Proceedings of the 15th International Symposium on the
Packaging and Transportation of Radioactive Material
PATRAM 2007
October 21-26, 2007, Miami, Florida, USA

EARLY STRUCTURAL TESTING OF TYPE B RADIOACTIVE MATERIAL PACKAGES IN THE US TO ENVIRONMENTS BEYOND THE REGULATORY PACKAGE STRUCTURAL TEST STANDARDS

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ABSTRACT

During the 1950's to the 1970's, when many new packages were being designed for the transport of a wide variety of radioactive materials, methods to analyze the response of package structures to structural accident environments had not been well developed. During this period, test programs, on obsolete and new casks, were undertaken on behalf of the U.S. Department of Energy and the Japanese Power Reactor and Nuclear Fuel Development Corporation. At the Oak Ridge National Laboratory (ORNL), studies focused on how such packages reacted to the structural test environments specified in the Transport Regulations. At Sandia National Laboratories (SNL), studies focused primarily on tests that went beyond those required by the regulations. Two of the cask designs tested at ORNL were also tested to extreme environments at SNL, which allowed direct comparison of results for the different test environments. In addition, SNL exposed other casks to test conditions that were more extreme than were required by the regulations. Unfortunately, much of the original documentation regarding these tests and their results is no longer readily available or is degrading with time. The documentation relating to these tests and their results have been surveyed; this paper presents a summary from this survey. Where possible, the results of the regulatory tests are compared with the results of the tests to the other environments. A significantly expanded version of this paper has been published in Vol. 18, No. 3 of the international journal "*Packaging, Transport, Storage & Security of Radioactive Material*".

INTRODUCTION

During the 1950's to the 1970's, when many new packages were being designed for the transport of a wide variety of radioactive materials, methods to analyze the response of package structures to structural accident environments had not been well developed. During this period many different package designs were conceived and tested to determine how they reacted to various insults such as impacts and fires. While international regulatory test standards were promulgated as early as 1964[1], and in fact various domestic test standards had earlier been established[2], there was much to be learned (1) about how to analyze and/or test these various packages to provide assurance that they would meet the existing regulatory design, test and acceptance standards prior to their fabrication; and (2) concerning the manner in which these packages would behave in so-called "real accident environments".

Test programs, on obsolete and new casks, were undertaken on behalf of the U.S. Department of Energy (DOE) and its predecessor organizations and the Japanese Power Reactor and Nuclear Fuel Development Corporation (currently known as the Japan Atomic Energy Agency). At the Oak Ridge National Laboratory (ORNL), studies focused on how such packages reacted to structural test environments specified in the Transport Regulations. At Sandia National Laboratories (SNL), studies focused both on structural and thermal tests that went beyond those required by the regulations. This paper addresses the structural tests; a companion paper[3] addresses the thermal tests. Two cask designs tested at ORNL were also tested to extreme environments at SNL; thus allowing direct

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* Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94-AL85000.

comparison of results for the different test environments. In addition, SNL exposed other casks to test conditions that were more extreme than were required by the regulations. Un-irradiated fuel assemblies were included in some of the tests and comparisons of their response to regulatory and other test environments were made; however, prediction as to how these assemblies would have reacted had they been irradiated were not attempted.

Unfortunately, much of the original documentation regarding these tests and their results is no longer readily available or is degrading with time. The documentation relating to these tests and their results have been surveyed; this paper presents a summary from this survey. The first part of this paper describes the structural testing of three casks in accordance with regulatory standards, two of which were obsolete irradiated fuel casks, the third of which was a newly designed cask for the transport of fresh nuclear fuel. The second part of this report discusses structural testing of casks to various structural environments different from those specified in the Transport Regulations. Where possible, the results of the regulatory tests are compared with the results of the tests to the other environments.

REGULATORY STRUCTURAL TESTING

Under the sponsorship of the DOE and its predecessor organizations, a series of regulatory drop tests were performed on obsolete spent nuclear fuel (SNF) and irradiated capsule casks. The results of the testing of two of these casks are briefly summarized here.

9 m Regulatory Drop Test of the BE-83 cask

A cask, identified by the Bureau of Explosives as number BE-83, had been used for the transport irradiated test capsules. This obsolete cask, which weighed approximately 3.05 t, was a simple cylinder of mild-steel with a lead-lined pot-type container with no energy-absorbing protection. The cask was dropped from a height of 9 m and oriented to land on its bottom. For this regulatory drop test performed at ORNL[4], the impact surface was a 5.5-m square, 11 cm thick steel plate imbedded in a reinforced concrete pad. The concrete pad had a 3 m long, 0.92 m diameter central column of concrete sunk in bedrock. For these tests, piezoelectric transducer type accelerometers measured package accelerations, photographic coverage was provided, and detailed measurements were obtained during post-test examinations.

Following the drop test, a detailed visual inspection showed that the steel plate at the top of the cask was no longer flat; it had displaced approximately 1.3 cm. In addition, the lead gamma shield had pulled away from the underside of the top steel plate an additional 1.3 cm as is shown in Figure 1(a). This lead movement was measured directly by cutting two holes in the top steel plate. The lead had deformed and flowed on impact, causing the lower portion of the cask, just above its bottom, to expand in its radial dimension. In addition, the weld joining the bottom steel plate and the outer shell failed and cracked through an arc of 106 degrees as shown in Figure 1(b); the crack was sufficiently wide to permit the entry of a 2.4 mm thickness gage.

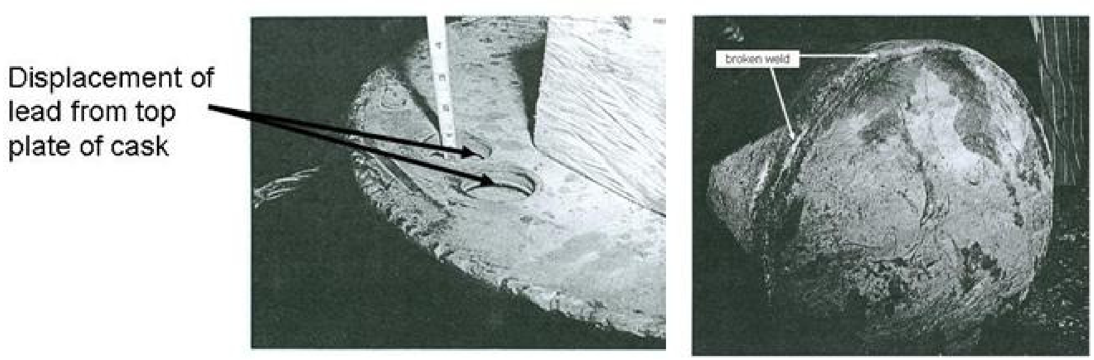

Fig. 1. BE-83 cask (a) lead displacement from the top plate; (b) bottom with a broken weld.

9 m Regulatory Drop Tests of a 20.5 t Cask

A second cask, which was fabricated and licensed in 1963, was originally designed to transport SNF irradiated fuel from the Dresden nuclear reactor. The cask was 3.73 m (147 inches) long, 0.96 m (38 inches) in diameter and weighed 20.5 t. Two regulatory drop tests were performed on this cask. For the tests, this cask was retro-fitted with a balsa wood filled impact limiter on its closure end. It was dropped from a height of 9-m. The impact target was a massive reinforced concrete block weighing approximately 670 t with a 30-cm thick armor plate surface.

A cask of this same design was used in the truck/trailer/cask, high-velocity impact tests as discussed later in this paper. Figure 2(a) shows the cask being inserted into the impact limiter prior to the drop. The steel cylinder that protrudes beyond the original (orange) cask is an extension that was originally designed to increase the internal cavity length. Figure 2(b) shows the cask following the impact. The impact limiter was removed revealing a pipe that had been bent and partially sheared by the movement of the impact limiter relative to the cask itself at the time of impact. The closure end of the cask sustained very limited damage (see Figure 3a); it had the internal steel sheath of the impact limiter still enclosing the extension piece of the cask, which had been "swaged" on so tightly that it remained with the cask after prying the rest of the impact limiter off the cask.

The cask was later used to study the damage that could occur to a fuel assembly it might be transporting. An un-irradiated fuel assembly designed for the NS Savannah merchant ship was made available. The assembly was placed in the cask cavity on a positioning framework. The cask was suspended at about a 30º angle to the horizontal and dropped from a height of 9 m to provide what is commonly called a "slap-down" test environment. When the cask was opened and the un-irradiated fuel assembly was removed (see Figure 3b), it was evident that it had sustained significant damage and parts of the hardware holding the fuel rods in place had broken; however, there was no evidence of the fuel pins rupturing.

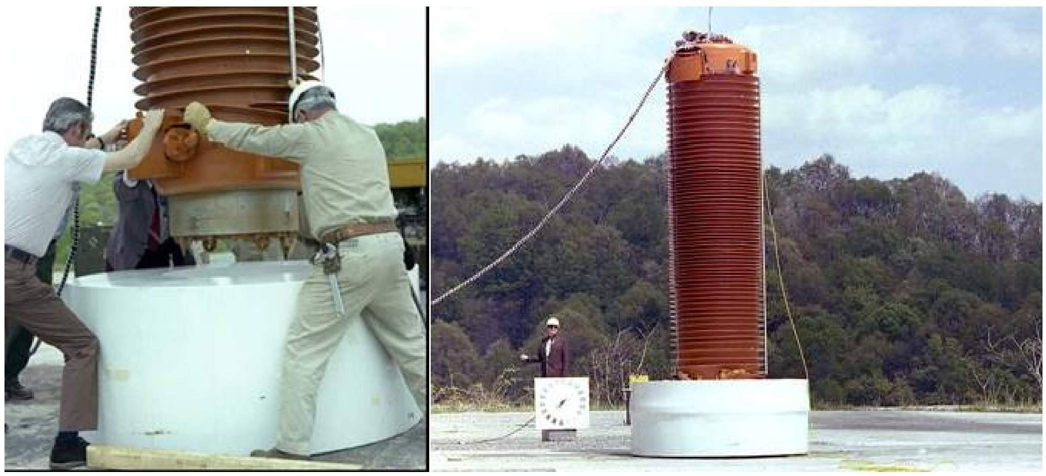

Fig. 2. The 20.5 t cask (a) being assembled with impact limiter prior to 9 m drop tests; (b) after 9 m end-on drop.

Fig. 3. (a) The closure end of the 20.5 t cask with the impact limiter removed after the 9 m end-on impact; (b) the NS Savannah fuel assembly following the 9 m slapdown impact test.

<u>Drop and Puncture Test of a 2 t Mixed-oxide Fresh Fuel Cask</u>

A series of regulatory tests were performed on a new, 2 t shipping cask designed by the Power Reactor and Nuclear Fuel Development Corporation (PNC) of Japan (now Japan Atomic Energy Agency) to transport special nuclear materials (SNM). The testing was part of a joint program that emphasized studies related to the safe shipping of SNM. The regulatory structural tests are described in this section.

The cask included a specially designed basket and one simulated fresh-fuel assembly. The cask consisted of thin concentric steel shells; with annular spaces filled with balsa wood. The central portion of the cask had additional shielding in the form of steel, cemented vermiculite and resin. The head was fitted with both an inner and outer lid;

the inner lid used three O-ring seals. The cask sat on two pedestals that were keyed to fit into the cask hold-down equipment to prevent rolling when the cask was stored.

The cask used for the regulatory drop and puncture tests had previously been used in the full-scale vehicle system test that is described later in this paper. In that test the cask was virtually undamaged. After the drop and puncture tests, the cask was placed back in the damaged transport vehicle and was then exposed to a fire test [3].

For the regulatory tests, the cask was dropped from 9 m in two separate orientations (side on pedestal and corner); and was then dropped from 1 m onto a 15-cm diameter 4340 steel punch puncture probe in four different orientations (bottom, pedestal, corner and angle).

The drop test target consisted of a block of reinforced concrete weighing approximately 225 t covered with a 10-cm thick steel armor plating. It met the International Atomic Energy Agency criteria for an unyielding target [5].

In each test, the cask was instrumented with strain gages and accelerometers. The test data also included high speed photometric data, and resulting deformations to the cask. Leak tests were also performed after the second test and after the full test series.

After completing the regulatory drop and puncture tests series and a one hour fire test [6], the outer head was removed and the leak test indicated that the seal was intact. In addition, after all of the tests were conducted, a series of leak tests were conducted on the helium-filled fuel pins in the simulated fuel bundle, which indicated the pins were intact, no helium was detected. Finally, a small hole was drilled into each pin to determine if they were still filled with helium; they were. These tests indicated that the fuel pins retained their integrity through the complete testing program.

STRUCTURAL TESTING BEYOND REGULATORY REQUIREMENTS

The following summarizes the results of structural testing of packages beyond regulatory environments, including tests of the same designs to regulatory environments described above.

Large Drop Height Tests onto Hard Prairie Soil

The large drop height tests were performed at SNL[7] in New Mexico. The soil at the drop site was classified as hard prairie, which is a hard sandy silt soil with a small amount of clay; about 2.5 to 5 cm of loose surface dirt covering a much harder layer that required a pick or bar to dig. A helicopter lifted and dropped each cask to free-fall from a height of 610 m. For these tests, photographic coverage was provided, and detailed measurements were obtained during the test and during post-test examinations.

The BE-83 cask design that was tested for the 9 m regulatory drop described above was first tested. During the drop test, the cylindrical axis of the BE-83 cask rotated from the vertical by approximately 100º during the 610 m descent, resulting in a near side-on impact with the closure end slightly lower. The impact velocity was 110 m/s. Figure 4(a) shows the hole in the desert after impact before excavation; the case was completely buried to a depth of 2.44 m during the impact. Figure 4(b) shows the cask after it was excavated. No significant deformation was observed. The lifting lugs were sheared off as a result of the combined impact and recovery effects. No observable lead slump was observed.

Fig. 4. BE-83 cask (a) completely buried as the result of 610 m drop from helicopter onto hardpan desert soil; (b) after excavation.

Even though the impact velocity was substantially higher, there was less damage to the cask from the 610 m drop onto hard prairie soil than there was for the 9 m impact test conducted at ORNL which, as noted previously, suffered weld failures in the outer shell of the cask. Despite the more significant structural damage in the 9 m impact test, both casks would have safely contained their contents without release.

An obsolete Oak Ridge Research Reactor OD-1 Spent Fuel Carrier, which was originally approved by DOT under Special Permit No. 5660 to ship ORR-type irradiated fuel elements, was a stainless steel clad, lead shielded upright cylindrical container with square base weighing 7410 kg. It was also dropped from a helicopter under the same conditions as the BE-83 cask. The orientation of the cask was vertical at release from the helicopter, but it rotated approximately 30º during its descent from 610 m. The tie-down (square) plate was the first part of the cask to contact the ground. The cask was buried to a depth of 1.28 m into the earth, and the impact velocity was 103 m/s. The partially excavated cask is shown in Figure 5(a); the fully excavated cask is shown in Fig. 5(b). The tie-down plate was deformed, with its superstructure crushed at the point of impact. The lead shielding inside of the outer shell slumped approximately 20 mm with respect to the outer shell. The cask displayed slight bulging at a point 15 percent of the length above its base. The closure bolts, located in ring on the top, were all canted inward, which made the closure plug difficult to remove. Measurements of the inner cavity indicated a reduction of about 1 mm in its diameter. The inner basket was not visibly damaged, but it was difficult to remove because of the inner cavity distortion.

Fig. 5. OD-1 cask (a) during excavation after 610 m drop from helicopter onto hardpan desert soil; (b) after excavation.

Full Scale Vehicle Testing with Obsolete Casks

In an attempt to understand the dynamics of extra severe transportation accidents and to evaluate existing and developing computational techniques for predicting the dynamic response of shipping casks involved with vehicular system crashes, the Energy, Research and Development Administration (ERDA) – the predecessor to DOE – undertook a program with SNL to investigate these areas. This program, which began in 1975, encompassed three distinct major efforts[8]: (1) computations using the (SHOCK) [9] and (HONDO)[10] computer codes to predict the effect of extra-severe accident environments and to calculate the damage incurred by casks as the result the accidents; (2) testing of 1/8-scale model transportation systems; and (3) confirmatory testing with full scale events using representative models, i.e. the Full Scale Vehicle Testing (FSVT) program.

After extensive study and deliberation, while concurrently acknowledging that the tests were not intended to validate regulatory standards, the test scenarios selected were: (a) crashes of a tractor-trailer rig carrying a SNF cask into a massive concrete barrier at 100 and 130 km/hr, (b) high-speed, 130 km/hr, impact of a locomotive into a truck-mounted SNF cask at a simulated grade crossing, and (c) impact of 130 km/hr of a special railcar carrying a SNF cask, followed by exposure to fire (this latter test is described in a companion paper [3]). Out-of-service and older shipping systems, commercial truck tractors and trailers, and a surplus locomotive were obtained. The shipping systems were modified to make them more representative of current designs. The basic construction of the casks used in the FSVT program, were of steel-lead-steel construction.

Truck impact tests of 20.5 t cask: For the tractor-trailer impact test series, an obsolete SNF cask weighing 20.5 t complete with its normal transport trailer and tie-downs was used. This was the same cask design that was evaluated in the head-on and slap-down, 9 m regulatory drop tests at ORNL as described above. In its original configuration, the cask was mounted with the head facing the rear of the trailer. Since most modern casks are shipped head forward, this test cask was reversed on the trailer to better simulate current transport conditions. The cask was attached to the tie-down structure by bolted connections at the base and head of the cask. In reversing the cask, the original bolted and welded connections were duplicated to secure the tie-down structure to the trailer. Balsa wood steel sheathed impact limiters, designed by techniques currently in use at that time, were added to the cask to evaluate the effectiveness of impact limiting devices in accident conditions. Two structurally sound, standard cab-over, tandem-axle, diesel-powered tractor were used for the two impact tests. The cask, which was practically undamaged in the first test, was equipped with a new front impact limiter and reused in the second test.

The target used in the FSVT program was designed to be very massive and rigid. It consisted of a very heavily reinforced concrete wall 3.05 m thick keyed into a massive heavily reinforced foundation. The target wall and foundation had a combined mass of approximately 630 t. For all practical purposes, considering the masses and velocities involved in the tests, the target was essentially unyielding. An object of this size and weight is rarely, if ever, found along normal highway routes. For each test, the cask was loaded with an un-irradiated NS Savannah merchant ship reactor fuel assembly ballasted to the weight of a conventional PWR fuel assembly.

Figure 6(a) shows the cask and transport system during the 100 km/hr test; and Figure 6(b) shows the cask and transport system following the impact. As predicted by the pretest analyses, the tractor was completely destroyed in the crash. Although the cask tie-downs did not break loose during impact, posttest inspection of the debris indicated that the cask tie-downs had been close to failure. The cask remained intact, sustaining only superficial damage to the external surface. The cask head was easily removed, and the fuel assembly was found to be intact and undamaged.

Fig. 6. 20.5 t SNF cask/transport system (a) during impact of at 100 km/hr; and (b) following impact.

Since the cask sustained little damage in the first test, it was cleaned, repainted, loaded with a fuel assembly, and remounted on an identical tractor/trailer transport system for the second test at greater impact velocity. The second test was conducted at a velocity of 135 km/hr. The tractor and trailer were demolished and a portion of the impact limiter in contact with the cask was completely crushed even though the tie-downs held until the final stages of impact. Figure 7(a) shows the truck cask system at impact. Figure 7(b) shows the condition of the cask and transport system after the impact test.

After removal of the cask from the trailer, seepage at the rate of about two drops of water per minute was detected from the cask head. The seepage later stopped after approximately 100 cc of fluid was released. As shown in Figure 8(a), the lid of the cask was “peened” onto the cask body. The front of the cask had bulged as predicted. Several dents found on the surface of the cask head were caused by the impact of the cask with the trailer fifth wheel pin, which was forced in front of the cask by the buckling of the trailer. The cask head was removed with great difficulty after which inspection of the fuel assembly revealed deformation at the impact end.

Some fuel pin buckling occurred as shown in Figure 8(b). This buckling was similar to that experienced by a comparable fuel assembly in the regulatory drop tests (see Figure 3(b)); however, no clad failure was detected.

Fig. 7. 20.5 t SNF cask and transport system (a) during impact of at 135 km/hr;
(b) following impact.

Fig. 8. The 20.5 t cask (a) head end after 135 km/hr impact;
(b) condition of fuel assembly with ballast after the 135 km/hr impact.

Grade crossing impact test of 109 t rail locomotive into the 22.7 t truck-mounted cask: An obsolete 22.7 t cask was impacted by a locomotive traveling at 130 km/hr. Figure 9(a) shows the locomotive and truck cask and trailer during impact at 130 km/hr. Figure 9(b) shows the resulting damage to the full scale cask. Leak testing of the cask after impact indicated a small leak in the head seal, when the cask was pressurized. However, it was determined that, had the cask contained cooling water as it was originally designed to do, this leakage would have caused essentially no risk to the public. The cask head was removed without difficulty and the fuel was found to be intact with only slight bowing.

Fig. 9. Locomotive (a) impacting the truck cask and trailer at 130 km/hr grade crossing test; and
(b) post test damage to the cask.

A ballasted, un-irradiated NS Savannah merchant ship reactor fuel assembly that was in the cask during the locomotive impact experienced some bowing of the fuel pins in the fuel assembly; however, no clad failure was detected. In addition, the effects on the fuel assembly from this accident-simulating test were compared directly with the effects on the fuel assembly in the regulatory 9 m slapdown drop test as shown in Figure 3(b)). More bowing of fuel pins was observed in the slapdown test than in the locomotive/cask impact test.

<u>*Impact test of a special railcar and cask system*</u>: The third accident scenario simulated in the FSVT program involved the impact of a 68.2 t railcar carrying a 61.8 t cask at 130 km/hr into the massive barrier. This cask, while similar in construction to those tested earlier, was larger, capable of containing more SNF elements. The special railcar system consisted of a heavy steel frame and was equipped with two three-axle trucks. Secondary cooling systems, that were used to facilitate rapid handling upon receipt, are shown at both ends of the cask. Part of the railcar system was the cask encasement structure comprised of heavy steel components welded together, including a bolted down cover. Within the encasement structure, a cylindrical spacer (or filler) unit served to constrain any movement of the shipping cask. The complete system weighed about 136 t. For the test, a non-radioactive fuel assembly was placed in the cask cavity along with nine “dummy” (i.e. mass-modeled) assemblies.

The full scale test was conducted at a velocity of approximately130 km/hr. Figure 10(a) shows the railcar and cask before impact, with the array of rockets that were used to propel the system to the impact speed. Figure 10(b) shows the railcar and cask after impact. The impact resulted in extensive damage to the railcar structure but the damage to the target was minimal and target deflection was negligible. The cask body was un-deformed except for minor deformations to the external cooling fins. There was no leakage. Subsequent examination of the fuel assembly indicated that the fuel pins were undamaged. Only the support bracket at the end of the bundle was slightly distorted.

Fig. 10. Special railcar/cask system (a) prior to testing; and (b) after 130 km/hr impact test.

<u>Truck Impact Test of 2 t Mixed-oxide Fresh Fuel Cask</u>

The PNC shipping system that was tested consisted of a special tractor-trailer and a fresh fuel shipping cask for breeder reactor fuel. The full scale test was conducted with a specially constructed system patterned after the PNC prototype that was designed and constructed by SNL. It utilized one cask and two dummy mass modeled casks. Figure 11(a) shows the full scale system prior to the test. The PNC transport system struck the target at approximately 93 km/hr. The system after the impact test is shown in Figure 11(b). After the test, the cask interior was carefully inspected with a mirror and telescope and no defects were found. The cask was also leak-tested, and it was concluded that the cask’s leak tightness was not affected by the impact test.

in recovery of packages after such accidents would not be exposed to any radiation of significance.

Figure 11. PNC SNM transport system (a) before 93 km/hr impact test; and (b) after 93 km/hr impact test.

CONCLUSION

The regulatory and other tests described in this paper summarize a large body of work that was undertaken over a period of more than a decade with a view to assessing how robust radioactive material casks, designed to regulatory standards, behave in extreme structural environments. An expanded version of this paper has been published in Vol. 18, No. 3 of the international journal "*Packaging, Transport, Storage & Security of Radioactive Material*"[15]. This paper includes summary details of the design of the casks tested, the analytical and scale modeling that was undertaken, and the results of full scale test measurements.

The tests showed that, without exception the cask designs that were tested were not stressed in excess of the environments resulting from exposure of the designs to the regulatory standards. In addition, for those tests with simulated contents, the contents were well protected, and it is expected that personnel involved

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