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Abstract

Following the massive earthquake and resulting tsunami damage in March of 2011 at the Fukushima Daiichi nuclear power plant in Japan, interest was amplified for what was done for recovery at the Three Mile Island Unit 2 (TMI-2) in the United States following its meltdown in 1979. Many parallels could be drawn between to two accidents. This paper presents the results of research done into the TMI-2 recovery effort and its applicability to the Fukushima Daiichi cleanup. This research focused on three topics: packaging, transportation, and disposition. This research work was performed as a collaboration between Japan's Central Research Institute of Electric Power Industry (CRIEPI) and the Idaho National Laboratory (INL). Hundreds of TMI-2 related documents were searched and pertinent information was gleaned from these documents. Other important information was also obtained by interviewing employees who were involved first hand in various aspects of the TMI-2 cleanup effort. This paper is organized into three main sections: (1) Transport from Three Mile Island to Central Facilities Area at INL, (2) Transport from INL Central Receiving Facility to INL Test Area North (TAN) and wet storage at TAN, and (3) Transport from TAN to INL Idaho Nuclear Technology and Engineering Center (INTEC) and Dry Storage at INTEC. Within each of these sections, lessons learned from performing recovery activities are presented and their applicability to the Fukushima Daiichi nuclear power plant cleanup are outlined.

Transport from Three Mile Island to Central Facilities Area at INL

Canister Designs

The TMI-2 damaged core debris consisted of approximately 125 tons of spent fuel and core debris. This material was packaged into 342 sealed stainless steel canisters. The canisters were l4-in. in diameter with a length of 150 in. The canisters were equipped with 3/8-in. drain and l/4-in. vent fittings. There were three types of canisters used for the TMI-2 damaged core debris (see Figure 1).[1]

1. *Fuel canisters.* These canisters contain partially intact fuel assemblies and core debris large enough to pick up and load using mechanical devices. Examples of the core debris include fuel rods, spacer grids, control rod spider hubs, end fittings, springs, and fuel pellets. The fuel canisters have an empty weight of approximately 1,200 lb (544 kg) and a maximum loaded weight of approximately 2,900 lb (1,315 kg). There are 268 fuel canisters.
2. *Knockout canisters.* These canisters contain TMI-2 core debris that was vacuumed from the TMI-2 reactor vessel and coolant system. The debris particle sizes vary from 140 microns to the size of a fuel pellet (0.375 in. in diameter × 0.60 in. long). The knockout canisters have an empty weight of approximately 1,046 lb (474 kg) and a maximum loaded weight of approximately 2,900 lb (1,315 kg). There are 12 knockout canisters.

3. *Filter canisters.* These canisters contain fine core debris obtained from filling the knockout canisters. The filter canisters have an empty weight of approximately 1,440 lb (653 kg) and a maximum loaded weight of approximately 2,500 lb (1,134 kg). There are 62 filter canisters.

The canisters were designed to use existing fuel transfer equipment between the containment pool and the Spent Fuel Building. The Spent Fuel Building was designed to store used fuel for decay prior to shipping. This building provided for canister loading and storage while transportation issues were being resolved. It also allowed the shipment to continue while in containment issues (such as the microbe bloom) were being worked. It also eliminated the cost of new transfer equipment and storage facilities at TMI. In addition, the common external dimensions, maximum weights, common vent and drain ports, and identical handling designs greatly simplified in facility handling, cask loading, cask shipping, unloading, and storage operations.

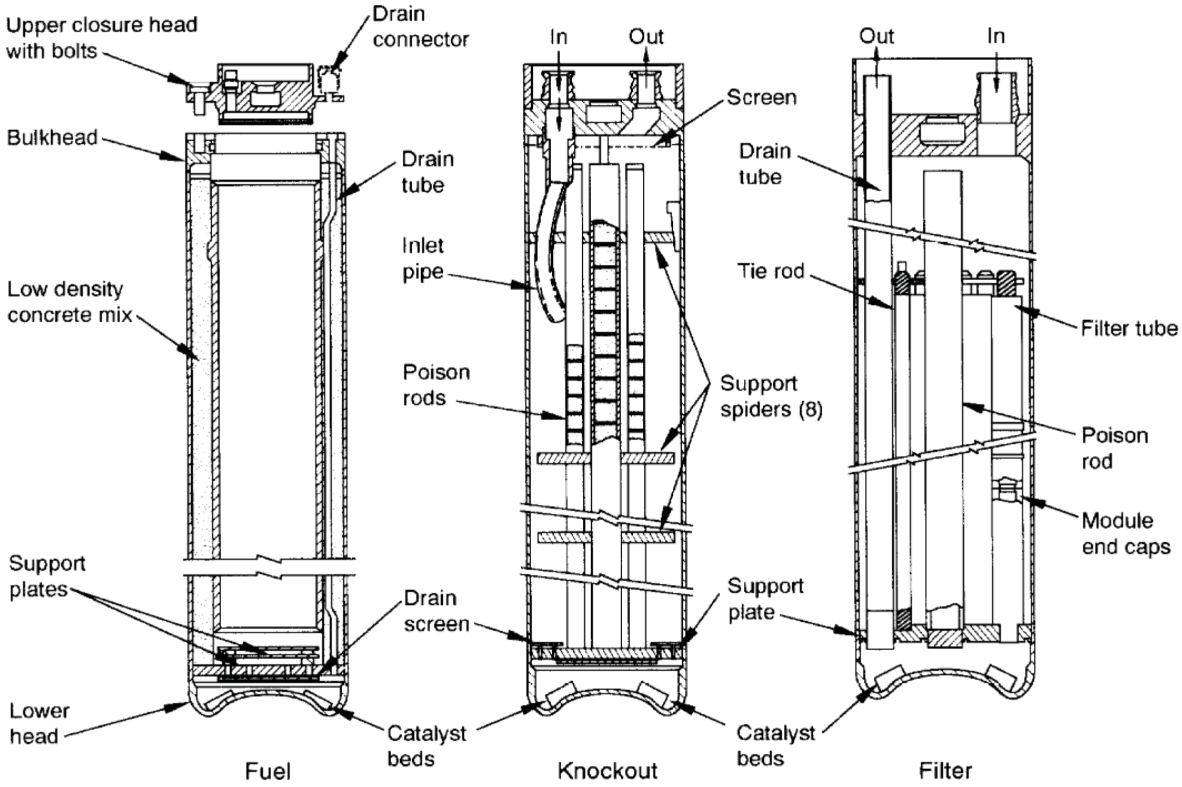

Figure 1. Core Debris Canisters.

The fuel canister was a receptacle for large pieces of core debris that could be picked up by the defueling grapple and placed in the canister. For this reason, the upper closure head was removable to permit easy access for debris loading. An internal shroud controlled the size of the internal cavity and provided a means of encapsulating the neutron absorbing material used for criticality control (Boral).

Lessons Learned

Because DOE made a requirement that the fuel rubble be kept in a safe physical dimension (for criticality safety), a filler material needed to be used to ensure this physical configuration. It was decided to use a low density concrete for this filler material. The use of a low density concrete (LICON) in the canister as filler material was not the best choice. The presence of water in the LICON mixture is extremely difficult to remove. Many debris components require oxygen leaving a net surplus of hydrogen.

That must be vented. The canister cannot be permanently sealed during subsequent storage. Other options could be explored, such as aluminum or glass beads.

Applicability to Fukushima Daiichi Nuclear Power Station

It is likely that canisters will need to be used for packaging the damaged fuel at Fukushima. The TMI canisters were designed to be used for PWR fuel. The Fukushima fuel is BWR fuel which has different size specifications and fuel array sizes (TMI-2 was 15×15 and BWRs are typically 8×8 arrays with different element lengths from TMI). Therefore, TEPCO could not use the exact canister design used for TMI fuel debris. The Fukushima fuel has a higher burnup as well causing higher decay heat which will change the design specifications from TMI. However, TEPCO could greatly benefit by considering the design used for TMI and learning from the canister experience gained by using the core debris canisters. The canister design used was very conservative but provided a wide margin of safety which enabled obtaining regulatory approval in a timely manner. It is strongly recommended to investigate better options to replace LICON for use in the fuel canister.

It is recommended that TEPCO inspect the fuel transfer systems from the Reactor Building to external storage pools and if possible use them both for transfer and interim storage.

TEPCO will need to account for microbial induced corrosion in their canisters. With the introduction of sea water into the reactor, microbial contamination will almost certainly occur. This could possibly be dealt with in a similar manner as TMI using antimicrobial additives to the water.

If it is decided to reprocess the Fukushima fuel, a different canister design should be used in Japan since the TMI canister was not designed to be opened and unloaded. Also, if reprocessing, the reprocessing facility needs to be aware that various other extraneous debris may end up in the fuel debris canister (such as rags, broken tools, plastic, etc.).

Transport Cask Loading System

Design

The design process used by GPU Nuclear and NuPac in developing the dry cask loading equipment included some general requirements applicable to all components.

The use of these general requirements and several TMI-2 facility-specific requirements ensured that the equipment provided by NuPac was designed to meet the needs of GPU Nuclear for dry cask loading in the TMI-2 truck bay.

Lessons Learned

The major concern with cask loading activities was handling of the heavy loads in the Fuel Handling Building (FHB). TMI-2 had a heavy load handling program approved by NRC that was expanded to allow for dry loading of a shipping cask. The program complied with the requirements of NUREG-0612 for safe load paths; use of approved procedures; trained and qualified operators; special and standard lifting devices; crane design; and crane inspection, testing, and maintenance.

Heavy-load drop concerns caused a major change in the dry loading approach during development of the cask handling equipment. From mid-1984 until January 1985, the dry loading concept had proceeded based on using the FHB overhead crane for rotating of the shipping cask from horizontal to vertical and back down to horizontal. In this concept, the cask would not have been removed from the railcar. The railcar would have been stabilized by jacks for cask rotation. A lifting yoke would have been attached to a set of trunnions at the upper end of the cask and a lift by the crane used to rotate the cask to vertical.

During lowering to horizontal, the crane would have controlled the cask's rotation. Accident analyses identified that failure of the FHB crane during cask rotation would have resulted in a slapdown of the cask onto the railcar. The potential damage to the truck bay and FHB equipment in the basement was unacceptable to GPU Nuclear.

The initial consideration was to provide hydraulic snubbers between the cask and skid to prevent an uncontrolled slapdown of the cask. Further discussions and evaluations showed that the cask hydraulic lift assembly (CHLA) could be used instead of the crane and therefore eliminated potential failure of the FHB crane during this operation. However, several complications arose with the division of responsibilities between GPU Nuclear and EG&G Idaho for the handling equipment. The transport skid was clearly in EG&G Idaho's scope, but as designed, required modification to accommodate the CHLA. Also, a lifting yoke had been included in EG&G Idaho's scope to provide for use at TMI-2 with the casks, but was not needed with use of the CHLA. Since the CHLA was performing the function of the FHB crane, GPU Nuclear was responsible for providing the CHLA. However, since the design of the CHLA required close integration with redesign of the skid, EG&G Idaho agreed to include procurement of the CHLA under EG&G Idaho's cask procurement contract.

All parties involved agreed that an integrated test of the system needed to be performed before use. The integrated test of the cask loading equipment (at the Hanford Engineering Development Laboratory) was very successful not only in achieving the objectives but in doing so away from TMI-2, where small anomalies in installation and checkout of the equipment would have been frustrating and much more costly to correct. Several necessary mechanical and electrical modifications and equipment improvements were uncovered by the integrated test. Changes were engineered and implemented within hours and days rather than days or weeks had the equipment been set up at TMI-2 initially. The test enabled many TMI-2 operators to gain first-hand knowledge of the equipment's design and operation, including an understanding of the functional requirements by direct discussions with NuPac's design engineers. This transfer of information was very valuable to the straightforward installation and use of the equipment at TMI-2. The integrated test lasted a month, including initial system assembly, testing, disassembly, and packing for the shipment to TMI-2. The cost effectiveness of the integrated test was indicated by the fact that equipment went from receipt at TMI-2 to NRC approval for use in less than two months.

Applicability to Fukushima Daiichi Nuclear Power Station

It would be valuable to perform integrated testing of the cask loading equipment designed for use at Fukushima before using the equipment on casks actually loaded with fuel debris. Problems can be uncovered and corrected before handling radioactive material. Also operators can gain first-hand knowledge and experience of the equipments operation. With planning and appropriate equipment, large casks can be used in limited facilities.

Shipment from TMI to CFA

The TMI-2 shipments began on July 20, 1986, and were completed on May 9, 1990. There were a total of 49 cask loads transported by 22 rail shipments over about 3.8 years. Cask load 47 contained only six canisters, for a total of 342 canisters of TMI-2 core debris transported to the INL. There was an average of 90 canisters shipped per year. The cross-country trip required about four days (several hours less than four days as operational efficiencies improved).[1] The maximum shipping times were limited by the safe shipping window of the most restrictive canister.

The shipments from TMI to INL were as a dedicated rail shipment over a predetermined route. The train comprised of the engine buffer cars, one to three casks and a caboose. The buffer cars were loaded with a rock ballast and located between the engine and first cask, between each cask, and between the last cask and the caboose. The cars were to ensure separation between the casks in case of accident and to reduce radiation to personnel during transport. The empty casks were returned to TMI as routine freight. At the time of shipment, use of a caboose was being phased out of rail service and another car would be needed in the future to transport personnel. In addition, at that time security escorts were not required but would probably be needed today. Representatives of the INL rode on the first few train shipments as an escort. These representatives were to provide expertise in case of a large accident.

Lessons Learned

The shipping campaign from Three Mile Island to Idaho was a very successful project. It has been used as a model for transporting spent fuel since then. There were a number of things which helped the success of the shipping campaign. A few of them are described below:

Working Closely with Elected Officials

DOE, in conjunction with other Federal agencies, was implementing national policy affirmed by two U.S. presidents, in activities and support of the cleanup of the TMI-2 accident. Those DOE activities, including acceptance and transport of the TMI-2 core debris, were frequently reviewed by Congressional committees through the process of testimony on technical progress and DOE budget authorizations. Accordingly, there was approval at the highest levels of government for the transport activity.

Public Relations Plan

The TMI-2 Program did a credible job in preparing a public relations plan before the campaign started. The program accepted and enhanced all established public relations procedures, prepared and distributed program briefs and videos, co-hosted a media day, made public announcements, performed prenotification activities, and met with some State and public officials.

Interfacing Equipment with Facilities

Equipment interfaces, both at the INL and TMI-2, took a lot of planning, teamwork, and honest and open communication. The integrated test of all cask handling and cask loading equipment that was performed at the Maintenance and Support Facility of the Fast Flux Test Facility of the Hanford Engineering Development Laboratory was very valuable for confirming cask-to-handling equipment fit up, training of GPU Nuclear personnel, development of procedures, and generally proving system performance. The test resulted in a much smoother installation and startup of equipment at the TMI-2 facility.

Licensing, Teamwork, Problem Prevention, and Attention to Quality Assurance

Perhaps one of the best keys to success for all activities related to transport of the TMI-2 core debris was teamwork, attention to detail, emphasis on prevention of and/or early detection of problems, and stringent QA aimed at preventing problems. These policies were practiced throughout all technical activities, from design of the cask system to storage of canisters at the INL. Many examples are cited in the text. The whole experience of the cask licensing process is one example: proper use of testing, "in process" discussions with the regulatory agency, on-the-spot QA and engineering oversight, and so forth.[1]

Applicability to Fukushima Daiichi Nuclear Power Station

If it is decided to ship the damaged Fukushima fuel across public roadways or railways, then there is much to learn from the very successful transport of TMI fuel to Idaho.

When planning a spent fuel transportation route, plan out alternate routes all along the preferred route. Sometimes detours need to occur because of accidents ahead on the route or other events. It saves a lot of time and money to have alternate routes already planned and approved for use.

It is helpful to have a project representative on board the shipment. This reduces fears of the transportation crew and the public.

It was advantageous to have double containment for the shipment of the TMI fuel (canister and cask). It significantly reduced the consequences of accident and attack scenarios. This also helped to reduce concerns of citizens and public officers.

Transport from CFA to TAN and wet storage at TAN

Canister Water-Filling and Wet Storage at TAN

Preparing the canisters for long-term storage required that (a) each canister be filled with water; (b) each canister be locked into a storage module; (c) each module be transferred into the storage pool and placed in a designated location; and (d) a vent tube be installed on each canister for continuous venting. Although the canisters were shipped dewatered to satisfy transportation safety requirements, each was refilled and stored water-filled, but continuously vented, to ensure safe long-term storage at the INL.

Lessons Learned

In January 1986, one of the NuPac 125-B casks was delivered to the INL, and a dry run of the entire sequence of receipt and storage operations at the INL was performed. Handling equipment was tested and modified as needed. The environmental cover and two overpacks were removed from the cask, and the cask and skid were transferred from the railcar to the transporter. Once the dry run operations at CFA were completed, the loaded transporter was shipped to TAN and backed into the Hot Shop for personnel training and to test the Hot Shop equipment. The cask was transferred from the transporter to the work platform; both lids and the shield plugs were removed; and the dummy canister was moved in and out of each of the seven canister cavities in the ICV of the cask. This dry run thoroughly tested all of the cask and canister handling equipment and the operating procedures. Several needed improvements were identified.

The first was that the mechanical dynamometer between the overhead crane hook and the canister grapple could not always be read during removal of the canister. The dynamometer was needed to monitor the load on the grapple during the lift of a canister from a cask. This ensured that the canister did not bind up in the cask and overload the grapple. The dynamometer was replaced with a load cell that had an electronic readout in the operating gallery area that could be easily read by the technicians.

Secondly, the ability of the technicians to see the canisters being lowered into the storage module in the vestibule pool needed to be improved. Visibility was improved by adding a pan, zoom, and tilt capability to the underwater camera system and by installing better underwater lighting.

Finally, the canister grapple designed at TMI-2 for TMI-2 equipment was not fully compatible with the remote handling operations needed in the Hot Shop. The side loads on the grapple from electrical control cords caused the grapple, as originally designed, to hang at an angle that made it difficult to engage canisters remotely. The grapple was modified to specifically meet the needs of the Hot Shop.

While in wet storage at TAN, the TMI fuel continued to produce hydrogen which was vented out through the canister venting system. Periodically, the vent tube system would temporarily plug and then release causing a spray of potentially dangerous water out the top of the canister venting system.

Applicability to Fukushima Daiichi Nuclear Power Station

Once it is decided where the damaged fuel from Fukushima will be transported to for storage, the handling equipment at the storage facility needs to have sufficient remote cameras to perform canister handling operations.

The grapple system needs to be designed and tested to prevent the canister from releasing from the grapple while moving.

If a canister venting system is use for Fukushima fuel in wet storage, steps should be taken to mitigate the plugging of the canister venting system (which could cause a buildup of pressure followed by a spray of water out the top of the vent).

Transport from TAN to INTEC and Dry Storage at INTEC

Removal from Wet Storage and Preparation for Transfer

In 1998, the U.S. Department of Energy directed the operators of the INL to begin encapsulating the TMI canisters (which were in wet storage at TAN) into dry storage canisters (DSCs).The project to move all of the TMI canisters from wet storage at TAN to dry storage was a very successful project and completed six weeks ahead of schedule.

Lessons Learned

It was determined that the TMI canisters must be stored vented because of the continuous buildup of hydrogen gas. The hydrogen gas is from the water used in the manufacture of the LICON.

Initially manual TIG welding was used for welding operations on the DSC. This resulted in higher dose rates for welders and welder fatigue. Automatic MIG welding was implemented and resulted in drastic improvements.

Storing new DSCs in a clean environment is essential to subsequent operations. The DSCs were fabricated using carbon steel materials that rust. Seal and weld surfaces needed protection during storage. However, protection materials must be compatible with subsequent welding operations.

There were many innovations, techniques, lessons learned, and approaches used to achieve program success. These include:

- A systems approach to proposal and specification requirements was used to select the welding system and conducted the welding system readiness assessments for the program.
- Because there were no flaws in the automated welding, a novel in-situ cracking technique was developed to generate a crack on the mockup assembly welds to validate that the remote inspection system could ascertain weld defect indications at each layer in the weld joint.
- A validation or readiness assessment of the welding system, on a mockup DSC weld-out with complete destructive and non-destructive evaluation of the welds, was performed prior to purchase of welding services. The use of mockup DSCs were invaluable in measuring the readiness of the subcontractor vendors, the functionality of the welding system, validating the operating procedures, and training the operators.
- Dry-run procedure validation performed during a mockup assembly weld-out enhanced the operating procedure prior to start-up.
- A subcontractor welding service was employed to perform the welding, furnish the welding system, and provide the system spare parts with a full-time service technician. This helped relieve the facility

operations of maintaining the welding system, having spare parts, and hiring extra staff for the short term program.

- Using a rugged proprietary welding system designed with redundancy or dual components and built for the radioactive environment was paramount in achieving success of the program.[19]

Applicability to Fukushima Daiichi Nuclear Power Station

If it is decided to use a DSC at Fukushima, it is recommended that automated welding be used for welding operations on the DSC. This will improve efficiency and decrease worker dose.

It is recommended to not use LICON or any other water based or hydrogen generating material for criticality control in the fuel debris canister.

Onsite Shipment to INTEC

The OS197 transfer system includes the transfer cask, transfer trailer, skid positioning system, and hydraulic ram system. Dry shield canisters, which contain up to 12 TMI-2 core debris canisters, were placed inside the OS197 transfer cask during the TAN and INTEC transports. The OS197 transfer system was designed by VECTRA Technologies, Inc., and was licensed [10 CFR 72 "Licensing Requirements for the Independent Storage of Spent Nuclear Fuel and High-level Radioactive Waste," *Code of Federal Regulations,* Office of the Federal Register.] by the Nuclear Regulatory Commission (NRC) for onsite transport of irradiated fuel assemblies. Since the intended use of the transfer system was for slow moving onsite applications only and not for transport over public highways, the system design, maintenance, inspection, and attachment of the transfer cask to the skid positioning system and transfer trailer, were not in compliance with DOT Federal Motor Carrier Safety Regulations.

Changes of interpretation of DOT rules required that a short section of road between TAN and INTEC was declared “Public Highway.” That section of road was closed for the short time necessary to transport the shipping cask between DOE controlled areas. This required DOE to obtain a State of Idaho permit with public notification for road closure.

Figure 2. TMI core debris moved by truck and trailer from Test Area North (TAN) to INTEC.

The 342 canisters of core debris were stored in underwater storage at TAN-607 from 1986 to 2001. Upon removal, the canisters had an estimated unshielded dose rate from 50 to 150 rem/hr at 1 m. The decay heat per canister was estimated to be a maximum of 60 W with the average being only 29 W. Prior to loading the TMI-2 canisters in NUHOMS dry shielded canisters (DSCs) for transport to INTEC, the TMI-2 canisters were dewatered, heated, and vacuum dried.

Lessons Learned

It was discovered that the DSCs needed to be loaded with canisters such that they were weight balanced. If they were not balanced then while the hydraulic ram was inserting the DSC into the concrete vault, the DSC tended to rotate. This caused a problem because the vent assembly on the DSC would then not line up with the corresponding cut-out in the end of the NUHOMS vault.

Applicability to Fukushima Daiichi Nuclear Power Station

If a vented DSC is used with the NUHOMS storage system in Japan, weight balancing the DSC will need to be taken into consideration.

Dry Storage in NUHOMS at INTEC

The U.S. Department of Energy (DOE) chose a modified NUHOMS® spent fuel storage system, designated NUHOMS®-12T, which is used at the independent spent fuel storage installation (ISFSI) constructed at the INL at the INTEC location. The INL TMI-2 ISFSI design is based on the currently licensed NUHOMS® system. The NUHOMS® system has an extensive licensing and technical basis. The original NUHOMS® Topical Report (NUH-001, Revision 1A, NRC Project No. M-39) was approved by the United States Nuclear Regulatory Commission (NRC) on March 28, 1986 for storage of seven spent pressurized water reactor (PWR) fuel assemblies.

After initial loading of an HSM, the license (Technical Specifications) surveillance requirements included periodic leak testing of the DSC vent housing seals, monitoring of HSM radiation levels at the front door and end shield walls, radiation monitoring of DSC vent system HEPA filters, and sampling the gas inside the DSC for hydrogen. Periodic leak testing of the DSC vent housing seals was performed within seven days after insertion of a DSC into and HSM, and every five years during storage operations. HSM radiation levels at the front door and end shield walls were measured within 24 hours after completing an HSM loading. Radiation monitoring of DSC vent system HEPA filters was performed monthly during the first year, quarterly during the second through fifth years, and annually thereafter. Sampling the gas inside the DSC for hydrogen was performed monthly during the first year, and annually thereafter.

The Radiological Environmental Monitoring Program required by the license was designed to monitor two potential radiation exposure pathways; direct radiation and airborne radioactivity. Thermoluminescent dosimetry stations are located around the perimeter of the ISFSI protected area and the dosimeters are exchanged quarterly. A 7-day air sample is collected each month and analyzed for gross alpha and beta radioactivity. Gamma spectroscopy is performed on composited air samples to monitor for Cs-137.

Lessons Learned

During a 2011 inspection of the ISFSI, the NRC noted that significant degradation of the exterior concrete on the HSMs had occurred over the recent years due to water intrusion and the annual thawing and freezing cycle. The condition had been monitored for several years by the licensee and the operating contractor. The condition, best characterized as severe cracks radiating from the through-hole penetrations in the HSM roof corners, was mitigated in 2011. The licensee awaits the NRC for a return inspection of the mitigative condition. The aging management program for the ISFSI includes a periodic concrete surface monitoring program for the HSMs.

In early 2012 the NRC requested from Transnuclear, Inc. (ML12033A211) a list of all ISFSI sites utilizing Certificate of Compliance (CoC) No. 1004 in conjunction with through-hole HSM roof penetrations. Transnuclear, Inc. responded with a list of six sites (TMI-2 ISFSI inclusive) that use the HSM design with through-hole roof penetrations (CoC 1004, 1029, and 1030 plus certain other site-specific licenses). In a separate letter (ML120100134) from the NRC SFST to Region IV, SFST stated they believe inspection and maintenance activities by licensees should focus on early identification and mitigation of potential degradation in penetrations and appropriate aging management maintenance actions should be incorporated into the license renewal. Additional recommendations were made with regard to NRC inspections, review of changes to HSM designs, and inclusion of appropriate aging management plans in license renewal applications.

Applicability to Fukushima Daiichi Nuclear Power Station

If the Fukushima Daiichi Nuclear Power Station is located in an area where outdoor dry cask storage systems (DCSS) could be subject to freeze/thaw cycles, the DCSS design should minimize the possibility for water intrusion into concrete structures. The use of surface sealants is also recommended.

REFERENCES

1. *Three Mile Island Core Debris Packaging, Transportation, and Storage Summary*, INL, INL/LTD-11-22779,September 2011