# Dry Cask Storage Characterization Project

*Interim Progress Report – June 2000*

**1000157**

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Technical Progress

EPRI Project Manager

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# ABSTRACT

A Castor V/21 cask containing 21 spent PWR fuel assemblies (rod burnups in the 30-35 GWd/MTU range) has been in storage at the Idaho National Environmental and Engineering Laboratory (INEEL) since 1985. This cask represents one of the longest storage periods in the current fleet of licensed dry storage containers in the US. Given that current dry storage cask licenses are only for 20 years, and several cask systems are approaching the end of the initial license period, it is necessary to establish a technical basis for extended storage. Consequently, NRC, EPRI, and DOE have embarked upon a project, the Dry Cask Storage Characterization (DCSC) Project, to assess the integrity of this cask in order to establish a partial basis for extended dry storage in existing licensed casks. This interim report discusses the results of testing at INEEL in 1999 and early 2000. Subsequent reports will cover additional work related to the integrity of the spent fuel cladding.

In September 1999, the Castor cask was reopened and the fuel assemblies and selected rods were visually inspected in the Test Area North (TAN) facility at INEEL. The concrete storage pad, cask, and the stored fuel rods appeared to be unchanged by the long storage duration. There was no gross evidence of any damage to the pad, cask, or cladding. For example, there was no evidence of significant cladding creep or rod bow. There was some crud adherent to the rods, but no crud appears to have fallen into either the spacers or cask bottom. Samples of the crud were taken from the rods for chemical and radiological analysis (specified by ANL). While these results were encouraging, they only provided limited information. The cask itself maintained its shielding and gas barrier functions with no indication of degradation of those functions between 1985 and 1999.

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# 1 BACKGROUND

## 1.1 Regulations

Most nuclear power plants in the United States were not originally designed with a storage capacity for the spent fuel generated over the operating life by their reactors. Utilities originally planned for spent fuel to remain in the spent fuel pool for a few years after discharge, and then to be sent to a reprocessing facility. Since reprocessing has been eliminated, and no other option for spent fuel disposition currently exists, utilities expanded the storage capacity of their spent fuel pools by using high-density storage racks. This has been a short-term solution with many utilities having reached, or soon will reach, their spent fuel pool storage capacity (Fisher and Howe, 1998). Utilities have developed independent spent fuel storage installations as a means of expanding their spent fuel storage capacity on an interim basis until the geologic repository is available to accept spent fuel for permanent storage.

The Nuclear Regulatory Commission promulgated 10 CFR Part 72 (Title 10, 1999) for the independent storage of spent nuclear fuel and high-level radioactive waste outside reactor spent fuel pools. Part 72 currently limits the license term for an independent spent fuel storage installation to 20 years from the date of issuance. In preparation for possible license renewal, the Nuclear Regulatory Commission, Office of Nuclear Material and Safeguards, Spent Fuel Project Office, is developing the technical basis for renewals of licenses and Certificates of Compliance for dry storage systems for spent nuclear fuel and high-level radioactive waste at independent spent fuel storage installation sites. These renewals would cover periods from 20 to 100 years, and would require development of a technical basis for ensuring continued safe performance under the extended service conditions. An analysis of past performance of selected components of these systems is required as part of that technical basis. The components include the spent fuel and all structures, systems, and components with functions important to safety. The safety functions, which apply for normal, off-normal, and accident conditions are as follows: maintain subcriticality, maintain confinement, ensure that radiation rates and doses to workers and the public do not exceed acceptable levels and remain as low as reasonably achievable, maintain retrievability, and ensure heat removal as needed to meet the safety requirements.

## 1.2 Objectives and Scope

In the mid-1980s, the Department of Energy (DOE) procured three prototype dry storage casks for testing at the Idaho National Engineering and Environmental Laboratory (INEEL) : MC-10, TN-24P, and Castor V-21. The primary purpose of the test was to benchmark thermal and radiological codes and to determine the thermal and radiological characteristics of the three casks. The Castor V/21 cask was loaded with irradiated assemblies from the Surry Nuclear Station and then tested in a series of configurations using a variety of fill gases. Since the tests were not intended to be fundamental fuel behavior tests, the fuel prior to the tests had undergone only minimal characterization consisting of visual examination of the outside of the assemblies and ultrasonic examination to ensure no breached rods would be included. During the tests, the temperature at various locations was monitored and the cover gas was periodically analyzed to determine if any leaking rods had developed. None was found. The details of these tests have been reported in a number of documents.

At present, a project that is jointly funded by NRC-RES, EPRI, DOE-RW, and DOE-EM to examine the fuel in dry storage at INEEL is being conducted. This project will yield confirmatory data to be used by licensees submitting an application (January 2004 for the first licensee) for continuing dry storage beyond 20 years. The objectives of the Dry Cask Storage Characterization Program are to :

(1) determine the long-term integrity of dry storage cask systems and spent nuclear fuel under dry storage conditions, and

(2) provide data to establish the technical bases and criteria for evaluating the safety of spent-fuel storage and transportation systems, and for extending dry cask storage licenses.

Phase 1 of this program involves the movement of a dry storage cask from the INEEL storage area to the INEEL TAN facility; obtaining temperature readings of the cask exteriors and performing a radiation survey; video and photographic inspection of the cask, seals, selected fuel assemblies or canisters and fuel rods; and returning the cask to storage. The specific tasks in the project are as follows:

Task 1.1 - Equipment

Design and fabricate or purchase of equipment and fixtures necessary to (1) move the cask, (2) remove and replace fuel assemblies or canisters, (3) remove fuel rods, and (4) videotape and photograph the external and internal surfaces of the cask, fuel assemblies or canisters, and fuel rods.

Task 1.2 - Procedures and Training

Develop procedures, obtain required reviews and approvals, perform needed training, and other pertinent activities associated with (1) movement of the cask, (2) removal of the designated fuel assemblies or canisters, (3) removal of fuel rods, (4) returning the fuel assemblies or canisters to the cask, and (5) returning the cask to storage.

Task 1.3 - Hot Shop/Cell Rental

Use of the TAN Hot Shop and Hot Cell and TAN operations oversight.

Task 1.4 - Inspection of Cask and Internals

Activities include (1) temperature readings of the cask exterior; (2) radiation survey; (3) video and photographic inspections of the cask exterior and interior, seal, and storage pad, (4) video and photographic inspections of five assemblies and five canisters, and five fuel rods selected from one fuel assembly and one fuel canister, (5) obtain crud and smear samples, and (6) temporary storage of the fuel rods until transported to ANL for Phase 2 evaluations. A list of assemblies, canisters, and fuel rods selected for inspection shall be provided to all participants (NRC, EPRI, DOE) for review and approval.

Task 1.5 - Transportation

Transportation of the fuel rods, and crud and smear samples to ANL-W and the return of the fuel rod pieces and other material (e.g., crud samples) to the TAN facilities for permanent storage.

Task 1.6 - Consultant

Participants may obtain consultants to assist in the selection of fuel assemblies, canisters and rods. Participants may also have consultants present during the examinations of the cask and contents to provide on-the-spot guidance and recommendations about this aspect of the evaluations to ensure the best possible data are obtained. There is no cost to this program for the consulting services obtained by the participants.

Task 1.7 - Reports

Report(s) will be prepared on the inspection of the dry cask storage system and stored nuclear fuel.

Task 1.8 - Program Management

Activities required for the effective management of this cooperative research program. Examples of responsibilities/functions are: TAN oversight, establishment of and adherence to program budget and schedule, program coordination, preparing monthly letter status reports, travel, report reviews, obtaining financial support from others, and miscellaneous administrative support.

Phase 2 of the program (not yet initiated as of June 2000) involves non-destructive, destructive, and mechanical examinations of dry-stored spent nuclear fuel elements. This will provide quantitative and qualitative information concerning the integrity of the fuel. Examples of the type of information that will be obtained include: in-situ creep; percentage of fission gas release, internal rod pressure; oxide thickness, hydride morphology and orientation, residual cladding thickness, cladding microstructure; hydrogen content; creep rates, breakaway temperature; tensile strengths; and ductility. These tasks will take place at either ANL-West or ANL-East. Phase 2 tasks are:

Task 2.1 - Transportation

Activities at ANL-W associated with the transportation of the fuel rods from the Test Area North (TAN) facilities at INEEL to ANL-W, the fuel rod segments from ANL-W to ANL-E, and the return of the fuel rod pieces and other material from ANL-W and ANL-E to the TAN facilities for permanent storage.

Task 2.2 - Procedures and Approvals

Develop procedures, obtain required reviews and approvals, perform needed training, and other pertinent activities associated with the non-destructive, destructive, and mechanical property examinations of the spent nuclear fuel.

Task 2.3 - Examination and Characterization of Spent Nuclear Fuel

Activities include (a) profilometry, (b) fission gas release, (c) metallography, (d) cladding hydrogen analysis, (e) creep tests, (f) cladding stress-rupture tests, (g) cladding tensile tests, and (h) transmission electron microscopy.

Task 2.4 - Final Reports

Publication of reports on the examination and characterization of the spent nuclear fuel stored in the Castor-V/21 cask.

Task 2.5 - Program Management

Activities required for the effective management of this cooperative research program. Examples of responsibilities/functions are: establishment of and adherence to program budget and schedule, program coordination, preparing monthly letter status reports, travel, report reviews, and miscellaneous administrative support.

Task 2.6 - Consultant

Participants may obtain consultants to assist in the selection of fuel assemblies, canisters and rods. Participants may also have consultants present during the examinations of the cask and contents to provide on-the-spot guidance and recommendations about this aspect of the evaluations to ensure the best possible data are obtained. There is no cost to this program for the consulting services obtained by the participants.

Deliverables:

EPRI interim reports of the inspection of the dry cask storage system and stored nuclear fuel. Video tapes and photographs of the inspection of the dry cask storage system and stored nuclear fuel.

The following sections in this interim report describe the ‘Phase 1’ activities related to temperature, dose, and visual inspections of the Castor V/21 cask, cask internals, and the stored fuel that were completed in 1999 and early 2000. Subsequent interim and/or final reports will describe the remainder of the Phase 1 and all of the Phase 2 work.

## 1.3 CASTOR-V/21 CASK

### *1.3.1 Cask Body*

The cask body is a one piece cylindrical structure composed of ductile cast iron in modular graphite form. This material exhibits good strength and ductility, as well as providing effective gamma shielding. The overall external dimensions of the cask body are 4886 mm (16 ft.) high and 2385 mm (8 ft.) in diameter (Figure 1-1). The external surface has 73 heat transfer fins that run circumferentially around the cask, and is coated with epoxy paint for corrosion protection and ease of decontamination.

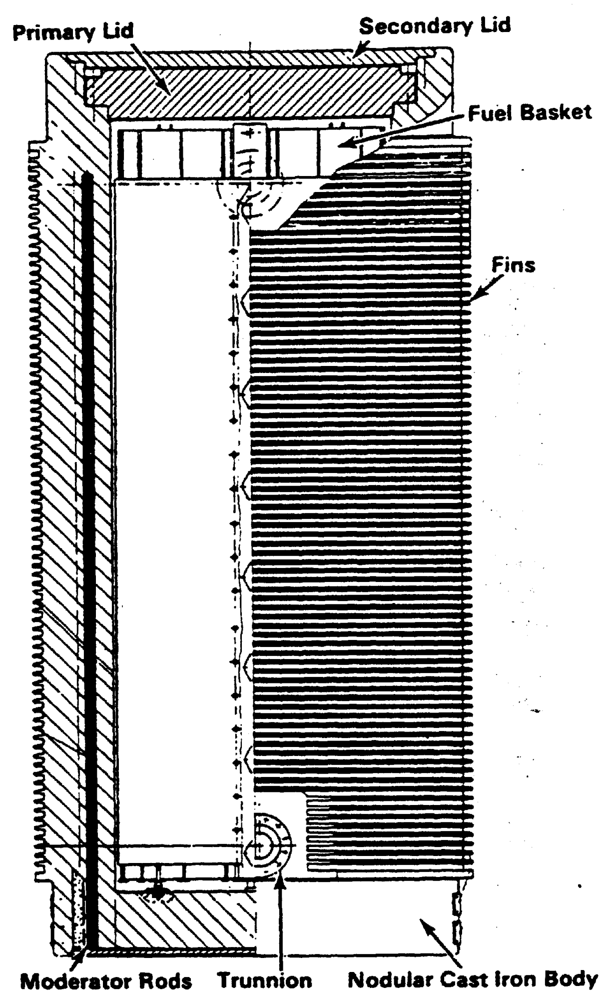


**Figure 1-1. Castor-V/21 PWR Spent Fuel Storage Cask**

The cask body wall, excluding fins, is 380 mm (15 in.) thick. Incorporated within the wall of the body are polyethylene moderator rods to provide neutron shielding. Two concentric rows of these 60-mm (2.3-in.) nominal diameter rods are distributed around the cask perimeter (Figure 1-2). Two lifting trunnions are bolted on each end of the cask body.

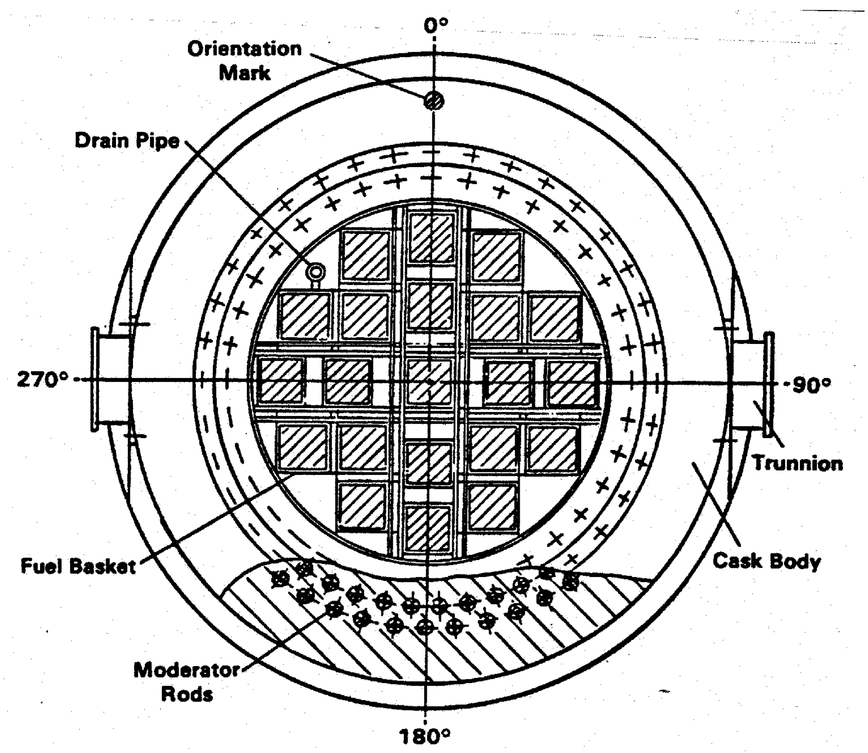


**Figure 1-2. CASTOR-V/21 Cask Cross Section**

The diameter of the inner cavity is 1527 mm (5 ft.), and the overall inner cavity length is 4152 mm (163 in.). Precision-machined surfaces are provided at the open end of the cask cavity for positive gasket sealing, and bolt holes are included at these locations to secure the two cask lids. The interior cavity surfaces, including sealing surfaces, have a galvanic applied nickel plating.

### *1.3.2 Spent Fuel Basket*

The spent fuel basket (Figure 1-2) is a cylindrical structure of welded stainless steel plate, and borated stainless steel plate, having a boron content of approximately 1% for criticality control. The basket comprises an array of 21 square fuel tubes/channels that provide structural support and positive positioning of the fuel assemblies. The basket overall height is 4110 mm (13.5 ft.) including the four 130-mm-diameter (5-in.) pedestals that support the basket and fuel weight on the bottom of the cask cavity. The basket outside diameter of 1524 mm (5 ft.) fits tightly in the cask cavity inner diameter of 1527 mm (5 ft.). The depth of each fuel tube is 4050 mm (13.3 ft.). A spacing of 74 mm (3 in.) is present between the top of the basket cavity and the underside of the primary lid, thus accommodating a fuel assembly length of 4124 mm (162 in.) and supporting convection heat transfer. The final assembly results in a clearance of approximately

60 mm (2.3 in.) between the top of the fuel assemblies and the bottom of the primary lid, for a reference fuel assembly of 4064 mm (160 in.).

The basket layout results in inter-fuel tube spaces that act as flux traps for criticality control and channels to support free convection heat transfer. The basket design ensures a subcritical configuration under worst-case conditions, and the basket structure physically protects the fuel under normal and accident conditions.

A pipe with an inner diameter of 42 mm (1.6 in.) and a lead-in funnel at the top is welded to the side of a fuel tube near the outer circumference of the basket. The pipe location corresponds to a penetration in the primary lid and the low side of the slope in the cask cavity bottom. The pipe provides a path for a flanged pipe used to fill and drain the cask.

### *1.3.3 Primary Lid*

A stainless steel primary lid, 1785 mm (6 ft.) in diameter and 290 mm (12 in.) thick, is provided (Figure 1-3). Forty-four bolt holes are machined near the lid perimeter to secure the lid to the cask body. Two grooves machined around the lid underside, inside the bolt circle, are provided for O-ring gaskets (Figure 1-4). The inner groove accepts a metal O-ring, which serves as the first barrier between stored fuel and the environment. The outer grove accepts an elastomer O-ring. A 10-mm-diameter (0.5-in.) penetration through the lid provides access to the annulus between the two seals to perform post-assembly leak testing. This penetration is plugged when not in use.

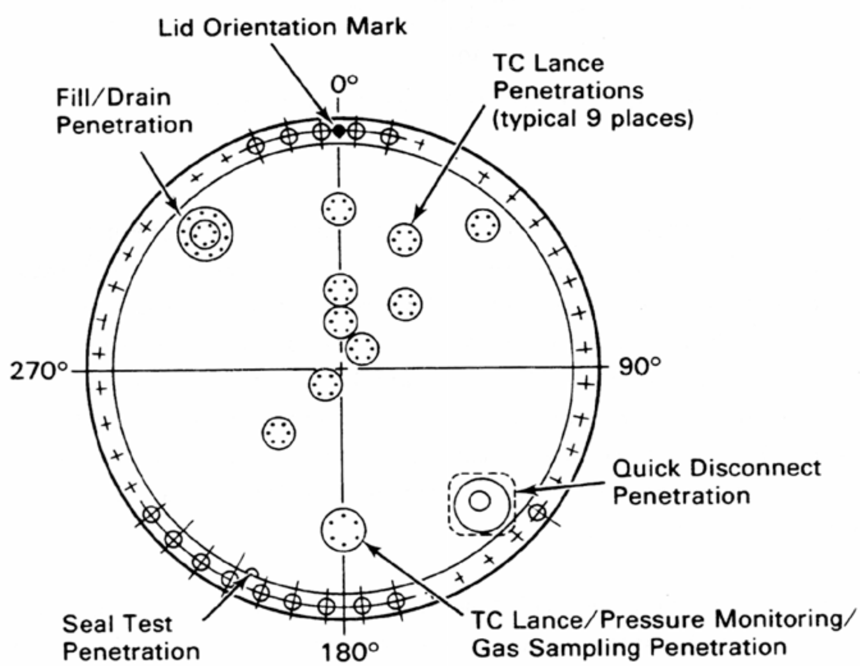


**Figure 1-3. Castor V/21 Primary Test Lid**

Three penetrations through the lid are provided for various cask operations. A 35-mm-diameter (1.4-in.) straight-through penetration is used for water fill/drain operations. This penetration is located near the perimeter of the lid and is normally sealed with two flanges equipped with elastomer O-rings. This location corresponds to the pipe attached to the fuel basket. The other two penetrations, spaced next to each other and covered by a single flange, are also located near the lid perimeter, but 180 degrees from the fill/drain penetration. The through-lid penetration at this location is equipped with a quick-disconnect fitting used for vacuum drying and backfilling with gas. The second penetration at this location leads to the lower edge of the lid. Although not needed for the CASTOR-V/21, this penetration could be used for leak-testing an optional third lid gasket. This penetration is sealed by a gasketed seal plug in addition to the top cover flange.

The primary lid used during testing was not a standard lid and has 10 additional penetrations for fuel assembly guide tube instrumentation [thermocouple (TC) lances]. The pattern of the 10 fuel assembly instrumentation penetrations was selected to measure radial temperature profiles across the basket in the spent fuel assemblies.

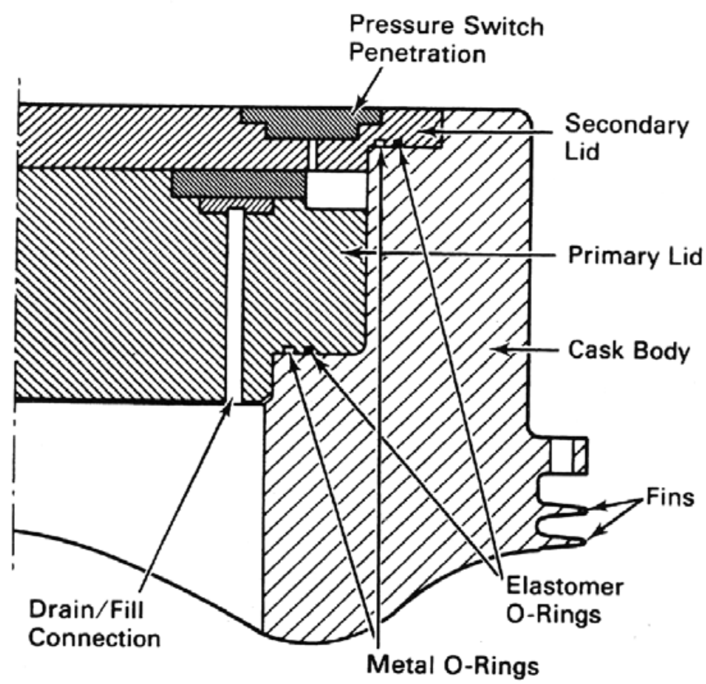


**Figure 1-4. Castor-V/21 Cask Lid System**

### *1.3.4 Secondary Lid*

The stainless steel secondary lid is 2007 mm (79 in.) in diameter and 90 mm (3.5 in.) thick (Figure 1-4). Forty-eight bolt holes are machined near the lid perimeter to secure the lid to the cask body. Two concentric grooves located inside the bolt circle on the underside are provided for a metal O-ring/elastomer O-ring sealing system of the same design as that used on the primary lid. Three normally sealed penetrations are provided for various cask operations (Figure 1-4). A 10-mm-diameter (0.4-in.) penetration through the lid provides access to the annulus between the two seals for post-assembly seal testing. A gasketed seal plug is used to close this penetration.

A second penetration is equipped with a quick-disconnect fitting, which is used for vacuum drying and gas backfilling of the primary/secondary inter-lid space. A 130-mm-diameter (5-in.) cover plate and gasket secured by six 12-mm (0.5-in.) bolts is in place when this penetration is not used. The third penetration provides a pressure sensing port between the inner-lid space and a pressure switch mounted in the secondary lid. The pressure switch is the primary component of the cask seal monitoring system.

The secondary lid was not used during the CASTOR-V/21 cask performance test because of interference with fuel assembly instrumentation leads. Therefore, dose rates discussed in Section 4 were obtained on the primary lid exterior surface. Addition of the secondary lid will greatly reduce measured dose rate values.

# 2 INSPECTIONS AND TESTS

The following inspections and tests are described in this section:

- Long-term surveillance of the concrete pad upon which the casks rest. Objective: look for any degradation of the concrete pad.
- Cask exterior visual inspection. Objective: look for any visual indications of degradation.
- Cask lid bolts. Objective: look for degradation such as rust.
- Cask lid seals. Objective: look for signs of corrosion, wear, or scoring of the seals that may lead to loss of the pressure boundary.
- Cask interior and basket inspections. Objectives: look for signs of corrosion, presence of crud spalled from fuel assemblies; gouging; and integrity of basket welds.
- Fuel assembly visual inspections. Objectives: look for signs of additional corrosion or other cladding degradation; determine if assemblies have bowed or otherwise corroded that may cause difficulty removing the assemblies from the cask.

## 2.1 Long-Term Surveillance Pad

### *2.1.1 Description of pad*

Facilities were constructed in 1985 directly to the west of TAN-607, adjacent to the rail track that exits the TAN Hot Shop, for the long-term surveillance of several dry storage cask. The facilities consisted of a concrete pad for the dry storage casks, a data acquisition building, and a weather station.

The concrete pad was designed to hold six spent fuel storage casks. The size of the pad is approximately 28.7 m (94’ 4”) long by 12.1 m (39’8” feet) wide. The pad consists of 0.61 m (2 feet) thickness of concrete on top of a minimum of 30 cm (12 inches) of compacted subbase of pit run gravel. The concrete was reinforced with two mats of #6 steel reinforcement bar spaced 18 cm (7 inches) on center (each way); the mats were each embedded 10 cm (4 inches) below and above the top and bottom surfaces of the pad, respectively. The concrete was covered and kept wet during the first few weeks of the curing period to ensure maximum strength and durability. The design strength of the concrete was 28MPa (4000 psi); the 28-day post-cure compression strength averaged 30MPa (4400 psi).

Although it was designed to hold six storage casks, the pad held four dry storage casks, including the Castor V/21. The Castor V/21 cask was located approximately 29 m (43 feet) from the west edge and 4.3 m (14 feet) from the north edge of the pad.

### 2.1.2 Pad inspection

The evaluation of the integrity of the 15-year old storage pad consisted of the testing of the structural soundness of the surface of the concrete and a visual assessment of the physical condition of the concrete surface, particularly at and immediately around the cask location.

The structural soundness of the concrete was determined by ASTM test standard C805-94 (Test Method for Rebound Number of Hardened Concrete, also known as the Swiss hammer test). The Swiss hammer test was performed on the concrete surface in 9 places in a 37.2 $m^2$ (400 $ft^2$) area centered on the placement of the Castor V/21 cask, of which 5 places were selected in the area under the cask. The nine test results, which ranged from 28MPa (4050 psi) to 41MPa (5900 psi), averaged at 33MPa (4800 psi) and demonstrated that the structural integrity of the concrete pad still meets or exceeds the 28MPa (4050 psi) design strength of the concrete.

The pad was also visually inspected for evidence of degradation and structural failure. The surface of the whole pad did not exhibit any evidence of structural failure of the concrete, such as open cracks or cracks with displacements in elevation of the surface. The surface of the concrete did not exhibit any evidence of spallation of the surface, exposed aggregate, or aggregate pop-out from the surface. The surface was solid and exhibited only minor wear and environmental weathering, well within the extent of weathering expected for the cold and windy climate of Idaho. The broom-finished unpainted surface exhibited only a network of faint, fine surface shrinkage cracks, less than 0.8mm (1/32 inch) wide and of superficial depth, and a few rust stains under the cask from lightly rusted bolts on the cask. Similar cracks were prevalent across the entire surface of the pad, and were not associated with the cask locations. Tests with a straight taught line across the 6.1m x 6.1m (20’ x 20’) grid indicated that there was no sag or vertical displacement in the concrete associated with the crack network; measurements with a straight edge and the taught line indicated only localized variations in the elevation of the concrete that were less than 3.2mm (1/8 inch). The localized variations in elevation were not associated with the location of the cask, and were most likely an artifact of the screeding and finishing when the concrete was originally poured.

## 2.2 Cask Exterior

The secondary lid of the cask is made of stainless steel recovered by epoxy painting. It was observed in order to notice any modification of its surface. It appeared that the cask had not undergone any real damage but some small superficially corroded areas were noticed where the epoxy paint had peeled. The epoxy may contain UV inhibitors, which would not have been uniformly mixed, and the densification of which may have cause peeling of the exterior layer, or this latter could be due to chocks during the handling of the container when it was previously moved.

## 2.3 Cask Lid Bolts

The cask is sealed by two lids, the outer secondary and the inner primary lid. The secondary lid is secured with 48 bolts and the primary lid with 44 bolts. The 44 bolts of the primary lid were individually inspected visually for their physical condition, specifically for evidence of cracks, pitting corrosion, general corrosion, thread damage, and any discoloration.

All bolts were in satisfactory condition. None had any indications of pitting or general corrosion, cracks, thread damage, discoloration, or any defects or indications of potential failure. All bolts had a deposit of graphitic thread lubrication over the threaded area of the shaft. Nine of the bolts also had residues of a light gray/white material on the threads that resembled tape residue, and residue of a red compound, probably a thread compound.

The lids were removed using an overhead crane. The operation was sensitive because of the tight clearance the lid and the cask. The procedure for opening the V-21 cask was checked and torque values on the bolts were not recorded for opening the cask.

## 2.4 Cask Lid Seals

The Castor V/21 primary and secondary lids are each sealed by two concentric O-ring seals. The primary lid has a metal and an elastomer O-ring housed in separate O-ring grooves. The O-rings of the primary lid were inspected immediately after opening of the cask and after replacement of the O-rings. The objectives of the inspection were to evaluate the condition of the seals for potential degradation due to:

- oxidation of the elastomer and metal seals;
- thermal degradation of the elastomer seal;
- embrittlement or hardening, including cracking, crazing and evidence of loss of elasticity or ductility; and
- physical damage to the seals, such as scratches across the seal surfaces, dents, and seal deformation.

### *2.4.1 Description of the seals*

The seals are metal O-ring, 1600 mm x 1580.2 mm x 9.9 mm, Helicoflex type HN 200, manufactured from the following materials :

- outside lining : aluminum,
- inside lining : 304 L or 316 L stainless steel,
- spring : Nimonic or Inconel.

## 2.5 Remote Inspection

The O-rings of the primary lid were inspected by remote video camera immediately after opening of the cask and by direct visual examination after replacement of the O-rings prior to re-sealing the cask. The initial remote camera inspection occurred on September 8, 1999, when the primary lid was first opened. The O-rings on the primary lid were re-inspected by remote camera on September 20, 1999. Obviously, the remote camera inspection of the seals (before removal from lid) permitted the inspection only of the compression surface contacting the cask, rather than the whole surface of the seal. The remote inspection used three video cameras mounted on work stand (work platform) at 120° intervals around the top perimeter of the cask.

The resolution and color rendition of the cameras were checked daily with a resolution chart (with alphabet characters ranging in height from 0.063 inches to 0.10 inches) and a Kodak color resolution chart. The magnification and resolution of the remote cameras were sufficient to discern fine defects; in the initial inspection immediately upon opening the cask, we were able to identify clearly a long fine hair (presumably human hair) that was looped across the two O-rings of the primary lid. The O-rings were also inspected by direct visual examination on March 28, 2000, after they were removed from the primary lid, for a complete examination of the whole surface of the seals.

The O-rings in the primary lid were in excellent condition. The remote visual inspection immediately upon opening the cask and removal of the primary lid indicated that the elastomer and the metal O-rings were free of breaks, cracks, crazing, delamination, pull-outs, oxidation or other evidence of degradation of the O-rings.

The compression area of each seal were in excellent condition, with no visible damage to the seating (compression) area of the O-ring seal. The only defect that was visible by remote camera was an imperfect splice joint in the elastomer O-ring. The compression sealing area of the metal O-ring was quite reflective, glinting in the natural illumination in the hot shop, indicating that no corrosion or excessive oxidation had occurred. The compression area of the metal O-ring was textured due to the impression of the machining marks from the mating metal seal surface of the cask body. The metal compression surface did not show any evidence of breaks, scratches, dents, distortion, or corrosion.

The O-rings, particularly the elastomer, did exhibit random, crisply-delineated patches of light surface discoloration, appearing gray against the black color of the elastomer. These patches were often associated with similar areas of light discoloration on the metal flange of the lid, especially in the bolt circle area of the flange. In several areas on the bolt circle of the lid flange, the discoloration patches formed particularly thick surface films and had partially peeled. From the peeled sections, it was obvious that the discolored areas were polymeric films, and most likely are deposits of excess anti-galling and anti-seizing compounds used on the lid bolts. Slight amounts of the anti-seize compound were also evident on the land of the flange between the two O-ring grooves, and may be responsible for the random particles of ‘dirt’ on the sides and a few dark discolorations or ‘smudges’ on the metal O-ring compression surface.

The discolorations on the compression surface of the metal O-ring were usually associated with similar gray discoloration on the elastomer seal and with deposits/films of material on the metal flange of the bolt circle. It seems possible that excess fluid anti-seize compound may have run off the lid bolts onto the solid sealing surface of the cask body, and wicked onto the elastomer and the metal O-rings before the bolts and the lid were torqued down.

The O-rings were re-inspected by remote video approximately two weeks after the initial inspection. In the interim, the primary lid was removed and replaced daily (without bolting) on the cask as part of the fuel and cask inspection process. On the second remote inspection, the condition of the O-rings was unchanged, except that the metal O-ring exhibited a few pin-point indentations, typically less than 1 mm in dimension, in the compression area of the seal. Quite likely these point indentations were the consequence of small amounts of grit on the cask body seal surface, deposited there by the seal protector or by air currents. A swab collected a small but visible amount of grime from the seal surface on the cask body.

The precision-machined seal seat of the cask body was in excellent condition. The surface of the seat was clean, brightly reflective, and free of corrosion, scratches, cracks, dents, or other forms of degradation that could affect the quality of the seal. However, the surface was lightly coated with a thin film whose optical density varied, and seemed to be associated with patches of excess thread lubricant in the bolt circle area. Except for occasional small dense spots, the film was generally faint and difficult to define. However, two continuous, concentric bright circular lines were discernable on the seal seat, equivalent to the imprint of the O-ring seals, where the film was absent.

### *2.5.1 Direct Visual Inspection*

Finally, the O-ring seals were examined by direct visual inspection after they were replaced with fresh O-rings prior to re-sealing the cask. The whole surface of the seals, including the edges, was examined.

The elastomer was still firmly resilient in consistency, flexible, and limber, with no evidence of embrittlement, stiffness, or depolymerization. Bending, pulling, twisting, and coiling the elastomer into a 30cm (12 inches) diameter coil did not cause fracture or stress failure. There was no physical evidence of delamination or pull-out of material, spallation, or chalking. The black elastomer surface exhibited a satin matte sheen and was free of breaks, cuts, scratches, cracks or craze defects. There was no evidence of oxidation or physical degradation of the elastomer.

The elastomer O-ring was fabricated with a 45° scarf splice joint. As was noted in the remote camera inspections, the splice joint was slightly misaligned and partially open; the glue did not completely fill the gaps in the joint as shown in the figures. However, the joint still had good strength, and could not be pulled apart manually.

The elastomer exhibited numerous sharply-defined gray patches on all surfaces. These patches were not associated with surface relief or differences in flexibility, resiliency, or firmness of the polymer and had a 'graphitic' sheen, suggesting that they are probably caused by excess anti-seize lubricant that was used on the lid bolts. These 'graphitic' patches were much more numerous on the back side of the elastomer, which contacted the seat of the O-ring groove in the lid, suggesting that the anti-seize lubricant was used as an aid to hold the seal in place during lid assembly.

The metal O-ring was also in good condition and was still ductile, as indicated by a few slight kinks, bends, and fresh surface scratches imparted by handling during removal from the lid. The metal showed no evidence of gross embrittlement such as cracks, either in the body of the seal or at the handling defects. In general, the metal surface exhibited a metallic luster, and showed no evidence of corrosion or extensive oxidation. The flattened contact surfaces bore the imprint of the machine marks of the O-ring groove and the mating seal surface of the cask body.

The top surface of the metal O-ring, which was in contact with the seat of the O-ring groove, did not have any defects except for a few fresh (unoxidized) shallow scratches that have been attributed to handling damage during removal from the lid. The bottom surface, which was in contact with the seal surface of the cask body, exhibited approximately 20 small pin-point indentations into the surface. The indentations were typically less than 1mm in lateral dimension and did not appear to puncture the thickness of the metal O-ring. Since these were not spotted in the initial remote camera inspection, these features are being attributed to compression damage from environmental grit on the seal surface of the cask body. The grit was probably transfer from the bottom of the seal protector to the seal area during the fuel examination operations.

### *2.5.2 Observations and results*

On the metal seals were observed :

- several pinpoint indentations, some on sealing surface; typically <0.5 mm dia, probably <0.5 mm deep
- several light scratches, a few across the sealing surface; most have metal glint in scratch root, indicating fresh scratches
- no evidence of significant general corrosion, pitting corrosion, stains
- sealing surface defined by the impression of the machining marks from the seal surface on cask
- no evidence of significant oxidation or spallation of these fine line features
- no deformation of the individual line impressions despite numerous cycles of lid removal/replacement during fuel inspection

## 2.6 Cask Interior

The Castor V/21 cask is a one-piece cylinder manufactured from ductile cast iron in nodular graphitic form. The external dimensions of the cask body is 4886 mm (16 ft) high and 2385 mm (8 ft) external diameter. The internal diameter is 1527 mm (5 ft) and the cavity length is 4152mm (163 inches). The internal surfaces of the cask, including the sealing surfaces, were galvanically coated with nickel plating.

The fuel basket is a cylindrical barrel that is partitioned into an array of 21 square fuel tubes in a quadrant layout. The basket is fabricated from welded stainless steel and borated stainless steel plate for criticality control; the borated steel contains approximately 1% boron. Each fuel tube separated from the adjacent tube by channels that act as flux traps for criticality control and as channels for convective heat transfer. The basket has an outer diameter of 1524 mm and a gross length of 4110 mm, including the four 130 mm diameter pedestals at the bottom of the basket. The basket fits snugly within the cask, with only 3 mm total diametric free play and 74 mm between the bottom of the primary lid and the top of the basket.

The objectives of examination of the cask interior were to inspect the exposed, accessible internal surfaces of the cask structure for evidence of cask and/or basket degradation caused by long-term storage. For the cask cavity, the visual inspection focussed on evidence of corrosion and crack formation in the sidewalls and the bottom of the cask, particularly in the bottom corner, as well as the failure of the nickel coating by blistering, delamination, corrosion, or discoloration. For the fuel basket, the inspection focussed on evidence of new cracks in welds or in walls of fuel tubes, propogation of existing cracks in welds, corrosion and discoloration of fuel tube walls, and accumulations of oxide particles on bottom support brackets and at the bottom of cask in each fuel tube.

### *2.6.1 Method of inspection*

Most of the cask inner wall and bottom was not accessible to visual inspection due to the size and tightly fitting characteristics of the basket. At the top of the cask, only approximately 8 cm (3 inches) of sidewall was exposed above the top of the basket and the rebate below the seal area of the cask body (i.e., the sidewall area between the top of the basket and the bottom of the lid), the 5 cm (2-inch) step of the rebate, and approximately 25 cm (10 inches) of sidewall between the primary and secondary seal seats. The floor of the cask was accessible only through the 21 fuel tubes. The bottom corner and 2-5 cm (1-2 inches) height of cask sidewall was partially accessible through a few of the larger flux traps (only ≈ 9cm (3.5) inches at the widest) at the periphery of the basket.

The inspection of the inner wall at the top of the cask was performed by remotely using three video cameras mounted on work stand (work platform) at 120° intervals around the top perimeter of the cask. The floor and the bottom corner of the cask were examined with a radiation-tolerant miniature (pencil) camera and light mounted at the end of a 4.5m (15 ft.) pole. The pencil camera head was a cylindrical unit approximately 1.3 cm (0.5 inch) in diameter and 6.4 cm (2.5 inches) long. As with the video cameras, the pencil camera resolution was checked daily with the resolution and color charts.

Because of the tight clearances for access to the bottom corner and sidewall of the cask, the examination was attempted initially with a borescope, but failed because of the narrow field of view, short working distance, short depth of field, and poor dynamic response of the borescope camera.

### 2.6.2 Interior Cask Sidewall

The upper exposed area of the inner sidewall of the cask was in very good condition. The galvanically-applied nickel coating was still intact and did not show any evidence of blistering, peeling, cracking, delamination, or corrosion.

The nickel-plated sidewall was free of significant defects. However, a few isolated minor, superficial features or imperfections were visible in the visual inspection; these appeared to be light scuff and faint scrape marks that were most likely created during the initial installation of the basket in the cask. Adjacent to fuel tube D3 (at the 270° with respect to the 0° orientation mark), the sidewall had an imperfection that initial inspection identified as a blister or dimple. However, close examination of the illumination shadows indicated that the feature was a shallow depression (dimple) about 2 cm in diameter and probably only approximately a millimeter deep, with the nickel coating still intact. The visible surface of the sidewall also had several isolated, randomly-oriented superficial lines that could be surface deposits (from abrasion by a softer material) or superficial scrapes. These features are quite faint, with no discernible vertical dimensions, burrs, ridged edges or plow marks that usually are associated with scratches that penetrate coatings or gall a surface.

Considering the tight fit of the basket within the cask body, the nickel coating on the upper sidewall shows little evidence of damage due to insertion of the basket. The only discernible feature that might constitute significant coating damage was a black mark on the sidewall at the level of and coincident with the corner of fuel tube D3. However, the black surface mark appeared to be superficial, and did not have any burrs or dimensional relief indicative of substantial abrasion damage, corrosion product formation, or cracks. While the feature is coincident in location with the corner of fuel tube D3, it cannot be the result of abrasion by the corner of the fuel tube (by vibration from cask handling), for the fuel tube is separated from the wall by the thickness of the steel barrel plate comprising the outer rim of the basket. Instead, this feature may be the result of abrasion during insertion of the tightly-fitting basket into the cask or from vertical thermal expansion of the tightly-fitting basket barrel wall during the 1985 thermal tests. The upper sidewall has several similar, less distinct blemishes that could be construed as light scuffing or abrasion of the nickel coating from contact during the insertion of the basket into the cask body. These features consist of black ‘scuffs’ and spots on the nickel surface, as if the nickel plating was lightly abraded from the high points of the rough as-machined surface of the cask body. These features have no discernible relief, implying negligible superficial damage at worst, and have no evidence of more than possibly superficial surface corrosion, as might have occurred prior to sealing the cask in 1985. Furthermore, there was no evidence of delamination and peeling of the nickel layer around these features, or of subsurface corrosion or blistering in the areas surrounding the features, which could be the expected effect from a corrosive, oxidizing environment.

### *2.6.3 Interior Cask Bottom and Bottom Sidewall*

The cask bottom and bottom sidewall could be inspected only to a limited extent by access through the 21 fuel tubes and the eight channels at the perimeter of the basket. Access via the remaining flux traps was prevented by the tight dimensions of the traps and the structural gussets and spacers in the cavities of the traps. In addition, the inspection of the whole area of the cask floor was hampered by the small clearance (≈3.8 cm (1.5 inches)) between the bottom of the basket and the cask floor.

The floor of the cask was of roughly-grained as-cast texture, overcoated with the nickel plating. The floor of the cask turned smoothly up into the sidewall, so that the first centimeter or two of sidewall was also generally of rough as-cast texture. The sidewall above the bottom corner radius was smoother than the floor, as if it had been machined to remove the as-cast texture prior to nickel plating.

The nickel plating on the floor and bottom sidewall was generally clean and quite reflective despite the as-cast texture. There was no evidence of any corrosion, cracks, or flaws in the nickel plating, such as blistering or delamination, in the floor, corner, or sidewall of the cask. In general, the bottom sidewall was quite clean and reflective, particularly those areas that were machined prior to nickel plating. There were, however, isolated areas that appeared to be covered with light-colored spots of material that were not reflective and had no relief. These patches appeared to be mineral spots, as if deposited from residual water in the cask (as from evaporation of residual plating solution or rinse water). These flat, light-colored spots did not appear to contain much material as they had no relief (depth); neighboring areas were free of these deposits. They did not appear to be caused by corrosion or oxidation, nor was the integrity or adherence of the nickel plating affected by them.

Small grains of debris were thinly scattered over most of the cask floor. The debris ranged from sandlike particles of submillimeter to several millimeter size, to long slivers of material several millimeters in length. These generally appeared to have been deposited after the nickel plating of the surface, since the larger particles were dark in color and not reflective. Similar material had accumulated on the horizontal bars at the bottom of each fuel tube, on which the fuel assemblies rested. Much of the sand-like debris probably consists welding slag or grinding swarf from the basket. However, some of the debris appeared to consist of slivers of metal, and may be slivers of stainless steel gouged from the fuel tube walls by insertion and extraction of the fuel assemblies, since the fuel tube walls exhibited much evidence of scraping by the fuel assemblies.

Samples of the particulate debris on the cask floor were retrieved with tape swabs. The locations of the samples are summarized in Table 2.1.

**Table 2.1. Characterization of the particulate debris retrieved from the cask floor. Location of the samples taken from the Castor V/21 cask for characterization.**

| Sample Number | Method of Sampling | Location of Sample Material |
|---|---|---|
| V/21-1 | tape pad on rod (1) | cask floor at fuel tube A1 |
| V/21-3 | tape pad on rod | cask floor at fuel tube C5 |
| V/21-10 | tape pad on rod | cask floor at fuel tube D5 |
| V/21-12 | tape pad on rod | cask floor at fuel tube D6 |
| V/21-14 | tape pad on rod | cask floor at fuel tube A4 |
| V/21-15 | tape pad on rod | Control, exposed to Hot Shop ambient environment and manipulated like samples |
| V/21-16 | tape pad on rod | Control, exposed to Hot Shop ambient environment and manipulated like samples |
| V/21-17 | tape pad on rod | cask floor between fuel tube C8 and barrel wall |
| V/21-18 | tape pad on rod | cask floor between fuel tube D8 and barrel wall |

1)For retrieval of small granular debris from the bottom of the cask, white nuclear grade duct tape was fastened to a flat foam pad mounted to the end of a 4.6 m (15 foot) steel rod.

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The visual inspection, SEM, and EDS results suggest that the visible grains are primarily steel slivers or steel oxide particles from the steel fuel basket. The slivers are probably the result of scraping or abrasion of the steel fuel tube walls by the fuel assemblies during past insertions and extractions. The walls of the fuel tubes have long, straight, deep axial (vertical) scratches that are consistent with abrasion by the fuel assembly components during insertion or removal. Moreover, the roots of those scratches glint in the camera lighting, indicating that the scratches are relatively unoxidized and not a characteristic of the mill finish of the plate steel. The larger oxide particles are probably residual pieces of welding slag that were dislodged from the basket; the smaller particles of oxide and steel are probably grinding residue dislodged from the basket.

The radiation/chemical analysis or the crud samples were analyzed at the Idaho Nuclear Technology and Engineering Center (INTEC) in November 1999. Samples include those taken from fuel assemblies and the bottom of the cask interior. The test for “iron-phase” was completed and was not conclusive due to the insufficient amount of “loose” material for sample analysis. Consideration is being given to performing this analysis again using material scraped from the bottom of the fuel rods during the Hot Cell work.

All of the samples show low levels of radioactivity, primarily due to Co-60, a component of crud. The other common radioisotopes associated with crud were below detection limits for the test. In addition, Cs-137, one of the primary gamma-emitting fission products, was also below detection limits. The gamma analyses suggest that the debris on the floor of the cask may contain some crud particles; because the crud constituents other than Co-60 were below detection limits, the mass of crud contamination is small and probably consistent with the limited amount of crud that might have been scraped off the fuel assemblies during insertion into and extraction from the fuel tubes.

## 2.7 Fuel Assembly Basket

The accessible portions of the fuel assembly basket inside the cask were inspected visually, using the three remote video cameras positioned around the top rim of the cask, and the pencil camera used to inspect the floor. The fuel basket was examined for evidence of further corrosion of the plate surface, the welds and associated heat affected zone, the junction between stainless steel and borated stainless, and contact points between the stainless steel structure and the zircaloy fuel assemby structure, such as on the steel brackets at the bottom of each fuel tube that support the weight of the fuel assemblies. In addition, the welds in the basket structure were inspected for failure, both for propogation of the cracks in the known broken welds and for initiation of new cracks in other welds.

### *2.7.1 Basket Condition*

Only the surfaces of the basket directly accessible to the video and pencil cameras were inspected. The basket was inspected while in place within the cask. The extremely tight diametral clearance between the basket and cask wall (≈3 mm) prevented the unloading and extraction of the basket from the cask. The top surfaces of the basket were inspected by the three video cameras mounted around the top of the cask. With the fuel assemblies removed, the interior surfaces of the 21 fuel tubes and eight ungussetted air channels were inspected with the pencil camera system. The interior surfaces of the flux traps and the triangular air spaces at the perimeter of the basket could not be inspected with the pencil camera, for these spaces were obstructed by welded spacers and gussets, or were too narrow to permit insertion of the pencil camera.

The fuel basket was in good condition, comparable to the surface condition in the 1985 video tapes (EPRI 4887). In fact, some of the images of the tops of the basket in the 1985 video tapes looked worse (more oxide scale) that in the 1999 inspections, an effect of the difference in lighting conditions. The basket structure showed no evidence of corrosion beyond the mill surface finish and the heat tarnish in the heat affected zones of the welds. The fabricator of the basket had left the mill surface finish on the steel plate components of the basket; no attempt had been made to remove the native oxide, stencils, construction layout marks, or environmental stains on the as-supplied steel stock.

Therefore, most of the surfaces of the basket structure had a light-gray non-reflective surface, as well as superficial oxide tarnish in the region of many of the welds. However, some of the interior surfaces of the fuel tubes bore the marks of spot (rotary) surface grinding that ‘skinned’ the flat surfaces; these ground surfaces were still brightly reflective under the camera illumination, indicating that neither significant air oxidation nor corrosion had occurred since the fabrication of the basket. There was no evidence of corrosion due to incompatibility between the stainless steel and the borated steel, nor was there evidence of corrosion or degradation at the contact between the stainless steel 304 bottom nozzle of the fuel assemblies and the bottom support plates in the fuel tubes. No cracks or similar degradation was seen in the steel plate components, except for some of the welds as noted below.

### *2.7.2 Basket Welds*

The 1985 inspection of the basket after the completion of the heat transfer performance tests identified eight broken welds in the top of the basket (EPRI 4887). The affected welds are identified in Figure 2-1. The welds cracked as a consequence of the stresses created by the differential thermal expansion of the tightly-fitting basket within the cask during the tests. An objective of the 1999 inspections was to re-examine the affected welds for any changes in configuration, and to examine other accessible welds in the basket structure for cracks or corrosion. Unfortunately, the stitch welds of the structure are located in the flux trap and spacer channels, not inside the 21 fuel tubes. Therefore, the only accessible welds were the welds visible at the top of the basket and a few others.

The eight known broken welds appeared to be the same as in the 1985 inspection. The four welds in the corners of the central fuel tube All involved welds of stainless steel to borated stainless steel, whereas the four welds joining the fuel tubes in clusters A8/A5/A6, B6/B5/B8, C8/C5/C6, and D6/D5/D8 involved only stainless steel. The 1999 inspection confirmed that five welds were broken clear through, and three had substantial cracks that propagated partially through the top stitch weld. The narrowness of the flux traps and the supports within blocked the views of the stitch welds below the top welds from the top-side video cameras, and prevented the insertion of the pencil camera assembly. Therefore, the condition of those welds could not be determined.

The top stitch welds throughout the top of the basket were inspected, as well as the welds of the top-most struts within the flux traps. Except for the eight known cracked welds, the remaining welds look like they are all in good condition.

The stitch welds in the triangular air channels at the perimeter of the basket were examined with the pencil camera system. The gusset- and strut-free channels were just large enough to permit insertion of the pencil camera for viewing the stitch welds attaching the fuel basket partition plates to the basket barrel.

The inspections found that all eight of the top stitch welds were cracked, and seven of the eight bottom welds. The intermediate welds did not appear to be cracked.

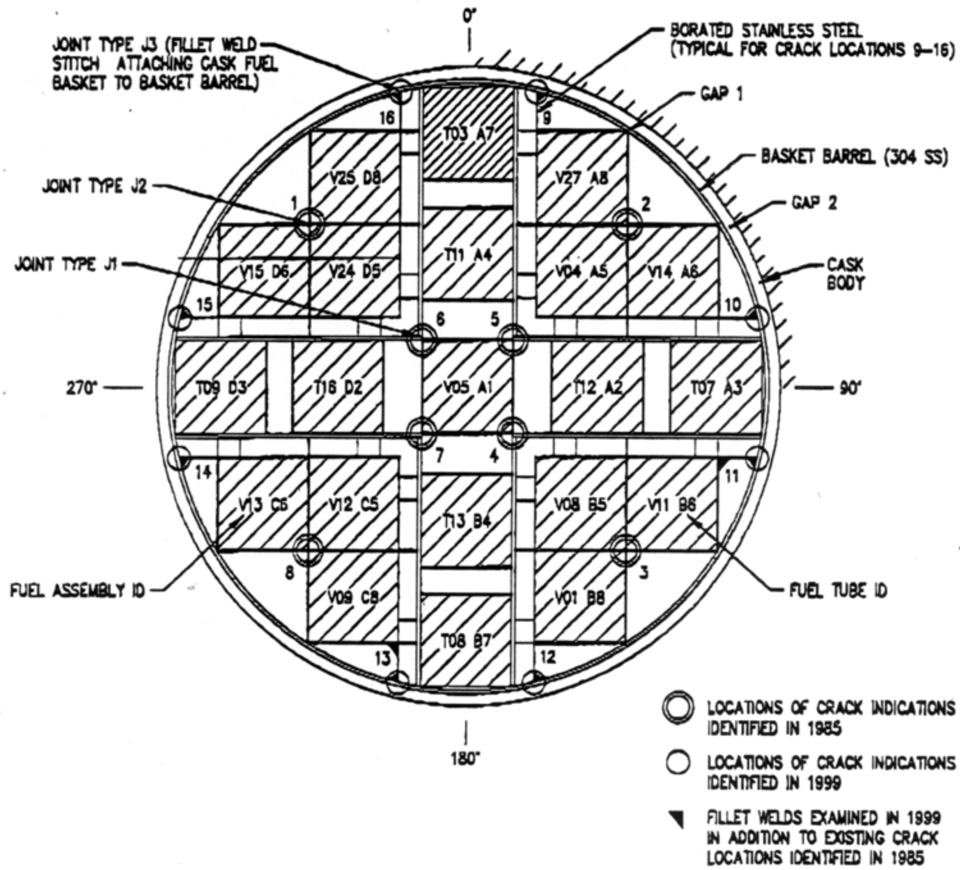



**Figure 2-1. Castor-V/21 Basket Crack Indication Locations**

Additional cracks in basket welds (as shown in Figure 2-2.) were associated with stainless/borated steel junctions welds in fuel tubes.

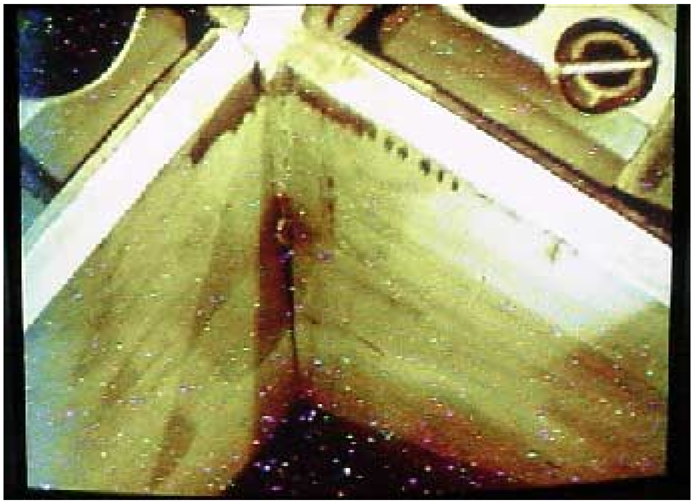


**Figure 2-2. Cracks in basket welds**

## 2.8 Fuel Assemblies

### *2.8.1 Purpose of the inspection*

The inspection searched for evidence of change in the structure and integrity of the fuel assemblies: changes in corrosion and crud deposits on nozzles, grid spacers, rod cladding; additional corrosion, loose or lightly adherent corrosion product or crud; evidence of spallation or flaking; physical degradation or damage to nozzles, spacers, fuel rods; cracks, bowing of rods, or distortion.

### 2.8.2 Method of inspection and lifting force measurements

The visual inspection requires the removal of the fuel assembly from the basket (Fig. 2-3 ).

**Fig 2-3. Fuel assembly being lifted**

Table 2 provides the fuel assembly weight and the force required to start lifting each assembly out of the V-21 cask. The lifting force measurements indicate little ‘sticking’ of the assemblies during removal suggesting that no significant bowing of the assemblies or development of corrosion products causing adherence to the cask floor occurred.

Once the assembly was lifted out of cask basket, the inspectors identified the assembly serial number and its orientation with respect to basket. They checked the relative uniformity of fuel rod lengths by clearance between tops of rods and top nozzle, then scanned the four sides using the three remotely operated cameras. After the visual inspection, the fuel assembly was returned to its original channel in the cask, maintaining the original orientation.

Once the fuel assembly was removed, the entire length of the four external surfaces were inspected by three remotely operated video cameras with zoom capabilities. Figures 2-4 shows an example of the condition of the assemblies.

**Table 2-2. Fuel Assembly Examination Sequence and Lift Force Measurements**

| Fuel Assembly ID | Inspection Sequence | Selected for closer examination | Grapple + fuel wt, lb | Force to start lifting, lb |
|---|---|---|---|---|
| VO5 | 1 | YES | 1414.5 | 1436 |
| TO3 | 2 | | 1421 | 1472 |
| V27 | 3 | | 1419 | 1457 |
| V04 | 4 | | 1419 | 1439 |
| V14 | 5 | | 1415 | 1446 |
| TO7 | 6 | | 1419 | 1434 |
| T12 | 7 | | 1415 | 1442 |
| V08 | 8 | | 1412 | 1431 |
| V11 | 9 | | 1407 | 1421 |
| V01 | 10 | | 1415 | 1433 |
| T08 | 11 | | 1410 | 1431 |
| V09 | 12 | | 1412 | 1440 |
| V12 | 13 | YES | 1403 | 1420 |
| V13 | 14 | | 1417 | 1442 |
| T09 | 15 | | 1410 | 1428 |
| T16 | 16 | | 1413 | 1441 |
| V24 | 17 | YES | 1410 | 1430 |
| V15 | 18 | YES | 1408 | 1433 |
| V25 | 19 | | 1413 | 1426 |
| T13 | 20 | | 1412 | 1427 |
| T11 | 21 | YES | 1410 | 1420 |

The assemblies were in a generally good condition, which had not changed since the 1985 inspection. The general visual survey revealed a dark gray oxide layer under ambient cell lights, and light tan by video. The inspection found no increase in the oxide layer thickness. There was no formation of a loose oxide scale or particles between the fuel rods of the grid spacers or on the bottom nozzles.

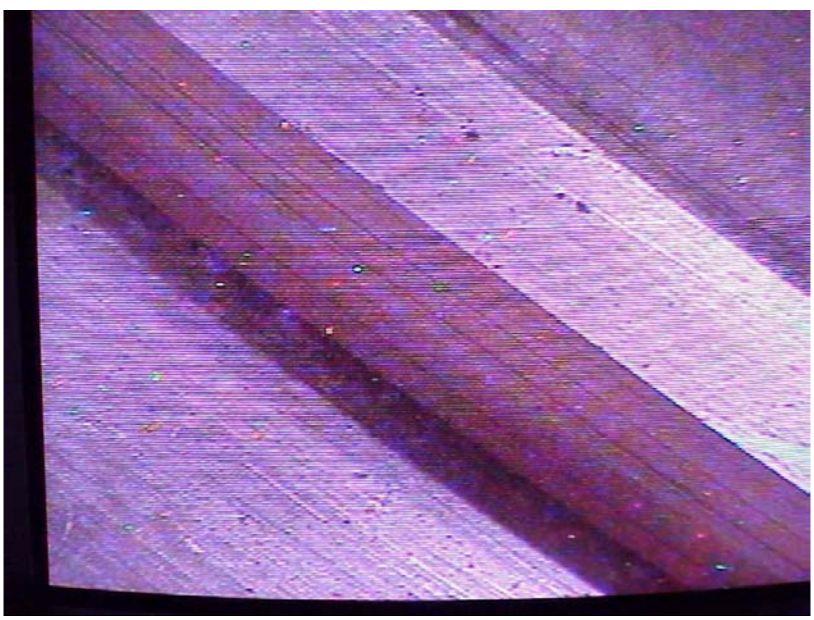


**Fig 2-4. Close-up of rods via video.**

## 2.9 Cask temperatures

Storage systems must be designed to allow ready retrieval of spent fuel for further processing or disposal (10CFR Part 72). The spent fuel cladding must be protected against degradation by thermally activated processes by keeping the storage temperature down. Spent fuel storage or handling systems must be designed with a heat-removal capacity without active cooling systems. The conditions in the second storage period will be less severe than in the first storage period since the decay heat decreases with time. The decreasing decay heat requires less heat removal capacity during the extended licensing period. As a condition for re-licensing, the thermal requirements during the extended storage period must be met.

### *2.9.1 Internal temperature*

Internal temperature measurements during the 1999 testing were taken, but only to provide a general indication of temperatures inside the cask. This is because the thermocouple lance system used in 1985 was no longer available for the tests in 1999. Thus, the temperatures inside the cask had to be measured with the lid off.

Internal temperatures were recorded on September 29, 1999, between approximately 4 pm and 5 pm. The cask lid was removed every workday morning at approximately 7:30-8 am, and by procedure was replaced nightly at the end of the day's activities (generally between 7 and 9:30 pm). When these temperature measurements started, the lid had been off the cask for approximately 8 hours.

The bolts were removed from the primary lid on September 7, 1999, and the primary lid was first removed on September 8, 1999. Between Sept. 8 and 29, the lid had been open generally 5 days per week and about 10 hours per day, with at least 8 hours of convective cooling on that day and the gradual convective cooling achieved during the working days prior to that measurement. Therefore, the contents would have cooled considerably.

The temperature was measured with a Type J thermocouple inserted into the control rod guide tube. It was expected that the upper portions of the fuel assembly would exhibit the highest temperatures due to convection. To approximate the best position, the temperature in V05 (fuel tube A1) were quickly measured at three positions:

- after 12 minutes, 0.6m (2 feet) below the top nozzle, 152.1° C;
- after 5 minutes, 1.5m (five feet) below the top nozzle, <140° C;
- and after 10 minutes, 0.3m (one foot) below the top nozzle, 146.5° C.

Within 10 minutes or so, the temperatures equilibrated to within 0.1C/min (0.2°F/min) rise; the temperature readings were recorded for at least the last five minutes of equilibration. The final readings at 10 minutes (12 mins for V05), measured approximately 0.6m (2 feet) beneath the top nozzle, were as follows in Table 2-3.

**Table 2-3. Internal temperature**

| Assembly ID | Fuel Tube ID | Temperature |
|---|---|---|
| V05 | A1 (center of basket) | 152.1° C |
| T11 | A4 (between center and outer tubes) | 154.6° C |
| T03 | A7 (outer tube, at 0° mark on cask) | 122.8° C |

Plots of the readings at one minute intervals indicated that the equilibration was close to completion at 10 minutes; the final true equilibration temperature might be at most 2-3C (5 degrees Fahrenheit) higher.

The hottest zone in the hottest of the three measured assemblies was 154°C at the end of 10 minutes equilibration, when the rate of rise was still 0.1C/min (0.2°F/min). A plot of the data indicated that the temperature would eventually equilibrate between 155 and 160°C.

It must be emphasized that these results pertain only to the conditions at the time of measurement and represent an estimation of the maximal temperature of the assembly. It was considered as satisfactory that the air temperatures were well below 200°C. More rigorous measurements of the actual rod surface temperatures to get a better assessment of the impact on using aluminum for the laydown fixture were not executed. since it was assumed that T11, with its high burn up, was thermally the hottest or at least representative of the hottest assemblies It is nevertheless true that with the cask lid in place, the final equilibrium temperature will be higher.

# 3 RADIATION SURVEY

## 3.1 Objectives

Radiation shielding and confinement features that are sufficient to meet all necessary requirements of 10 CFR Part 72 must be maintained as long as the spent fuel is to be stored. Since the radioactive and thermal source terms are decreasing, a dry storage cask that met the requirements for the first license period will also meet those for the second license period, provided that material alterations have not led to unexpected behavior or decreased capabilities of factors important to safety.

The radiation survey must evaluate eventual degradation of the shielding for neutron radiation, for gamma radiation, and compare measurements to calculated, decay-adjusted, dose rates.

## 3.2 Method(s) of measurement

In the 1985 EPRI study (EPRI NP-4887), gamma dose rates were measured on the surface of the cask with thermoluminescent dosimeters (TLDs). Neutron dose rates were measured with track etch dosimeters (TEDs). Portable hand-held survey instruments were also used to measure both gamma and neutron dose rates. There were three different sets of readings (including INEEL and PNL data), and the data are in good agreement all together, and are therefore reliable.

The measurements executed in August 1999 were made using TLD and TED during only one set of experimentation. Exterior surface dose rate instrumentation on the Castor V-21 cask consisted of :

1. TLDs to measure gamma dose rates
2. TEDs to measure neutron dose rates, and
3. Portable hand-held survey instruments to measure both gamma and neutron dose rates.

The data obtained are not sufficiently reliable, they only give trends.

## 3.3 Observations

Figure 3-1 and 3-2 show the dose rates measured on the bottom of the cask in 1985 and in 1999, depending on the distance to the center of the cask.

Figure 3-3 and 3-4 show the dose rates measured on the side of the casks in 1985 and in 1999, depending on the distance from the cask bottom.

Figure 3-5 and 3-6 show the dose rates measured on the top of the cask in 1985 and in 1999, depending on the distance to the center of the cask.

Fig. 3-1. BOTTOM Dose rates 1985 (Dosimeter TLD and TED)

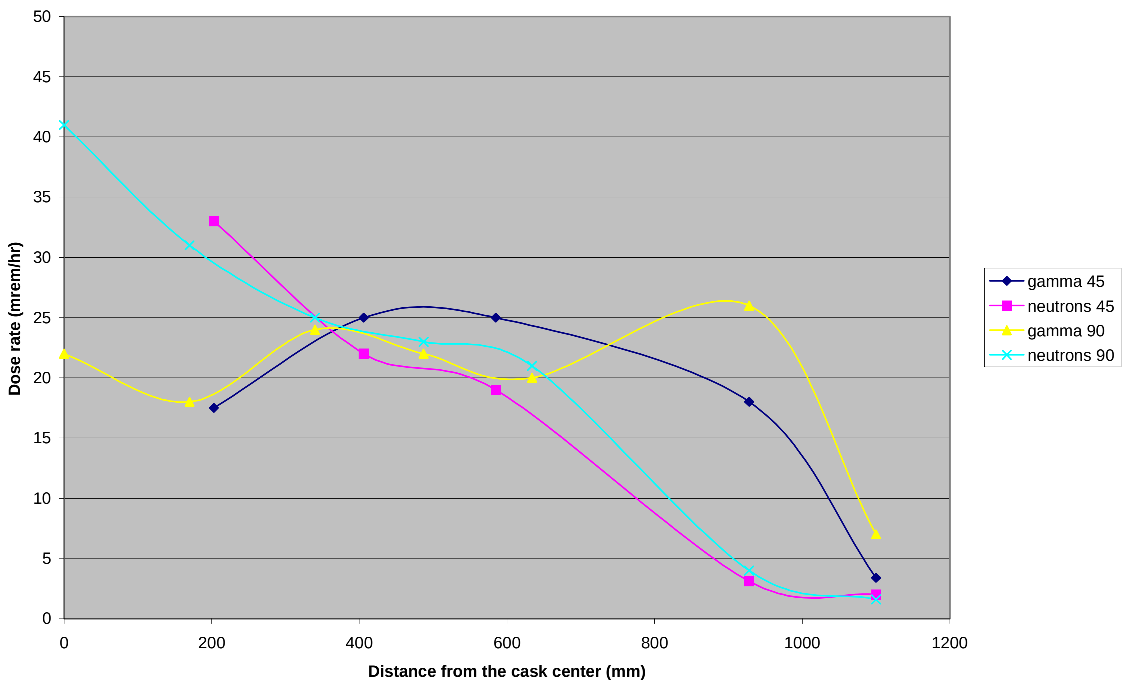



Fig. 3-2. BOTTOM Dose rates 1999 (Dosimeter TLD and TED)

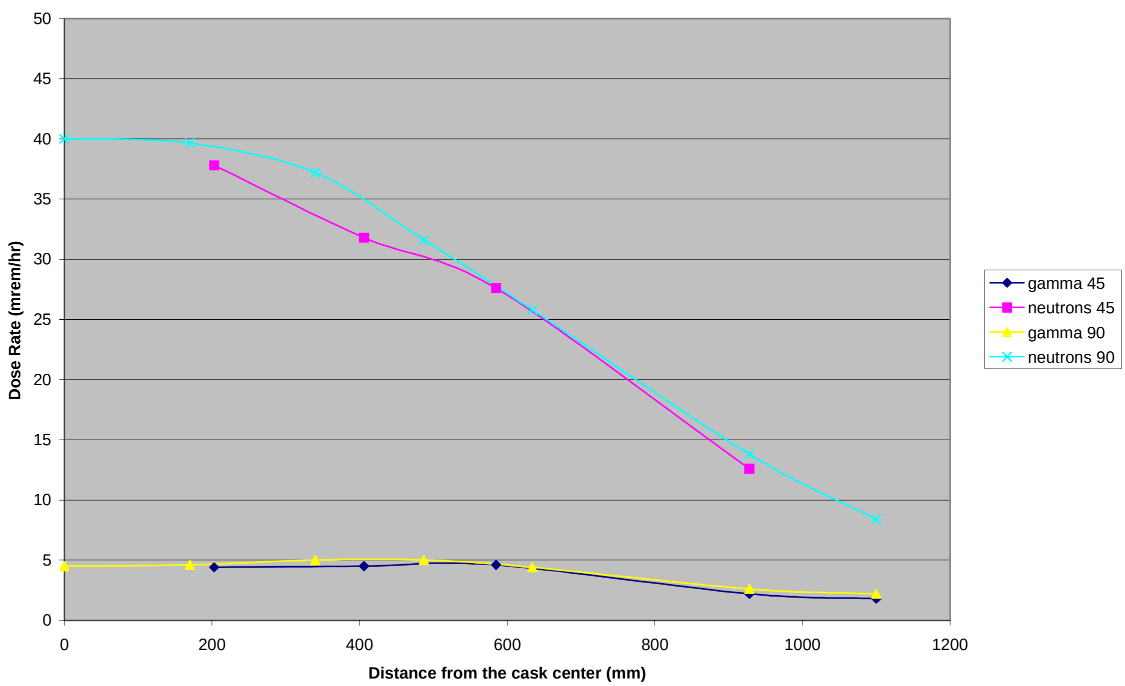


**Fig. 3-3. SIDE Dose rates 1985 (Dosimeter TLD and TED)**

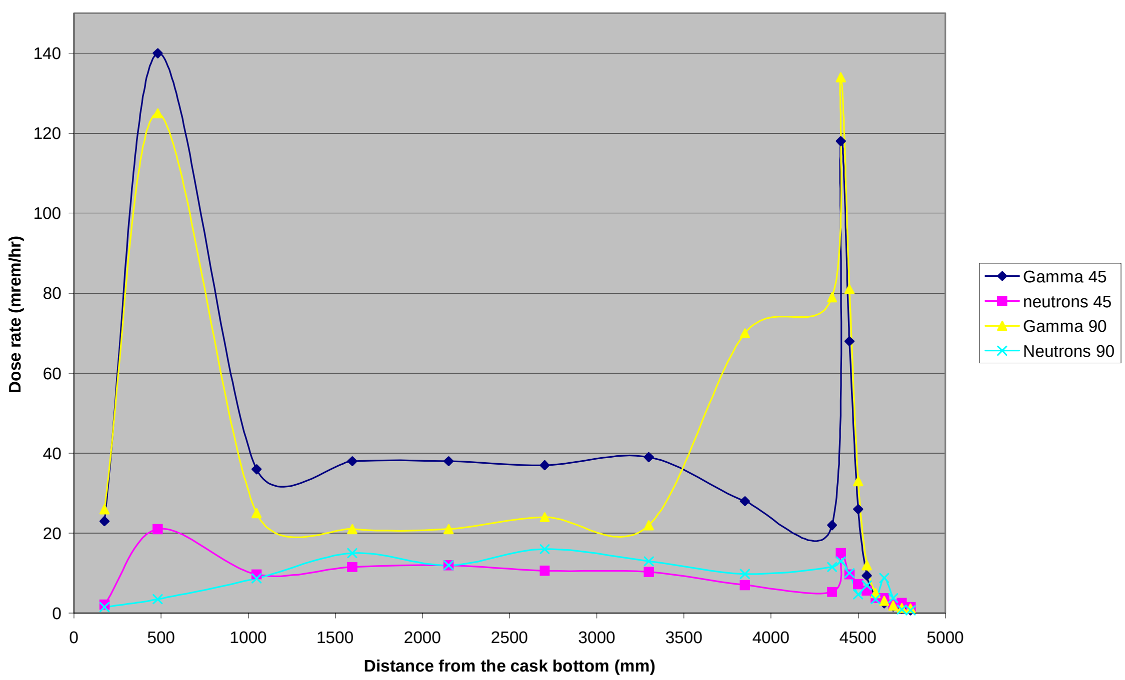



**Fig. 3-4. SIDE Dose rates 1999 (Dosimeter TLD and TED)**

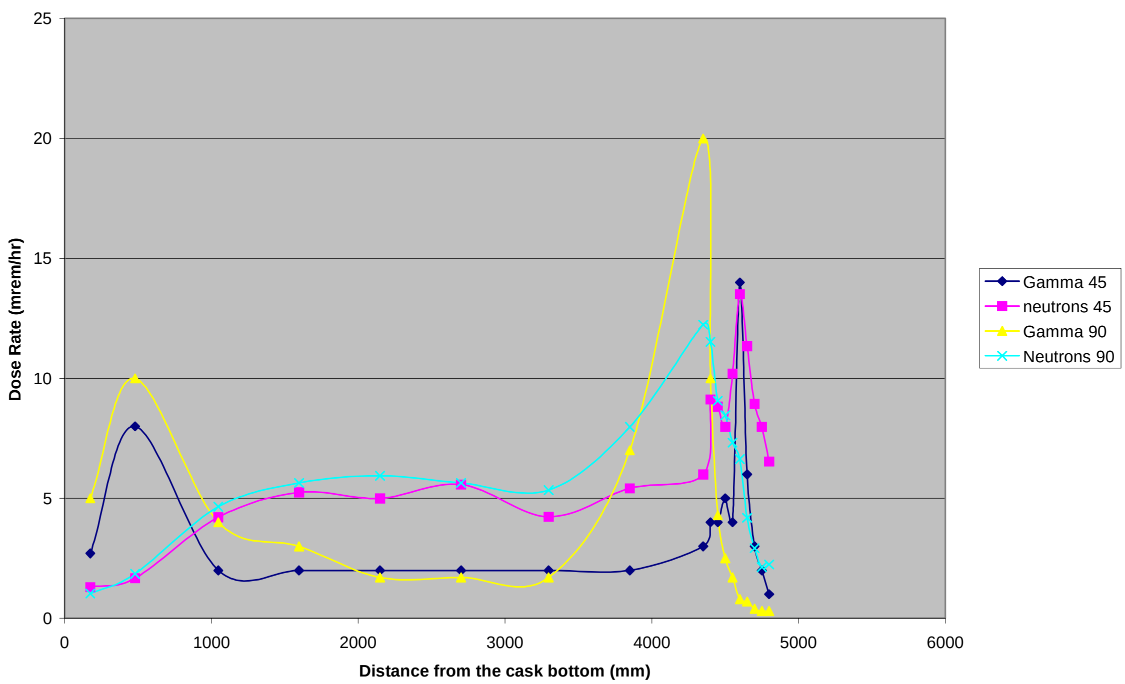


**Fig. 3-5. TOP Dose rates 1985 (Dosimeter, TLD and TED)**

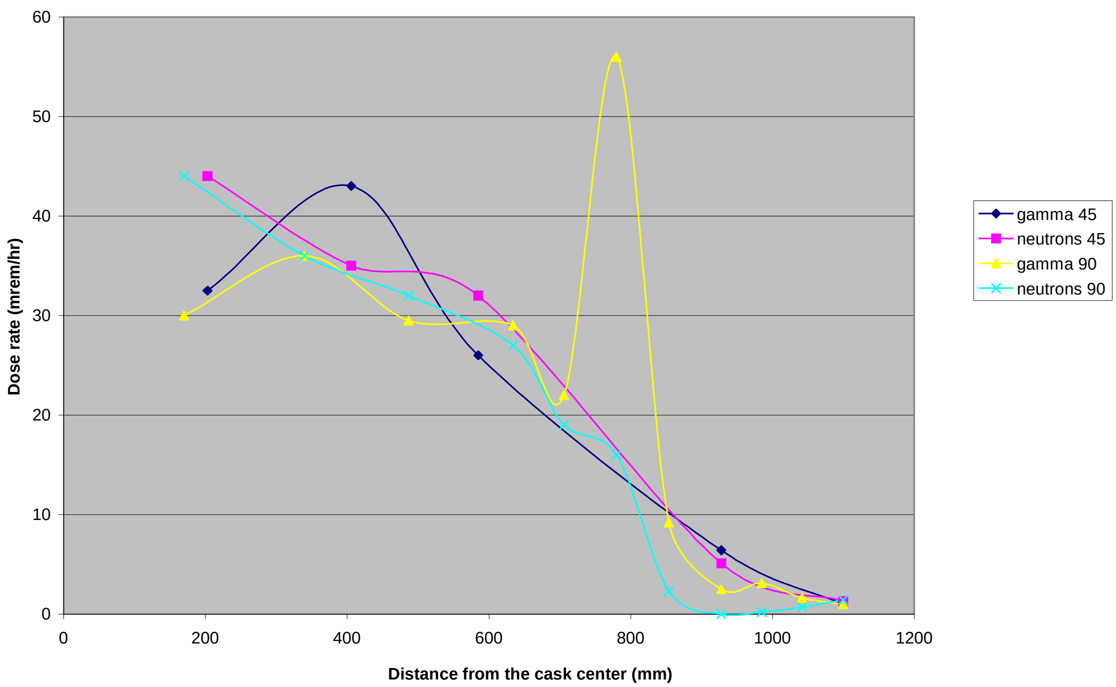
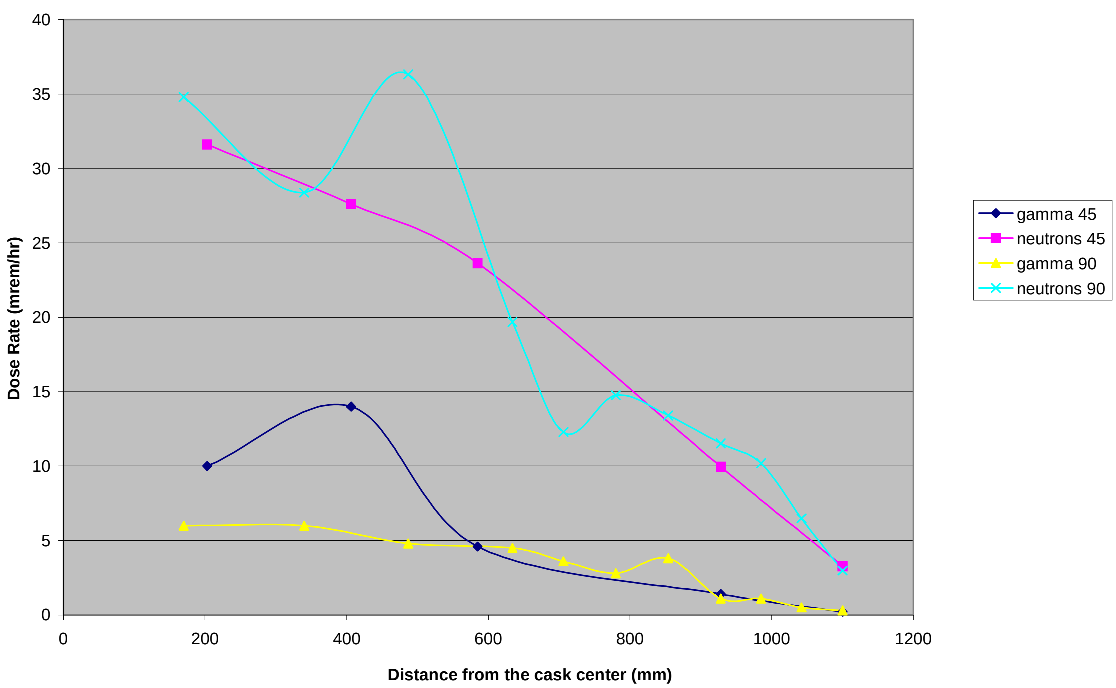



**Fig. 3-6. TOP Dose rates 1999 (Dosimete, TLD and TED)**



### 3.3.1 Gamma contributors

In 1985, a germanium spectrometer was used to look at the energies of the source gammas. The major radionuclides identified were 60Co and 144Ce/Pr at the top and bottom of the cask, and 144Ce/Pr, 134Cs, and 154Eu on the side. The dominance of 60Co at the top and bottom was due to the activation of the stainless steel on the ends of the fuel assemblies. The primary contributor at the side was 144Ce/Pr, a fission product present in the spent fuel.

### 3.3.2 Dose rates at the bottom

At the bottom, the gamma dose rate profile obtained with TLDs is reasonably uniform (18 to 25 mrem/hr) from the centerline of the bottom to a radius of approximately 93 cm, but drops off to less than 5 mrem/hr at the edge of the bottom. The neutron dose rate profile peaks at the centerpoint of the bottom (41 mrem/hr) and uniformly decreases to less than 5 mrem/hr at the edge of the bottom. (EPRI 1985)

Comparing these results with those from 1999, we notice that the data follow more obvious trends (radioactive decay has eliminated the side-effects). Gamma dose rates were attenuated from an average 20 mrem/hr to less than 5 mrem/hr, which means an average factor 4 decay in 15 years.

On the contrary, the 1999 data for neutron are clearly not reliable. For example, in some instances they show an increase in neutron dose rate.

### 3.3.3 Dose rates on the sides

Dose rates measured on the exterior surface (fin tips) of the cask are presented in figures 3-3 and 3-4, additional data are included in Appendix A. Obviously, data regarding the side dose rates seem more accurate. Gamma dose rate profiles from 1985 have significant peaks (140 mrem/hr) near the ends of the cask. The peaks correspond to the upper and lower end fittings of the Surry PWR spent fuel assemblies. Peaks in gamma dose rates occurred adjacent to the higher decay heat assemblies (1.8 kW) located near 45 degrees and 135 degrees.

Neutron dose rates near the cask ends show only slight peaks (< 21 mrem/hr). Total gamma and neutron dose rates on the remainder of the side of the cask are relatively low, less than 50 mrem/hr.

The 1999 data show a general decay. The gamma profile was reduced by an average factor 15: from 140 to 8 mrem/hr near the bottom, from 120 to 14 mrem/hr near the top of the cask, and from 30 to 2 mrem/hr on the reminder of the side of the cask.

The decay regarding the neutron is less important. The peak at the bottom disappeared, the dose passing from 20 to 3 mrem/hr. On the medium part the dose decreased from 14 to 6 mrem/hr. And the slight peak near the top decreased from less than 20 to less than 15 mrem/hr.

### *3.3.4 Dose rates on the top*

The gamma dose rate trend across the top at all angles between 1985 and 1999 looks relatively consistent: 1999 dose rates are roughly 15 to 45% of the 1985 values. Gamma surface dose rates in 1999 never exceed 18mrem/hr.

The neutron dose rates across the top between 1985 and 1999 are more difficult to figure out although, in general, 1999 dose rates are roughly 70 to 80% of the 1985 values.

When we get to the outer radii, things look less clear: 1999 dose rates look higher than the 1985 dose rates. However, the trend in both the 1985 and 1999 neutron dose rates is that dose rates fall off pretty rapidly getting to the outer elevations.

### *3.3.5 Conclusion*

It is apparent the shielding performance of the cask met by far the design goal of less than 200 mrem/hr, which they already met in 1985. Moreover, the outer secondary lid is in place during normal operation, which substantially reduces neutron and gamma dose rates.

The 1999 dose rate data generally support the conclusion that dose rates have decreased since 1985, as would be expected due to radioactive decay. There are a few instances where this conclusion is less clear. It appears likely that the cases where 1999 dose rates look higher than the 1985 data are due to the survey being taken in not exactly the same location as in 1985 or perhaps poor quality dose rate measurements. In any case, there is no obvious evidence of a degradation in the performance of the gamma or neutron shielding between 1985 and 1999 that calls into question the long-term ability of the cask to maintain adequate shielding.

# 4 GAS SURVEY

## 4.1 Background

One of the primary concerns of the study of the Castor V-21 cask was whether degradation of the spent fuel cladding due to the initial thermal testing or long term storage would lead to the release of gaseous fission products. In addition, it is important to maintain a low oxygen environment inside the cask to minimize oxidation of the cladding and spent fuel. In 1985, the cask cover gas was sampled several times during performance testing, to evaluate the integrity of the spent fuel rods and the cask lid seals. Each sample was collected in a separate 500-cc stainless steel cylinder equipped only with quick disconnect-fittings and no bellows-sealed valves as part of the closure. The cylinders were checked for leaks prior to sampling. Because only quick disconnect-fittings were used for the cylinder closure, the cover gas samples in the cylinders were diluted with ambient air from the vicinity of the sampling apparatus, air that leaked into the cylinder during shipment, and argon introduced at Lawrence Livermore National Laboratory (LLNL) when it was necessary for valves to be fitted to the cylinder quick-disconnects in an argon atmosphere to perform the sample analyses. In many cases, this dilution was made more severe by the collection of small amounts of cask cover gas, presumably due to short equilibration times between the cask and the sample bottle during the actual cask cover gas collection procedure. The end effect of small, diluted samples on the cover gas analyses is to increase detection limits, increase measurement uncertainties, and introduce questions of sample validity.

## 4.2 1985 Data

The results of the LLNL gas analyses from 1985 are presented in Table 4-1. Mass spectra were analyzed for all common fixed gases with masses less than 100. Only N2, O2, He, Ar, and CO2 concentrations above 0.01% are detected in any of the samples. Analyses of the other species reported are of marginal reliability. Water is reported as a lower limit due to absorption on vessel walls. The accuracy of the mass spectra measurements is noted in Table 4-1. It is obvious that significant amounts of air were introduced in each gas sample. The problem was traced to leaking quick-disconnects on each sample cylinder.

**Table 4-1**

1985 CASK GAS SAMPLE COMPOSITION
(Volume Percent)

| LLNL Sample No. | Sample Run No. | He | $N_2$ | $O_2$ | A | CO2 | CO | $H_2O$ | $N_2O$ | $H_2$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1C | 89.05 | 6.021 | 1.350 | 3.496 | 0.050 | <0.1 | >0.01 | <0.01 | <0.01 |
| 2 | 1A | 69.30 | 21.90 | 5.967 | 2.798 | 0.029 | <0.01 | >0.01 | <0.01 | <0.01 |
| 3 | 1B | 62.51 | 25.57 | 6.692 | 5.148 | 0.033 | <0.1 | >0.01 | <0.01 | <0.01 |
| 4 | 1D | 59.59 | 17.59 | 4.110 | 18.66 | 0.048 | <0.01 | >0.01 | <0.01 | <0.01 |
| 5 | 2A | <0.01 | 95.34 | 1.180 | 3.457 | 0.017 | <0.01 | >0.01 | <0.01 | <0.01 |
| 6 | 2B | <0.01 | 90.58 | 6.81 | 2.581 | 0.024 | <0.01 | >0.03 | <0.01 | <0.01 |
| 7 | 2C | 0.031 | 68.79 | 3.134 | 27.95 | 0.059 | <0.01 | >0.02 | 0.019 | <0.01 |
| 8 | 2D | 0.042 | 70.08 | 8.43 | 21.29 | 0.153 | <0.01 | >0.01 | <0.01 | <0.01 |
| 9 | 4B | 70.59 | 14.23 | 5.95 | 9.09 | 0.060 | <0.1 | >0.05 | <0.01 | 0.018 |
| 10 | 4A | 32.38 | 50.55 | 13.31 | 3.700 | 0.053 | <0.01 | >0.02 | <0.01 | <0.01 |
| 11 | 4C | 65.69 | 1.560 | 0.156 | 32.58 | <0.01 | <0.01 | >0.01 | <0.01 | <0.01 |
| 12 | 4D | <0.01 | 76.94 | 20.26 | 2.746 | 0.054 | <0.01 | >0.01 | <0.01 | <0.01 |
| 13 | 5A | 0.050 | 74.92 | 11.441 | 13.43 | 0.120 | <0.01 | >0.02 | 0.015 | 0.016 |
| 14 | 5B | <0.01 | 73.95 | 18.77 | 7.217 | 0.060 | <0.01 | >0.02 | <0.01 | <0.01 |
| 15 | 5C | 0.048 | 85.63 | 5.559 | 8.533 | 0.065 | <0.01 | >0.01 | <0.01 | 0.159 |
| 16 | 5D | 0.068 | 91.06 | 0.158 | 8.462 | 0.044 | <0.01 | >0.01 | <0.01 | 0.207 |

[a] Species present in mass spectra at 0.01% or more. Accuracy of these measurements is ±0.2% of 1 unit in the least significant digit.

It was generally expected that the screening analysis would agree with the processed $^{85}$Kr result. However, for these samples the screening counts were significantly greater than the processed krypton results. Tritium would not be detected by the screening analysis. Argon-79 and $^{14}CH_4$, the other long-lived beta emitters that might be present, were not detected during an exploratory analysis of Sample four in February 1986. Similarly, no $^{127}$Xe was found in xenon separated from the sample.

Because screening was done in November 1985 and processing in February 1986 (for Sample four), the possibility of sample contamination with short-lived fission xenon or possibly other activities accompanying the air leakage cannot be ruled out. To recheck the screening analysis, this measurement was repeated in February. Unfortunately, the sample was severely diluted with air. The results at that time were below the detection limit as defined, but were above background and consistent with the previous measurement. The analysis indicated the presence of a long-lived beta-emitting gas, which is not Ar, Kr, Xe, $^{14}C$, or T, in the cover gas. The consistency between sample pairs is generally good and strongly suggests that the measured activity is associated with the cask gases. The disparity between screening and processed concentrations remains unexplained. However, the relatively low amounts or $^{85}Kr$ detected indicate that no leaking fuel rods were present in the cask during performance testing. This is particularly significant because the first few assemblies loaded in the cask were exposed to air for approximately 200 h during incremental loading of the cask and fuel assembly/basket inspections at a reduced temperature.

## 4.3 1999 Data

Table 4-2. presents results of the mass spectrometric analyses of Castor V-21 cask gas samples taken in July 1999 and analyzed on August 31, 1999. Radiochemical analyses were performed on approximately 10 std-cc of gas from each bomb. On addition to the analyzes shown in the table, the analytical procedure followed also checked for the presence of Ne, Kr and Xe; measurable quantities were not detected. A separate scan for organic species was also run on each sample, none were detected.

**Table 4-2. 1999 Results of Gas Analyses (in mole percent)**

| | H2 | He | a | O2 | Ar | CO2 | 85Kr |
|---|---|---|---|---|---|---|---|
| V-21 #1<br>1110 | ND | 98.45 | 1.38 | 0.08 | 0.01 | 0.08 | ND |
| V-21 #2<br>1125 | ND | 98.82 | 1.08 | <0.01 | 0.01 | 0.08 | ND |

## 4.4 Conclusion on gas survey

It appears that no major leakage of air into the cask occurred between 1985 and 1999. It also appears that none of the fuel rods in the stored assemblies have leaked over the same time period.

# 5 CONCLUSION

A series of examinations in 1999 and early 2000 to investigate the integrity of the Castor V/21 cask were undertaken. The examinations reported in this interim report include:

- Radiation survey of the cask surface and at 1 and 2 meters with comparison to the 1985 radiation survey;
- Gas analysis of the internal atmosphere to check for the presence of air ingress into the container past the lid seal and for the presence of fission gases that would suggest cladding failure;
- Integrity of the concrete pad upon which the Castor V/21 has rested since 1985;
- Integrity of the inner and outer O-rings on the lid for signs of corrosion or wear;
- Assembly lifting force measurements to see if there is any resistance to pulling the assemblies back out of the cask basket channels due to corrosion or excessive rod bowing;
- Visual inspection of the outside of each assembly for indications of additional corrosion, crud spallation or other damage; and
- Visual inspection of the cask basket welds and internals for indications of additional corrosion or degradation.

There is no evidence of significant degradation of the Castor V/21 cask systems important to safety from the time of initial loading of the cask in 1985 up to the time of testing in 1999. Supporting evidence for this lack of significant degradation are summarized as follows:

- The 1999 radiation survey suggests that doses are generally lower than in 1985 – as would be expected. Doses are now well below the 200 mrem/hr contact limit. Due to potential errors or uncertainties in some of the 1985 and 1999 measurements, trends in doses between 1985 and 1999 are not always easy to determine, however. Nevertheless, the dose trend is down suggesting that radiation shielding materials in the cask – both gamma and neutron – are maintaining their function.
- Gas analyses show neither signs of air ingress into the container nor signs of cladding failure leading to fission product release. Visual examination of the cask lid O-rings suggest they were, indeed, in adequate condition to maintain a seal.
- There was no evidence of major crud spallation from the fuel rod surfaces.
- The concrete pad did not show any sign of failure. Strength measurements did not show any evidence of strength loss. Only small cracks typical of a normal, small amount of shrinkage were noticed. Concrete conditions immediately below the cask were similar to that of other areas.
- All materials inside the cask – including the assemblies themselves – appeared the same as they did in 1985.

Subsequent testing forming part of the continuing Dry Cask Storage Characterization Project will include non destructive and destructive examination of the cladding from assembly T-11. This work will be reported in a later interim or final report.

APPENDIX A

## DOSIMETER RADIATION MEASUREMENTS FROM CASTOR V/21 CASK PERFORMANCE TEST

| | LOCATION | | | Dose rates at contact 1985 | | Dose rate at contact 1999 | | Rate | |
|---|---|---|---|---|---|---|---|---|---|
| | Angle, {a} | Elevation {b} | Exposure | TLD Dose Rate | TED Dose Rate | Real time | Real Time Neutron | 1999/1985 | |
| | | or radius {c} | Time | Gamma | Neutron | Gamma | Neutron | | |
| | Degrees | mm | hr | mrem/hr | mrem equivalent/hr | mR/hr | mrem equivalent/ hr | % | % |
| **SIDE** | **45** | 175 | 41.77 | 23 | 2.1 | 2.7 | 1.296 | 11.74 | 61.71 |
| | | 480 | 41.77 | 140 | 21 {f} | 8 | 1.668 | 5.71 | 7.94 |
| | | 1048 | 41.73 | 36 | 9.7 | 2 | 4.212 | 5.56 | 43.42 |
| | | 1597 | 41.73 | 38 | 11.5 | 2 | 5.25 | 5.26 | 45.65 |
| | | 2149 | 41.73 | 38 | 12 | 2 | 4.998 | 5.26 | 41.65 |
| | | 2701 | 41.73 | 37 | 10.6 | 2 | 5.574 | 5.41 | 52.58 |
| | | 3298 | 41.73 | 39 | 10.3 | 2 | 4.23 | 5.13 | 41.07 |
| | | 3850 | 41.72 | 28 | 7 | 2 | 5.412 | 7.14 | 77.31 |
| | | 4350 | 41.72 | 22 | 5.3 | 3 | 6 | 13.64 | 113.21 |
| | | 4400 | 41.72 | 118 | 15 | 4 | 9.12 | 3.39 | 60.80 |
| | | 4450 | 41.7 | 68 | 9.7 | 4 | 8.82 | 5.88 | 90.93 |
| | | 4500 | 41.7 | 26 | 7.3 | 5 | 7.98 | 19.23 | 109.32 |
| | | 4550 | 41.7 | 9.4 | 5.6 | 4 | 10.2 | 42.55 | 182.14 |
| | | 4600 | 41.7 | 4.3 | 3.8 | 14 | 13.5 | 325.58 | 355.26 |
| | | 4650 | 41.7 | 2.5 | 3.8 | 6 | 11.34 | 240.00 | 298.42 |
| | | 4700 | 41.65 | 1.6 | 2.1 | 3 | 8.94 | 187.50 | 425.71 |
| | | 4750 | 41.63 | 1.1 | 2.6 | 2 | 7.98 | 181.82 | 306.92 |
| | | 4800 | 41.63 | 0.7 | 1.5 | 1 | 6.54 | 142.86 | 436.00 |
| | **60** | 2701 | 41.62 | 31 | 13 | 2 | 5.646 | 6.45 | 43.43 |
| | **75** | 2701 | 41.62 | 23 | 11 | 2 | 5.178 | 8.70 | 47.07 |
| | **90** | 175 | 41.5 | 26 | 1.5 | 5 | 1.03 | 19.23 | 68.67 |
| | | 480 | 41.5 | 125 | 3.5 | 10 | 1.85 | 8.00 | 52.86 |
| | | 1048 | 41.48 | 25 | 8.7 | 4 | 4.65 | 16.00 | 53.45 |
| | | 1597 | 41.48 | 21 | 15 | 3 | 5.64 | 14.29 | 37.60 |
| | | 2149 | 41.45 | 21 | 12 | 1.7 | 5.94 | 8.10 | 49.50 |
| | | 2701 | 41.43 | 24 | 16 | 1.7 | 5.64 | 7.08 | 35.25 |
| | | 3298 | 41.43 | 22 | 13 | 1.7 | 5.34 | 7.73 | 41.08 |
| | | 3850 | 41.43 | 70 | 9.8 | 7 | 7.98 | 10.00 | 81.43 |
| | | 4350 | 41.42 | 79 | 11.5 | 20 | 12.24 | 25.32 | 106.43 |
| | | 4400 | 41.4 | 134 | 13 | 10 | 11.52 | 7.46 | 88.62 |
| | | 4450 | 41.38 | 81 | 10 | 4.3 | 9.06 | 5.31 | 90.60 |
| | | 4500 | 41.38 | 33 | 4.7 | 2.5 | 8.46 | 7.58 | 180.00 |
| | | 4550 | 41.37 | 12 | 6.9 | 1.7 | 7.32 | 14.17 | 106.09 |
| | | 4600 | 41.35 | 5 | 3.5 | 0.8 | 6.64 | 16.00 | 189.71 |

| | LOCATION | | | Dose rates at contact 1985 | | Dose rate at contact 1999 | | Rate 1999/1985 | |
|---|---|---|---|---|---|---|---|---|---|
| | Angle, {a} | Elevation {b} | Exposure | TLD Dose Rate | TED Dose Rate | Real time | Real Time Neutron | | |
| | | or radius {c} | Time | Gamma | Neutron | Gamma | Neutron | | |
| | Degrees | mm | hr | mrem/hr | mrem equivalent/hr | mrem/hr | mrem equivalent/ hr | % | % |
| **SIDE** | **90** | 4650 | 41.33 | 3.1 | 8.8 | 0.7 | 4.19 | 22.58 | 47.61 |
| | | 4700 | 41.32 | 1.9 | 3.8 | 0.4 | 2.92 | 21.05 | 76.84 |
| | | 4750 | 41.32 | 1.3 | 0.9 | 0.3 | 2.13 | 23.08 | 236.67 |
| | | 4800 | 41.32 | 1.2 | 0.7 | 0.3 | 2.24 | 25.00 | 320.00 |
| | **105** | 2701 | 41.33 | 24 | 14 | 1.4 | 6.3 | 5.83 | 45.00 |
| | **120** | 2701 | 41.3 | 31 | 9.3 | 1.4 | 5.62 | 4.52 | 60.43 |
| | **72,73** | 2149 | 21.23 | 23 | 15 | | | | |
| | **73,74** | 2149 | 21.23 | 24 | 17 | | | | |
| | **74,75** | 2149 | 21.23 | 23 | 14 | | | | |
| | **75,76** | 2149 | 21.23 | 22 | 11 | | | | |
| | **76,77** | 2149 | 21.23 | 25 | 13 | | | | |
| | **77,78** | 2149 | 21.23 | 24 | 7 | | | | |
| | **Trunnion, 90** | -- | 17.5 | 19 | 8.1 | | | | |
| | **Trunnion, 90** | -- | 17.48 | 42 | 27 | | | | |
| **TOP** | | | | | | | | | |
| | **45** | 203 | 41.3 | 32.5 | 44 | 10 | 31.62 | 30.77 | 71.86 |
| | | 406 | 41.28 | 43 | 35 | 14 | 27.6 | 32.56 | 78.86 |
| | | 585 | 41.2 | 26 | 32 | 4.6 | 23.64 | 17.69 | 73.88 |
| | | 928 | 41.2 | 6.4 | 5.1 | 1.4 | 9.96 | 21.88 | 195.29 |
| | | 1100 | 41.18 | 1 | 1.3 | 0.2 | 3.28 | 20.00 | 252.31 |
| | **90** | 170 | 41.18 | 30 | 44 | 6 | 34.8 | 20.00 | 79.09 |
| | | 340 | 41.17 | 36 | 36 | 6 | 28.38 | 16.67 | 78.83 |
| | | 487 | 41.15 | 29.5 | 32 | 4.8 | 36.32 | 16.27 | 113.50 |
| | | 634 | 41.12 | 29 | 27 | 4.5 | 19.68 | 15.52 | 72.89 |
| | | 706 | 41.05 | 22 | 19 | 3.6 | 12.28 | 16.36 | 64.63 |
| | | 780 | 41.07 | 56 | 16 | 2.8 | 14.76 | 5.00 | 92.25 |
| | | 854 | 41.07 | 9.2 | 2.3 | 3.8 | 13.4 | 41.30 | 582.61 |
| | | 928 | 41.07 | 2.5 | 3.1 {f} | 1.1 | 11.52 | 44.00 | 371.61 |
| | | 985 | 41.05 | 3.1 | 0.2 | 1.1 | 10.2 | 35.48 | 5100.00 |
| | | 1042 | 41.03 | 1.6 | 0.7 | 0.5 | 6.48 | 31.25 | 925.71 |
| | | 1100 | 40.95 | 1 | 1.4 | 0.3 | 2.98 | 30.00 | 212.86 |
| | | 0 | 40.95 | 40 | 44 | 18 | 35.34 | 45.00 | 80.32 |
| | **Fill valve** | -- | 17.57 | 196 | 30 | | | | |
| | **Hole at 180** | -- | 17.52 | 32 | 13 | | | | |

| LOCATION | | | Dose rates at contact 1985 | | Dose rate at contact 1999 | | Rate | |
|---|---|---|---|---|---|---|---|---|
| Angle, {a} | Elevation {b} | Exposure | TLD Dose Rate | TED Dose Rate | Real time | Real Time Neutron | 1999/1985 | |
| | or radius {c} | Time | Gamma | Neutron | Gamma | Neutron | | |
| Degrees | mm | hr | mrem/hr | mrem equivalent/hr | Mrem/hr | mrem equivalent/ hr | % | % |
| **BOTTOM** | | | | | | | | |
| **90** | 0 | 23.53 | 22 | 41 | 4.5 | 40 | 20.45 | 97.56 |
| | 170 | 23.42 | 18 | 31 | 4.6 | 39.66 | 25.56 | 127.94 |
| | 340 | 23.4 | 24 | 25 | 5 | 37.2 | 20.83 | 148.80 |
| | 487 | 23.4 | 22 | 23 | 5 | 31.62 | 22.73 | 137.48 |
| | 634 | 23.38 | 20 | 21 | 4.4 | 25.8 | 22.00 | 122.86 |
| | 928 | 23.3 | 26 | 5 | 2.6 | 13.8 | 10.00 | 276.00 |
| | 1100 | 23.3 | 7 | 1.6 | 2.2 | 8.4 | 31.43 | 525.00 |
| **45** | 203 | 23.53 | 17.5 | 33 | 4.4 | 37.8 | 25.14 | 114.55 |
| | 406 | 23.48 | 25 | 22 | 4.5 | 31.8 | 18.00 | 144.55 |
| | 585 | 23.45 | 25 | 19 | 4.6 | 27.6 | 18.40 | 145.26 |
| | 928 | 23.42 | 18 | 3.1 | 2.2 | 12.6 | 12.22 | 406.45 |
| | 1100 | 23.4 | 3.4 | -- | 1.8 | 7.5 | 52.94 | #VALUE |

| |
|---|
| {a} from 0 orientation mark |
| {b} from exterior bottom of cask |
| {c} from cask centerline |
| {f} problem with processing dosimeter |

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