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DEMONSTRATION FUEL ELEMENT SHIPPING CASK
FROM LAMINATED URANIUM METAL-TESTING PROGRAM

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ABSTRACT

This paper covers the highlights of the Paducah Gaseous Diffusion Plant nondestructive and destructive testing programs performed on the "Demonstration Fuel Element Shipping Cask from Laminated Uranium Metal."

The demonstration cask was instrumented with electrical accelerometers and strain gauges, mechanical accelerometers, mechanical compressometers, and thermocouples during various phases of the testing program to determine the ability of the cask to withstand normal transportation and hypothetical accident conditions. Existing penetrations were used for instrumenting the cask to avoid violating the integrity of the cask by installing special instrument penetrations through the cask walls. Limited quantitative data was obtained during each phase of the testing program, and motion-picture and still photography were used to document the tests. Extensive physical measurements, cladding pressure tests, and dye penetrant weld tests were made throughout the testing program to determine the extent of the cask damage.

The cask damage resulting from the nondestructive and hypothetical accident testing programs was of a superficial nature, and it was limited to the deformation of fins and other sacrificial members near the points of impact. There was no leakage of liquid to the outside of the cask during any hypothetical accident test, and all of the dimensional changes were small except for those in the impact areas. No dimensional change experienced during the testing program would prevent the cask from being used for shipping spent fuel elements safely. The cask successfully met the applicable

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AEC Chapter 0529, 10 CFR 71, and IAEA Safety Series 6 transportation and hypothetical accident series for shipping radioactive materials. This project has proven the technical feasibility of using laminated uranium metal for structural and shielding materials in large radioactive material shipping casks.

INTRODUCTION

The cask was subjected to an extensive series of nondestructive and destructive tests following fabrication by using experimentally verified procedures and instrument systems developed during the testing of the quarter scale model of the demonstration cask. The design, fabrication, and testing phases of the quarter scale model program were reported by Clifford¹ in June, 1968.

The demonstration fuel element cask testing program was designed to meet the following objectives:

- a. Demonstrate the ability of the cask to pass the normal transit and hypothetical accident series as outlined in applicable regulations in AEC Chapter 0529, 10 CFR 71, and IAEA Safety Series 6.
- b. Demonstrate the adequacy of the cask design criteria, developed through engineering studies and the quarter scale model testing program, for producing large fuel element shipping casks.
- c. Provide limited amounts of engineering data for the design, evaluation, and fabrication of full size stainless steel clad uranium metal fuel element shipping casks.
- d. Provide information for studies underway at ORNL to evaluate cask designs and predict the integrity of casks.

NONDESTRUCTIVE TESTING PROGRAM

Introduction

The nondestructive testing program consisted of a heat transfer test, a thermal shock test, a low temperature exposure test, a normal transit test, and a radiation attenuation test. This test series was made according to the above sequence except for the radiation attenuation test which was made after the destructive testing program was completed.

Heat Dissipation Test

A heat dissipation test was conducted on the demonstration cask to establish the ability of a full size cask of this type to dissipate the heat load generated by four Indian Point spent fuel elements without exceeding the cask design specifications.

The cask was equipped with an electrical heater, 62 chromel-alumel thermocouples, a 7-inch thick heat insulation lid, and the necessary electrical controls and instrumentation. Figure 1 shows a photograph of the test assembly.

A 43,500 BTU/hour electrical heat load was generated inside the dry cavity while the cask was in the horizontal position and exposed to an ambient temperature of 86°F. The test heat load was based on a decay heat load of 8,000 BTU/hour per foot of cavity length plus the appropriate solar heat load. The 8,000 BTU/hour heat load is over twice the heat load expected from shipping four spent Indian Point core A fuel elements in a full size cask of this type.

Calculations have shown that the cask would meet the design pressure and temperature specifications if it were tested under 130°F ambient temperature conditions, in sunlight, with the expected decay heat load generated inside the cavity.

The equilibrium heat transfer data is presented in figure 2, and the cask design specifications are as follows:

① INSIDE BOTTOM

② BOTTOM WALL SECTION

③ MIDDLE WALL SECTION

④ TOP WALL SECTION

⑤ BOTTOM OF LID

⑥ TOP OF LID

OUTSIDE
BOTTOM

DATE	AMPS	VOLTS	AMB. TEMP.	BTU / HR
2/25/68	16.7	458	86	43,500

OUTSIDE BOTTOM											
1	2	3	4	5	6	7	8	9	10	11	12
215	209	210	213	213	207	205	211	210	209	217	221

TOP OF LID							
13	14	15	16	17	18	19	
131	127	125	125	123	122	349	

BOLT FLANGE		
20	21	22
224	224	215

TOP RING
23
140

TOP O.D.
24
236

BOTTOM OF LID					
25	26	27	28	29	30
1000	1000	1000	985	927	795

INSIDE BOTTOM		
31	32	33
331	308	200

INSIDE WALL								
BOTTOM			MIDDLE			TOP		
34	35	36	37	38	39	40	41	42
336	320	312	423	410	402	413	378	391

OUTSIDE WALL									
BOTTOM			MIDDLE			TOP			
43	44	45	46	47	48	49	50	51	
248	223	225	307	273	275	278	250	249	

FIN EDGE									
BOTTOM			MIDDLE			TOP			
52	53	54	55	56	57	58	59	60	
206	158	158	252	182	185	238	178	171	

HTR. WALL	
61	62
957	947

TEMPERATURE DATA IN °F

Internal temperature	375°F
Fin temperature	250°F
Maximum pressure	250 psig
Operating pressure	170 psig
Minimum ambient temperature	-40°F
Maximum ambient temperature	130°F

Thermal Shock Test

A thermal shock test was conducted on the demonstration cask to determine the ability of the cask to withstand immersion in cold water when the cask was near its normal operating temperature.

The cask was submerged in a 25,000 gallon tank of water immediately following the cask heat dissipation test. Figure 3 shows the cask being immersed in the cooling water. The average inside cladding temperature was 310°F when the test was started. The water temperature near the cask was 45°F at the start of the test and 48°F at the time the test was terminated. The cask was immersed at 0.35 feet per second, and the average internal cask temperature decreased at a rate of 2.2°F per minute until the test was terminated when the average internal cask temperature reached 100°F.

The following standard inspection tests were made on the cask, after each phase of the nondestructive and destructive testing program, to determine the extent of the cask damage:

- a. The cask cladding was soap tested by pressuring the cladding volume to 5 psig with helium, and all accessible cladding welds were tested with dye penetrant.
- b. The cask cavity was hydrostatically tested at 375 psig.
- c. Precision measurements were made on the cask.

The standard inspection tests, made after the heat dissipation and thermal shock tests, showed no cladding failures or dimensional changes which could affect the performance of the cask.

Low Temperature Exposure Test

A low temperature exposure test was conducted on the demonstration cask to establish the ability of the cask to withstand a -40°F environment without sustaining structural failures.

A 4.5-foot diameter by 8-foot high open top steel tank was insulated with polyurethane foam and mounted on a 6-inch thick wooden pallet. Copper-constantan thermocouples were installed on the inside and outside walls of the cask and on the inside of the tank to measure the test temperatures.

The cask was placed in the tank and the tank was filled to near the top of the cask with a 45% methanol-water solution containing dry ice. The cask was cooled until all of the test temperatures were below -40°F . The cask cavity was hydrostatically tested at a pressure of 375 psig by using -45°F methanol solution for the test fluid without a leak developing in the cask. The average temperature of the cask was below -40°F for six hours prior to the time that the hydrostatic test was conducted. Figure 4 shows the demonstration cask being removed from the low temperature exposure bath.

The standard inspection tests, made after the low temperature exposure test, showed no cladding failures or dimensional changes which could affect the performance of the cask.

Normal Transit Test

The demonstration cask was shipped from Paducah, Kentucky, to Oak Ridge, Tennessee, by railcar and returned to Paducah by a truck trailer shipment to demonstrate the ability of the cask and tie-down systems to withstand normal transit conditions and a series of severe railroad switching operations. Electrical accelerometer, cavity pressure, skid load cell, and tie-down strain gauge data were obtained during the shipments through the cooperation of the Environmental Data Analysis Group of the Sandia Corporation at Albuquerque, New Mexico. Figures 5 and 6 show photographs of the rail and truck shipments.

A 2500-pound simulated fuel element assembly was installed inside the cask to represent the weight of four full-length Indian Point core A fuel elements securely positioned against the cask lid. The cavity-free volume was filled to 90% with a water soluble fluorescent leak detection oil and pressurized to 200 psig with nitrogen. The railcar and truck trailer were modified to accommodate horizontal cask tie-down systems designed to meet applicable regulations for shipping radioactive materials, although no material of this type was shipped during the tests.

A large quantity of analytical data was obtained by Sandia personnel during both shipments to define the cask environmental and tie-down strain conditions. A preliminary analysis of this data has shown that the maximum steady state rail and truck acceleration rates were as shown in table 1.

Table 1. Normal Transit Test
Maximum Acceleration Rates

Operation and Instrument Location	Acceleration Rates (g)		
	Longitudinal	Transverse	Vertical
Railcar switching - tie-down pedestal	5.75	4.50	6.00
Railcar switching - shipping skid	4.70	2.30	4.50
Railcar at 50 mph - shipping skid	0.75	0.75	0.75
Railcar run-in, run-out at 40 mph - near coupling	4.50	2.00	2.00
Railcar run-in, run-out at 40 mph - shipping skid	2.00	1.00	1.00
Truck on concrete road at 50 mph - tie-down pedestal	< 1.00	< 1.00	1.50
Truck into dip and railroad tracks at 40 mph - tie-down pedestal	< 1.00	< 1.00	3.00

The maximum longitudinal loading conditions for the tie-down bars between the railcar anchor studs and the ends of the shipping skid were as follows:

Railcar switching operations	8000 lbs.
Railcar running at 50 mph	3000 lbs.
Railcar run-in, run-out impact conditions	3000 lbs.

The nitrogen pressure was monitored throughout both trips, and no indications of a cavity leak developed. The tie-down systems performed as designed, and no damage was sustained by the cask or tie-down systems when the railcar was switched under heavy impact loading conditions.

The standard inspection tests, made after the normal transit tests, showed no cladding failures or dimensional changes which could affect the performance of the cask.

DESTRUCTIVE TESTING PROGRAM

Introduction

The destructive testing program consisted of a 30-foot free fall drop test, a 40-inch free fall drop puncture test, and a thermal exposure test. This test series was made according to the above sequence, and it was followed by a radiation attenuation test.

30-Foot Free Fall Closure Edge Drop Test

The demonstration cask, containing a simulated fuel element with a mass equivalent to the weight of four full-length Indian Point core A fuel elements, was drop tested on its closure edge on an essentially immovable surface to demonstrate the ability of the cask to withstand physical damage and prevent radioactive material from escaping to the outside of the cask. Limited amounts of quantitative data were obtained to measure the cask and fuel assembly impact loading conditions and to determine stresses generated in critical cladding areas near the point of impact.

The cask was equipped with two electrical accelerometers and seventeen strain gauge assemblies, as shown in figure 7, and a mechanical accelerometer was mounted on the bottom outside surface of the cask. Two mechanical accelerometers were also mounted on the impact end of the

Accelerometer #1

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NOTES

- Four longitudinal lid stud strain gauges spaced equally from the point of impact
- Six 60° static strain gauge rosettes spaced evenly around the outside stainless
- Six 60° static strain gauge rosettes spaced evenly around the inside stainless steel cladding
- ▲ 60° dynamic strain gauge rosettes

simulated fuel element assembly, and the assembly was positioned securely against the cask lid through a spring loading device. The cavity was filled to 90% with a water soluble fluorescent leak detection oil and pressurized to 200 psig with nitrogen.

The cask was rigged to drop at an angle of $18^{\circ}45'$ from the vertical to place the center of gravity of the cask directly over the point of impact. The cask and simulated fuel element weighed 28,190 pounds which gave a drop test pad-to-cask weight ratio of 10.7 to 1. Normal and high speed motion picture photography was used to document all phases of the drop test. Figure 8 shows a photograph of the drop test area and figure 9 shows a view of the cask closure end damage.

The instrument data obtained during the test showed the following maximum deceleration values:

Bottom of lid (electrical accelerometer)	468g
Bottom of cask (electrical accelerometer)	215g
Bottom of cask (mechanical accelerometer)	230g
Simulated fuel element (mechanical accelerometers)	<200g

The cask was on the drop test pad for 20 milliseconds before it rebounded approximately nine inches, and it was off the pad 120 milliseconds before pad contact was re-established. Stress values in excess of the cladding yield point were indicated for localized cladding areas on the inside and outside of the cask, but in no case was there an indication of a cladding failure. The maximum stresses calculated for the lid bolts indicated that none of the bolts were stressed to two-thirds of their yield point.

The 250 psig cavity rupture disk was blown to a pressure relief volume designed to prevent the fluorescent oil from escaping to the outside of the cask. This relief system allowed precise measurements to be made on the amount of oil which leaked across the lid gasket after the time of impact.

The generation of high pressure hydraulic systems in a shipping cask, under impact loading conditions, is obviously not restricted to

uranium shielded casks. Accordingly, the design and testing of an optimum pressure relief system never was intended to be within the scope of this project.

An ultraviolet light inspection of the lid, cask surfaces, drop test pad, and the absorbent paper between the lid and cavity wall showed that 0.1 to 0.2 milliliters of fluorescent oil leaked across the lid seal, but none of the oil reached the outside surfaces of the cask. This type of inspection can detect the presence of 0.1 milliliter of the oil used. The cask cavity contained approximately 108 liters of oil.

The cask cavity pressure was 165 psig five hours after the drop test was completed; however, there was no additional pressure drop during the next twenty-four hours. The pressure drop was probably due to nitrogen absorbed into the fluorescent oil in the cask cavity. Tests have confirmed that the oil will absorb approximately the same amount of nitrogen that was lost during the drop test operation.

The damaged impact fins were removed from the cask with an air blast cutting torch, and it was necessary to remove all of the undamaged lid studs and free two jammed studs before the lid could be removed without difficulty. The jammed studs were freed by scarfing away a small amount of the lid flange around each of the jammed studs. The steps required to remove the lid could have been performed safely if the cask had contained a spent fuel element assembly.

An inspection of the cask showed that the impact damage was isolated to approximately half of the closure end impact fins and to a small section of the stud flange that the fins were welded to. Seven of the lid studs, near the point of impact, were finger tight after the test due to the deformation of the stud flange. The remainder of the lid bolts were still torqued to 50 to 480 foot-pounds. The original lid bolt torque was 500 foot-pounds.

The standard inspection tests, made after the 30-foot free fall test, showed no cladding failures or dimensional changes which could affect the performance of the cask. The precision measurements made on the cask

showed that the maximum change in cavity diameter was located near the top of the cavity. This dimensional change was -0.053 inches.

The results of the 30-foot drop test demonstrated the ability of the cask to pass the hypothetical accident free fall test specifications in the applicable regulations.

40-Inch Free Fall Puncture Test

The demonstration cask was drop tested from a height of forty inches onto an essentially immovable 6-inch diameter by 8-inch high mild steel piston to demonstrate the ability of the cask to withstand physical damage and prevent the release of radioactive material to the outside of the cask. Limited amounts of quantitative data were obtained at the time of impact to measure the cask deceleration, cladding stresses, and vertical diameter profile along the length of the cavity.

The cask was equipped with an electrical accelerometer, two electrical strain gauges, and nine mechanical compressometers as shown in figure 10. The cavity was filled to 90% with a water soluble fluorescent oil and pressurized to 200 psig with nitrogen.

The cask was dropped in the horizontal position with its center of gravity directly over the drop test piston. The cask weighed 25,480 pounds which gave a drop test pad-to-cask weight ratio of 11.9 to 1.

Normal and high speed color motion picture photography was used to document all phases of the drop test. Figure 11 shows a photograph of the drop test area, figure 12 shows a photograph of the cask on the drop test piston, and figure 13 shows a view of the heat transfer fin damage produced by the piston.

The accelerometer mounted directly above the point of impact showed a maximum deceleration of 78 g, and the calculated stress values at the strain gauge locations were below the yield point for the cladding material. The cask was on the drop test piston 42 milliseconds before it rebounded approximately five inches, and it was off the pad for 221 milliseconds before piston contact was re-established. The mechanical compressometers indicated that the maximum nonpermanent change in a

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NOTE:

▲ 60° Dynamic Strain Gauge Rosettes

40 INCH FREE FALL
PISTON PUNCTURE TEST

cavity diameter was -0.47 inches and that this change took place above the point of impact. The cavity diameter profile, measured by the compressometers, changed from -0.25 inches near the top of the cavity through the maximum diameter deflection to a -0.025 inch change near the bottom of the cavity.

The 200 psig cavity pressure decreased to 182 psig within twenty-four hours after the cask was pressurized. Therefore, the cavity was repressurized to 200 psig immediately before the drop test was made. The cask pressure was 190 psig after the test was completed. There were no signs of a lid gasket leak, and the pressure loss was probably due to nitrogen absorbed into the fluorescent oil used in the cask cavity.

An ultraviolet light inspection of the lid, cask surfaces, drop test pad, and the absorbent paper between the lid and the cavity wall showed that there was no loss of fluorescent oil from the cask cavity during the drop test. The 250 psig cavity rupture disk was blown to a pressure relief volume designed to prevent the fluorescent oil from escaping to the outside of the cask.

There was no loosening of the lid studs or other indications of unsatisfactory cask performance during this test, and no difficulties were encountered in removing the lid from the cask.

The standard cask tests, made after the 40-inch free fall test, showed no cladding failures or dimensional changes which could affect the performance of the cask. The precision measurements made on the cask showed that the maximum permanent change in a cavity diameter was located near the point of impact. This change in diameter was -0.095 inches.

The results of this test demonstrated the ability of the cask to pass the hypothetical accident puncture test conditions specified in applicable regulations.

Thermal Exposure Test

The demonstration cask was fire tested for forty-five minutes with a dry cavity in a 20-foot square by 2-foot deep fire pit to demonstrate

the ability of the cask to withstand the effects of a 1475°F thermal exposure test as defined in the applicable regulations.

The cask was instrumented with 10 internal cladding, 18 external cladding, and 18 flame chromel-alumel thermocouples. The locations of the cask and fire zone thermocouples are shown in figures 14 and 15, respectively. The fire test temperatures were recorded on two high-speed recorders which were calibrated to print a temperature point every 1.5 seconds. The thermocouples were mounted on the cask and in the fire zone as shown in figures 16 and 17, respectively. The temperature recording system was paralleled with a secondary temperature indicator capable of reading all the test temperatures and a standby motor generator set capable of furnishing the test power requirements in the event of a power failure.

The cask was placed in a horizontal position in the fire pit by supporting its ends on reinforced cast refractory pedestals. The longitudinal center line of the cask was located 30 inches above the initial fuel level in the pit, and 2500 gallons of kerosene were burned during the test. A 6.5 to 8.5-foot fire wall was maintained around the cask during this test, and three 8 by 15-foot sheet metal wind deflectors were used to control the flame temperatures around the cask. An analysis of the fire test data showed that the following temperature conditions existed for over 30 consecutive minutes during the test:

Average fire temperature at center line of cask	1500°F
Average fire temperature at top of cask	1536°F
Average fire temperature 15 inches above cask	1400°F
Maximum outside cladding temperature	1520°F

Figures 18 and 19 show photographs of the test area before and during the fire test, respectively. Figure 20 shows a photograph of the test area after completion of the fire test.

The cask was allowed to cool under ambient temperature conditions for three hours before it was cooled to an average temperature of 150°F with water from a 2-1/2 inch fire hose.

NOTES:

- Four thermocouples spaced evenly around the outside stainless steel cladding.
- Four thermocouples spaced evenly around the inside stainless steel cladding. These thermocouples will be opposite thermocouples on the outside cladding.
- ▲ Single thermocouples.

NOTE

Thermocouple locations 30", 45", and 60" above initial fire pit oil level.

$\frac{3}{16}$ inch diameter magnesium oxide and stainless steel sheathed, 22 gauge chromel-alumel thermocouple mount used on the outside of the demonstration fuel element cask. The stainless steel sheath was tack welded to the cask to limit thermocouple motion, and the thermocouple wires were heliarc welded individually to the cask.

28 gauge, high temperature glass insulated thermocouple were mount for the inside of the cask. The glass insulation was stripped from the fused end of the thermocouple wire to a point near the hole through the $\frac{1}{2} \times \frac{1}{2} \times \frac{1}{16}$ stainless steel thermocouple mounting plate, and the plate was tack welded to the inside cladding of the cask to produce a pressed fit between the fused thermocouple joint and the cladding.

$\frac{3}{16}$ inch diameter magnesium oxide and stainless steel sheathed, 22 gauge chromel-alumel thermocouples were used in the fire zone by heliarc welding the stainless steel sheath and the thermocouple wires to 2" X 2" X $\frac{1}{4}$ stainless steel coupons.

The standard inspection tests, made after the thermal exposure test, showed that there was no loosening of lid studs during the fire and no cladding failures or dimensional changes which could affect the performance of the cask. The lid gaskets were inspected for fire damage, but no significant fire damage was found. The fire damage to the fluoro-elastomer ring gasket was of a minor nature and less severe than expected.

The results of the demonstration cask fire testing program demonstrated the ability of the cask to withstand the hypothetical accident thermal exposure conditions specified in the applicable regulations.

Attempts to measure internal cladding temperatures were not successful due to the incorrect temperature measurements obtained from the cavity thermocouples. The type of thermocouple used inside the cask was pretested satisfactorily at 2000°F, but it failed to perform properly during the fire test. This failure was probably caused by the thermocouple wire conduit bending in the fire zone and causing the wires to short out.

RADIATION ATTENUATION TEST

Although the radiation attenuation test is a part of the nondestructive testing program, it was conducted after the completion of the destructive testing sequence. A 90,000 curie ^{60}Co source was used in this test which was designed to demonstrate the ability of this type of cask to transport four Indian Point core A spent fuel elements without exceeding applicable regulations for the safe transport of radioactive materials.

The test was performed in the Los Alamos Scientific Laboratory CMB-14 hot cell area by loading five 0.94-inch diameter by 8.5-inch long aluminum jacketed ^{60}Co capsules equally throughout the length of the cask cavity. This method of installing the test source was selected to approximate the radiation attenuation requirements that would be required if four cavity length Indian Point core A spent fuel element

sections were loaded in the cask. Figure 21 shows a photograph of a ^{60}Co capsule being loaded into the cask in the hot cell test area.

Background radiation measurements were made on all of the accessible external surfaces of the cask and one meter from the center of the cask cavity. None of these measurements exceeded a dose rate of 1.25 mr/hr. Similar measurements were made after the test source and the lid were installed in the cask cavity. The average dose rate measured on the external cylindrical surfaces of the cask was 16.6 mr/hr, with the dose rates ranging from 9.9 to 19.3 mr/hr. The average dose rate one meter from the center of the cavity was 3.3 mr/hr, with the dose rates ranging from 1.0 to 6.7 mr/hr. The dose rate measurements made on the external surface of the lid and the bottom of the cask were 1.3 and 3.0 mr/hr, respectively. No abnormal radiation dose rates were found around the lid joint or the drain and vent line penetrations in the top and bottom sections of the cask.

The demonstration cask was designed to attenuate the radiation from four cavity length Indian Point core A spent fuel element sections to 200 mr/hr at any point on the external surface of the cask and to 10 mr/hr one meter from the center of the cask.

CONCLUSIONS

The demonstration cask testing program established the ability of the cask to pass the applicable normal transportation and hypothetical accident conditions specified in AEC Chapter 0529, 10 CFR 71, and IAEA Safety Series 6 and to provide more than the required radiation attenuation to meet the cask design criteria. The dimensional changes resulting from the destructive tests were small, and they would not impair the ability of the cask for making radioactive material shipments safely.

This program has proven the technical feasibility of using stainless steel clad laminated uranium metal structures for radiation shielding and structural members in large radioactive material shipping casks.

REFERENCE

1. C. B. Clifford, The Design, Fabrication and Testing of a Quarter Scale Model of the Demonstration Uranium Fuel Element Shipping Cask, KY-546 (June 10, 1968).