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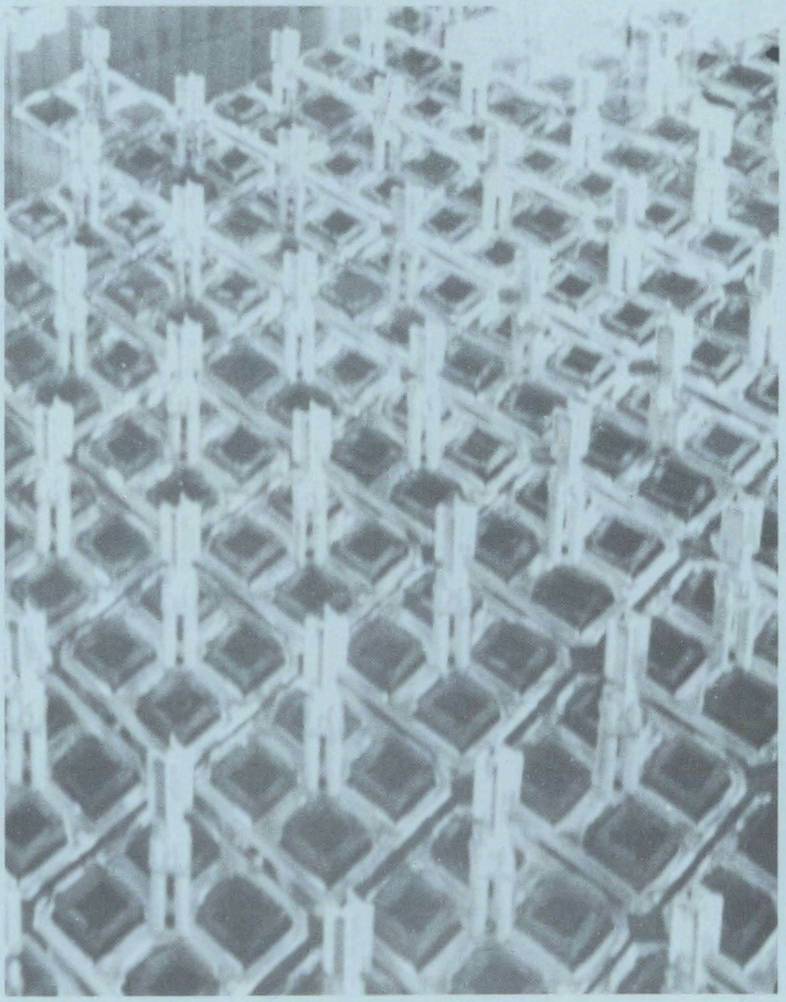
Status of Rod Consolidation

April 1985



Prepared for the U.S. Department of Energy
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STATUS OF ROD CONSOLIDATION

W. J. Bailey

April 1985

Prepared for
the U.S. Department of Energy
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Pacific Northwest Laboratory
Richland, Washington 99352

I. SUMMARY

Several rod consolidation systems have been demonstrated in the United States with simulated boiling water reactor (BWR) and pressurized water reactor (PWR) fuel. The first U.S. consolidation of irradiated fuel was successfully demonstrated with four PWR fuel assemblies at the Oconee Nuclear Station in October-November 1982(1-3) and with one PWR fuel assembly at Maine Yankee in August 1983.(4) Maine Yankee has received approval from the U.S. Nuclear Regulatory Commission (NRC) to consolidate up to 20 fuel assemblies.(5) There are two other upcoming rod consolidation demonstrations with irradiated fuel.(6) Twelve spent BWR fuel assemblies are to be involved in a demonstration at the Brown Ferry Nuclear Power Plant (equipment was delivered to the site in June 1983) under an interagency agreement between the U.S. Department of Energy (DOE) and the Tennessee Valley Authority (TVA). Five to 10 spent PWR fuel assemblies are currently scheduled to be consolidated in 1985 as part of a comprehensive program by Northeast Utilities Service Co. (NUSCO) with support from the Electric Power Research Institute (EPRI) and Baltimore Gas & Electric Co. The objective of the NUSCO program is to develop benchmarked analytical methods and related data on consolidated fuel characteristics to support licensing of the storage of consolidated fuel in a nuclear spent fuel pool and to demonstrate fuel consolidation with production-scale equipment and processes. Consolidated spent fuel will also be involved in the Virginia Electric and Power Company (VEPCO)/DOE-sponsored dry storage demonstration(6,7) at the Idaho National Engineering Laboratory (INEL), Idaho Falls, Idaho.

There has been no experience with extended wet or dry storage of consolidated fuel rods; however, problems are not expected.(8) One canister loaded with consolidated fuel rods (2:1 consolidation ratio) has been in wet storage at the Oconee Nuclear Station since the fall of 1982. It could serve as a lead test canister for future licensing activities. Acceptable dry storage conditions for consolidated fuel have yet to be defined.(9)

Results obtained by using the structural analysis methods that are employed for current operating licenses indicate that some spent fuel storage pools lack sufficient structural capacity for the additional weight associated with consolidated fuel. Use of more advanced analytical methods (i.e., finite element structural analysis techniques) has yielded results in one site-specific study(10) that indicated that structural modifications to the pool slab are not needed at that specific site to accommodate high-density spent fuel storage racks and consolidated fuel. Application of the advanced technique to the reanalysis of other pools has not been demonstrated yet.

The trend of favorable experience in the United States and other countries with spent fuel during handling and reconstitution operations should extend to rod consolidation. The frequency of unusual occurrences involving fuel damage from handling and transporting operations has been low and major mechanical damage has been sustained by only a few of the associated fuel assemblies.

A number of economic studies on rod consolidation and costs for storing consolidated fuel have been published recently. An economic assessment of five processes (one of which was disposal of unmodified spent fuel) is described in a 1984 report.(11) In that study, rod consolidation was judged to be the preferred process. Valid cost comparisons of eight spent fuel storage options, including rod consolidation, can be made as result of a recent EPRI-sponsored study that is discussed in a 1984 report.(12)

Two of the factors that need to be taken into account with rod consolidation are a) the effects on rods from their removal from the fuel assembly and b) the effects on rods as a result of the consolidation process. Potential components of both factors are described in the report. Discussed under (a) are scratches on the fuel rod surfaces, rod breakage, crud, extended burnup, and possible cladding embrittlement due to hydrogen injection at BWRs. Discussed under (b) are the increased water temperature (less than 10°C) because of closer packing of the rods, formation of crevices between rods in the close-packed mode, contact with dissimilar metals, and the potential for rapid heating of fuel rods following the loss of water from a spent fuel storage pool.

Another factor that plays an important role in rod consolidation is the cost of disposal of the nonfuel-bearing components of the fuel assembly. Also, the dose rate from the components--especially Inconel spacer grids--can affect the handling procedures.

Several licensing issues that exist are described.

A list of recommendations is provided.

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FIGURES

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II. INTRODUCTION

Several light-water reactors (LWRs) in the United States will reach their presently authorized spent fuel storage pool capacities by 1984-1986. The U.S. Department of Energy (DOE) recently estimated the number of U.S. commercial LWRs that will need additional spent fuel storage capacity.(13-17) The U.S. Nuclear Regulatory Commission (NRC) has also examined spent fuel storage needs and generally agrees with DOE's assessment.(14,18) During the period from 1984 through 1990, DOE estimates that between 8 (assuming maximum reracking and full intra-utility shipments) and 23 LWRs (assuming maximum reracking only) will require additional space. Rod consolidation was not included in either of these DOE estimates because it is not yet a licensed technology for general application. However, four spent PWR fuel assemblies at the Oconee Nuclear Station and one spent PWR fuel assembly at Maine Yankee have been consolidated. Rod consolidation involves mechanically removing the fuel rods from the fuel assembly hardware and placing them either in another grid with closer spacing or in a close-packed array in a canister without a spacer grid. Of the several methods under investigation to supplement conventional wet storage[a] methods, rod consolidation[b] is a leading candidate for more efficient utilization of existing space in storage pools (rod consolidation also represents the base case for geologic disposal of unreprocessed spent fuel).(11,19) Rod consolidation has the potential to be applied to dry storage of LWR fuel.

Economic studies on rod consolidation and costs for storing consolidated fuel have been published by several authors.(10-12,21-25) A recent report(11) contains the results of an evaluation, using the disposal of unmodified spent fuel as the reference process, of these four alternative processes: end fitting removal, fission gas venting and resealing, fuel bundle disassembly and close packing of fuel rods, and fuel shearing and immobilization. The processes were assessed in each of these four areas: technical, operating,

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[a] Storage of spent fuel in water-filled pools is commonly called wet storage.

[b] The term "compaction" is sometimes used interchangeably with the term "consolidation."

safety/risk, and economics. The economic assessment dominated the resultant ranking of the alternatives. The process of fuel bundle disassembly and close packing of fuel rods ranked first as the preferred method. In one paper,(22) the cost of rod consolidation, using a patented system, is stated to be below $5.50 per kilogram of uranium. In an evaluation by TVA of a typical twin-unit PWR station, the results for the median case showed that "...the potential overall savings of an integrated cask system [i.e., a system in which the same cask is employed for storage, transport and disposal] compared to a new pool storage could be as much as $100 million when using consolidated fuel."(20,21) In an EPRI-sponsored study, Boeing Engineering and Construction Co. analyzed eight storage systems: pools, dry wells, vaults, casks, silos, reracking, double tiering, and rod consolidation.(12) EPRI indicates that this comprehensive set of cost data will enable valid cost comparisons for the eight spent fuel storage options to be made by utilities.

Storage of extended burnup and consolidated fuel in casks is discussed in a recent paper that was prepared by Ridihalgh, Eggers and Associates (REA).(26) It is indicated in the paper that designs of spent fuel storage and transport casks to accommodate such fuel are influenced in three key areas: heat dissipation, shielding, and nuclear criticality safety. According to the REA study, the required cooling times between discharge and placement in a cask (assuming the same cask heat load in all cases) would be 5 yr for previous design-basis fuel assemblies, up to 9 yr for extended burnup fuel assemblies, 11.5 yr for 2:1 consolidated fuel rods, and 23 yr for consolidated extended burnup fuel. For spent fuel assemblies, the gamma ray shielding needs are roughly proportional to burnup and inversely proportional to time since discharge. Consolidation of spent fuel has little impact on the gamma ray shielding requirements because of the self-shielding effects. A cask with neutron shielding that was adequate for the previous design-basis fuel would have a total external dose rate that is two or three times higher if extended burnup fuel is contained. Because the extended burnup fuel has a higher initial enrichment than the previous design-basis fuel, spacing changes in casks are needed; hence, it might be necessary to take credit for fuel burnup to reduce storage and transportation costs.

Fuel cladding durability is the most important materials consideration in wet storage technology. As a result, it is important to assess the impact of rod consolidation on the integrity of spent fuel during subsequent storage. In U.S. pools, most (~95%) of the fuel cladding is Zircaloy but a small amount (~5%) is stainless steel.(27) Typical BWR fuel bundle(a) and PWR fuel assembly parameters are shown in Tables 1 and 2, respectively.

The fuel and pool component integrity studies in the Commercial Spent Fuel Management (CSFM) Program(b) provide a useful basis from which to establish an integrity assessment more specific to rod consolidation. The CSFM Program at Pacific Northwest Laboratory (PNL)(c) has conducted investigations of LWR fuel behavior

TABLE 1. Typical BWR Fuel Bundle Parameters

	BWR Fuel Assembly Type		
Rod array	7 x 7	8 x 8	8 x 8R
Number of Fuel rods	49	60 to 63	62
Rod outside diameter, mm	14.30	12.52 to 12.74	12.27
Rod length, m	4.09	3.99 to 4.09	4.20
Fuel bundle weight, kg	272 to 310	← 275 to 322 →	

TABLE 2. Typical PWR Fuel Assembly Parameters

	PWR Fuel Assembly Type			
Rod array	14 x 14	15 x 15	16 x 16	17 x 17
Number of fuel rods	176 to 179	204 to 208	236	264
Rod outside diameter, mm	10.72 to 11.18	10.72 to 10.92	9.70	9.50 to 9.63
Rod length, m	3.71 to 3.87	3.80 to 3.90	4.09	3.85 to 3.88
Fuel assembly weight, kg	485 to 776	564 to 703	650 to 657	656 to 683

(a) The terms "fuel bundle" and "fuel assembly" are used interchangeably by the nuclear industry, although generally the former term is associated with BWRs and the latter with PWRs. A BWR fuel assembly consists of the fuel bundle and the open-ended channel that encloses the bundle.

(b) Sponsored by the U.S. Department of Energy (DOE).

(c) Operated for DOE by Battelle Memorial Institute.

in extended water storage. PNL studies have included examination of the world's oldest pool-stored, Zircaloy-clad fuel; stainless steel-clad fuel that had been stored 5 years in a PWR borated water pool; and defective fuel rods that had failed during reactor service and had been in wet storage for 5 to 8 years. The data base provided by these and related examinations in Canada, the Federal Republic of Germany (FRG), and the United Kingdom indicates that Zircaloy-clad fuel shows no evidence of significant degradation in water storage. Stainless steel-clad fuel has not shown evidence of pool-induced degradation, but there have been a few instances of stress corrosion cracking in other stainless steel components such as PWR spent fuel pool piping(28) and fuel assembly hardware.(29) Measures to avoid stress corrosion cracking regimes have been identified in parametric studies.(30)

The present objective of the CSFM program is to encourage the development of the technology for spent nuclear fuel rod consolidation in existing power reactor water storage basins.

III. DISCUSSION

Discussed below are the current status of rod consolidation; relevant experience with fuel handling, rod removal, and fuel assembly reconstitution; integrity aspects of rods when they are removed from the fuel assembly; and the effects on rods as a result of rod consolidation.

A. CURRENT STATUS OF ROD CONSOLIDATION

Rod consolidation equipment has been developed by several U.S. companies, including: Allied General Nuclear Services (AGNS);(31-34) Nuclear Assurance Corporation (NAC)(35-38) in cooperation with DOE and TVA; U.S. Tool & Die (UST&D), Inc.;(22,39) and Westinghouse Electric Corporation (W).(40) Combustion Engineering (C-E) is responsible for the design, development, and demonstration of the rod consolidation equipment in a program sponsored by the Electric Power Research Institute (EPRI) and Northeast Utilities Service Company (NUSCD).(1) See Table 3 and Table 4.

1. Cold Demonstrations

The AGNS system was successfully demonstrated with Westinghouse PWR 17 x 17 simulated fuel assemblies.(32) The NAC system was demonstrated with six dummy fuel assemblies (representative of all PWR fuel designs) at the AGNS facility.(35) The UST&D equipment was demonstrated with a simulated BWR fuel assembly at the AGNS facility. The Westinghouse system was demonstrated with simulated fuel at Westinghouse's Spartanburg, South Carolina, Service Center.(1) The mechanical cell at the General Electric Morris Operation, which was designed for remote in-air disassembly of spent fuel, has been tested with simulated fuel bundles.(41)

2. Hot Demonstrations

During the period from mid-October to mid-November 1982, the first U.S. consolidation of actual spent fuel was demonstrated at Duke Power Company's Oconee Nuclear Station.(1-3) The consolidation process flow diagram is shown in Figure 1. The demonstration involved the Westinghouse rod consolidation system (Figures 2 through 5) and four Oconee-2 (PWR) fuel assemblies

TABLE 3. Designers and Manufacturers of Consolidation Equipment(4)

Designers[a]	Orientation		Environment		Comments
	Vertical	Horizontal	Wet	Dry	
Nuclear Assurance Corporation (NAC)	X		X		NAC has demonstrated consolidation of six different "dummy" PWR assemblies representing all manufacturers of PWR fuel.
U.S. Tool & Die, Inc.	X		X		Testing was conducted on "dummy" fuel assemblies. In one pulling operation, the fuel rods are funneled into their consolidation container. However, both ends of the container must be sealed after the fuel rods are in the container. A 2:1 consolidation ratio was achieved.
Westinghouse Electric Corporation (W)	X		X		W demonstrated the consolidation equipment on four irradiated PWR fuel assemblies at the Oconee Nuclear Station in 1982. The equipment has built-in rod array control after removal. A 2:1 consolidation ratio was achieved in one canister.
Allied General Nuclear Services (AGNS) Spent Fuel Consolidation at the Barnwell Nuclear Fuel Plant (BNFP)		X		X	The demonstration has shown that dry-remote consolidation is possible. Horizontal consolidation equipment requires a larger floor area but less height than vertical equipment. A 2:1 consolidation ratio was achieved with dummy PWR fuel.

(a) Spent Fuel Storage Seminar sponsored by the Institute of Nuclear Materials Management in January 1984.

TABLE 4. Future Consolidation Endeavors with DOE Participation(4)

Designers[a]	Orientation		Environment		Comments
	Vertical	Horizontal	Wet	Dry	
Allied General Nuclear Services (AGNS) and Nuclear Assurance Corporation (NAC)	X			X	Twelve irradiated BWR fuel assemblies at the Browns Ferry Station are to be consolidated under an interagency agreement between DOE and Tennessee Valley Authority (TVA). The equipment was built for DOE by AGNS, using the detailed design provided by NAC. The equipment was delivered to TVA in June 1983.
Combustion Engineering (C-E)	X		X		The project is planned by Northeast Utilities Service Co. (NUSCO). The demonstration will disassemble 5 to 10 irradiated PWR assemblies. Commencement is currently scheduled for 1985 (DOE and NUSCO are negotiating a cooperative agreement).

(a) Spent Fuel Storage Seminar sponsored by the Institute of Nuclear Materials Management in January 1984.

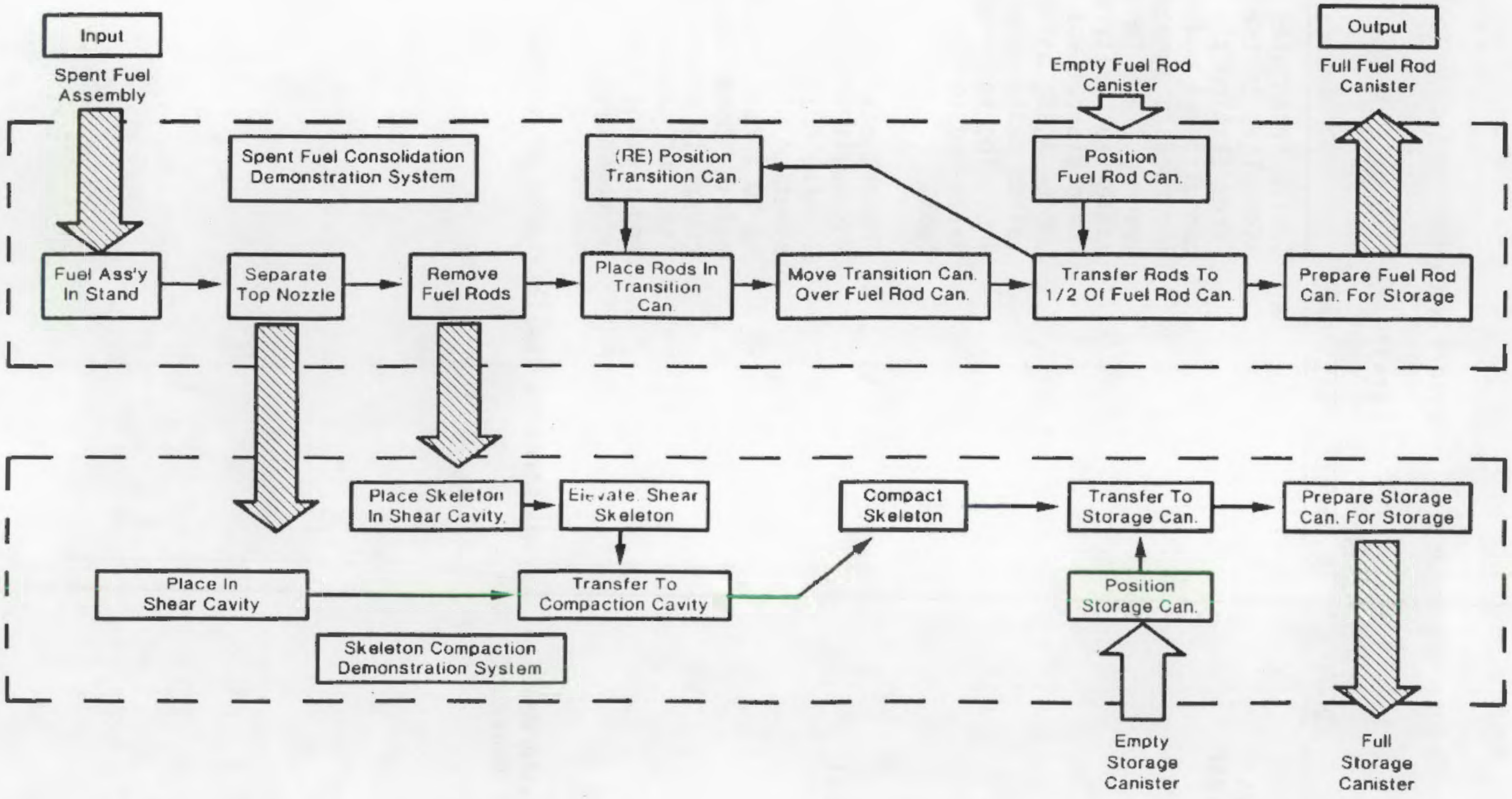

FIGURE 1. Fuel Consolidation Process Flow(2)

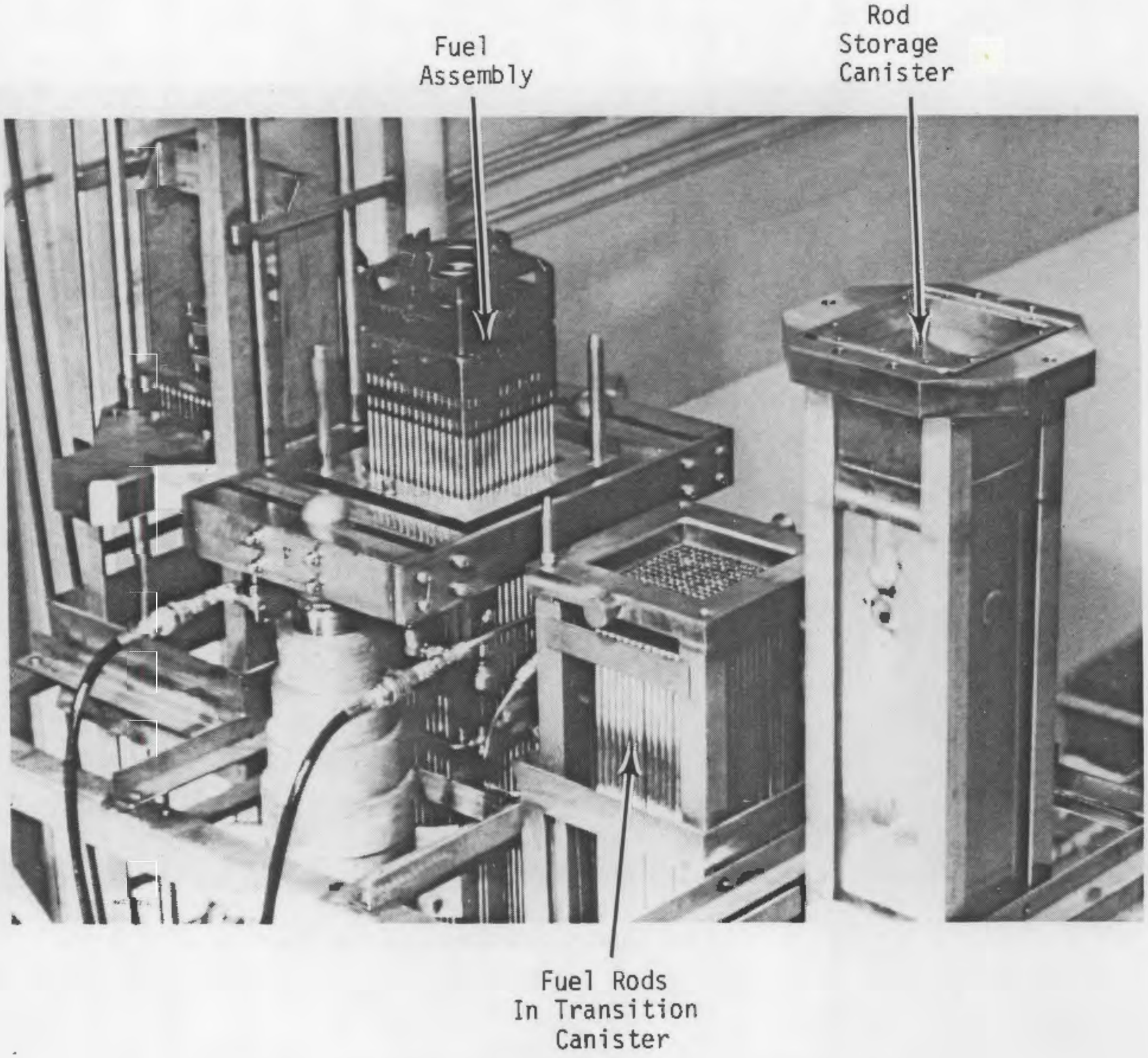

FIGURE 2. Fuel Rod Repackaging Subsystem(2)

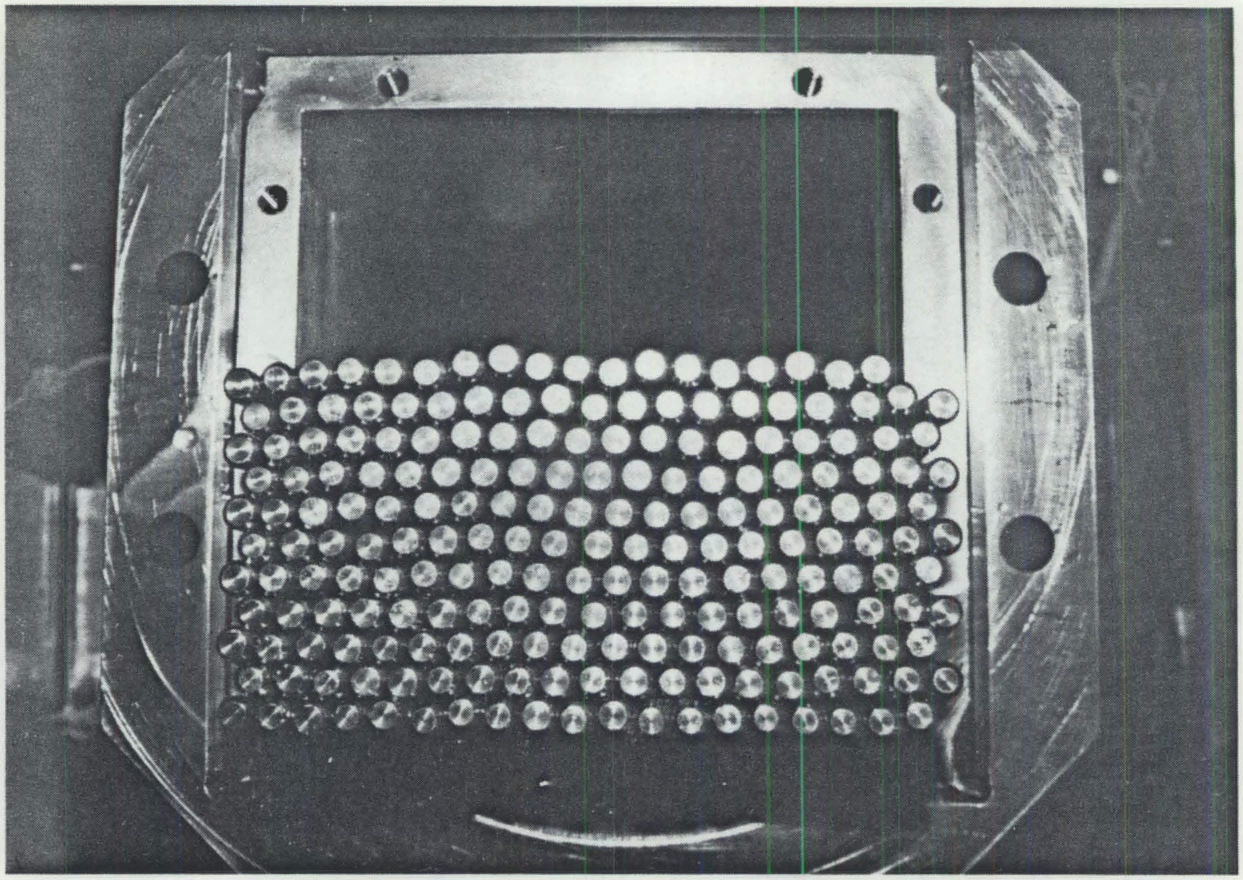

FIGURE 3. Top of Loaded Rod Storage Canister(2)

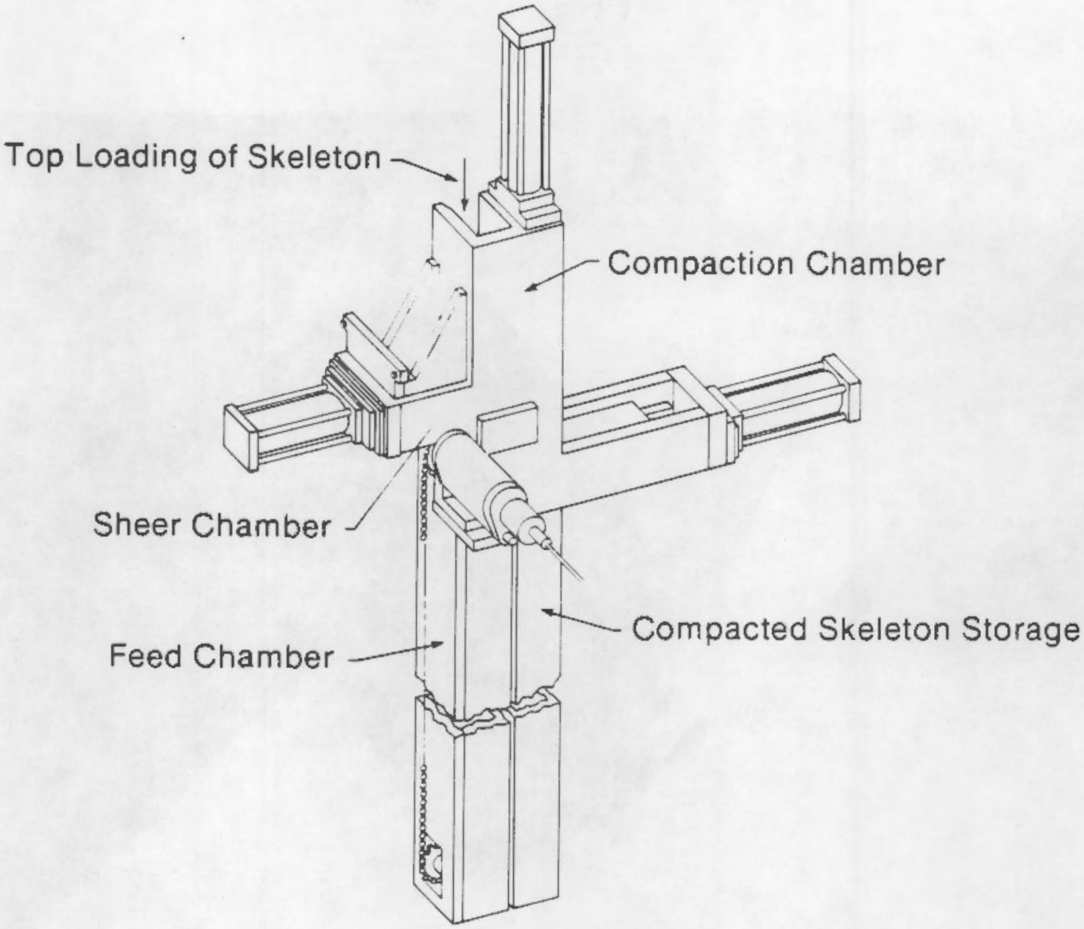

FIGURE 4. Skeleton Compaction Subsystem(2)

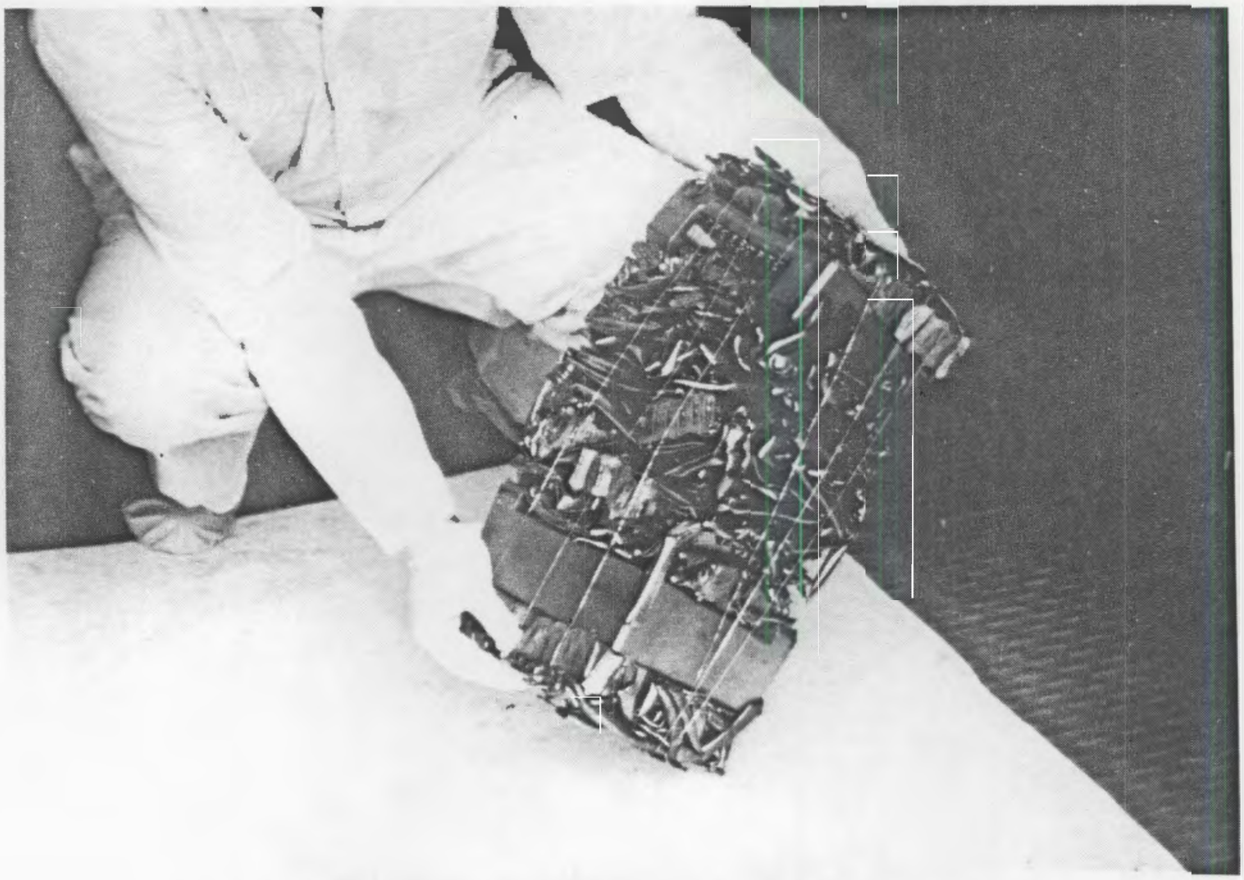

FIGURE 5. Compacted Westinghouse Fuel Bundle Skeleton(2)
(6-to-1 volume reduction)

(Table 5). All the rods in an assembly were pulled simultaneously and consolidated simultaneously;(1,42) a consolidation ratio of 2:1 was achieved in one canister.(2,4) The rod pulling forces are measured and are discussed in Section III, C, 2. The dispersion of crud during pulling of the rods in this demonstration is described in Section III, C, 3. For demonstration purposes, tool operations and movements were controlled manually.(2) With the first two assemblies, some mechanical problems were encountered but were solved.(1-3) The mechanical problems included: auxiliary equipment was needed because of differences between test conditions and actual conditions (20-ft and 40-ft deep pools, respectively), cutters of a different design were required because the irradiated thimble tubes were more difficult to cut than unirradiated tubes, and two-weeks time was lost because of a misloaded canister (some rods were left projecting out of the canister because an air-operated motor that controlled the downward movement of the fuel rods into the canister failed to operate). The consolidation equipment was developed specifically for Babcock & Wilcox fuel, but Westinghouse indicates that the equipment is adaptable to other PWR and BWR fuel. Westinghouse states(1) that the equipment needs further development to automate the process and make it economical for large-scale consolidation. One canister of the consolidated fuel rods has been in wet storage at the Oconee Nuclear Station since the fall of 1982.

TABLE 5. Fuel Bundle Characteristics(2)

Bundle Type	B&W Mark B-3 (15 x 15 Lattice)
Fuel Rod OD, in.	0.430
Materials	
End Fittings (2)	Type 316L stainless steel
Spacer Grids (8)	Inconel 718
Fuel Rod Cladding (208)	Zircaloy-4
Guide Tubes (16) and Instrumentation Tube (1)	Zircaloy-4
Discharge Date	5/28/77
Initial Enrichment, wt% nominal	2.75
Final Enrichment, wt% avg	0.9172
MWd/MTU Burnup, MWd/MTU avg	26,548
Decay Heat (at consolidation), W avg	990
Skeleton Activity (at consolidation), Curies avg	598.3

One irradiated PWR fuel assembly was consolidated at Maine Yankee in August 1983, using equipment that was designed for removing individual rods and inserting them into a storage array.(4) The consolidation ratio achieved was 1.6:1.

In addition to disassembly equipment for the fuel assemblies, a rod consolidation concept also requires an associated nonfuel-bearing component handling system. An example of such a system for PWR fuel is shown in Figure 4; the compacted nonfuel-bearing material is shown in Figure 5. Disassembly of a BWR fuel bundle generates a large volume (amounts to 10-20% of the bundle weight) of nonfuel, radioactive components (e.g., upper and lower end fittings, spacer grids, water tubes).(41,43)

The compacted nonfuel-bearing structural components (Figure 5) from the four spent PWR fuel assemblies involved in the Duke Power Company/Westinghouse Electric Corporation hot demonstration of rod consolidation were placed in three canisters. Initial dose rates were lower than the dose rates eventually measured; the difference was attributed to the activation of cobalt impurities in the Inconel spacer grids. Those canisters were shipped (one per cask) from the Oconee Nuclear Station to Barnwell, South Carolina, for disposal in 1983. The components from 1 1/2 assemblies were shipped in each of two shipments and the components from one assembly in the third shipment. Westinghouse said that the total cost ($49,231) of the three shipments is in no way representative of disposal costs that may be expected in a production program where each shipment would include structural components from a large number of fuel assemblies. For production consolidation programs, Westinghouse says the cost per assembly would be less than that experienced by Duke Power Company's Oconee Nuclear Station because the nonfuel-bearing components from six to eight fuel assemblies would be compacted into one canister and shipping casks with capacities up to 24 canisters could be used.

In addition to the rod consolidation to be performed at Maine Yankee (see Section III, A, 3), there are two other upcoming rod consolidation demonstrations with irradiated fuel (Table 4).(6) Twelve spent BWR fuel assemblies that have been stored in the spent fuel storage pool for a minimum of 2 years after reactor discharge are to be involved in one demonstration, which will employ the NAC consolidation system, at the Browns Ferry Nuclear Power Plant under an interagency agreement between DOE and TVA.(44) All parts of the NAC system have been shipped to TVA but the system has not yet been installed. The canisters for the demonstration have been shipped to and accepted by TVA. This demonstration with irradiated BWR fuel is to be done in the Browns Ferry-2 spent fuel pool and may take place in 1985. It is planned to obtain a consolidation ratio of 1.6:1 in a new closer spaced grid and 2:1 in an "open" (non-gridded) canister.(20)

Five to 10 spent PWR fuel assemblies are to be involved in the other demonstration, which is currently scheduled for completion in 1985 under a project planned by NUSCO that will use equipment designed by Combustion Engineering. These activities are part of a comprehensive program by NUSCO with support from EPRI and Baltimore Gas & Electric Co.(45) The objective of the program is to develop benchmarked analytical methods and related data on consolidated fuel characteristics to support licensing of the storage of consolidated fuel in a nuclear spent fuel pool and to demonstrate fuel consolidation with production-scale equipment and processes.

Consolidated spent fuel will also be involved in DOE-sponsored dry storage demonstrations(6,7) at INEL. Two casks at INEL will be loaded with fuel that has been consolidated, using specially designed equipment at the facility. Actual testing is scheduled to begin in early 1986 and continue through 1987.

Under the CSFM Program, PNL plans to further define the fuel rod integrity aspects of rod consolidation activities during participation in the upcoming demonstrations.

3. Licensing Applications, Actions, and Issues

Rod consolidation has not been licensed for general application at U.S. reactors. However, an application was submitted to the NRC for licensing of rod consolidation at Maine Yankee. The NRC completed their review of the application and issued a Safety Evaluation and Environmental Impact Appraisal.(46) The state of Maine ordered Central Maine Power Co. to withdraw its application to the NRC for licensing of large-scale rod consolidation at

Maine Yankee; however, it would allow up to 20 fuel assemblies to be consolidated.(47) The NRC approved Amendment No. 75 to the Maine Yankee operating license, which includes authorization to consolidate a maximum of 20 fuel assemblies.(5)

For some spent fuel storage pools, the results obtained by using the structural analysis methods that are employed for the current operating licenses indicate that the pools lack sufficient structural capacity for the additional weight associated with consolidated fuel. It is stated in a recent paper(10) that use of more advanced analytical methods (i.e., finite element structural analysis techniques) yielded results in a site-specific study indicating that structural modifications to the pool slab are not needed at that specific site to accommodate high-density spent fuel storage racks and consolidated fuel. Application of the advanced technique to the reanalysis of other pools has not been demonstrated yet. It will be of interest to see if the use of the more advanced structural analysis methods will be accepted by the NRC in pool licensing applications to show that some unmodified pools possess adequate structural capacity to store consolidated fuel.

Several potential licensing issues exist. One is the possibility of rapid heating of the fuel rods following the loss of water from the spent fuel storage pool (see Section III, D, 4). Another issue is whether methods and procedures can be developed so one can establish and routinely verify the amount of fuel present without having to have accountability on a rod basis (see Section III, A, 5). Another issue is meeting the licensing requirement for criticality safety with consolidated fuel in some existing spent fuel storage racks (see Section III, A, 6). Acceptable dry storage conditions for consolidated fuel have yet to be defined.(9)

The rod consolidation demonstration with irradiated fuel at the Oconee Nuclear Station by Duke Power Company and Westinghouse Electric Corporation required no license amendment and was performed on the basis of 10 CFR 50.59.(2)

4. ANS-57.10 Standard: Design Criteria for Consolidation of LWR Spent Fuel

Working Group ANS-57.10 was organized to develop the standard entitled "Design Criteria for Consolidation of LWR Spent Fuel." The first meeting of the Working Group was held in July 1983, the second in November 1983, and the third in March 1984. The fourth meeting of the 14-man working group was held in October 1984, at which time the rough draft of the standard was reviewed and revised. Rod consolidation in a wet or dry environment and in a vertical or horizontal orientation is included in the draft. At present, it is indicated in the draft that a rod is to be judged as damaged or failed by means of visual inspection. Rod breakage is considered a Design Event-II type of occurrence.(a) The schedule for the standard is as follows: first draft of public review in March 1985 and the draft for ballot in October 1985.

5. Accountability/Safeguards Studies

Safeguards issues that might arise in licensing rod consolidation were investigated in a recent EPRI study.(48) A major concern involves the ability to 1) accurately establish the amount of nuclear fuel present in each container holding consolidated rods and 2) provide a means to verify, on a routine basis at appropriate intervals, that the fuel continues to reside in the container. Ways to achieve these objectives but yet avoid accountability on a rod basis (an advantage because it is difficult to identify serial numbers on each rod after irradiation) are described. It is indicated that until rod consolidation is licensed there is no guarantee that the methods and procedures described in the study will be accepted by the regulatory agencies.

6. Criticality Accident Analysis

The effect of introducing consolidated fuel rods in containers (gridded or ungridded) into spent fuel storage pools has been assessed in criticality analyses.(49-52) Because of rod distortion (e.g., bowing) and other effects, it is likely that consolidated rods will be in a looser, more irregular array in the container than an idealized close-packed array. Such arrangements, however, are quite subcritical (i.e., the effective multiplication factor, k_{eff}, is less

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(a) An event that, although not occurring regularly, can be expected to occur with moderate frequency or on the order of once during any year of rod consolidation system operation.

than 0.95).(49,52) The reactivity of a completely filled container is less than that of a standard fuel assembly, but the reactivity of the container is a function of the number of rods loaded in it. As a result, for spent fuel storage racks that store consolidated fuel rods, the limiting case--and, fortunately, one that is highly unlikely to occur--would be a rack loaded with partially filled, optimally moderated containers.(50)

During handling operations, some fuel rods have been dropped: the total number is equivalent to a few more than the complement of rods in a single BWR fuel bundle.(53) Accidents with consolidated fuel could result in some fuel rod rearrangements that could become supercritical. The most severe case appears to involve spilling of rods (as few as 100) from a container into the racks of stored spent fuel in a pool.(49) However, all present plans involve consolidating fully "burned" fuel and when burnup credit is considered, a critical condition cannot arise from the accident described. During handling operations at a spent fuel storage pool in 1975, an irradiated BWR fuel assembly was inadvertently dropped because of improper grappling.(54,55) When it was subsequently pulled to a vertical position, all the fuel rods fell out of the assembly into the spent fuel cask pit, but no criticality incident occurred. Apparently, the fuel assembly separated because the tie rods and/or tie rod keepers sheared when the assembly hit the pool floor. Several mechanical means are suggested in the paper(49) for preventing those certain fuel rod rearrangements from occurring during consolidation operations, including inserting spacers to exclude fuel rods from rack (and shipping cask) cavities and employing careful mechanical designs to assure integrity of fixed poisons and containers.

Consolidated fuel can be safely stored in spent fuel storage racks of existing designs, but in some cases it may not be possible to meet the licensing requirements for criticality safety unless additional fixed neutron poison is installed or a licensed method for verifying fuel burnup becomes available.(50) During the past year in discussions between the NRC and utilities, the NRC has indicated a willingness to accept burnup credit as part of the safety analyses for both the disassembly and storage modes of rod consolidation.

B. RELEVANT EXPERIENCE WITH FUEL HANDLING, ROD REMOVAL, AND FUEL ASSEMBLY RECONSTITUTION

1. General Fuel Handling Experience at Reactor Cores, Spent Fuel Pools, and Other Facilities

Tens of thousands of LWR fuel bundles have been satisfactorily moved during normal handling operations at commercial power reactors and independent spent fuel storage facilities in the United States.(53) PNL has evaluated 130 cases (105 domestic and 25 foreign) of known or suspected damage to fuel as a result of handling and/or transporting operations. Irradiated fuel was involved in all but 11 of the cases.(53,56-58) About 310 domestic and foreign fuel bundles have been involved in some unusual occurrences, ranging from slightly non-normal to abnormal events.(53) Very few of those bundles suffered major mechanical damage due to handling operations and very few bundles are known to have suffered damage from normal transporting operations. Most of the bundles involved in the events were from PWRs.

During handling operations, 35 fuel bundles (32 domestic and 3 foreign) have been dropped, 3 bundles have fallen from a vertical to a horizontal position, and 3 have tilted a few tens of degrees from vertical and come to rest against another object. Distances that fuel bundles have been dropped in water have ranged from a few centimeters up to 9.1 m (30 ft). In only the case where a fuel bundle was dropped 9.1 m was there a momentary release of airborne radioactivity.(a)

The recent IAEA survey(59) of wet storage experience with water reactor fuel indicates that responses from about 35% of the pool operators show that a total of about 30 fuel assemblies have been dropped. The other 65% of the pool operators reported that no assemblies have been dropped. There were no serious consequences (e.g., radioactive contamination or fission product release) associated with these incidents. The IAEA report indicates that in a few cases where assemblies were dropped, damage to the fuel assembly structural components resulted "...in disruption of the assembly into individual rods, which

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(a) The bundle dropped onto another irradiated bundle and there was a momentary release of airborne radioactivity when the latter bundle was moved.

remained intact" (i.e., the structural components were damaged enough so that the intact rods were released).

PNL studies(53,56-58) show that a few fuel rods have been bent and some fuel rods have fallen out of fuel bundles during handling operations. Only six rods have been broken in the United States and only a few rods, representing an unknown very small fraction of the rods handled, have been broken in Germany during handling operations. However, in most cases when fuel was damaged during handling, there was only minor degradation of the fuel bundle components and no breaching of the fuel cladding or releases of radioactive gases or solids.

Several recent incidents are described below. Two fuel rods--one known to be failed and the other from a bundle that was a known leaker--from domestic BWR fuel bundles broke: one rod as it was being withdrawn from the bundle and the other rod as it was being placed in an inspection fixture.(60-63) A PWR fuel assembly fell damaging several other fuel assemblies during refueling; however, no breach of cladding was found on any assembly.(64) A PWR fuel assembly was dropped at a spent fuel pool when a crane cable parted, but no signs of cladding damage were noted.(65)

Over 5,100 spent fuel bundles have been transported in the United States.(66) The PNL studies(53,56-58) indicated that 14 or fewer bundles (≤ 9 domestic PWR, 4 foreign PWR, and 1 foreign BWR) were found or suspected to have been damaged during transporting operations. Of those, six or fewer were new (unirradiated) domestic PWR fuel bundles that were shipped to a reactor. The other eight were irradiated fuel bundles (included five where the fuel rods developed cladding defects during reactor operation) that were shipped from reactors. Damage to sound irradiated fuel during transporting operations has apparently been minor; however, little is known on the subject. It was recently reported(67) that 21 fuel rods in new domestic BWR fuel bundles had some minor wear, which was probably caused by vibration when the fuel was being transported to the reactor. Seven spent BWR fuel assemblies were recently involved in a cask shipment incident.(68) When the driver attempted to avoid another truck, the trailer carrying the cask containing the BWR fuel assemblies separated from the tractor. There was no damage to trailer or tractor, and radiation levels were normal. After reattachment, the tractor and trailer proceeded to the destination, where the fuel was unloaded.

2. Removal of Fuel Rods from LWR Fuel Assemblies for Reconstitution, Inspection, or Reprocessing

For a number of years, fuel assemblies containing failed fuel rods have been reconstituted (i.e., repaired for return to service by removing and replacing the defective rods) at reactor pools in the United States and other countries. Experience with rod removal and fuel assembly reconstitution has been described by a number of authors.(40,41,69-79) Over 51,000 fuel rods have been routinely and satisfactorily removed from fuel bundles in the United States for nondestructive testing and repair purposes.(72) Reconstitution operations, initially performed on only BWR fuel, are now routinely conducted on BWR and some PWR fuel. Several thousand irradiated fuel bundles have been successfully reconstituted in the United States and other countries. General Electric Company has successfully disassembled, inspected, and reconstituted over 1000 BWR fuel bundles using underwater equipment.(41) The equipment was designed to adapt a standard BWR fuel preparation machine to fuel reconstitution operations. A Swedish report(70) indicates that not a single rod was dropped during the reconstitution of 1085 BWR fuel assemblies. Over 80 MTU of spent fuel with burnups to 39,000 MWd/MTU was disassembled dry at a European reprocessing plant.(73) Practically no fuel rods were broken during the row-by-row disassembly operation, which involved pulling the rods out of the spacers. A Belgian paper(74) indicates that reconstitution of BWR and PWR fuel ..."has proven very successful in that it has not raised any safety issue nor incident likely to deteriorate the rod or assembly quality."

While rod consolidation operations may or may not be more complex than fuel assembly reconstitution, the current base of experience with underwater handling operations suggests that fuel assembly handling and rod removal can be accomplished without major difficulty or impaired safety for the pool operators or the public.

C. INTEGRITY ASPECTS OF RODS WHEN THEY ARE REMOVED FROM THE FUEL ASSEMBLY

Rods may be removed singly, in rows or groups, or simultaneously from a fuel assembly. One problem with multiple rod grappling in some consolidation operations is that the rods could become somewhat disarrayed while suspended from the grapple.(35) That problem could occur if improper fixtures are used or if the equipment fails. Another problem with multiple rod grappling, and one that could be potentially more difficult to resolve, is a rod that sticks (i.e., it resists removal with its companions) in the fuel assembly. Such stuck rods have to be dealt with on an individual basis. Fuel rods removed from the fuel assemblies are not designed to be self-supporting; hence, the rods are not easy to grapple after they have been removed from the assembly.(41) The strength of the fuel assembly structural hardware may be exceeded if all the fuel rods are pulled simultaneously;(32) however, this concern is not a problem when proper fixturing is used. For example, in the Duke Power Company/Westinghouse Electric Corporation demonstration, clamps were utilized at each of the spacer grid locations to preclude grid movement and buckling of the fuel assembly structural components under high axial tensile forces. Spent fuel rods are flexible. They can have irradiation-induced bows of up to 13 cm (5 in.) over their length.(22) Currently, rod bow is not a major concern during reactor operation, but about a decade ago there were a few "...cases where adjacent rods contacted each other and in at least one instance, rods snaked past each other."(80)

The integrity aspects of rod removal include: scratching of fuel rod surfaces, breaking of fuel rods, effects of crud, effects of extended burnup, and effects of hydrogen injection on BWR fuel rods.(69,81)

1. Scratching of Fuel Rod Surfaces

Spacer grid contacts make narrow scratches through the oxide film into the cladding metal when rods are removed from assemblies (see comments in Section VI.B regarding spacer grid spring relaxation). The exposed metal (Zircaloy or stainless steel) is resistant to oxidation at pool storage temperatures.(69,82) Initiation of significant localized corrosion (e.g., intergranular corrosion) is not likely on the exposed stainless steel unless the metal is sensitized.(a) LWR fuel operating conditions are generally not conducive to sensitization. Exposed Zircaloy can become susceptible to hydriding at low temperatures, but recommendations are given in Section III, D, 3 to select materials and pool chemistry conditions that will avoid significant hydriding.

2. Breaking of Fuel Rods

The experience base for fuel assembly reconstitution suggests that rods can be removed from assembly hardware without substantial breakage.(69) It is important to note that this favorable rod breakage experience was not gained from a random population of spent fuel but from a biased sample designated for reconstitution because they contained defective fuel rods. In the Duke Power Company/Westinghouse Electric Corporation demonstration with four spent fuel assemblies,(3) the force required to pull all 208 rods simultaneously from an assembly was 500, 950, 1400, and 1940 pounds (or an average of ~2.4 to ~9.3 pounds per rod). It was indicated in a paper(22) that the average force required to withdraw a fuel rod from a fuel assembly can be about 4.5 to 6.8 kg (10 to 15 lb) with an underwater consolidation operation. A factor in low breakage is that spacer grid springs tend to relax during reactor operation.(83) An EPRI report(81) states that examinations of many irradiated fuel rods indicate that sufficient spacer grid force remains to prevent vibration-induced wear. A paper(22) indicates that the force exerted by the spring on the rod decreased to less than 20% of the original value.

Investigators indicate that handling operations in spent fuel pools can accommodate failed rods and the inadvertent breaking of rods (including prepressurized rods).(70,71) Swedish investigators intentionally drilled into three irradiated fuel rods and found only small releases of volatile radioactive species.(70) If a fuel rod had broken during the Duke Power Company/Westinghouse Electric Corporation hot demonstration, the associated procedure(3) called for the upper segment of the rod to be retrieved by placing the assembly in a recovery stand. The recovery stand is one of the four locations

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(a) A thermally induced metallurgical process that depletes chromium from metal adjacent to grain boundaries, rendering the depleted metal prone to corrosion.

in the fuel rod consolidation system stand. The recovery stand is used to temporarily store a fuel assembly in its original pitch while the problem is solved. According to the procedure, the lower segment of the rod would be retrieved after cutting away enough segments of the fuel assembly structural components to expose the rod segment. The broken rod segments would be placed in a canister designated for stray rods.

It is indicated in several references(58,60) that the irradiated fuel rods that broke during handling (see Section III,B,1.) were known earlier to be defective or to have come from leaky fuel assemblies. Hence, it is hypothesized that the potential for rod breakage can be reduced substantially if fuel assemblies containing known or suspected defective rods are excluded from the rod consolidation operation. The two fuel assembly inspection techniques routinely used at domestic plants are visual inspection and leak testing (sipping) and many of the assemblies with defective rods can be identified with those techniques. However, if you rely on the results from only visual inspection or from only sipping, you can inadvertantly overlook some assemblies with defective rods.(72) If only fuel assemblies are inspected (i.e., there is no disassembly for individual rod inspection), there has been in the past an inherent difficulty in accurately determining the total number of failed fuel rods present in a given assembly. An ultrasonic method has been developed(84) that detects moisture inside failed rods and this technique, the Failed Fuel Rod Detection System (FFRDS), has several advantages. It is fast,(a) can be used <u>without</u> disassembling the fuel assembly, and can provide a clear indication of the exact location of the failed rods. The FFRDS appears capable of detecting most defects, but there is not now a basis to claim that it detects every defect. As of the end of 1983, a total of 150,000 fuel rods in both BWR and PWR fuel assemblies have been inspected by the FFRDS at foreign and U.S. plants (e.g., Calvert Cliffs, Farley, Millstone-2, Turkey Point-3, and Surry).(60)

(a) Average inspection time per fuel assembly is 30-50 minutes, including all fuel handling (i.e., moving the fuel assembly to the FFRDS and back). Actual FFRDS inspection time is 5 minutes for a BWR fuel assembly and 7 minutes for a PWR fuel assembly.

There is also the potential for impairment of cladding integrity (the concern would be breaching of the cladding and release of the "free volatile" radionuclides) during the handling and transport of fuel rods that sustained some damage short of cladding failure during prior duty.(58) Even if the fuel rods are removed from the fuel assembly and individually inspected, there is no reasonably established procedure available yet for detecting fuel rods with incipient defects (i.e., cracks that extend part way through the wall of the cladding).(72,85)

3. Effects of Crud(69)

The principal source of radiation dose to pool operators comes from dissolved and/or particulate species in the pool water, not from the direct shine from the stored fuel assemblies. Therefore, it is important to minimize the inventory of radioactive species in the water. Crud deposits (radioactive oxide deposits overlaying the zirconium oxide film on the cladding) tend to loosen during fuel handling. Some irradiated PWR fuel assemblies that have been in wet storage at Duke Power's Oconee Nuclear Station since 1974-1977 were recently examined at the pool as part of the PNL study and a considerable amount of crud came loose during the handling operation--crud that appeared adherent in 1978 peeled off in flakes in 1982.(86)

The spent fuel used in the Duke Power Company/Westinghouse Electric Corporation rod consolidation demonstration during the period from mid-October to mid-November 1982 had been discharged from Oconee-2 on May 28, 1977, and had an average burnup of 26,548 MWd/MTU.(2) Dispersion of crud during pulling of the rods was annoying--it slowed down operations until the cloud of crud settled--but was not a serious consideration. The crud dispersion had no appreciable effect on the radioactivity level or personnel exposure. The report(3) by Duke Power Company and Westinghouse Electric Corporation indicates that the attempt to isolate the crud release through the use of a suction filtering system was unsuccessful. The report states that during the rod pulling phase of the operation a large amount of crud was scraped off the fuel rods, as was expected. The suction filtering system's performance proved less than adequate to rapidly remove the suspended crud particles and maintain water clarity. The system was too small to handle the volume of water at a fast enough rate. Hence, water clarity was only achieved after allowing the suspended crud particles to settle.

During removal of single rods, the loose crud inventories have been minimal and are controlled by the pool cleanup systems (ion exchange, filtration, and skimmers, which remove material from the pool surface). During a fuel assembly reconstitution campaign in Sweden,(70) a vacuum device was used to collect the crud that came loose when the fuel rods were drawn through the spacer grids. When several rods are removed simultaneously, the crud release may be substantial. Rod consolidation equipment designs include provisions for local cleanup systems to augment normal pool cleanup and capture the bursts of crud before they disperse to the pool. Crud could have an adverse effect on the rod removal operation if it is sufficiently loose to accumulate on and/or abrade surfaces that guide the fuel rods into the consolidated rod container. That aspect can best be evaluated during early demonstrations with irradiated rods. For dry storage of consolidated fuel, the generation of particulate crud could be a severe problem. However, not all fuel batches will have the same crud properties. In particular, there are major differences in crud properties and inventories between BWR and PWR fuel. Crud deposition on fuel rods is highly variable even in reactors of similar design.(87) An EPRI study(81) involves a review and analysis of specific incidents that resulted in heavy crud deposits and of the factors involved.

4. Effects of Extended Burnup

A current industry problem is the uncertainty about the waterside corrosion rates of Zircaloy as reactor residence increases.(81) However, anticipated changes in fuel assembly characteristics caused by extended burnup are not expected to adversely affect the fuel rod integrity during water storage.(88) Mechanical operations involved in disassembly fuel, especially extended-burnup fuel, may eventually result in a higher incidence of failed fuel rods, although indications of a higher failure rate are not apparent at present.(31) Spent fuel assemblies from extended burnup demonstration programs are just now beginning to reach goal burnups (average assembly burnups are planned to be as high as 55,000 MWd/MTU). Four PWR fuel assemblies have successfully achieved burnups of ~55,400 MWd/MTU and were recently discharged.(81) Postirradiation examinations indicate that the assemblies are leak tight and that, in contrast to diameter reductions (amounted to a total of ~4 mils, maximum) observed after earlier cycles, the majority of the rods increased in diameter (rods were still a maximum of ~3 mils smaller in diameter than they were initially) during the last (fifth) cycle of irradiation.

5. Effects of Hydrogen Injection on BWR Fuel Rods

Intergranular stress corrosion cracking (IGSCC) of stainless steel pipes at BWRs has caused costly downtime and repairs.(81) Recent EPRI reports(89) indicate that IGSCC can be suppressed by continuously injecting 2.0-ppm hydrogen into the BWR primary coolant and by carefully controlling coolant water purity. General Electric Company is endorsing hydrogen injection but may require modified fuel warranties with utilities employing the process because the fuel may be affected by the process.(90) Possible embrittlement of the Zircaloy cladding due to hydrogen pickup is the primary concern but there is also some uncertainty about Zircaloy's oxidation rate in transition cycles.(81) EPRI has initiated a program at Dresden-2 to study the effects of hydrogen injection and plans to conduct a detailed examination of the fuel.(90) The aim of the surveillance program is to confirm that the hydrogen injection process does not result in an unacceptably high hydrogen content in the Zircaloy cladding.(81)

D. EFFECTS ON RODS AS A RESULT OF ROD CONSOLIDATION

The effects of rod consolidation include: increased temperature, creation of rod-to-rod crevices, dissimilar metal contacts, and potential of rapid heating of fuel rods following loss of water from the spent fuel storage pool.(69)

1. Increased Temperature

Closer packing of the fuel rods will tend to increase water temperatures around the rods; however, the temperature increase is expected to be less than

10°C. The rods already have survived reactor operating temperatures, so the increased temperature associated with the temporary increased thermal load on the pool will be mild by comparison.

If consolidated rods are to be placed in dry storage, fuel heat loads must be selected to meet temperature limitations associated with licensing requirements.(8) Acceptable dry storage conditions for consolidated fuel have yet to be defined.(9)

2. Formation of Rod-to-Rod Crevices

In the close-packed mode, the fuel rods will be in contact, creating many rod-to-rod crevices. Zircaloy is not expected to be susceptible to crevice corrosion under normal pool chemistry conditions provided that a) pool water purity is maintained, and b) prolonged local boiling does not occur.(69) By following appropriate administrative procedures, crevice corrosion of Zircaloy and stainless steel is not expected to occur during wet (or dry) storage.

3. Dissimilar Metal Contacts(8)

Zircaloy and stainless steels are generally tolerant of contacts with other relatively noble metals (e.g., Inconel) under reactor and pool conditions. Aluminum racks have not appeared to cause problems in the storage of fuel assemblies containing Zircaloy-clad or stainless steel-clad fuel because the aluminum rack contacts the stainless steel end fittings on the fuel assembly rather than the Zircaloy cladding on the fuel. Direct coupling to aluminum has resulted in accelerated hydriding of Zircaloy if several factors are presented simultaneously: 1) a sufficient temperature (to date, hydriding rates appear to be low below about 50 to 60°C), 2) impure water chemistries, and 3) coupling to a source that renders the Zircaloy sufficiently cathodic.(82) The oxide film on Zircaloy-clad fuel will tend to suppress hydriding, except at scratches.

Use of aluminum racks and/or storage canisters for consolidated fuel should only be undertaken after a careful review of the expected storage conditions and the likelihood of galvanically induced hydriding of the Zircaloy cladding. That type of hydriding has been observed at temperatures under 100°C but not under pool storage conditions. At normal pool temperatures and water chemistries, galvanic hydriding of Zircaloy will probably not occur. However, avoiding direct contact between Zircaloy and active metals such as aluminum appears prudent where relatively long pool residences are anticipated.(69)

4. Potential for Rapid Heating of Fuel Rods Following Loss of Water from the Spent Fuel Storage Pool

Existing spent fuel storage pools are being enlarged and modified to accommodate growing quantities of spent fuel assemblies in higher density configurations. The safety of such configurations with spent fuel assemblies has been studied and has included consideration of a hypothetical low-probability accident involving drainage of the water from the pool.(91-93) The likelihood of a severe pool drainage incident has been judged to be extremely low.(91) If certain design modifications are made, automatic coolability can be ensured for most accidents involving pool drainage; overheating of spent fuel can also be averted by other techniques (e.g., use of an emergency water spray).(92) It is stated in American National Standard ANSI/ANS-57.7-1981(94) that if designers adhere to the requirements of that standard, they may exclude certain events, including total loss of spent fuel storage pool water as a possible Design Event IV.(a)

The possibility of rapid heating of spent fuel assemblies (because of oxidation of the Zircaloy in air) following the complete loss of pool water has emerged as a regulatory issue in recent years.(91,95) Wet and dry storage of consolidated fuel will also come under scrutiny; however, dry air storage in casks will likely supersede concerns for pool drainage. Two papers(95,96) on drained pool studies were presented recently; those studies are also described in a report(97) currently being prepared for the U.S. Nuclear Regulatory Commission (NRC) on this issue. Results of the analysis from one of those papers(96) shows that with 17 x 17 PWR fuel assemblies in high racking density storage configurations, propagation of self-sustaining zirconium oxidation in a drained spent fuel pool may occur in fuel that has been out of the reactor less than three years. An advantage in most rod consolidation applications is that

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(a) "Design Event IV consists of that set of possible events that, because of their consequences, may result in the maximum potential impact on the immediate environs."(94)

they will involve aged fuel (i.e., the fuel will have been out of the reactor for more than three years). The Standard Contract for Spent Nuclear Fuel Disposal between the utilities and DOE denotes as standard fuel assemblies those that have cooled for a minimum of five years. In all likelihood, utilities will not find it necessary to consolidate spent nuclear fuel that has cooled for less than 15 years, and certainly not those fuel assemblies that have less than 10 years of cooling.

IV. CONCLUSIONS AND RECOMMENDATIONS

Rod consolidation operations have been successfully demonstrated in the United States. Some mechanical problems were encountered during the Westinghouse/Duke Power demonstration but were solved.(1-3) The mechanical problems included the following: auxiliary equipment was needed because of differences between test conditions and actual conditions (20-ft and 40-ft deep pools, respectively), cutters of a different design were required because the irradiated thimble tubes were more difficult to cut than unirradiated tubes, and a canister was misloaded. Westinghouse indicates(1) that their equipment needs further development work to automate the processes and make it economical for large-scale use.

The cost of disposal of the nonfuel-bearing components from the fuel assemblies is an important factor in rod consolidation. Also, the dose rate from the components can affect the handling procedures.(3) One key engineering variable associated with the disposal of such components is the dose rate from the cobalt-60 that is formed by activation of the cobalt impurities in those components (e.g., Inconel spacer grids).

There has been no experience with extended storage (wet or dry) of consolidated rods but problems are not expected. The anticipated difficulty noted in a 1982 paper(8) in meeting dry storage cask temperature limits with consolidated fuel will likely be resolved by consolidating old fuel with a sufficiently low decay heat level. A detailed thermal-hydraulic computer code model for analyzing consolidated spent fuel rods in dry storage has been developed and is described in a recent report.(98) The model has been shown to successfully predict temperature and airflow distributions in dry storage systems for both consolidated and unconsolidated spent fuel rods. However, for consolidated fuel, experimental data are needed to evaluate the model and analyses of multi-canister storage systems are also needed.

It will be of interest to see if the use of the more advanced structural analysis methods will be accepted by the NRC in pool licensing applications to show that some unmodified pools possess adequate structural capacity to store consolidated fuel.

The trend of favorable experience in the United States and other countries with spent water reactor fuel during handling and reconstitution operations should extend to rod consolidation. Tens of thousands of LWR fuel assemblies have been satisfactorily moved during normal handling operations at commercial power reactors and independent spent fuel storage facilities in the United States. Over 51,000 fuel rods have been removed from United States assemblies for nondestructive testing and repair purposes. Several thousand domestic and foreign BWR and PWR fuel assemblies have been successfully reconstituted. The frequency of unusual occurrences involving fuel damage from handling and transporting operations has been low. Nearly all of these unusual occurrences have had only minor or negligible effects on spent fuel storage facility operations. Generally, the damage to the fuel was minor and involved no breaching of the fuel cladding or release of radioactive gases or solids. The current base of underwater handling experience suggests that fuel assembly handling and rod removal and consolidation can be accomplished without major difficulty or impaired safety for the spent fuel pool operators or the public.

A few rods with incipient defects (i.e., cracks generated during reactor service that extend part way through the fuel cladding) can be expected among the consolidated rods.(72,85)

Crud loosened from the surface of rods during fuel handling can slow down rod consolidation operations by decreasing visibility in the pool water. Loose crud might accumulate on and/or abrade surfaces that guide the fuel rods into the consolidated rod canister.

Consolidation operations with extended burnup fuel may result in a higher incidence of rod failures but this is not apparent at present.(31)

The likelihood of a severe pool drainage incident has been judged to be extremely low; however, the possibility of rapid heating of spent fuel assemblies due to oxidation of the Zircaloy in air following the complete or partial loss of pool water has emerged as a regulatory issue in recent years.(91,95) Wet and dry storage of consolidated fuel will, of course, also come under scrutiny. An advantage in most rod consolidation applications is that they will involve aged fuel.

Recommendations from this study include the following:

- It will be important to monitor the upcoming demonstrations that involve spent BWR and PWR fuel to further define the fuel rod integrity aspects of rod consolidation activities.
- Relevant handling and reconstitution operations and incident reports need to be monitored and rod consolidation studies and experience in the United States and other countries need to be followed closely, especially those involving irradiated fuel.
- The potential for rod breakage can be reduced if assemblies containing known or suspected defective rods are excluded from the rod consolidation operation.
- Rod consolidation demonstrations with irradiated fuel rods should include an evaluation of the effect of loose crud because it could affect consolidation operations.
- When pursuing rod consolidation technology, careful consideration needs to be given to the disposal of the nonfuel-bearing components from the fuel assemblies.
- Handling and reconstitution experience with higher burnup fuel (over 28,000 MWd/MTU in BWRs and over 36,000 MWd/MTU in PWRs) needs to be factored into rod consolidation studies as that information becomes available to aid in planning in the event that such fuel needs to be consolidated in the future.
- Licensing concerns need to be identified with the NRC and methods to resolve these concerns also need to be identified.

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