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DESIGN AND SCALE MODEL TESTING OF THE NuPac 125-B RAIL CASK*

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Abstract

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The NuPac 125-B package was developed for defuelling the damaged Three Mile Island Unit II (TMI-2) reactor. The nature and impact of these requirements on the design and licensing of a transport package are discussed. Loading and unloading of the NuPac 125-B differs from conventional fuel cask handling procedures owing to facility features and limitations at both TMI-2 and the receiving station. All transfers are 'dry' and the cask is never placed in a conventional fuel loading pool. In addition, the cask design was affected by the unique requirements for double containment of the TMI-2 fuel material, an accelerated development schedule, and limits imposed on impact loads experienced by the fuel debris canisters. Licensing activities involved analyses correlated with drop and puncture tests conducted on a 1/4 scale cask model. All structural details of the NuPac 125-B were accurately represented in these tests and analyses. Excellent correlation was found between analytical predictions and model behaviour on the impact events, and basic structural design and analysis assumptions were validated. Used together, integrated test and analysis demonstrations are shown to accelerate the design and licensing process.

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1. THE NUPAC 125-B CASK

The NuPac 125-B, see Figure 1, was developed by Nuclear Packaging, Inc. (NuPac) is a safe means of transporting the damaged Three Mile Island Unit II (TMI-2) core from the TMI site at Middletown, Pennsylvania, to the Idaho Nuclear Engineering Laboratory (INEL) at Idaho Falls, Idaho. A companion paper [1] presented at this symposium presents an overview of the integrated transport program.

The NuPac 125-B cask is a rail cask designed to transport up to seven (7) canisters at one time. Each canister will contain portions of the TMI-2 core in the form of partial pressurized water reactor (PWR) fuel assemblies, core rubble (140 µm to larger than fuel pellet size), and small fines (0.5 to 840 µm). The canisters are identified, respectively, as fuel, knockout, and filter canisters. The NuPac 125-B cask provides two levels of "leaktight" containment for the canisters during normal and hypothetical accident conditions.

The outer vessel of the NuPac 125-B cask, which provides primary containment and an environmental barrier, consists of a conventional stainless steel and lead cask body with forged ends surrounded by a stainless steel fire shield. The inner vessel provides secondary containment for the canisters. It is fabricated of stainless steel and neutron-absorbing materials, and contains seven cavities for the canisters. Each canister is axially protected by honeycomb energy absorbers located within the inner vessel at each end of the canister.

Steel-sheathed polyurethane foam-filled energy absorbers (overpacks) are attached at each end of the outer vessel to protect against normal and hypothetical accident conditions. The cask is passively cooled because the maximum decay heat per canister is only 100 watts. The gross weight of the package, including seven canisters weighing a maximum of 1336 kg (2,940 lbs) each, is 82,500 kg (181,500 lbs).

2. CASK HANDLING & SUPPORT EQUIPMENT

Loading and unloading of the NuPac 125-B differs from conventional fuel cask handling procedures due to facility features and limitations at both TMI-2 and INEL. Both canister transfers are "dry" and the cask is never placed in a conventional fuel loading pool. In both loading and unloading sequences the NuPac 125-B and its transport skid are separated and lifted from the eight axle rail car after removing six attachment pins on each side of the skid.

At TMI-2 overhead crane and floor loading limitations preclude a conventional "rotate to vertical and lift-off" handling of the cask. Instead, the rail car and cask (with

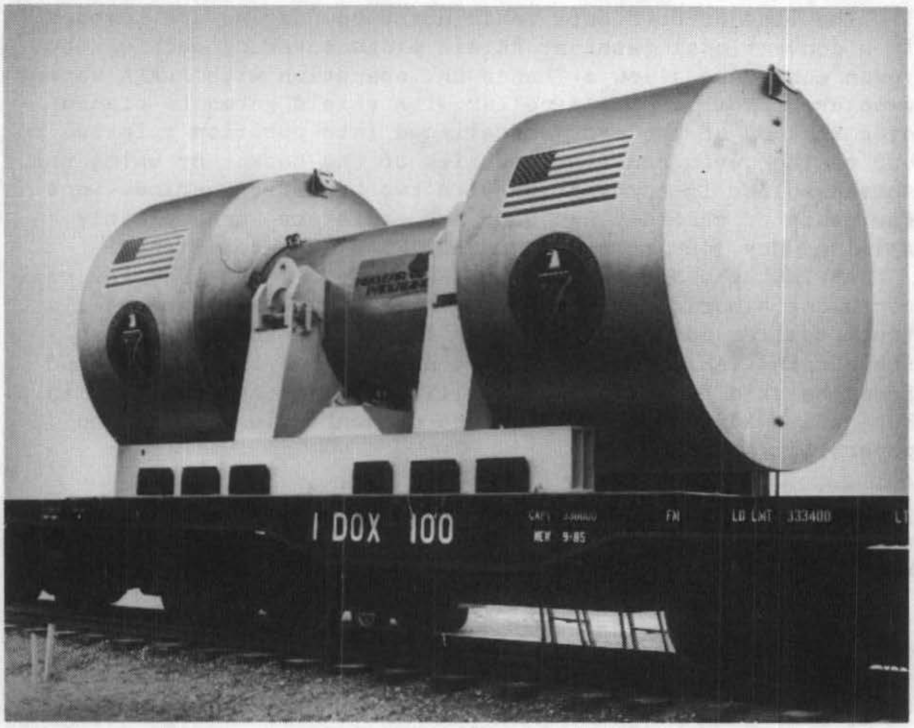

FIG. 1. NuPac 125-B rail cask USA/9200/B(M)F.

cask impact limiters removed) are brought into the loading bay at TMI-2 and positioned partially under a cask work platform attached to the floor. Next, a special lifting machine is attached to the horizontal skid and cask that lifts both free from the rail car. The rail car is next removed from the loading bay and the skid is lowered to the floor where it is mechanically pinned in place using the rail car attachment fittings. The cask skid is then fitted with a hydraulic assembly comprised of a hydraulic power supply (pump, fluid reservoir) and a microprocessor-driven control console plus two massive hydraulic cylinders attached to the cask lifting trunnions. This hydraulic assembly is next energized to rotate the cask from a horizontal position to a vertical position where the cask is mechanically attached at the top to the work platform. The system providing seismic restraint during the loading sequence is comprised of the work platform, its attachment to the cask, and the mechanical attachments of the skid to the floor.

The lids of both cask containment boundaries are removed in a conventional fashion; shield plugs covering each of the seven canisters allow a "hands-on" operation with ALARA worker exposure. Next a shield collar with shield gates is placed over the top of the cask and aligned into position relative to one of the seven canister cavities of the cask. By using the shield collar in combination with two transfer machines--one for canister shield plugs, one for canisters--a completely shielded dry loading of the NuPac 125-B is accomplished.

At INEL the NuPac 125-B and skid are removed from the rail car using a horizontal lifting beam and placed upon a special truck trailer for transport from the rail head to the Test Area North (TAN) facility. Once at TAN, the cask is hoisted from the skid by a conventional lifting yoke and unloaded in a hot-cell. Additional details are presented in a companion paper [1].

3. CASK DESIGN CHALLENGES

The unique nature of the TMI-2 defueling activity imposed several unusual design requirements. The most important of these include: dry loading/unloading, fuel material characteristics requiring double containment, accelerated development and canister impact load limits.

3.1 Dry loading and unloading

Dry loading and unloading requires features that allow removal of cask lids without exposing workers to excessive radiation doses. In the NuPac 125-B design this is accomplished by seven removable canister shield plugs stepped into the top forging of the inner vessel. The shield plugs block radiation streaming from the fuel debris canisters when cask lids are removed.

3.2 Double containment

U.S. NRC regulations 10CFR71.63 requires double containment of plutonium when shipping quantities exceed 20 curies (740 GBq) per package. Spent fuel rods are exempt from this requirement, presumably reflecting the containment provided by intact fuel cladding. For the TMI-2 fuel debris with no distinct cladding barrier, double containment was mandatory. Double containment in the NuPac 125-B package was achieved by adding within the cask body a completely independent removable inner vessel. Release rate considerations further dictated that both levels of containment be "leaktight", per ANSI Standard N14.5.

3.3 Accelerated Development

TMI-2 defueling schedules required licensed casks and equipment on-site, ready for use approximately 18 months after contract award. Approximately half this period was devoted to design while the remaining time was devoted to parallel ("fast-track") licensing activities and fabrication of two casks, rail cars and auxiliary support equipment including a complete dry-loading fuel canister transfer system. Equipment deliveries were completed in December 1985 to February 1986; approximately seven months after release for fabrication. The U.S. NRC granted a Certificate of Compliance, USA/9200/B(M)F, in April 1986; less than ten months after application submittal.

An accelerated development schedule of this nature required a focused licensing approach comprised of integrated analysis and testing plus a high degree of design conservatism to allow quick, simplified demonstrations of regulatory compliance. From a structural design standpoint, this mandates conservative linear elastic analysis techniques and linear elastic behavior of important components of the inner and outer vessels for hypothetical accident events. For events which induce compressive stresses on containment components, limits were established at approximately 0.6 of yield stress to guarantee no buckling or instability.

3.4 Impact loading limits

Impact loading limits on the fuel debris canisters were established prior to the start of cask design (100 g's lateral, 40 g's axial) to allow hydraulic and mechanical design of the canisters, including internal criticality features (shrouds and rods) to proceed independently. Thus, the cask impact limiters were designed to not only protect the cask from hypothetical accident events but also reduce impact loads on the canisters to specified limits. From a design standpoint this required unusually "soft" and large polyurethane foam impact limiters with precisely determined load and deformation behavior. For added design flexibility, axial metallic honeycomb energy absorbers were located at the ends of each canister. Two 1/4 scale engineering development tests were required to refine impact limiter performance. Supporting development tests also characterized the temperature dependent crush behavior of the polyurethane foam over the full range of probable service temperatures. One-quarter scale cask model confirmatory tests were conducted at ambient and "cold" ($-29^{o}C$) conditions.

4. LICENSING APPROACH

Typically, analyses are used to demonstrate the integrity of irradiated fuel packages under 10CFR71. The Safety Analysis Report [2] (SAR) for the NuPac 125-B cask augmented such a typical analytical approach with 1/4 scale drop and puncture tests. The use of both analysis and testing directly supported the accelerated development schedule. Either test or analysis are suitable means of demonstrating regulatory compliance, but each demonstration method has certain fundamental limitations. Test demonstrations tend to be of limited scope or are incomplete. Analysis demonstrations, on the other hand, are governed or limited by the acceptability of underlying assumptions and cannot be simply and directly related to regulatory performance requirements for containment integrity, shielding integrity and criticality control.

Used together, integrated test and analysis demonstrations overcome these individual shortcomings thus allowing an accelerated design and licensing process. More specifically, an integrated test and analysis provided benefits to the NuPac 125-B cask development activity, as follows:

- Test results benchmarked and confirmed the applicability of analytic methods for prediction of phenomena not directly tested.
- All important analysis assumptions were supported by physical tests.
- In those instances where analytic methods and supporting analytic acceptance criteria are uncertain, tests provided conclusive evidence of acceptable package performance (for example, buckling of shells due to external lead shield pressures).
- Loadings on canisters were accurately verified; thus satisfying an important cask-to-payload interface requirement.

5. QUARTER SCALE TESTS

The 1/4 scale test article had linear dimensions which were 1/4th those of the full-sized NuPac 125-B package; weight was 1/64th that of the full-sized package. The materials and material properties were identical to those of the full-sized NuPac 125-B package. All structural details of the NuPac 125-B were accurately represented in the 1/4 scale test model; certain nonstructural functional features were omitted, or not scaled, such as rupture ports, canister grapple sockets and surface finishes. While canister internals were not represented in this 1/4 scale cask model, canister impact behavior was demonstrated by other full-scale canister drop tests [2].

Drop heights remained identical to full size. Because the model was 1/4 scale, the puncture bars used also were 1/4 scale. The scaling relations show that impact-induced stresses in full and 1/4 scale are identical; as are all controlling structural limits, such as buckling and instability.

Test model performance acceptance criteria were developed to ensure preservation of containment integrity and criticality-safe geometry:

- containment vessel leak rates could not exceed 1.0×10^{-4} atm-cm^3/s,
- neither the cask body nor the inner vessel could undergo geometric changes that permanently altered the spacing or the shape of the payload canisters.

Seals themselves do not conveniently scale; however, performing a leak test of each vessel verified that the vessel had not deformed enough to compromise seal integrity or been ruptured as a result of the tests.

Different impact orientations of the cask impose maximum damage on different package components. Therefore, three 9 m (30 foot) drop tests and two puncture tests were conducted. The drop tests included an end drop onto the bottom impact limiter, an oblique drop onto the closure-end impact limiter, and a flat drop onto the side of the package. The flat end drop on the bottom end was intended to determine the peak acceleration response of the lids and closure bolts and to qualify the internal impact limiters within the inner vessel cells. The oblique impact on the lid was conducted at an angle intended to maximize cask body shell stresses. The side drop was intended to impart maximum loads to the inner vessel.

The 1 m (40 inch) puncture tests were directed at the side and closure end of the package. The side puncture event was intended to verify the integrity of the cask sidewall, and the puncture event was intended to verify the integrity of the cask lid.

The initial conditions for the tests must be at worst-case temperature and internal pressure for the feature under consideration. These were determined by analysis to be ambient pressure and -29° C (-20° F) for the bottom end and oblique drop tests and ambient pressure and ambient temperature for the side drop, side puncture, and end puncture tests. For all drop and puncture tests, the 1/4 scale model cask was instrumented with a series of accelerometers and strain gage rosettes. These data were recorded and reduced for correlation with analytic predictions. In addition, extensive visual observations were recorded by normal and high speed motion picture films and video media at two orthogonal orientations.

6. CONCLUSIONS

Excellent correlation was found between analytical predictions and model behavior for the impact events, and basic structural design and analysis assumptions were validated [2]. Deformations to energy absorbing elements occurred as predicted, and the external overpacks remained attached to the package although two attachment bolts failed. Overpack shell tearing was minor. Other damage to the package was confined to localized denting of the sidewall and slight ovalizing of the cask associated with side puncture. Helium leak tests verified that there was no detectable change in the "leaktight" containment features of both inner and outer vessels and analysis assumptions were validated. In conclusion, integrated test and analysis demonstrations, when used together, can accelerate the design and licensing process.

REFERENCES

[1] QUINN, G. J., et al., Paper IAEA-SM-256/237P, these Proceedings.

[2] "Safety Analysis Report for the NuPac 125-B Fuel Shipping Cask," Docket No. 71-9200, Rev. 2, February 1986.