STRUCTURAL ANALYSIS OF TMI-2 DEFUELING CANISTERS

E. J. McGuinn and P. C. Childress
Babcock & Wilcox
Nuclear Power Division
3315 Old Forest Road
Lynchburg, VA 24506-0935

ABSTRACT

The core debris from the damaged TMI-2 reactor will be stored and shipped in canisters designed by Babcock & Wilcox (B&W) for General Public Utilities Nuclear Corporation (GPUNC). Those canisters are of three different types - filter, knockout or fuel - and are described in greater detail in a companion paper, "Defueling Canister Designs for the TMI-2 Core Removal Program."[1] Structurally, the canisters consist of nearly identical pressure vessels encapsulating different internal modules depending on the function of the canister. For normal operating conditions, the pressure boundary components - the shell, upper head, and lower head - were analyzed to the requirements of Section VIII Division 1 of the ASME Code.[2] Design pressures of 150 psig (internal) and 30 psig (external) bound the actual operating environment.

As described in the GPUNC design specification, a canister can be subjected to any one of a series of postulated on-site accidents. For all cases, the design criteria is that for the predicted deformed geometry, criticality control of the canister contents must be maintained. The canister in conjunction with the shipping cask must also meet the requirements of Federal Regulation 10CFR71[3] for transportation accidents. In the filter and knockout canisters impact velocities for the various canister drops were used to determine the impact energy and associated impact forces. These forces were used in an ANSYS analysis to determine the structural deformations and stress levels in the internals. The fuel canister internals, with its complex geometry, was judged to be too difficult to rely on analytical solutions; geometric bounds were conservatively generated using estimates of material behavior and were then confirmed by a comprehensive drop test program.

INTRODUCTION

As part of the core removal system, the TMI-2 defueling canisters function as receptacles for the core debris during defueling and as long term storage containers afterwards. Three different types of canisters - fuel, filter and knockout - were designed for encapsulating the various sizes of debris. To accommodate large pieces of debris, the fuel canister incorporates a removable closure head. The filter and knockout canister are connected via piping couplings on the top head to either the vacuum (both canisters) or the water cleanup systems (filter only). After being loaded, the canisters are removed from the reactor work area for dewatering and storage. A single point pickup interface for the handling tool is located in the center of the upper head.

Loading imposed on the canister during its lifetime can be divided into two categories: normal operation and accident cases. Normal operations loads are very predictable and relatively small in magnitude. Accident cases are sub-divided into on-site drops and transportation events. After on-site drops, the canister must remain in a sub-critical condition but may experience minor deformations. During transportation accidents, the canister must meet the structural requirements of Federal Regulation 10CFR71.

NORMAL OPERATION ANALYSIS

Normal operation of the canister as part of the defueling system imposes relatively small loads on the canister. Its outer shell functions as the containment vessel and provides support for the criticality control poisons.

Pressure Vessel

Common to all three canister designs, the pressure retaining boundary (outer shell, upper and lower closure heads) are designed and analyzed as an ASME Code Section VIII pressure vessel. Plutonium material present within the core debris is classified as a toxic substance, therefore, a "lethal" classification is required for the canisters. The effect of this designation is to require major shell welds, circumferential and longitudinal, to be butt type welds with 100% radiographic (or ultrasonic in specific cases) inspection. Underwater storage exerts an external (crushing) pressure on the canister while an internal (bursting) pressure is developed inside the canister (filter and knockout) when part of the operating system. Design pressures of 150 psig internal/30 psig external bound the actual in-service conditions. A relief valve attached to the canister head limits the internal pressure to 15 psig during storage of a canister containing radioactive debris. A conservative upper bound of 20 mils for the corrosion allowance for the 30 year life of the canister is used in calculating the required thicknesses. After final assembly, the canister will be hydrostatically tested to 150% of the maximum design pressure as a final verification of both the design and manufacturing process. After successfully completing its hydro test, an ASME "U" stamp is applied to the canister.

Results from the ASME Code analysis (Table I) verify the adequacy of the canister for pressure loadings associated with normal operation.

TABLE I

Summary Of ASME Code Analysis

Component (Canister)	Criteria	Design Limit	Actual Value
Basic Shell (All)	Circumferential Stress	Allowable Pressure 325 psi	Design Pressure 155 psi
	Longitudinal Stress	Allowable Pressure 655 psi	Design Pressure 155 psi
	Stability	Allowable Pressure 73 psi	Design Pressure 30 psi
Lower Head (All)	Stability	Allowable Pressure 375 psi	Design Pressure 155 psi
Upper Head (Filter & Knockout)	Combined Stress	Required Thickness 1.16 inch	Actual Thickness 3.34 inch
Closure Head (Fuel)	Combined Stress	Required Thickness 1.60 inch	Actual Thickness 2.23 inch

Canister Internals

Loadings on the internals during normal conditions are relatively small. Dead weight of the internals and canister contents and the small pressure differentials are the only significant loads. In all the canisters the internals are supported axially by a lower plate assembly attached to the canister by a full circumferential fillet weld.

Loading of the fuel canister presents two unique scenarios for evaluation. First is the capability of the lower support plate assembly to absorb the impact of debris accidentally dropped into the canister. Results from the dynamic impact evaluation show that the support assembly can accommodate loads up to 350 lbs dropped the full canisters length without experiencing a failure of the plate-to-shell weld. Second is the resistance of the shroud inner wall to puncture or tearing during placement of debris within the canister. Examinations of the drop test shrouds showed no penetrations and indicate the inner wall is very resistant to debris impacts and scrapes.

A pocket recessed into the upper head serves as a receptacle for the tool used for lifting and handling the canister. For normal handling operations, a static plus dynamic loading factor of 1.15 times the static lifted weight considered in the design of this canister interface. Stress design factors of 3 times the static plus dynamic load for comparisons to the yield strength of the material and 5 for the ultimate strength comparisons were used.

ON-SITE ACCIDENT ANALYSIS

Postulated accidents that could occur during the normal sequence of handling operations have been defined as part of the design specification. For these cases, the design criteria is that for the predicted deformed geometry, structural integrity of poison components must be maintained and the canister must meet criticality requirements. Some local deformation of the canister is acceptable. Energy methods were used to determine the extent of the deformation of the shell and canister internals associated with the various postulated drops were used to compute the impact loads. Vector combinations of the axial and lateral components were used to determine the effects of drops at other angular orientations.

The vertical drop case deformations reflect the stiffness of the canister's outer shell without any interaction with the internals; therefore, the same deformation will occur irrespective of the canister type. For the bottom impact, shell deformations (less than 1/4" radially) occur below the lower support plate in the lower head region. This deformed shape also bounds the shell behavior for a head (upside-down canister) drop. Side drop loads differ between canister types as a function of the structural stiffness of the canister internals.

Fuel Canister

The fuel canisters (Fig. 1) do not experience any significant deformations during the vertical and side drops as demonstrated in a comprehensive test program. Lightweight concrete filling the void between the square inner shroud and circular outer shell provides continuous lateral support to both the outer shell and the shroud. This results in a distributed loading producing only insignificant deformations in the shroud. Testing also demonstrated that the lower support plate remains in place supporting the mass of the shroud, the concrete, and the payload. The lack of any significant deformation of the fuel canister or shroud makes the criticality analysis for the normal operation configuration applicable as well to the faulted case.

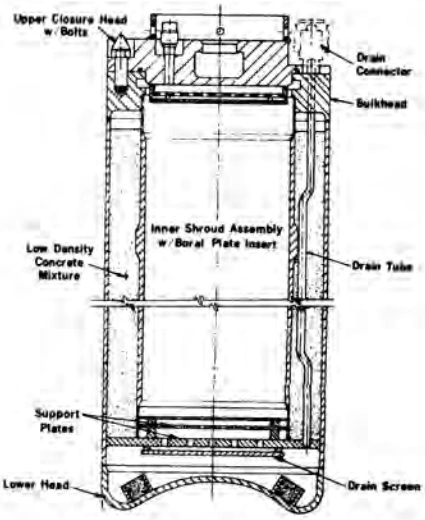

Fig. 1. Fuel Canister

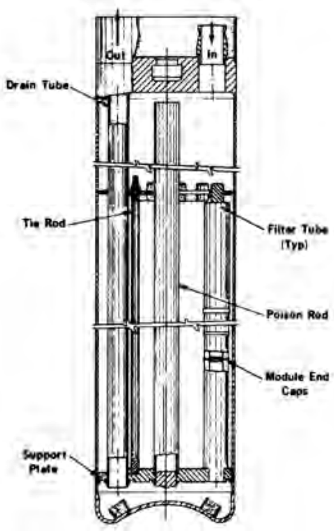

Fig. 2. Filter Canister.

Filter Canister

In the filter canister (Fig. 2) criticality control is provided by the central B_4C poison rod coupled with the mass of steel within the 17 filter element drain tubes and six tie rods. Acting as deflection limiters, the end caps of the filter modules limit the array deflection. To prevent any puncture loads from being imposed directly on the thin wall tube containing the B_4C powder, it is encapsulated within a thicker wall strongback tube. This tube-within-a-tube arrangement also precludes any concerns with buckling or crippling of the inner tube (containing the B_4C powder) since it is continuously supported by the strongback tube.

To study the consequences of filter (and knockout canister) horizontal drops, their internals were analyzed by finite element methods using the ANSYS[4] computer program using the nonlinear properties of the material. Geometric constraints imposed by the shell and internals components were accounted for by limiting the displacement of supports. The ANSYS model of the canister internal is a series of beams models (STIFF 20 elements) with appropriate end condition - Fixed-Fixed boundary for maximum stress or Free-Free for maximum displacements. Gap element (STIFF 40) were used to represent the interaction between the elements at the 11 inch intervals where the filter element end caps function like an intermediate support plate by limiting the beam deflections. The spatial arrangement of end caps was determined using a CAD/CAM program to model the "checkerboard" arrangement by allowing redistribution of the caps to fit the drop canister geometry. This represents a "freeze frame" before the array bounced back closer to the original position. Loads were applied to the ANSYS MODEL using acceleration loading factors.

Knockout Canister

Criticality control in the knockout canister is provided by the central poison rod coupled with four absorber rods, all containing vibra-packed B_4C powder. The spatial arrangement of these five tubes is maintained by a thick wall strongback tube completely encapsulating the free floating center poison tube and spider plates supporting the four smaller rods. The smaller poison rods are held axially by the lower support plate assembly. These six tubes - strongback, center poison tube and four poison rods - were modeled in ANSYS (Fig. 3) as interconnected beams. Gap elements represent the tube-in-a-tube clearances between the poison tube and the strong back. Deflections and spring rates for the support spiders were computed using a 2-D, nonlinear ANSYS model.

Results from the ANSYS analysis show that the criticality components remain essentially elastic during all postulated accidents and maximum instantaneous displacements are less than .75 inch. As in the case of the filter canister, the resultant "freeze frame" deformed geometry successfully meets the criticality criteria.

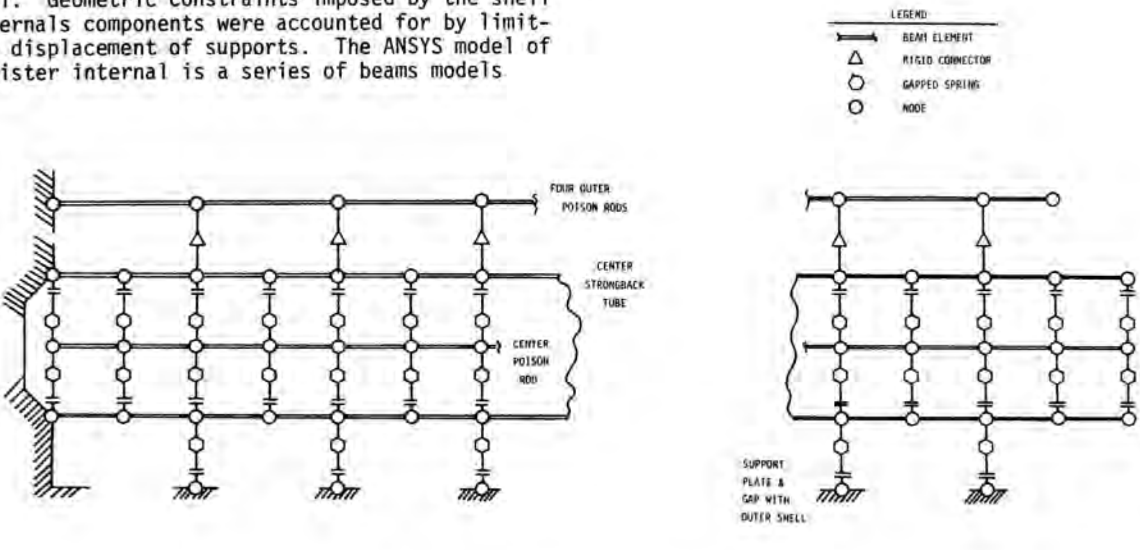

Fig. 3. Knockout Canister - ANSYS Model.

TRANSPORTATION ACCIDENT ANALYSIS

Contained within the Federal Regulation 10CFR71 are a series of hypothetical shipping accidents that are used to evaluate the structural integrity of packaging systems for radioactive materials. Generic in nature, these scenarios provide the framework to base the design and analysis of the shipping cask/canister combination. The NRC established guidelines (Regulatory Guide 7.6)[5] for the structural analysis of the canister to demonstrate compliance with the requirements of 10CFR71. While addressing only elastic behavior, the guidelines do not preclude appropriate nonlinear analysis of some cask/canister components. In general, Regulatory Guide 7.6 reflects the design criteria defined in Section III, (Appendix F) of the ASME Code for accident conditions. Nonlinear techniques were used and are justified on a case-by-case basis.

Differences between the on-site and shipping accident cases are primarily in the nature of the debris loading and magnitude of the imposed loads. While the lowest temperature experienced during on-site operation is 50°F, the canister can be exposed to sub-freezing temperatures over a long period of time during shipping. A frozen water/debris scenario results in a different mass distribution than that characteristic of a liquid slurry mixture: Dynamic load factors for the shipping accident are less than those resulting from an on-site drop since impact limiters reduce the loads imposed on the canister to 40 g's axial and 100 g's lateral.

Canister Analysis

As discussed regarding the on-site accidents case, the fuel canister does not experience any significant deformations as a result of the accidental drops. For the shipping accidents, the impact loads are considerably less. Therefore, the fuel canister normal configuration can be used for the criticality analysis associated with the shipping cask.

Lateral shipping loads on the filter canister are almost the same as values calculated for the on-site cases (100 g's vs 126 g's). Since the mass distribution on the closely packed internals is approximately the same, the methods of analysis developed for the on-site drop cases is also valid for the shipping cases. Results of the analysis show that the filter canister meets the NRC requirements in Reg. Guide 7.6.

Mass distribution plays an important part in the calculations of the internal loads developed in the knockout canister during impact events. The spatial arrangement of the five full length poison tubes - supported at 15 3/4 inch intervals by half-inch thick support plate - can accommodate a wide variety of postulated debris loadings. Frozen debris can build-up on the rods and supports causing eccentric loading on the internals. This compares to the on-site case where the debris slurry is relatively insensitive to the direction of inertia loads. The interaction between the rods and tubes was calculated using the ANSYS model described in the section on the on-site drop cases using a mass distribution representative of the worst case scenario for the frozen debris. Internal loads and deformed geometry computing from the ANSYS analysis were used in evaluation of the components.

SUMMARY

A combination of structural analysis and component testing has demonstrated that the defueling canisters are a safe, reliable means of encapsulating the TMI-2 core debris. Designed as an ASME Section VIII, Division 1 (Lethal) pressure vessel, the canister maintains a structural integrity when subjected to postulated on-site and transportation accidents. The canister meets its criticality requirements for all loading conditions.

REFERENCES

1. P.C. Childress and E.J. McGuinn, "Defueling Canister Designs for the TMI-2 Core Removal Program," Waste Management 85 Symposium, Tucson (1984).

2. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, 1983 Edition.

3. 10CFR71, "Packaging of Radioactive Material for Transport and Transportation of Radioactive Material Under Certain Conditions," Code of Federal Regulations.

4. Computer Code, "ANSYS" Revision 4.1, dated March 1, 1983, Swanson Analysis System, Inc., Houston, PA.

5. NRC Regulatory Guide 7.6, "Design Criteria for the Structural Analysis of Shipping Cask Containment Vessels," Revision 1, March 1978, U.S. Nuclear Regulatory Commission, Washington, D.C.