EXPERIENCE WITH FAILED OR DAMAGED SPENT FUEL AND ITS IMPACTS ON HANDLING

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EXPERIENCE WITH FAILED OR DAMAGED SPENT FUEL AND ITS IMPACTS ON HANDLING

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Spent fuel management planning needs to include consideration of failed or damaged spent light-water reactor (LWR)(b) fuel. Described in this paper, which was prepared under the Commercial Spent Fuel Management (CSFM) Program that is sponsored by the U.S. Department of Energy (DOE), are the following: the importance of fuel integrity and the behavior of failed fuel, the quantity and burnup of failed or damaged fuel in storage, types of defects, difficulties in evaluating data on failed or damaged fuel, experience with wet storage, experience with dry storage, handling of failed or damaged fuel, transporting of fuel, experience with higher burnup fuel, and conclusions.

IMPORTANCE OF FUEL INTEGRITY AND THE BEHAVIOR OF FAILED FUEL

Release of fission gases and particulates of fuel from irradiated fuel rods is prevented by the primary barrier, the fuel cladding. Hence, consideration of the integrity of the cladding on spent fuel is an important factor in spent fuel management planning. Regulation of spent fuel storage at facilities away from reactors is addressed in 10 CFR 72,(c) which requires that gross degradation of spent fuel and release of radioactive particulates be prevented. Inspection techniques are available to detect most fuel assemblies containing reactor-induced defects, although elimination of every failed or nearly failed fuel rod cannot be assured. As a result, the condition of spent LWR fuel is an important aspect to be considered in planning activities such as storing, handling (including examination, fuel assembly reconstitution, and rod consolidation), and shipping such fuel.

(a) The Pacific Northwest Laboratory (PNL) is operated by Battelle Memorial Institute for the U.S. Department of Energy under Contract DE-AC06-76RLO 1830.
(b) LWRs in the U.S. include boiling water reactors (BWRs) and pressurized water reactors (PWRs).
(c) Code of Federal Regulations (CFR).
At the end of 1988, the inventory of spent fuel in storage included over 62,700 LWR fuel assemblies (59% BWR and 41% PWR type). Nearly all of the fuel assemblies are stored at reactor sites; only about 5% are stored at other facilities such as Independent Spent Fuel Storage Installations (ISFSIs). Most (>97%) of the fuel assemblies contain Zircaloy-clad fuel rods; <3% contain stainless-steel-clad fuel rods. The utilities indicate that among the >62,700 fuel assemblies, there are >3,200 failed or damaged fuel assemblies. It should be noted that at the end of 1986, the utilities had reported that there were approximately 5,000 failed or damaged spent fuel assemblies in storage; however, the next year the utilities significantly reduced their estimates and indicated that there were nearly 2,400 failed or damaged fuel assemblies in storage at the end of 1987. The burnup distribution of the >3,200 failed or damaged fuel assemblies is shown below:

<table>
<thead>
<tr>
<th>Burnup Range, MWd/MTU</th>
<th>Number of Failed or Damaged Fuel Assemblies</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BWR</td>
</tr>
<tr>
<td>0 to 5,000</td>
<td>125</td>
</tr>
<tr>
<td>&gt;5,000 to 10,000</td>
<td>592</td>
</tr>
<tr>
<td>&gt;10,000 to 15,000</td>
<td>971</td>
</tr>
<tr>
<td>&gt;15,000 to 20,000</td>
<td>552</td>
</tr>
<tr>
<td>&gt;20,000 to 25,000</td>
<td>334</td>
</tr>
<tr>
<td>&gt;25,000 to 30,000</td>
<td>129</td>
</tr>
<tr>
<td>&gt;30,000 to 35,000</td>
<td>40</td>
</tr>
<tr>
<td>&gt;35,000 to 40,000</td>
<td>0</td>
</tr>
<tr>
<td>&gt;40,000 to 45,000</td>
<td>0</td>
</tr>
<tr>
<td>&gt;45,000 to 50,000</td>
<td>0</td>
</tr>
<tr>
<td>&gt;50,000 to 55,000</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>2,743</td>
</tr>
</tbody>
</table>

Most of the failed and damaged fuel is old; over 83% of it was discharged between 1969 and 1980. Of the failed and damaged fuel, about 11% of it from BWRs and about 53% of it from PWRs has been discharged and placed in storage between 1981 and 1988.
TYPES OF DEFECTS

Most of the cladding defects are small, and few are large. The utilities indicated in 1987 that of the failed or damaged fuel assemblies, only 35 required special handling and only one required encapsulation.

Failure types on fuel rods can vary over a wide range: from pinholes, small holes, and cracks to large defect areas (rare) in which fuel pellets are visually observable or are missing. Only a small fraction of the fuel rod cladding breaches are readily visible when fuel assemblies are visually inspected because the defects are generally too small for easy detection or they are located on interior rods. If breached fuel rods are allowed to continue operation in LWRs, they can sustain substantial secondary hydriding that can dominate the visual appearance. Such hydriding has led (especially in the early days) to misinterpretation of the primary cause of failure. Longitudinal splitting of the cladding, if noted under normal operating conditions, is now typically viewed as a secondary defect.

DIFFICULTIES IN EVALUATING DATA ON FAILED AND DAMAGED FUEL

It is difficult to evaluate data on failed and damaged fuel reported by industry for several reasons: 1) the definition of abnormal degradation is not uniform throughout the industry; 2) in many cases the number of fuel failures is inferred from indirect evidence; 3) in some cases only directly observed failures are counted; 4) in other cases, a group of fuel assemblies suspected or known to contain failed fuel rods is discharged but not inspected; and 5) whether the fuel is classed as failed can depend on how closely the fuel is inspected and on the capability of the inspection technique being used (in the case of leak testing, also called sipping, it can depend on when it takes place). Development and adoption of more uniform definitions of failed fuel and abnormal degradation would be helpful because it would make it easier to more accurately compare data from different reactors, utilities, and fuel vendors.

EXPERIENCE WITH WET STORAGE

Experience to date indicates that failed fuel has had a minimal impact on storage of spent fuel in water. A world survey showed that most
pools store fuel assemblies containing failed fuel rods on the same basis as intact assemblies; some pools (~30%) store fuel assemblies containing failed rods in canisters. Further degradation of cladding defects during storage does not appear to be occurring. An irradiated PWR fuel rod that had a large hole (nearly as wide as the rod diameter and about two rod diameters in length), and an associated 8-cm (3-in.) long section where fuel was missing, was examined after seven years in wet storage; the cladding breach and the missing section were determined to be no larger than before.

**EXPERIENCE WITH DRY STORAGE**

The successful experience to date with Zircaloy-clad fuel over a large range of dry storage conditions suggests that none of the potential failure mechanisms (e.g., stress rupture, stress corrosion cracking, hydrogen redistribution) is likely to have a significant influence on the dry storage of spent LWR fuel in inert gas or nitrogen. Current experience indicates that the incidence of cladding failures during dry storage will be low; however, some fuel rod failures cannot be ruled out (see comment above regarding inspection techniques). Even if fuel with cladding defects were placed in dry storage, or if defects develop during storage, such defects would not propagate if an inert or nitrogen cover gas is used. In general, the impact of a cladding defect that develops during dry storage is anticipated to involve release of fission gas to the sealed cask or canister, but essentially no release of fuel particles.

**HANDLING OF FAILED OR DAMAGED FUEL**

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 U.S. Only a few fuel assemblies have suffered major mechanical damage during handling (~250 in the U.S.). Fuel rods (a total of slightly more than the complement of one BWR fuel assembly) have fallen out of spent fuel assemblies during handling. There have been five cases in the U.S. where spent fuel assemblies have come apart during handling [the latest event was at Oyster Creek in 1987 and involved a previously damaged fuel assembly].
The likelihood of breaking rods is potentially higher with fuel rods with large cladding defects. Domestic experience to date indicates that only about seven rods—out of a biased sample of fuel assemblies (ones that were known to contain or suspected of containing failed or damaged fuel rods and were selected for examination, reconstitution, or rod consolidation) containing over 54,000 irradiated fuel rods—broke during handling, examination, fuel assembly reconstitution, or rod consolidation activities. Among the >54,000 rods were nearly 2,000 that were intentionally involved in rod consolidation operations. Among those 2,000 fuel rods were some that were known to have collapsed cladding (a result of in-reactor fuel densification and the coolant pressure). During rod consolidation operations, one rod with collapsed cladding released fission gas, but operators were able to resume work shortly after evacuating the work platform and taking necessary precautions. Another rod with collapsed cladding broke unexpectedly during handling operations subsequent to rod consolidation; the broken rod created no operations problems. One rod consolidation demonstration intentionally included an irradiated PWR fuel assembly with severely bowed fuel rods and showed that such rods can be accommodated.\(^\text{10}\) In another study, it was found that even after bowing up to three feet (or more), irradiated PWR fuel rods did not break.\(^\text{11}\)

**TRANSPORTING OF FUEL**

More than 5,100 fuel assemblies have been transported in the U.S. Very few fuel assemblies (<37 in the U.S.) have been damaged during normal transporting operations.\(^\text{8}\) There have been two events, one in France and one in the U.S., in which substantial radioactive releases have occurred when uncanned PWR fuel assemblies containing stainless-steel-clad fuel rods (known in the U.S. case to include some failed rods) were shipped in a dry but oxidizing atmosphere. Because of the event in the U.S.,\(^\text{12}\) which resulted in release of airborne contamination during the underwater unloading of a failed PWR spent fuel assembly, no more shipments of casks containing uncanned failed fuel with more than small cladding breaches (i.e., with cladding defects larger than pinholes or hairline cracks) are permitted in the U.S.
EXPERIENCE WITH HIGHER BURNUP FUEL

Average burnup levels have been increasing yearly, but fuel rod failure rates have not exhibited a similar trend.\(^{(13)}\) To date, the data indicate that extending burnup has not been detrimental to fuel performance. In 1989, five PWR fuel assemblies with burnups >58,000 MWd/MTU were discharged from U.S. PWRs. The only known occurrence in the U.S. of failure of fuel operating in the extended burnup range took place in a core having many debris-induced failures of fuel of traditional design.\(^{(14)}\) It will be important for spent fuel management planning to continue to maintain surveillance of the behavior of intact and failed or damaged spent fuel that is placed in wet and dry storage to gather additional evidence, in particular with higher burnup fuel, to assure that fuel integrity is being appropriately maintained.

CONCLUSIONS

The overall domestic nuclear fuel operating experience continues to be excellent: current fuel rod reliabilities are typically >99.99%, which corresponds to fuel rod failure rates of <0.01%.\(^{(2)}\) Fuel failure rates in the early days were higher, but the rates decreased as fuel failure mechanisms were identified and eliminated. Infrequent events have occurred in which fuel failed or was damaged during reactor service or in subsequent operations (e.g., handling, storage, rod consolidation, and shipping).\(^{(15)}\)

It is concluded that failed fuel has had minimal impact on the wet storage—even for an extended period—of spent LWR fuel; additional degradation of defective fuel does not appear to be occurring. Even if the spent fuel is inspected before being placed in dry storage, the presence of some failed fuel rods cannot be ruled out. However, even if fuel assemblies with failed rods are put in dry storage, or if cladding breaches develop during storage, the breaches are not expected to propagate if an inert or nitrogen cover gas is employed. Fuel handling experience to date at spent fuel storage pools indicates that failed and damaged fuel assemblies, failed fuel rods, and the inadvertent breaking of fuel rods (including prepressurized rods) can be accommodated. In general, when fuel has been damaged as a result of handling, there has been only minor degradation of the fuel.
assembly components, no breaching of the fuel cladding, and no release of radioactive fission gases or fuel particulates. Little information is available on damage that has been sustained by intact irradiated fuel during shipping, but the general indications are that the damage appears to have been minor. Problems did occur in two cases where uncanned fuel assemblies, known or suspected to contain failed fuel rods, were shipped in a dry, but oxidizing atmosphere.

REFERENCES


