PREPARATIONS TO LOAD, TRANSPORT, RECEIVE, AND STORE THE DAMAGED TMI-2 REACTOR CORE[a]

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ABSTRACT

The March 1979 incident at the Three Mile Island Nuclear Power Station (TMI) which damaged the core of the Unit 2 reactor resulted in numerous scientific and technical challenges. Some of those challenges involve removing, packaging, and transporting the core debris to the Idaho National Engineering Laboratory (INEL) for storage, examination, and preparation for final disposal. This paper highlights preparations for transporting the core debris from TMI to INEL and receiving and storing that material at INEL. Issues discussed include interfacing of equipment and facilities at TMI, loading operations, transportation activities using a newly designed cask, receiving and storing operations at INEL, and criticality control during storage. Key to the transportation effort was designing, testing, fabricating, and licensing two rail casks which individually provide double containment of the damaged fuel.

INTRODUCTION

The March 1979 incident at Unit 2 of the Three Mile Island Nuclear Power Station (TMI) resulted in a severely damaged core. Inspections using various video/sonar devices and sampling equipment revealed a cavity in the core, large amounts of rubble, partially intact fuel assemblies, and some resolidified molten materials. Part of the TMI-2 recovery effort includes removing the damaged core and transporting it to the Idaho National Engineering Laboratory (INEL) for research, examination, storage, and preparation for final disposal. GPU Nuclear Corporation (GPU Nuclear--owner/operator of TMI) and the U.S. Department of Energy (DOE) signed a contractual agreement in 1984 for acceptance of the TMI-2 core by DOE. Under terms of that contract, GPU Nuclear packages the estimated 125,000 kg of core debris in approximately 250 stainless steel canisters; DOE is responsible for transportation, storage, and final disposal of the core debris; and DOE also will study the core debris as part of its continuing research in nuclear reactor safety. GPU Nuclear began defueling operations in the fall of 1985, will begin delivering loaded canisters to DOE in May 1986, and will complete all deliveries by March 1988.

During the planning stages, EG&G Idaho, Inc. (prime contractor of INEL) investigated transporting canisters via truck or rail, using existing casks and/or fabricating and licensing new ones. Whereas available truck-mounted casks could transport one to three canisters each, the cost effectiveness of increased payload capacity of a rail cask resulted in the selection of a rail cask rather than a truck cask. The decision was made to transport canisters in a new design rail cask. Thus, the Nuclear Packaging Inc. (NuPac) 125-B Rail Cask was designed, tested, fabricated, and licensed specifically for transporting the TMI core debris to INEL (Fig. 1).

This paper highlights preparations for transporting the TMI-2 core debris from TMI to INEL and receiving and storing that material at INEL. Challenges discussed include interfacing equipment and facilities at TMI, loading canisters into the cask, developing and testing the cask, and receiving and storage operations at INEL.

Fig. 1. The NuPac 125-B Rail Cask being delivered by Nuclear Packaging, Inc., to the U.S. Department of Energy on 15 December 1985.

KEY PROJECT CONSIDERATIONS

At the beginning of this unique and complex undertaking, several considerations were deemed important, many of which were modified later or superseded by more relevant ones. Each consideration is listed below and accompanied by a brief explanation.

- Fuel Form--Initially, the core was presumed to contain some intact fuel assemblies, which the canisters would have to accommodate. Because video/sonar surveys of the core showed no full-length fuel assemblies, the canisters were shortened, reducing costs and enhancing safety.
- Dry Fuel--Originally, it was proposed that the core debris be transported dry, mitigating or circumventing concerns about gas generation, criticality, and pyrophoricity. However, that approach was both too expensive and technically complicated; therefore, it was abandoned in favor of transporting the debris in a wetted, drip-dry condition.

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- Catalytic Recombiners--Abandonment of the guideline that fuel debris would be transported dry necessitated developing a suitable catalyst for chemically recombining gases generated during transport by radiolytic decomposition of the small amount of water remaining in each canister after dewatering. At INEL, each canister is refilled with water and equipped with a passive vent system, which precludes internal accumulation of gas resulting from radiolytic decomposition of water.

- Leak Rate--To preclude the necessity of determining the isotopic inventory of contents in a containment vessel, the design leak-rate for the vessel must be less than 10^{-7} atm·cc/s (=3 cc/yr) for both normal and accident conditions. At that rate, a cask is considered "leak-tight" per ANSI N14.5. For the TMI-2 project, determining isotopic inventories in each canister would have been difficult, if not impossible.

- Double Containment--In order to transport nuclear material other than spent fuel assemblies containing more than 20 Ci of plutonium, that material must be doubly contained (per 10 CFR 71.63). In the case of damaged nuclear fuel from TMI, it originally was thought that the canister would provide the first level of containment and the cask the second level of containment. However, concern was voiced that each canister would not meet the rigorous leak tests required for a level of containment. Therefore, design requirements for the cask were altered so the cask would provide both levels of containment, with the canister functioning as a receptacle for core debris only. Thus, two new casks (NuPac 125-B Rail Cask) were designed, fabricated, and licensed specifically for transporting TMI core debris to INEL. Drop tests also were conducted on a 1/4-scale model of the NuPac 125-B Rail Cask to confirm structural analyses and demonstrate survivability of components during accident conditions.

- Weight Constraint--The major weight constraint was imposed by the receiving facility. The loaded weight of each canister must be less than or equal to 2800 lb, with an allowance that 5% of the canisters may weigh up to 2940 lb each. That constraint resulted from limits imposed by floor loading in the Water Pit and some equipment at the storage facility of INEL.

- Transport Method--Originally, use of truck-mounted casks was planned for transporting the fuel debris from TMI to INEL. But, each cask evaluated could transport only one to three canisters at a time. However, because the canister was not considered a level of containment, the need shifted to a cask which simultaneously provided increased payload capacity and two levels of containment. Those needs, plus perceived reductions in loading/unloading costs, resulted in the selection of a rail cask rather than a truck cask.

- Neutron Poisons--Because neutron poisons are built into each canister, the K-effective of each canister during normal operations and accident conditions is 0.95 or less. However, drop tests were conducted for expediting regulatory approval for use of specialized structures for criticality control during a hypothetical transport accident.

- Pool Draining Accident at INEL--Neutron poisons may not be used for controlling criticality in stored fissile materials at INEL, unless those poisons are inspected and verified periodically. Neutron poisons in each canister are not inspectable or verifiable; therefore, at INEL, they are presumed nonexistent as soon as a canister is placed in storage in the Water Pit. But, to control criticality stemming from a hypothetical earthquake-induced pool draining accident, each module of the storage rack in the Water Pit is equipped with removable and inspectable sheets of neutron poison.

- Pyrophoricity--Originally, there was concern that unoxidized zircaloy from damaged fuel rods would pose a pyrophoric hazard if exposed to air. That concern was nullified by filling each canister with core debris while submerged and purging each canister with an inert gas preparatory to transport. Furthermore, analysis of core debris samples demonstrated the nonpyrophoric nature of that material. At INEL, samples of core debris will be collected from selected canisters only after each canister is dewatered using an inert gas and opened following appropriate precautions.

PROJECT COMPONENTS

The operational sequence of getting core debris canisters from TMI into safe storage at INEL can be divided into three phases (Fig. 2): loading at TMI, transporting between TMI and INEL, and receiving/storing at INEL. Each phase necessitated resolving technical constraints before initiation of operations. The constraints were resolved in straightforward ways, resulting in development of hardware, technology, or regulatory guidelines that will benefit industry and government. The U.S. taxpayer also benefited, because his tax dollars were made to go further through hybridization of programs at INEL, sharing of hardware common to those programs, and judicious use of surplus hardware from previous programs at INEL.

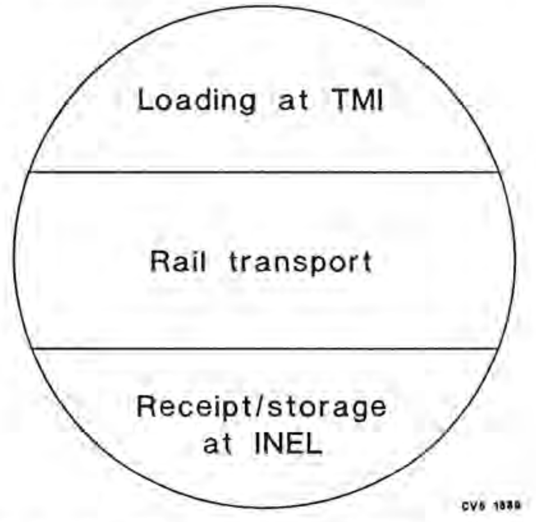

Fig. 2. Components of the TMI-2 core project.

CASK LOADING

Early in the project, GPU Nuclear evaluated the possibilities of loading the transport cask with canisters wet in the A Pool of Unit 2, or dry within the Truck Bay between the Auxiliary and Fuel Handling Buildings of Units 1 and 2. Whereas wet loading of fuel into a cask is the traditional practice, GPU

Nuclear decided that dry loading would better suit its needs, require less modification of existing equipment and facilities, and be faster and more economical. After GPU Nuclear opted for dry loading of the cask and the decision was made to develop the NuPac 125-B Rail Cask, the last technical hurdle at TMI was to interface the cask with facilities. Stipulations were that (a) the cask and loading operations in the Truck Bay not infringe on space dedicated to operation of Unit 1 and (b) operations and equipment not damage underlying support structures and electrical cabling for Unit 1.

Weight, space, and seismic constraints within the Truck Bay necessitated designing/constructing several pieces of equipment that simultaneously permit passage of the rail cask and railcar, are removable in part, and facilitate lifting the rail cask/transport skid assembly from the railcar. It is worth noting that equipment at TMI is required to withstand safe-shutdown earthquake criteria.

After the overpacks are removed from the rail cask, the railcar with cask is pushed into the Truck Bay, under both the tower and cask unloading station (Fig. 3). The screw jacks of the cask unloading station are connected to the transport skid and activated, lifting the rail cask and transport skid from the railcar. The railcar is withdrawn from the Truck Bay, the rail cask/transport skid assembly lowered onto the floor, and door of the Truck Bay closed. Next, the cask unloading station is decoupled from the transport skid, lifted, and stored out of the way. A pair of bolt-on hydraulic cylinders is fastened to the skid and lifting trunnions of the rail cask and activated, rotating the rail cask to vertical. A work platform is bolted to the tower. The cask is opened by removing the lids of the outer and inner vessels, and the shielded loading collar installed. The mini-hot cell withdraws and retains a shield plug from a predetermined tube in the cask (Fig. 4). The fuel transfer cask (Fig. 5) retrieves a dewatered and weighed canister from the A Pool and transfers the canister to the open tube of the cask. The canister is lowered from the fuel transfer cask into the tube (Fig. 6), and the shield plug replaced using the mini-hot cell. The canister transfer/loading process is repeated six more times. It is worth noting that the loading sequence is conducted as a hands-on operation and that radiation exposure to personnel is minimized by lead shielding built into the mini-hot cell, fuel transfer cask, and loading collar.

After loading is complete, each lid of the rail cask is replaced and leak-tested (to 10^{-3} atm·cc/s; leak-tight defined as 10^{-7} atm·cc/s), ensuring that the cask is assembled correctly. [Note that leak-testing is a hands-on operation in which shielding is provided by the shield plugs of the inner vessel.] The cask is returned to horizontal, lifted from the floor, and the railcar returned to the Truck Bay. The cask and skid are lowered onto the railcar, pinned in place, and the assembly moved outside the Truck Bay. There, the overpacks are secured to the rail cask, and the package is surveyed and certified for release to EG&G Idaho at the front gate of TMI (Fig. 7).

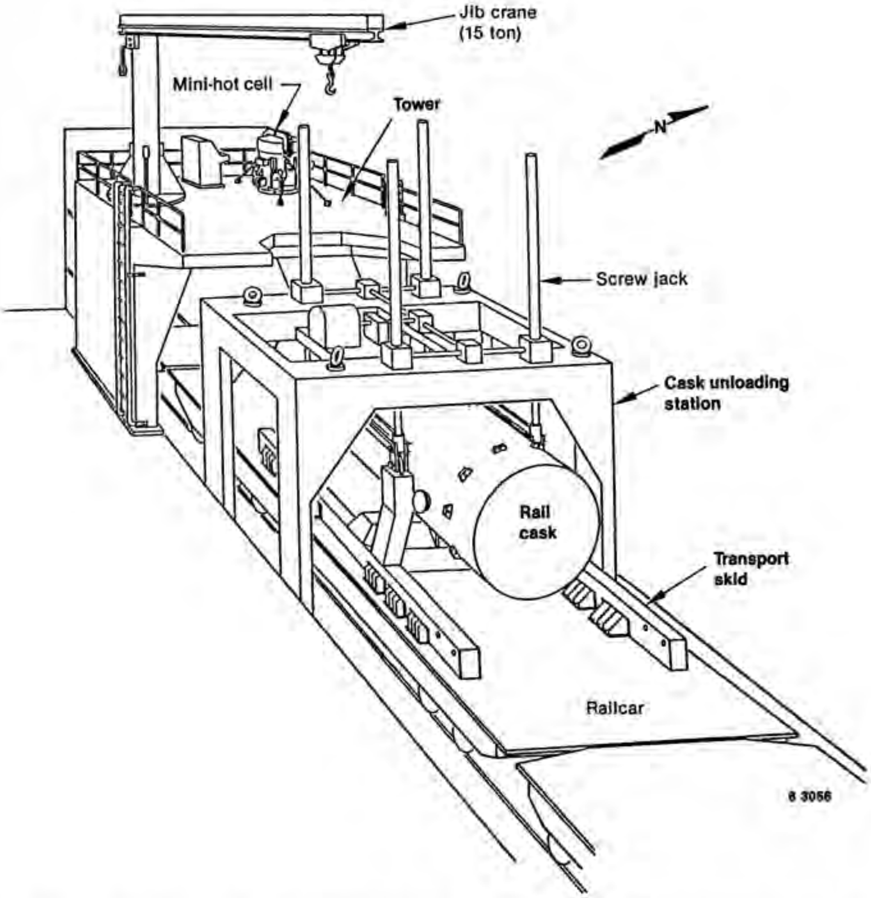

Fig. 3. Schematic of the NuPac 125-B Rail Cask and railcar positioned under the cask unloading station in the Truck Bay at TMI-2.

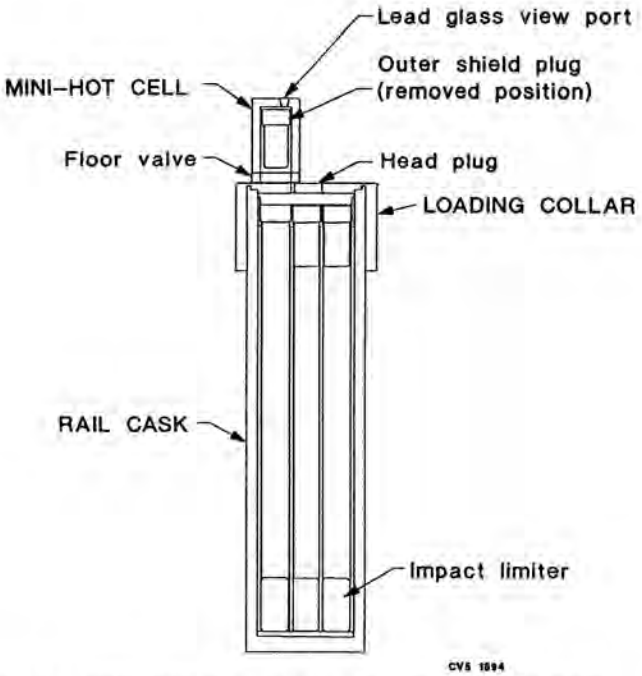

Fig. 4. Schematic of withdrawing a shield plug from the empty rail cask before loading a canister.

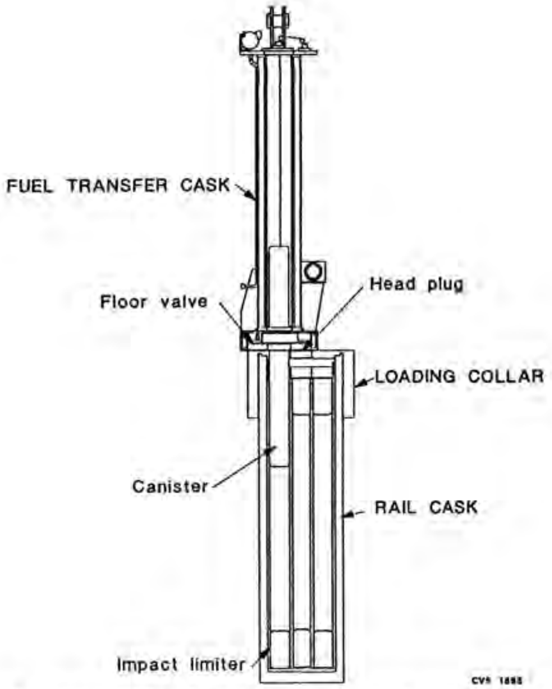

Fig. 6. Schematic showing a canister being loaded into the rail cask using the fuel transfer cask.

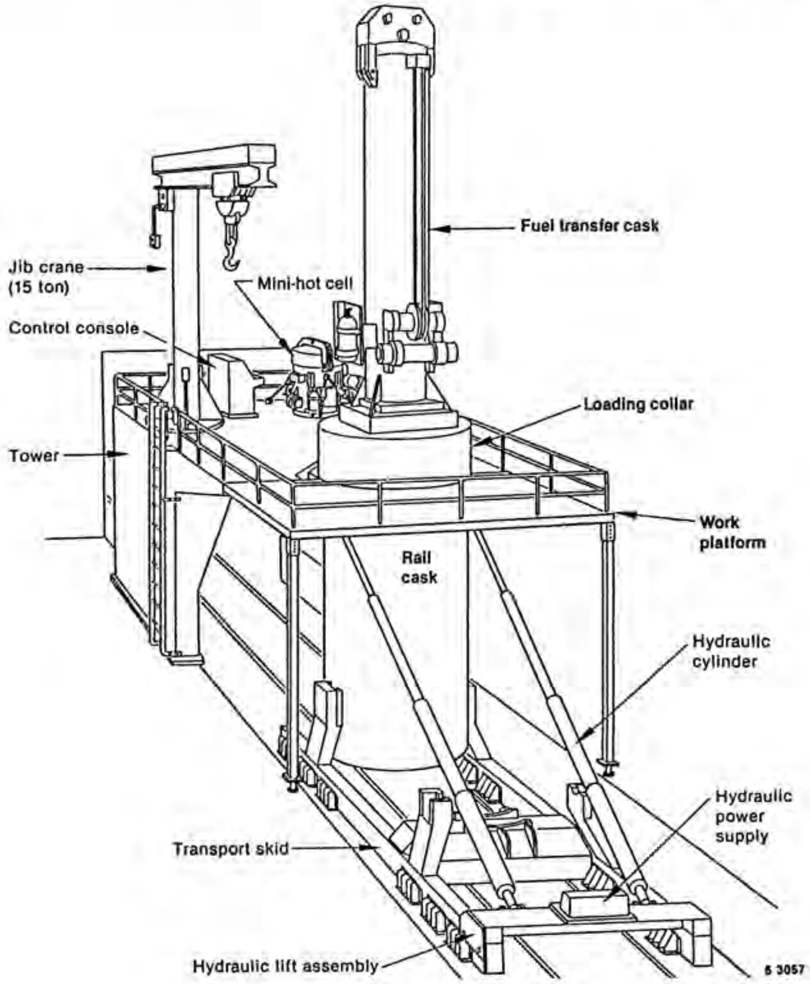

Fig. 5. Schematic of the NuPac 125-B Rail Cask being loaded with a core debris canister at TMI-2, using the shielded fuel transfer cask.

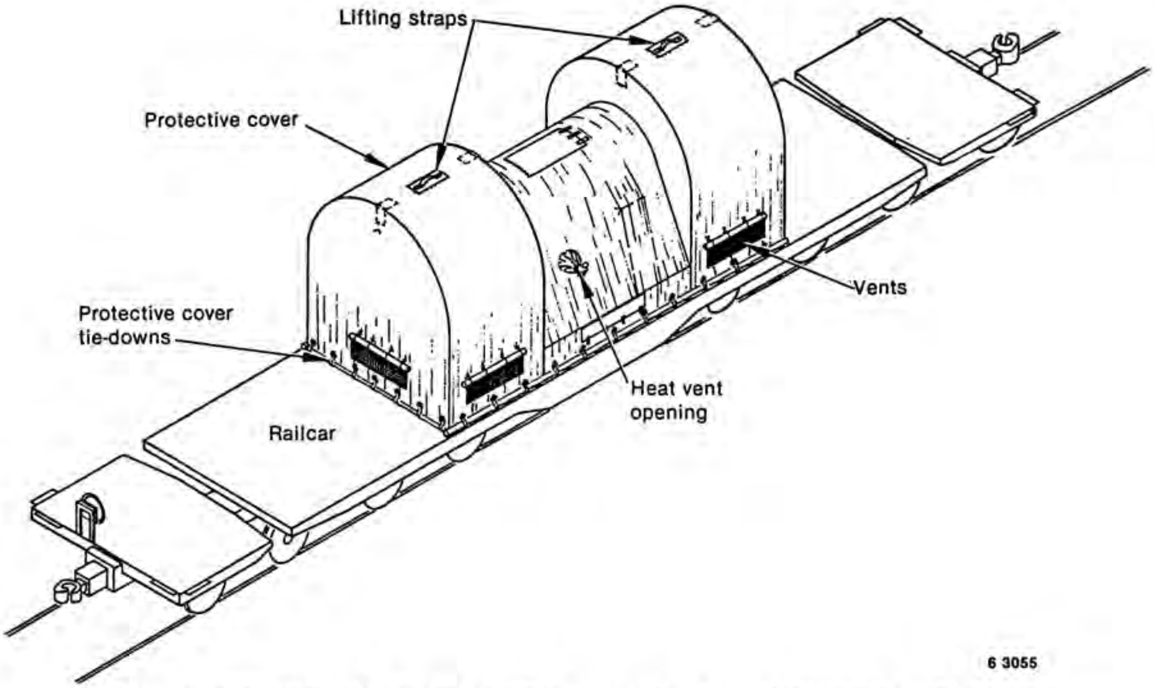

Fig. 7. Schematic showing the loaded, covered, and certified NuPac 125-B Rail Cask ready to leave TMI.

TRANSPORTATION

Transportation Strategy

When the decision was made to build the NuPac 125-B Rail Cask, the next activity involved evaluating different transportation strategies, namely whether to use regular train service or contract for exclusive use trains, and whether to use two, three, or more casks. Into that evaluation was factored the number of casks per shipment, buildup of canister inventory at TMI, safety considerations, duration of the transport campaign, and costs and schedules at TMI and INEL. The strategy selected involved using two casks, regular train service, and one cask per train. The railcars (Fig. 8) used to transport the casks are new; each has 8 axles and is capable of transporting a 150-ton load. [The loaded cask in the transport configuration weighs approximately 100 tons.]

Licensing

Heretofore, licensing a new design cask generally took several years after preliminary design, as well as additional time for fabrication after licensing. **However, the NuPac 125-B Rail Cask was designed and built (license pending) in less than 18 months. Such an** accomplishment was made possible by (a) the combined efforts and professional dedication of several commercial entities, a government contractor, several national laboratories, and two federal agencies; (b) completion of drop tests of the cask and canisters in a minimum time period; and (c) the willingness of the subcontractor (NuPac) to dedicate its resources to designing, testing, and building the rail cask within the limits of an abbreviated schedule.

Fig. 8. Photograph of the railcars used to transport the NuPac 125-B Rail Casks.

Drop testing first involved building 1/4-scale models of the cask (Fig. 9) and canisters and subjecting them to a series of five tests at the Transportation Technology Center of Sandia National Laboratories (SNL); then subjecting a full-scale core debris canister (Fig. 10) to a series of four tests by the Chemical Technology Division of Oak Ridge National Laboratory (ORNL). The drop tests at SNL [three from 30 ft onto a flat, unyielding surface (Fig. 11) and two from 40 in. onto a 1.5-in. stationary pin (Fig. 12)] demonstrated the integrity of the cask and satisfied concerns voiced by the U.S. Nuclear Regulatory Commission (NRC) regarding structural behavior of the cask during postulated accident scenarios. [Please observe in the vertical section through an overpack shown in Fig. 13, that the overpack exhibits damage sustained in the 30-ft, oblique drop test and also puncture damage sustained in the 40-in. vertical drop onto the stationary pin. But, note that the inner skin of the overpack shows no apparent damage from the tests.] The drop tests at ORNL [four from 30 ft onto a flat yielding surface, two of which were end-on (Fig. 14) to measure compressive buckling and tension loading of internals and two horizontal (Fig. 15) to measure bending and torsion of internals] demonstrated that tubes containing neutron poisons experienced no deformations beyond those postulated for maintaining criticality control during hypothetical accidents (Fig. 16).

Data from the tests were combined with an analytical study of the cask and canisters during both normal operations and hypothetical accident conditions. That synthesis constituted the Safety *Analysis Report for* the transport package, which was submitted to NRC as the licensing application. Although not required for regulatory approval, the testing program was the key to the straightforward licensing of the new cask.

Even though there was some risk in proceeding with fabrication of the cask before issuance of the Certificate of Compliance in February 1986, that risk was necessary and acceptable to meet the schedule for transporting core debris from TMI beginning in May 1986. Preparations for fabricating the cask began in the spring of 1985, with identification of subcontractors and procurement of material. Fabrication began in mid-summer, about the time the Safety Analysis Report was submitted to NRC. The first cask was accepted by DOE in mid-December 1985, and personnel training began in January 1986. The second cask was used in the integrated system test in February at the Hanford facility of DOE in the State of Washington. The integrated system test involved all cask loading and facility interfacing equipment described earlier. After the integrated system test, both casks were sent to TMI for use in more training of personnel. Loading of canisters into the cask began in April 1986.

Fig. 9. Photograph of the 1/4-scale model of the NuPac 125-B Rail Cask during a 30-ft, end-on drop test at Sandia National Laboratories.

Cask Description

The NuPac 125-B Rail Cask consists of a stainless steel vessel within a stainless steel and lead composite vessel (Fig. 17). Each vessel is closed with a leak-tight lid. The inner vessel is composed of a hub and spoke arrangement (Fig. 18) into which fit seven tubes (Fig. 19), each large enough to accommodate a canister. There are impact limiters (or energy absorbers) at the ends of each tube. The impact limiter at the blind (lower) end of each **tube is freely removable, whereas that at the** open (top) end is attached to a shield plug (see Fig. 4). Stainless steel plates surround the inner components, with thick stainless steel forgings on the ends. The spaces between the tubes and structural components are filled with special neutron absorbing material. The outer vessel is composed of two stainless steel layers, in between which is sandwiched a thick layer of lead for radiation shielding (Fig. 20). Energy absorbing overpacks protect each end of the cask. Each overpack consists of a stainless steel skin (Fig. 21) filled with compressible foam (Fig. 13). The cask, including

Fig. 10. Full-scale model of the TMI core debris canister before drop testing at Oak Ridge National Laboratory.

Fig. 11. Photograph of the 1/4-scale cask model being dropped from 30 ft during the oblique drop test at Sandia National Laboratories.

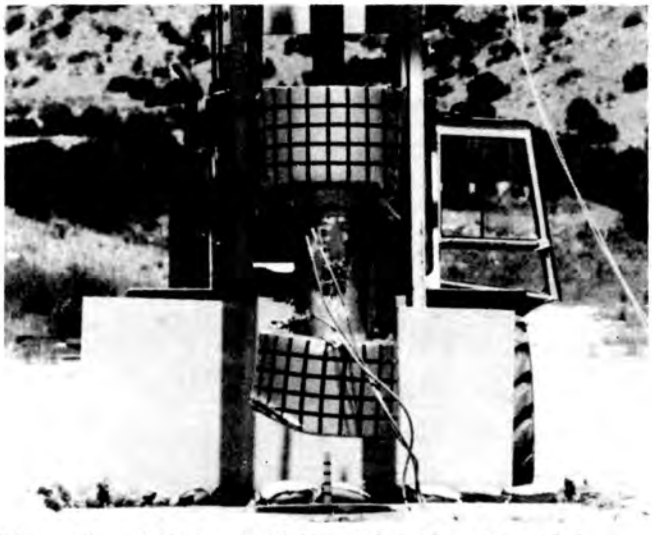

Fig. 12. Photograph of the 1/4-scale cask model just before impacting the pin in a 40-in. puncture test at Sandia National Laboratories.

Fig. 13. Cutaway view of the damaged overpack of the 1/4-scale cask model after the tests pictured in Figs. 11 and 12.

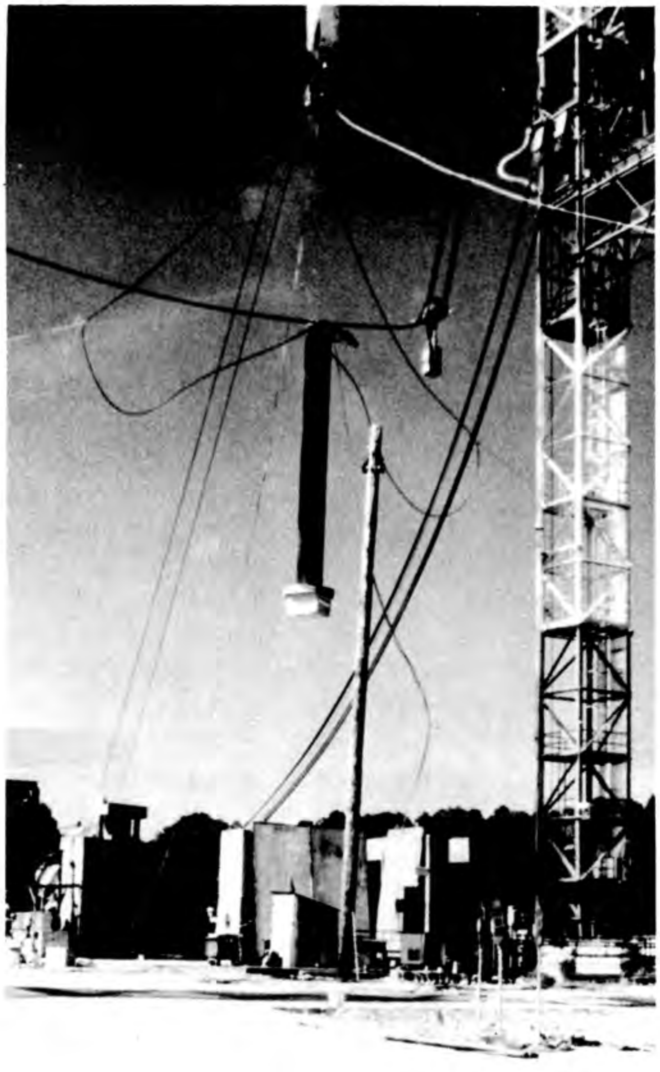

Fig. 14. Photograph of the end-on canister drop test at Oak Ridge National Laboratory.

Fig. 15. Photograph of the horizontal canister drop test at Oak Ridge National Laboratory.

Fig. 16. Photograph showing minor deformation of components after the canister drop tests.

Fig. 17. Photograph of the outer vessel of the NuPac 125-B Rail Cask.

Fig. 18. Photograph of the hub and spoke arrangement of the inner vessel of the NuPac 125-B Rail Cask.

Fig. 19. Photograph of the ends of the seven tubes of the inner vessel of the NuPac 125-B Rail Cask.

overpacks, is 280 inches long by 120 inches in diameter. The total loaded weight of the cask (with overpacks, seven canisters, and transport skid) is about 200,000 lb.

RECEIVING/STORAGE

The unloading and storage operations at INEL focus on (1) receiving the railcar bearing the cask at the Central Facilities Area (CFA) of INEL, (2) transferring the cask from the railcar to a truck transporter, (3) transporting the cask by roadway about 30 miles across INEL to the Hot Shop of Test Area North Building 607 (TAN-607), (4) remotely unloading the cask and storing the canisters in the Water Pit of the TAN-607 Complex, and (5) surveillance of the canisters during the storage period.

Fig. 20. Photograph of the kiln being built around the outer vessel of the NuPac 125-B Rail Cask before the lead pouring operations.

(a) Outer skin.

(b) Inner skin.

Fig. 21. Photograph of an overpack being fabricated for the NuPac 125-B Rail Cask.

At CFA, the NuPac 125-B Rail Cask is received as a routine shipment. The overpacks are removed and stored in a predesignated place near the gantry crane. That crane, mounted on rails and used years ago for manipulating gun barrels from large surface vessels, transfers the rail cask and transport skid from the railcar to the truck transporter owned by DOE (Fig. 22). Once on the transporter, the cask is hauled slowly to the Hot Shop of TAN-607. In the Hot Shop, most unloading operations involving the cask and canisters are remote. That is, after the cask is rotated to vertical (Fig. 23) and lifted from the skid and transporter, placed in a work platform (Fig. 24), tested for internal, airborne contamination, and opened, all operations involving manipulation of canisters are conducted remotely behind shielded barriers. Each canister is withdrawn from the cask, conveyed to the Vestibule of the Water Pit, and lowered into a storage module situated atop the pool cart at the bottom of the Vestibule (Fig. 25). Each module holds a maximum of six canisters (Fig. 26). When a storage module is full, each canister in the module is vented and filled with demineralized water. Then, the module is conveyed to the Water Pit, where modules simply are rowed together (not interconnected), forming a continuum termed the storage rack (Fig. 27). Computer analysis of a module has shown it to be

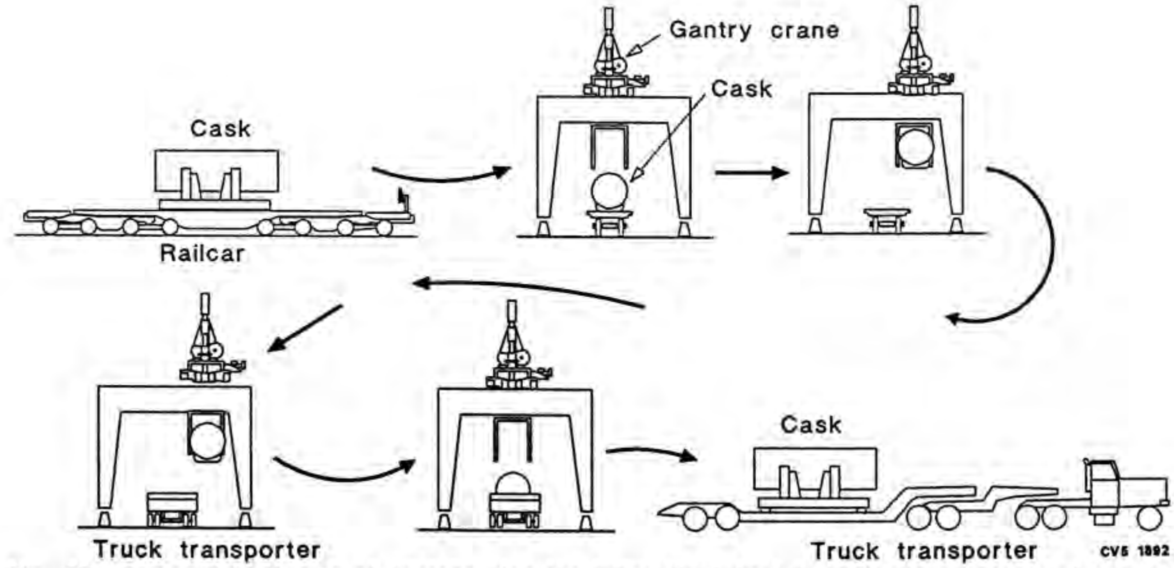

Fig. 22. Sequential diagram of transferring the NuPac 125-B Rail Cask (without overpacks) from the railcar to the truck transporter at INEL, using the gantry crane at Central Facilities Area.

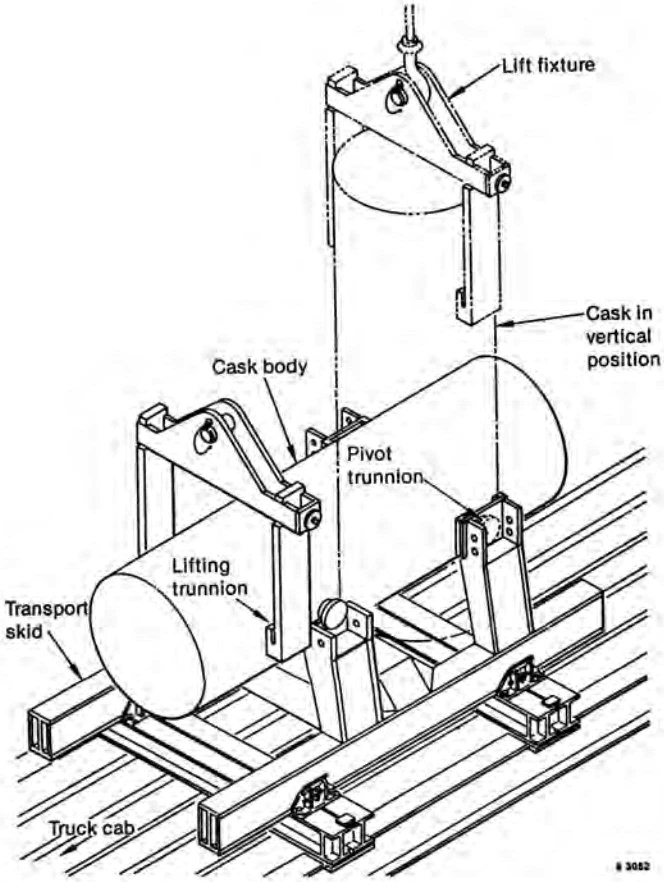

Fig. 23. Schematic of the cask being rotated to vertical before removal from the truck transporter in the Hot Shop of TAN-607.

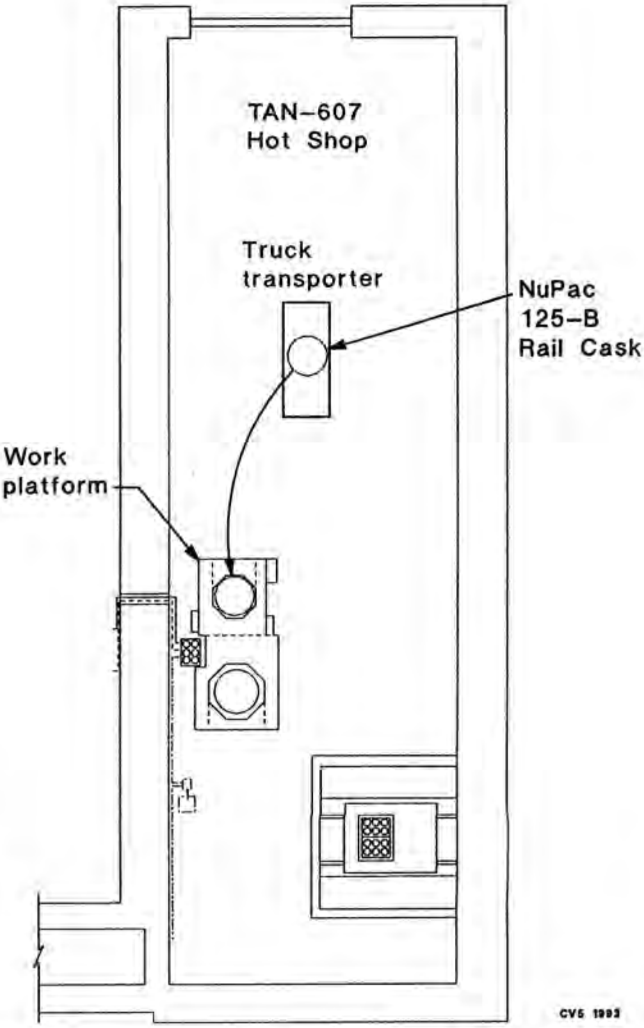

Fig. 24. Schematic of transferring the NuPac 125-B Rail Cask from the truck transporter to the work platform in the TAN-607 Hot Shop of INEL.

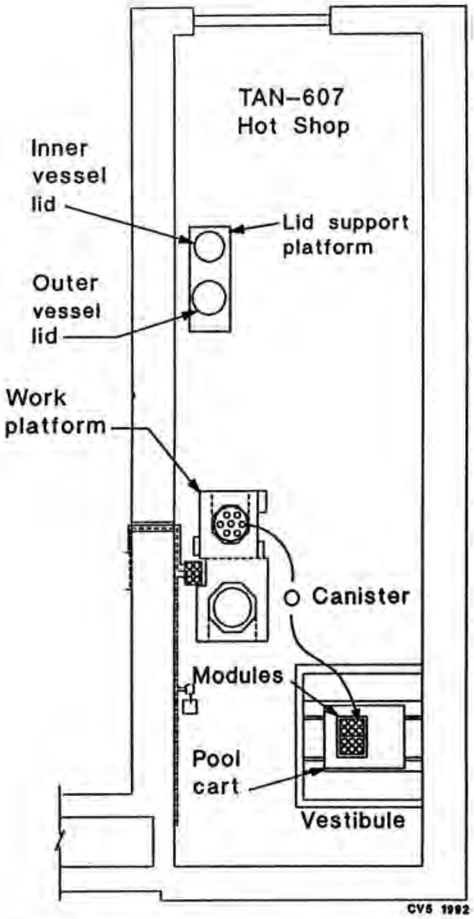

Fig. 25. Schematic of transferring a canister from the opened rail cask to the Vestibule in TAN-607 of INEL.

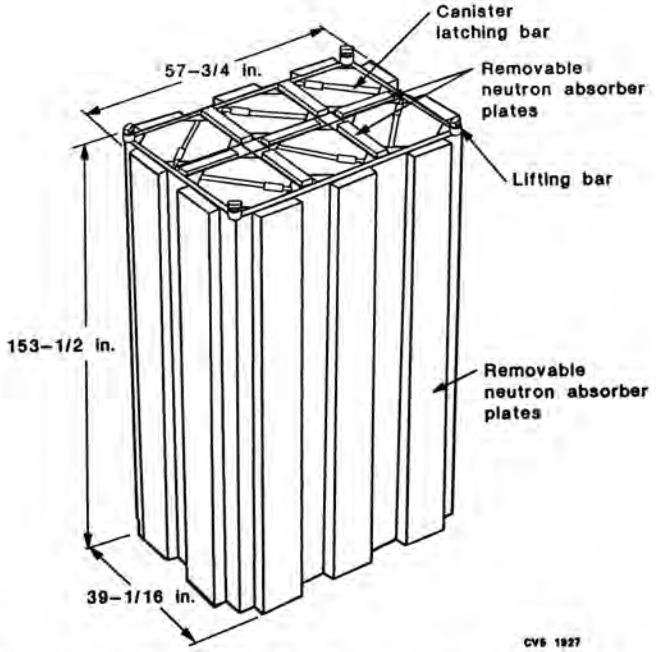

Fig. 26. Schematic of a storage module, showing the spaces for six TMI core debris canisters and the removable neutron absorbers.

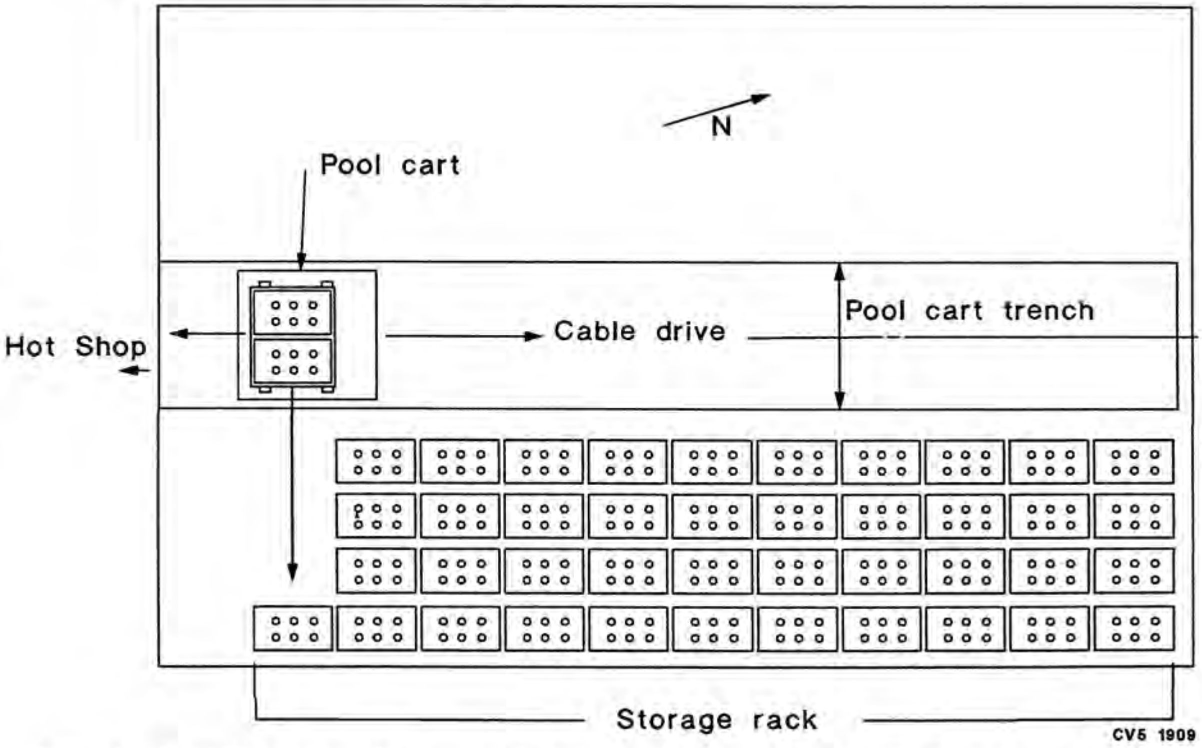

Fig. 27. Schematic of transferring modules with canisters from the Vestibule to the Water Pit of TAN-607 of INEL.

seismically stable and criticality safe in all accident orientations. Once each module is in place, a vent line is connected to each canister.

The storage of TMI core debris at INEL is planned for as long as 30 years. That means all storage equipment, including the canisters per se, must endure the environment of the Water Pit for 30 years minimum, and stored canister must be criticality safe under routine situations during that period. Although the chemical environment of the Water Pit is noncorrosive, submersion of metallic hardware for that length of time conceivably could effect localized rusting, which is why the hardware was fabricated from stainless steel. About the only maintenance anticipated on hardware will be replacement of seals in the connectors and fittings in the heads of canisters.

BENEFITS

Many benefits have been and are being realized from the TMI effort just described. The most notable ones include the following:

- Feasibility and economic evaluation will have been made of dry loading of nuclear fuel in the transport cycle from reactor to storage facility and/or terminal repository.
- Completion of the project will have demonstrated the safe transport and storage of damaged fuel, which is perceived by the public and some politicians to be the most hazardous material ever managed.
- New hardware (canisters, fuel transfer cask, and related equipment) was developed for manipulation of containers filled with damaged fuel.
- Industry and government now have a rail cask that provides double containment of damaged fuel.
- Acquisition of the NuPac 125-B Rail Cask is an example that cask procurement and licensing periods can be shortened.
- Acquisition of that cask is the pathfinder through the maze of institutional issues--not technical ones.
- Scientific communities will have a resource (core debris, samples, core bores) available at INEL for future examination and research. Because of that, TMI can be recognized as an experiment whose usefulness lies in benchmarking safety codes that predict reactor behavior during transients. That reduces the risks of a reoccurrence.

CONCLUSIONS

In conclusion, it is noteworthy that the technical challenges discussed in this paper were met within the present regulatory framework and guidelines because the federal entities, government contractors, and myriad of private industries involved had the resolve to openly discuss issues confronting all participants. Open dialogue was initiated early in the project, when it was realized that interfacing equipment with facilities at TMI would be complicated. Dialogue has continued throughout the project and will continue until all core debris is loaded safely into canisters, transported to Idaho, and stored at INEL.

Throughout the project, regulations (particularly those related to transportation) were accepted without argument and generally were satisfied by formulating conservative assumptions or mathematical approaches, or were demonstrated by the use of testable models. Where interpretations of regulations were warranted, each interpretation was developed through the combined efforts of the regulator and interested/affected parties.

Inevitably, though, open dialogue, plus a spirit of cooperation between diverse organizations regarding resolution of a politically sensitive issue like TMI invites advice, comment, and participation by officials from all levels of government and interested third parties. In the case of TMI, each piece of advice or comment offered by peripheral participants was responded to and/or resolved promptly and responsibly by appropriate members of the project. That type of positive attitude typifies the propensity for action which has pervaded the project since 1980. And that attitude is best exemplified by the combined efforts and commitments of all involved in designing equipment for defueling the damaged reactor, developing and licensing the NuPac 125-B Rail Cask, and readying facilities at TMI and INEL for packaging, transporting, receiving, and storing core debris canisters.