44 Years of Testing Radioactive Materials Packages at ORNL

Larry B. Shappert
Consultant, Oak Ridge National Laboratory, Oak Ridge, Tennessee, U.S.A.

Scott B. Ludwig
Oak Ridge National Laboratory, Oak Ridge, Tennessee, U.S.A.

Introduction

This paper briefly reviews the package testing at the Oak Ridge National Laboratory (ORNL) since 1960 and then examines the trends in the testing activities that occurred during the same period.

Radioactive material shipments have been made from ORNL since the 1940s. The first fully operating reactor built at the ORNL site was patterned after the graphite pile constructed by Enrico Fermi under Stagg Field in Chicago. After serving as a test bed for future reactors, it became useful as a producer of radioactive isotopes. The Isotopes Division was established at ORNL to furnish radioactive materials used in the medical community. Often these shipments have been transported by aircraft worldwide due to the short half-lives of many of the materials. This paper touches briefly on the lighter and smaller radioisotope packages that were being shipped from ORNL in large numbers and then deals with the testing of packages designed to handle large radioactive sources, such as spent fuel, and other fissile materials.

Packaging regulations

In the United States package regulations and package testing developed along parallel paths. The need to ship radioactive materials (RAM) before specific regulations were established forced the government to regulate such shipments under existing regulatory agencies. Regulations governing the packaging and shipment of RAM in the public domain were first introduced in the U.S. by the Interstate Commerce Commission (ICC) in the early 1950s [1]. In the late 1950s the U.S. proposed regulations for shipping irradiated fuel elements in the Code of Federal Regulations Title10 Part 72 [2]. Within this same time frame the International Atomic Energy Commission (IAEA) was organizing international working groups to address such radioactive shipments and published the first set of international regulations, identified as Safety Series 6 in 1961 [3].

During the drafting of the regulations, it was the intent of the Atomic Energy Commission and their consultants to make the analysis of packaging designs compatible with testing. This led to the concept of, among other ideas, the "impacting (a test piece) on a solid, unyielding, surface." The intent was to provide a known amount of kinetic energy which would create damage in the package with no damage to the impacting surface. More detailed discussion of the history of packaging and shipping regulations can be found in [4].

In the early years

The first radioisotope shipped from ORNL was 1 mCi of C-14. The shipment was made on August 2, 1946 to the University of Chicago. At that time there were no regulations governing the shipment of RAM and no testing of packages was required. As a result, packages for shipping isotopes that were designed and developed by ORNL were reviewed by staff members of the Bureau of Explosives, part of the American Association of Railroads, headquartered in New York. Additional isotopes were produced and additional packages were developed as the demand for isotopes increased. The main concern of the package designer was containment of the material and radiological protection of people. Once standards for packaging behavior started to be discussed, developed, and promulgated, testing of packages to those standards soon followed.

During the 1950s both research and power reactors were being designed and developed for civilian application. It was obvious that spent fuel shipments would require much more care than many of the smaller isotope shipments. However, small quantities of isotopes were already being shipped internationally. Thus, at ORNL, isotope packages were the first to be tested in response to draft regulations for these type shipments in the late 1950s. At that time U.S. regulations [5] proposed a drop height of 15 ft as one of the hypothetical accident conditions.

1960s

Testing in the 1960s at ORNL focused primarily on developing information that would: (1) support the effort to codify the developing regulations both in the U.S. and at the IAEA, and (2) generate information that could be used to design packages that would meet those regulations. The intent was to develop methods of certifying a packaging that would primarily rely on analysis. Testing of an actual prototype or model package would be employed only as needed to support the certification effort. However, testing of packages early on was critical in order to relate actual damage found in a test to analytical methodology being considered to predicting damage.

In May 1962, the Division of Reactor Development of the U.S. Atomic Energy Commission (USAEC) and the Johns Hopkins University of Baltimore, Maryland, sponsored a conference titled *Shipping Container Testing Program* aimed specifically at radioactive material shipments [6]. Although all attendees at that meeting were from the U.S., the British Testing Program was reviewed by R. Barker, then a staff member of the USAEC, which gave the meeting an international flavor.

Two important aspects of the developing regulations involved structural testing, specifically free drop tests to simulate general impact forces in an accident and puncture tests to simulate shear forces concentrated in a small area of the package. Because lead was a commonly used shielding material for gamma rays, initial testing at ORNL looked at how lead-shielded, steel-jacketed shipping casks would survive an impact onto a solid, unyielding surface and how thick the steel shells had to be in order to protect such a cask from being punctured in a punch test. There had been little, if any, testing like this since regulations were still in a state of flux and packagings to transport spent fuel were just being developed.

Initially a cylindrical, lead-shielded model was designed and drop-tested. The models varied in weight from about 2700 lb (1200 kg) to almost 12,000 lb (5400 kg). In addition to employing accelerometers and strain gages to monitor tests, the outside was painted with a brittle lacquer that reveals the stress pattern in the shell on impact (see Fig. 1).

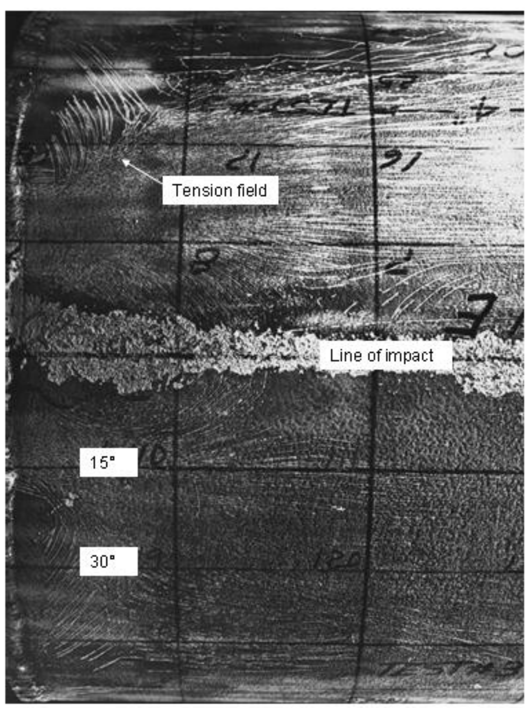

Fig. 1. Model cask tested with brittle lacquer

ORNL then initiated work to test various parts of a cask shipping system separately. In a series of tests, different thicknesses of steel plates (simulating an outer shell and backed by lead) were dropped onto a steel punch [7, 8]. The results from these tests were used to evaluate: (1) the point at which the steel would fail when impacting on a steel punch, and (2) the scaling behavior of reduced-scale test pieces (see Fig. 2). In addition, the curvature of the outer steel shell in a cylindrical cask design was also taken into account. Finally, large steel cubes filled with lead, the largest weighing 85,000 lbs (38,600 kg), were dropped onto a 6-in. (15-cm) diameter steel pin. This work formed the basis of the Nelms Equation which relates the thickness of the steel shell in a lead-shielded cask to the package weight and ultimate strength of the steel. Mathematically this equation states:

$$t = (W/S)^{0.71,}$$

where t is the thickness of steel in inches, W is the weight of the package in pounds, and S is the ultimate strength of the steel in psi.

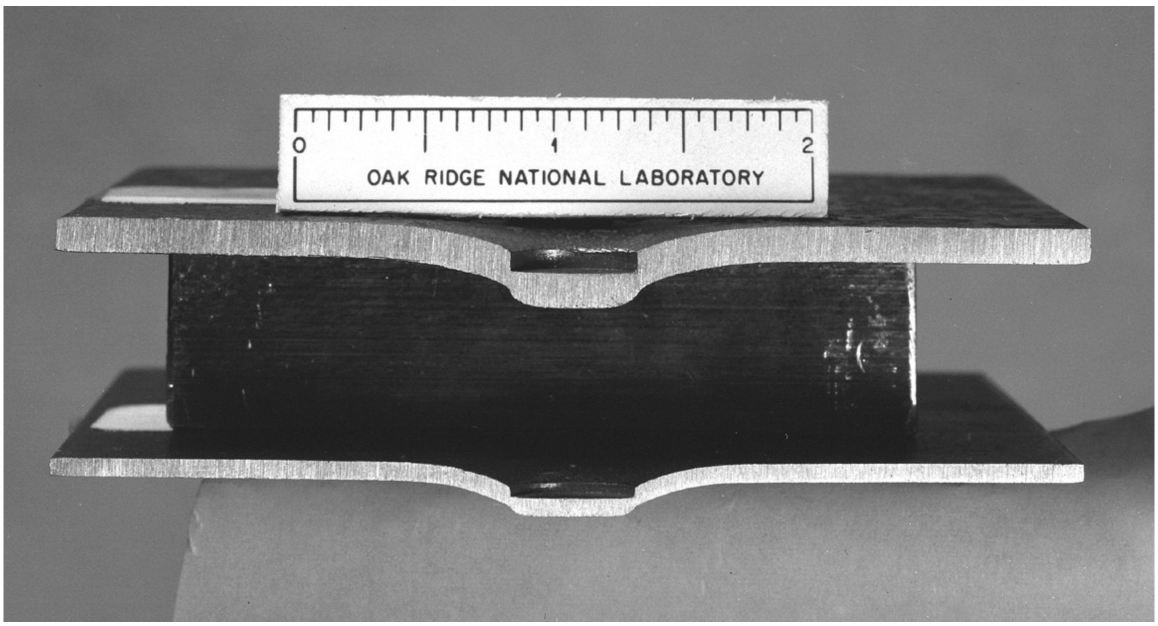

Fig. 2. Cross sections of steel test plates that were not punctured

The Franklin Institute (FI) in Philadelphia was a subcontractor to the USAEC during this period. The Institute tested small models and designed a rectangular lead-shielded spent fuel shipping cask. Because the full-size cask was very expensive and weighed many tons, FI requested ORNL to test a ¼-scale model of it. That model weighed 905 lbs (410 kg) and was dropped onto an unyielding target from 15 ft (4.5 m) and 10 ft (3 m) in various orientations and on a steel punch from 2 ft (0.6 m) and 4 ft (1.2 m). ORNL analyzed the energy that was absorbed in various parts of the package and provided this information to FI for comparison to their results from smaller models.

1970s

Information that was learned from testing and analysis of packagings and spent fuel behavior was assembled and published in the Cask Designers Guide in early 1970 [9]. Testing of package components continued throughout this decade. Fins and tubes in a pipe were studied to determine their energy-absorption capabilities when impacting on solid, unyielding surfaces. Both heat transfer fins and tubes packed inside a larger pipe can absorb significant amounts of energy in an impact (see Fig. 3). The stress-strain property of lead was investigated in detail to learn more about its energy-absorption capabilities under impact conditions.

It became apparent that testing of large lead-shielded casks would be necessary to confirm that information developed in scale models could be extrapolated to full-size packages with a high degree of confidence. To this end ORNL built a large impact pad at the Tower Shielding Facility (TSF). This facility has a large lift capacity, sufficient to elevate a 75-ton (68,000-kg) weight to a height of about 200 ft (60 m), and was chosen to drop-test many heavy packagings.

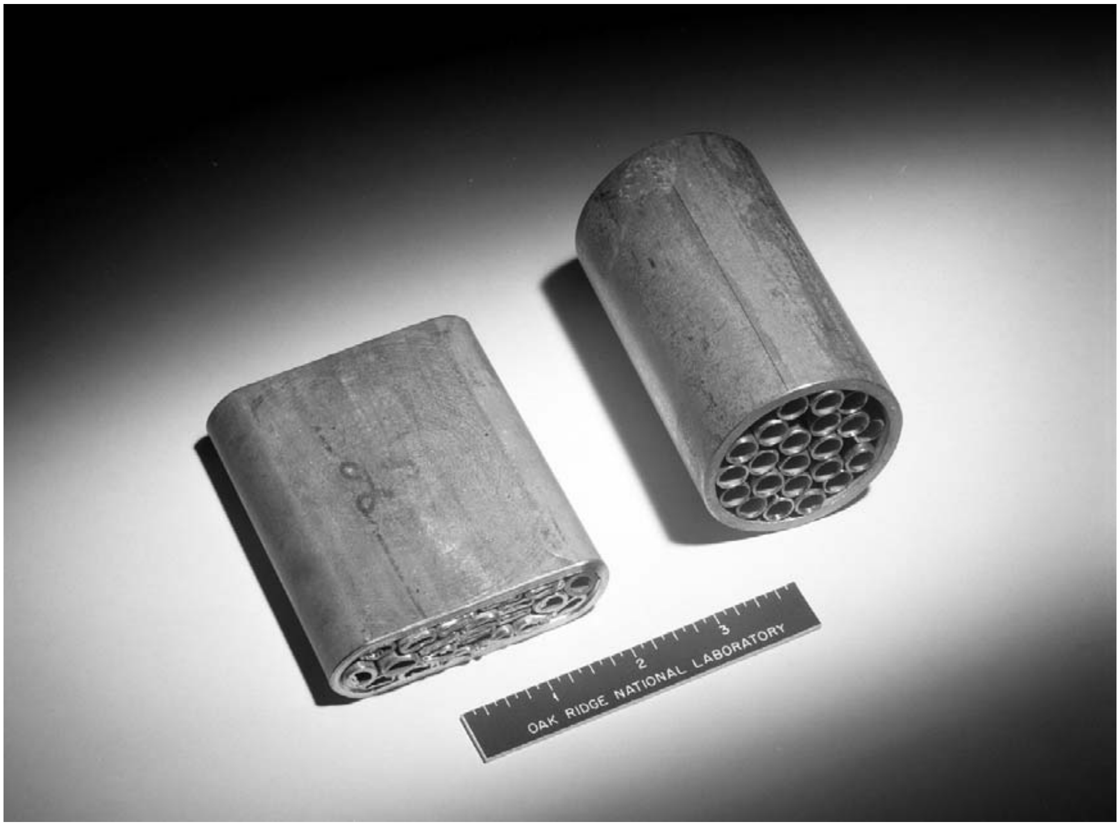

Fig. 3. Typical tube-in-pipe impact test results

Because of the great expense of designing and fabricating full-size casks for planned destruction, ORNL looked around for obsolete casks which were no longer being used. While it was recognized that such casks probably would not meet design requirements that were currently considered necessary, testing them would still provide a significant benchmark in certain aspects of model testing. In1974, the first obsolete cask was obtained and tested. This cask, which weighed about 6,000 lbs (2,700 kg) was dropped from a height of 30 ft (9 m) onto a steel impacting surface set in a large mass of concrete. This test showed that high-quality, full-penetration welding of the steel shell would be absolutely necessary. Damage and decelerations were measured and compared with predictions. Agreement between predictions and measurements was within 25%, which was considered reasonable considering the lack of high-quality material properties and a good theoretical model of material behavior in an impact.

A second obsolete cask was obtained for further testing. A 7,100 lb (3,200 kg) steel-clad, lead-shielded cask was selected since it was available and not contaminated. The cask was instrumented with strain gauges and piezoelectric accelerometers to measure the impact loading. It was dropped from 30 ft (9 m) and suffered both external structural damage and significant movement of the lead shielding [10]. A second model of this same cask design was sent to Sandia National Laboratories (SNL) where it was dropped from a helicopter from a height of 2000 ft (600 m) onto hardpan desert soil. The package tested at ORNL suffered more deformation than the identical package dropped at SNL [11].

A third, larger, cask was then chosen to study its behavior under impact conditions. The HWCTR cask weighed 47,000 lbs (21,200 kg), was 14.7 ft (4.5 m) long and 2.3 ft (0.7 m) in diameter. It was instrumented with accelerometers and strain gauges and initially dropped at a 30° angle from 30 ft (9 m) to evaluate bending in the middle of the cask under “slapdown” drop conditions. It was dropped end-on (see Fig. 4) in order to evaluate damage to the bolted closure. The package was also dropped with a balsa-wood impact limiter attached [12].

Fig. 3. An end-on drop of the HWCTR cask at the Tower Shielding Facility

1980s

The 1980s saw a number of both large and small packagings being tested at the TSF. Early in this decade an overpack consisting of a stainless steel shell containing wood was designed to protect 10- (9.1-MT) and 14-ton (12.7-MT) UF_6 cylinders. The first tests were made with the overpack containing a 10-ton (9.1-MT) cylinder with a surrogate material for the UF_6. This package, weighing 30,000 lbs (13,600 kg), was dropped from 30 ft (9 m) and was also fire tested in Chattanooga, TN.

A large overpack, identified as the Supertiger, was designed to protect drums used to ship radioactive waste. This packaging system, having a loaded weight of 50,000 lb (22,700 kg), was dropped from a height of 30 ft (9 m) to evaluate its ability to meet one of the hypothetical accident conditions.

In 1984, the initial design of an overpack to transport drums of TRU-contaminated material was drop tested for SNL. The package, loaded with surrogate material, weighed 50,000 lbs (22,700 kg) and was dropped from a height of 30 ft (9 m) also to evaluate its ability to meet one of the hypothetical accident conditions.

In 1988, ORNL tested a package designed to contain fissile, irradiated scrap that was to be withdrawn from the damaged core of the Three Mile Island reactor. The container, a steel pipe designed with several internal rods that contained nuclear poisons to maintain subcriticality of the fissile material, was cooled to -20° F (-29°C) and then dropped from a height of 30 ft (9 m). Following the drop, the test piece was x-rayed to determine whether the internal poison rods maintained their spatial geometry.

Between the tests of the larger packagings, a number of smaller, drum-size, packages were drop-tested at the TSF. All the tests that took place at ORNL from 1975 to 1990 are identified in [13].

1990s

During this decade, ORNL continued to test a wide variety of package designs, most of which were drum-size. In support of the Department of Energy's Defense Programs, the design efforts of the Y-12 National Security Complex in Oak Ridge required the testing of a variety of packages identified as DT-18, DT-19, DT-20, DT-22, and DT-23. The tests led to improved bolted drum closures and thermal protective features on these packages.

Larger packages were also tested to determine the behavior of impact limiters designed to protect spent fuel casks. HOLTEC International requested ORNL to test the impact limiters on a ¼-scale model of their HI-STAR 100 package. This series of tests took place over a period of 6 months and resulted in a redesign of the impact limiter. Staff from NRC witnessed a number of the tests and subsequently certified the package design, based in part on the results of the data generated in the tests.

A full-size fresh fuel package designed by Framatome-Cogema was also tested during this period. The testing consisted of a series of drops both from a height of 30 ft (9 m) and from 40 in. (1 m) onto the 6-in. (15-cm) diameter steel punch. Other fresh fuel package designs were tested for Nuclear Assurance Corp. and ABB-CE.

A revision to the Packaging Handbook was published and put on a CD in 1998 [14]. The revision more than doubled the size of the original document and covered more topics, such as standards, package life cycle and certification, testing, computer programs for thermal analysis, quality assurance, package fabrication, and maintenance – in addition to standard topics such as testing, structural analysis, materials, criticality, shielding, and containment.

2000s

In early 2000, the Oak Ridge Operations Office of the Department of Energy asked the Transportation Technologies Group (TTG) at ORNL to develop a method for retaining the lid on the top of an existing 50,000 lb (22,700 kg) MVST concrete-shielded storage package that had been designed to contain a 20,000 lb (9,100 kg) concrete monolith of Type A quantities of radioactive waste. TTG designed a steel cap and bottom plate that was held in place with 8 steel cables connecting the top cap and bottom plate. This system was built and tested and was found to successfully retain the lid. DOE approved the system and over 200 monoliths inside their concrete storage shields have now been safely transported to and disposed of at the Nevada Test Site in the western U.S.

Y-12 National Security Complex continued to use the TTG's facilities and experienced engineers to evaluate design improvements in their older packages as well as newly designed packages. These packages were subjected to both the normal condition of transport (NCT) and hypothetical accident condition (HAC) tests. For example, following impact testing, four ES-2100 packages were taken to Chattanooga, Tennessee, to a large forging furnace that could be controlled at a temperature ranging from 1500-1550°F (815-840°C). Temperatures were monitored by thermocouples attached to furnace walls and the test unit support cradle and recorded with a computer-based data-collection system. Following the thermal testing phase, the packages were returned to the TTG laboratory where they were opened and the inner containment vessels were leak checked. Internal temperature labels were then read to determine the maximum temperatures that had been reached by the internal components.

Also following drop-testing, four DPP-2 packages were taken to a furnace in Latrobe, Pennsylvania, where the same monitoring system was used to measure and record the temperatures on the packages and furnace walls. Following the thermal testing of these packages, they were returned to the TTG Laboratory where they were opened, inspected, and the inner containment vessels were leak-checked. It was determined that Kaolite 1600™, a new material used to provide the cushioning and insulating properties that are needed, worked as expected.

Framatome requested testing support for two fresh fuel packages modified to carry two PWR assemblies each. The first package was dropped from 30 ft (9 m) in a slap-down attitude and then dropped from 40 in. (1 m) onto a steel punch. The second package was dropped in a vertical (end-on) attitude. All tests went as planned and provided Framatome the information they required.

Duratek requested testing support for packages that were designed to transport low-level grouted concrete wastes from Fernald to Western disposal sites. The loaded package consisted of a cylindrical ½ -in. (12.7 mm) thick steel shell 75 ¾-in. (1.92-m) in diameter, 79 ¾-in. (2.02-m) tall, and weighed about 22,000 lbs (10 MT). The Duratek packages were dropped in three different orientations: a side drop, a vertical drop onto its lid, and a center-of-gravity drop over the top corner of the package from a height of 3 ft (0.91 m). It was determined that none of the dry material contained in the packages leaked and provided Duratek with the information they needed.

Trends in testing

In the past 4 ½ decades that ORNL has been testing packages several trends can be identified and these trends seem to be mirrored in testing activities around the world. The first trend can be seen in the types of packages tested. In the late 1950s, small isotope packages were initially being evaluated against regulations or guidelines that had been identified but not necessarily codified. Nuclear reactors were being built worldwide and it was expected that spent fuel would be shipped to a plant for reprocessing and production of high-level waste for disposal. At that time, lead was the choice for shielding radiation from high level waste and spent fuel. As a result, much effort went into examining the behavior of lead-shielded packages designed for this type of service.

By the 1970s and 1980s, methods of reducing the impact shock to a large, heavy package weighing many tons and carrying spent fuel were being evaluated. Packages containing depleted uranium (DU) shielding were tested. Impact limiters of various designs were also being tested. Extra-severe testing of packages was being carried out in several places around the world. Packages that had been designed to the then-current hypothetical accident testing regulations were found to have a large margin of safety and withstood very-severe real world accident conditions.

By the 1990s, lead shielding was out of favor due to environmental concerns and steel or (in Europe and Asia) nodular cast iron was the structural and shielding material of choice. New fresh fuel packages were being designed and tested for both PWR and BWR reactor fuel. Waste material was building up in many facilities around the world which needed to be consolidated and disposed of in an environmentally safe manner. As a result, more effort was focused on designing overpacks to shield and ship existing drums and cylinders filled with various types of radioactive waste to offsite processing and disposal facilities.

Current testing appears to continue the trend of the 1990s. Radioactive waste materials that have been accumulating and stored on site continues to be moved off-site and packages are being designed, modified, and tested to ensure they meet current regulations. Smaller packages continue to evolve and replace older designs which also require testing.

Trends in impact limiters

Most designers attempt to limit the deceleration of large packages to about 60 g's when impacting on a solid, unyielding surface. Of particular interest is protecting the closure area of a package. This is done by designing an impact limiter that will absorb much of the kinetic energy of a package when it is dropped. Impact limiters have been fabricated from wood of various types, steel pipes filled with steel tubing, and shells filled with metal honeycombs.

Wood was an initial favorite since it was easy to fabricate, light in weight, and could absorb significant energy in an impact. However, impact properties of wood can be affected by humidity, temperature, wood grain orientation, and exposure to moisture. Metal impact limiters are not significantly affected by these conditions and are now more often favored in the construction of impact limiters designed to protect large, heavy, shipping packages.

For smaller packages, the impact limiter can be inside the outer shell (e.g., drum) of the package. For many years Celotex™ was a material favored for both insulating and cushioning an internal containment vessel. However, the Celotex™ can burn at high temperatures, particularly if the outer shell has been punctured or been opened to air in an impact. As a result, many of the more recent small package designs now employ Kaolite 1600™, a mixture of portland cement and expanded vermiculite to provide the cushioning and insulating properties that are desired.

Conclusions

Testing of various packages that were designed to transport radioactive materials gathered momentum once regulations started to be promulgated. Initially small packages that were used to carry hundreds of shipments of medical isotopes were put through a series of "accident tests". These regulatory tests were quickly applied to packages that required more shielding and were much heavier. Studies aimed at developing analytical methods to predict damage were initiated and scale models of various packages were tested to evaluate the benefits of studying damage in a smaller model of a larger, heavier, package. This work was followed by the testing of individual components of packages, such as fins that could absorb energy in an impact, impact limiters, and bolted closures. Finally, some packages have been tested to conditions that are well beyond those required by regulatory standards. Package testing, which has been carried out in many different countries around the world, has shown that the NCT and HAC requirements which packages must be capable of withstanding, does provide excellent protection to the public from extremely severe accidents that might occasionally occur.

References

[1] A. Grella, *Summary of the Regulations Governing Transport of Radioactive Materials in the USA*, The International Journal of Radioactive Materials Transport, Nuclear Technology Publishing, Vol. 9, No. 4, pp. 279-292 (1999).

[2] L. R. Rogers, *Discussion of AEC Technical Transport Problems*, Shipping Container Testing Program – Report of Conference held at Johns Hopkins University, May 2-3, 1962, pp. 122-123, TID-7635 (August 1962).

[3] M. C. Janicki, and H. Lewis, *IAEA Transport Regulations – What Has Changed in 40 Years*, The International Journal of Radioactive Materials Transport, Nuclear Technology Publishing, Vol. 9, No. 4, pp. 269-277 (1999).

[4] R. B. Pope, Historical Background of the Development of Various Requirements in the International Regulations for the Safe Packaging and Transport of Radioactive Material, The 14th International Symposium on Packaging and Transportation of Radioactive Materials, Sept. 2004.

[5] Shipping Container Testing Program – Report of Conference held at Johns Hopkins University, May 2-3, 1962, p. 96,TID-7635 (August 1962).

[6] Ibid., pp. 122-123.

[7] A. E. Spaller, *Structural Analysis of Shipping Casks Vol. 2 Resistance to Puncture*, ORNL-TM-1312, Vol 2, Sept. 1966.

[8] H. A. Nelms, *Structural Analysis of Shipping Casks Vol. 3, Effects of Jacket Physical Properties and Curvature on Puncture Resistance*, ORNL-TM-1312, Vol.3 (June 1968).

[9] L. B. Shappert, Ed., *The Cask Designers Guide: A Guide for the Design, Fabrication, and Operation of Shipping Casks for Nuclear Applications*, ORNL-NSIC-68 (Feb. 1970).

[10] L. B. Shappert, et. al., *The Obsolete Cask Program: Test Number 2*, ORNL-TM-1312, Vol. 16, April 1975.

[11] J. D. McClure, et al, *Relative response of Type B Packages to Regulatory and other Impact Test Environments*, The 6th International Symposium on Packaging and Transportation of Radioactive Materials, pp. 1247-1253, (Nov. 1980).

[12] L. B. Shappert, et. al., *The Obsolete Cask Program : End-on Drop Tests With and Without an Impact Limiter and the 40-inch Puncture Test*, ORNL-TM-1312, Vol. 19 (1977).

[13] L. B. Shappert, *Test Facilities for Radioactive Material Transport Packages (Oak Ridge National Laboratory, USA)*, International Journal of Radioactive Materials Transport, Vol. 2 No. 4-5, 1991.

[14] L. B. Shappert, Ed., *The Radioactive Materials Packaging Handbook*, ORNL/TM-5003, (1998).