Oxidation of the spent UO2 to low density U3O8 or UO3 powder at the site of a cladding breach can cause propagation of the breach and a potential for release of respirable-size fuel powder. Even though less than 1% of the spent-fuel rods are breached, the oxidation reaction must be minimized during periods of storage, shipping, and handling when the fuel could be exposed to air. Gross degradation of the cladding through oxidation of the spent UO_2 to low-density U3O8 powder must also be prevented during transportation operations.

Because there were no data on the oxidation behavior of LWR spent fuel to provide guidance in developing acceptable storage conditions in an oxidizing atmosphere, testing was initiated in 1982 under the Commercial Spent Fuel Management Program (CSFMP) supported by the U.S. DOE Office of Civilian Radioactive Waste Management. The purpose of the testing at PNL is to determine the allowable storage temperature of spent nuclear fuel in air.

The data being generated in the spent-fuel oxidation test include 1) bare-UO_2-pellet weight gain as a function of time, temperature, and spent-fuel characteristics; 2) rod-segment weight gain and diametral strain as a function of time, temperature, and spent-fuel characteristics; and 3) observation/analysis of spent-fuel microstructural changes as a function of oxidation.

The UO_2 oxidation data being collected are needed to determine 1) the limiting conditions and system designs for dry storage of spent fuel in air; 2) the period and frequency for which monitoring IDS under low-temperature/long-term conditions will be required; 3) the limiting operating conditions and system designs for fuel handling, transportation, rod consolidation, and lag storage operations in air; and 4) the effects of abnormal storage conditions on fuel integrity following an incident.

CONCLUSIONS AND RECOMMENDATIONS

The following are conclusions and recommendations derived from the foregoing review:

- Wet storage continues to be the predominant spent-fuel storage method for the growing inventory of spent fuel in the United States and several other countries.
- Significant progress by U.S. utilities and DOE in solving spent-fuel storage problems has been realized through a variety of innovative approaches, e.g., developing rod consolidation.
- Rod consolidation of LWR spent fuel has been demonstrated on a limited basis in the U.S., but no production-scale campaigns have been conducted. Further advances in the development and demonstration of the practicality and economics of consolidation systems is needed to make them attractive for large-scale use.
- Recommended spent-fuel temperature-time conditions are expected to limit cladding breaches in fuel rods during dry storage in inert gas to less than 0.5% of the rods. If breaches occur during dry storage, they will consist of pin-hole cracks that do not compromise fuel confinement.
- Testing and modeling are under way to determine acceptable conditions for spent-fuel exposure to air.

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