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ABSTRACT

Information on spent fuel integrity is of interest in evaluating the impact of long-term dry storage on the behavior of spent fuel rods. Spent fuel used during cask performance tests at the Idaho National Engineering Laboratory (INEL) offers significant opportunities for confirmation of the benign nature of long-term dry storage. The cask performance tests conducted at INEL included visual observation and ultrasonic examination of the condition of the cladding, fuel rods, and fuel assembly hardware before dry storage and consolidation of the fuel; and a qualitative determination of the effect of dry storage and fuel consolidation on fission gas release from the spent fuel rods. A variety of cover gases and cask orientations were used during the cask performance tests. Cover gases included vacuum, nitrogen, and helium. The nitrogen and helium backfills were sampled and analyzed to detect leaking spent fuel rods. At the conclusion of each performance test, periodic gas sampling was conducted on each cask as part of a surveillance and monitoring activity. Continued surveillance and monitoring activities are being conducted for intact fuel in a CASTOR V/21 cask and for consolidated fuel in a VSC-17 cask. The results of the gas sampling activities are reported in this paper.

INTRODUCTION

In response to the Nuclear Waste Policy Act of 1982 (NWPA), a Solicitation for Cooperative Agreement Proposal (SCAP) was issued in May 1983 by the DOE-Richland Operations Office (DOE-RL) to help the private sector with their spent fuel storage problems, and proposals were received in August 1983. Virginia Power (VP) proposed that pressurized water reactor (PWR) spent fuel storage cask performance testing be conducted at a federal site in support of its at-reactor license demonstration. VP and DOE signed a Cooperative Agreement in March 1984, and VP signed a separate agreement with the Electric Power Research Institute (EPRI), essentially establishing a three-party cooperative agreement.

The scope of the Cooperative Agreement included performance tests of three different metal storage casks loaded with unconsolidated spent nuclear fuel. The tests were conducted at INEL. After cask performance testing with unconsolidated fuel was completed in the VP/DOE cooperative program, a decision was made by DOE and EPRI to extend the performance testing to include consolidated fuel in the Transnuclear, Inc., TN-24P cask. Dry rod consolidation was conducted at INEL as a separate DOE-only funded program.

Prior to testing, the Surry PWR spent fuel assemblies used in the cask performance tests were characterized using in-basin ultrasonic examinations and video scans. Cask internal cover gas samples were taken during testing. After testing, selected fuel assemblies were videotaped and photographed. Then fuel assemblies used in the TN-24P and MC-10 cask performance tests, along with a few Turkey Point reactor spent fuel assemblies, were consolidated and loaded into the TN-24P cask for a DOE-funded performance test. Later, a cooperative agreement was established with Sierra Nuclear Corporation (SNC), and 17 of the consolidated fuel canisters from the TN-24P cask were used in a performance test of SNC's ventilated concrete cask.

Performance test runs involved a combination of cover gases and cask orientations. The backfill environments used were vacuum, nitrogen, and helium; nitrogen and helium were sampled and analyzed to detect leaking spent fuel rods. The integrity of the fuel assemblies was determined from cover gas sampling (Creer 1986; McKinnon 1986, 1987a, 1987b, 1989, 1992, 1993). At the conclusion of each performance test, periodic gas sampling was conducted on each cask as part of a cask surveillance and monitoring activity.

This report combines the gas sampling information from the cask performance tests and cask monitoring activities. It documents the condition of the fuel from the Surry reactor prior to testing and the effect of testing on fuel integrity as ascertained through gas sampling during cask performance tests at INEL using both intact and consolidated PWR spent fuel. It also includes results of a prior test using boiling water reactor (BWR) spent fuel and the REA-2023 cask at Morris, Illinois. Recent gas sampling data associated with cask surveillance and monitoring at INEL is also included. The pretest condition of the fuel and the significant results obtained from gas sampling during and after performance testing are described as well.

Three types of spent fuel and five casks have been used during the cask performance testing and demonstration program. BWR 7x7 spent fuel assemblies were used for the performance test of the REA-2023 cask. Westinghouse 15x15 PWR was used in the CASTOR V/21, TN-24P, MC-10, and NUHOMS performance tests. A portion of this fuel was consolidated at INEL and used in performance tests of the TN-24P and VSC-17 casks (also at INEL). Table 1 gives a summary of the fuel used in each of the performance tests.

The BWR assemblies used during the REA 2023 cask performance test were a general Electric 7x7 design and were taken from the Nebraska Power Cooper Reactor. The intact PWR assemblies used in the performance tests conducted at INEL were taken from VP's Surry Reactors. After the performance tests using intact PWR fuel, INEL consolidated 48 PWR fuel assemblies of the Westinghouse 15x15 design into 24 canisters of consolidated fuel that were used in two subsequent cask performance tests. A description of the fuel is contained within the performance reports.

SPENT FUEL INTEGRITY

PRETEST FUEL INSPECTION Four examination methods were used to assess the integrity of the spent fuel used in the cask performance tests. Methods common to the PWR and BWR fuel included visual observations such as full-length black and white videos and color photographs; and analyses of the cover gas in the cask. In addition to these methods, the BWR spent fuel was examined by in-basin sipping and the PWR spent fuel from the VP's Surry Reactor was examined using an in-pool ultrasonic examination.

In-Basin Sipping In-basin sipping consisted of placing a hood over the selected BWR assembly and analyzing the water that was drawn off the top of the assembly. All the sipping data were compared with background readings to assess fuel integrity. Although the differences between the pretest and post-test radionuclide concentrations vary, the values were lower than if the assembly contained leaking fuel rods. The sipping results did not indicate any leaking fuel rods in any of the fuel assemblies used in the cask either before or after cask testing.

In-Basin Ultrasonic Inspections In-basin ultrasonic inspections were performed on PWR fuel at VP's Surry Reactor using the Babcock & Wilcox Failed Fuel Rod Detection System (FRDS). The FRDS system uses ultrasonic techniques to differentiate between leaking and non-leaking rods by detecting moisture in the former. Only Surry Reactor fuel assemblies with non-leaking fuel rods were used in the performance tests.

TABLE 1. Spent Fuel Assembly Characteristics

Cask	REA-2023	CASTOR V/21	TN-24P	TN-24P[(a)]	MC-10	VSC-17[(a)]
Fuel Type	BWR	PWR	PWR	PWR	PWR	PWR
Assembly Type	7 x 7	15 x 15	15 x 15	Consolidated 15 x 15	15 x 15	Consolidated 15 x 15
Burnup, GWd/MTU	24-28	24-35	29-32	24-35	24-35	26-35
Cooling Time, years	2.3-3.4	2.2-3.8	4.2	6.2-12.2	4.6-10.1	8.8-14.3
Enrichment, wt%	2.5	2.9-3.1	2.9-3.2	1.9-3.2	1.9-3.2	2.56-3.2
Assembly Decay Heat, W	235-300	1000-1800	832-919	701-1185	400-700	700-1050
Average, W	290	1350	860	970	530	877
Cask, kW	15.2	28.4	20.6	23.3	12.6	14.9

(a) Performance test using consolidated fuel in the cask.

Visual, Video, and Photographic Examinations The PWR fuel assemblies were examined visually to establish their general condition after shipment from VP, handling at the INEL hot shop, cask performance testing, and during consolidation. Similar exams were made of the Cooper BWR fuel during the REA 2023 performance tests at GE-Morris. Two kinds of visual examinations were used: black-and-white videos and color photography of selected fuel assemblies.

The black-and-white videos taken at GE-Morris, VP, and INEL did not provide sufficient detail to characterize the crud or very small features on the fuel rods. They did not reveal any indication of significant variations in the fuel rods after shipment, handling, and performance testing. The resolution of the videotapes did not provide enough information to adequately determine the integrity and condition of the fuel and fuel cladding. Examination of the video scans showed that all the fuel assemblies and fuel rods look basically the same when viewed from outside the assemblies. There was some discoloration of the fuel rod cladding in the area of the grid spacers, which was expected.

Color photographs showed that a typical orange/reddish crud (probably Fe_2O_3) was evenly deposited on all of the Zircaloy 2 cladding and fuel assembly hardware. There were no noticeable changes in the characteristics or adherence of the crud during handling operations involving the spent fuel assemblies at GE-Morris or INEL. Some scratches and worn spots were apparent on the spacer grids and some fuel rods, but these features did not change as a result of examination or handling operations. In general, the fuel rods were in excellent condition, with a very adherent crud layer.

Additional visual examinations of the fuel were conducted during the dry rod consolidation program. According to Vinjamuri (1988a, 1988b):

> No noticeable cladding defects in the rod surfaces were observed for any of the fuel processed. The oxide layer on the surface of the fuel rods appears to be intact and firmly attached to the cladding. The oxide layer does not appear to be loose, thick, soft, or powdery. However, the oxide layer and some of the zirconium cladding was scraped from the rod surface by the spacer grids as the rod was pulled during fuel consolidation. Very little crud buildup on the surfaces of the rods was observed. The surfaces of the rods displayed only a thin oxide layer, which had the appearance of surface discoloration rather than any rough or loose material. The rod surfaces are discolored near the spacer grids. The discoloration has an appearance of a dark mottling of the surface and is progressively more predominant from the middle of the rod length toward the rod bottom. The rods are generally clean, with limited amounts of clad discoloration and oxidation . . . The evidence of fuel rod growth since fabrication was visually obvious during the consolidation process.... Length variation between rods appears to be as much as 2 cm (0.8 inch). The rods that grew longer than others appeared to be randomly located within the fuel assembly.

CASK COVER GAS SAMPLING The cask cover gas was sampled several times during each cask performance test to evaluate the integrity of the spent fuel rods. Each sample was collected in a separate 500-cc stainless steel cylinder that had been leak-tested before sampling. Initially, during the CASTOR-V/21 cask performance test, the cylinders were equipped only with quick-disconnect fittings and no bellows-sealed valves as part of the closure. During the early sampling efforts with the CASTOR-V/21 cask, the cover gas samples in the cylinders were diluted with ambient air from the vicinity of the sampling apparatus, air that leaked into the cylinder during shipment, and argon introduced at Lawrence Livermore National Laboratory (LLNL). In many cases, this dilution was made more severe by the collection of small amounts of cask cover gas, presumably due to short equilibration times between the cask and the sample bottle during the actual cask cover gas collection procedure. The end effect of small, diluted samples on the cask cover gas analyses was to increase detection limits, increase measurement uncertainties, and introduce questions of sample validity. Once bellows-sealed valves were added to the sampling cylinders, the problem of air leakage into the sampling cylinders was eliminated.

Gas sample analysis included mass spectroscopy and radiochemical gamma analysis. Mass spectra were analyzed for all common fixed gases with masses less than 100 to verify the purity of backfill gas composition. Only N_2, 0_2, He, Ar, and CO_2 concentrations above 0.01% are detected in any of the samples. The integrity of the fuel rods was assessed from the radionuclide concentration based on gamma spectroscopy.

However, the relatively low amounts of ^{85}Kr detected indicate that no leaking fuel rods were present in the GNS CASTOR-V/21 and MC-10 casks during performance testing with unconsolidated fuel and up to about a year after testing. At this time, gas sampling in these casks was discontinued. The final gas sample from the CASTOR-V/21 cask during this period was taken in December 1986. In September 1994, the CASTOR cask was opened and backfilled with a fresh charge of helium gas. The pre- and post-test backfills were checked for purity. Gas samples taken in March 1995, after six months of gas residence in the cask, did not contain detectable amounts of krypton-85, which indicates no leaks from fuel rods during that storage period. This is particularly significant, because the first few assemblies loaded in the CASTOR-V/21 cask were exposed to air for approximately 200 hours during incremental loading of the cask and fuel assembly/basket inspections at a reduced temperature. In addition, after testing was completed and long-term surveillance started, all the fuel assemblies were in a 70% He and 30% air environment for approximately four months, because a quick disconnect fitting on the CASTOR-V/21 cask lid had not sealed properly.

Two casks loaded with intact fuel have shown krypton gas concentrations indicative of a leaking fuel rod. During the performance test of the REA-2023 cask, krypton gas was detected after the cask was rotated from a vertical to a horizontal orientation. The accumulated amount of krypton gas released to the cask was consistent with the release from a single fuel rod (Barner 1985; Guenther 1988). The cladding defect was assumed to be very small since the release rate was essentially linear during 2.5 months of testing. There was no confirmation of a leaking fuel rod either by visual inspection or sipping of the fuel assemblies after the cask test. The gas analyses provided the only indication of a leaking fuel rod. The leaking fuel rod had no impact on the basin operation or handling of the fuel assemblies subsequent to the cask test.

The other cask loaded with intact fuel that showed krypton levels indicative of a leaking fuel rod was the TN-24P cask. In this performance test, the cumulative amount of ^{85}Kr detected just after the cask was rotated from a vertical to a horizontal orientation indicated that a fuel rod had leaked during this portion of the test. The decay in the leak rate, as indicated by subsequent gas samples, indicates that the leak was small. It took several days to vent the gas from the fuel rod.

In May 1987, 36 of the 48 intact fuel assemblies in the TN-24P and MC-10 casks, plus 12 intact assemblies that had been in the Turkey Point Reactor, were consolidated into 24 consolidated fuel canisters as part of INEL's Dry Rod Consolidation Technology Project. The consolidated fuel canisters were then used in performance tests of the TN-24P and VSC-17 casks. During the fuel rod consolidation process, the exhaust gases from the consolidation area were monitored to detect the release of radioactive gases from the fuel that would indicate a cladding failure. In the consolidation reports (Vinjamuri 1988a, 1988b), one of the conclusions reached was that all fuel rods from the 48 assemblies were pulled and canisterized without rod failures.

Later, during the performance test of the TN-24P cask using consolidated fuel, ^{85}Kr was released to the cask. Based on a combination of ORIGEN2 predictions and experimental measurements (Barner 1985; Guenther 1988), it was estimated that four or more fuel rods may have developed leaks between the end of cask loading and the beginning of cask performance testing, three or more fuel rods during cask performance testing, and another five fuel rods in the six-month period following testing. The rate of ^{85}Kr release was observed to decrease with time from cask loading. Shortly after the last gas sample was taken from the fully loaded TN-24P cask, 17 canisters of consolidated fuel were removed from the TN-24P cask and loaded into the VSC-17 cask. The performance tests for the VSC-17 cask showed a nominal ^{85}Kr but not enough to indicate a new leaking fuel rod. Since the end of the VSC-17 performance testing in early 1991, until September 1994, the VSC-17 has been undisturbed. Recent gas samples, taken since September 1994, indicate that the atmosphere in the VSC-17 has not changed significantly. There has been a small amount of ^{85}Kr release, below the quantity expected for a single rod release, and there has been buildup of hydrogen in the cask. The amount of hydrogen is consistent with off-gassing of the RX277 neutron shield material in the lid. Similar amounts of hydrogen were observed during cask performance testing.

The amount of ^{85}Kr released during and after the TN-24P cask performance test with consolidated fuel is significantly higher than was released in previous cask testing with unconsolidated fuel. Before this test, four cask performance tests of similar duration and scope had been performed; only two indications of ^{85}Kr release were observed. The magnitude of the releases in the previous tests and surveillance periods indicated that each was limited to a single rod cladding breach. The previous tests involved about 16,700 spent fuel rods, whereas this test involved about 9800 rods. It is hypothesized that the greater magnitude of ^{85}Kr released in this test and post-test surveillance is due to additional cladding leaks caused by enlargement of incipient cladding flaws during pulling and flexing of the fuel rods in the consolidation process. The enlarged cladding flaws, combined with cladding creep during cask testing and surveillance periods, allowed leak paths to develop. The leakage has not affected operations.

SUMMARY

Radiochemical gamma analysis of gas samples from cask performance tests and subsequent cask surveillance and monitoring activities provides an indication of spent fuel integrity during dry storage. The gas sampling analysis indicates that dry storage of spent fuel in an inert atmosphere is benign. In general, fuel handling activities have a more significant impact on fuel rods than does extended dry storage in an inert atmosphere.

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