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Relevance of IAEA Tests to Severe Accidents in Nuclear Fuel Cycle Transport

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Introduction

The design and performance standards for packages used for the transport of radioactive materials, including nuclear fuel cycle materials, are defined in the IAEA Regulations TS-R-1 (1) in order to ensure safety under both normal and accident conditions of transport. The underlying philosophy is that safety is vested principally in the package. The design and performance criteria are related to the potential hazard – the more hazardous the material the tougher the package – and the testing requirements specified in the regulations reflect this.

Packages for nuclear fuel cycle materials

There are various categories of packages relevant to fuel cycle materials, including fissile materials such as enriched uranium hexafluoride (Hex) and fresh fuel. These are Industrial, Type A and Type B for materials of increasing potential hazard for surface transport and high duty Type C for air transport of potentially hazardous materials. Road, rail and sea transport are all commonly used for nuclear fuel cycle materials. Air transport has been used to a limited extent.

Industrial packages are used for low specific activity materials, typically uranium ore concentrate (UOC) or low level waste. Type A packages are typically for un-irradiated materials. Hex, which is a potential chemical hazard, is a special case. Type B packages are high duty packages which are used for the transport of some of the more radioactive nuclear fuel cycle materials, notably spent nuclear fuel, vitrified high-level radioactive waste (VHLW) and mixed oxide fuel (MOX). High duty Type C packages for air transport have only recently been specified in the Regulations and are intended for hazardous materials. They are likely to be used only for air transport of plutonium and MOX.

The detailed requirements for all these packages are set out in the IAEA Regulations and appropriate tests are specified. These tests and their safety significance are discussed below.

Test requirements for un-irradiated materials

Un-irradiated materials from the front end of the fuel cycle, i.e. UOC, Hex, uranium oxide powder and fresh fuel are relatively benign and the radiological hazard is low except in the event of a criticality excursion.

Industrial and Type A packages

Industrial and Type A packages for non-fissile low activity materials such as UOC and low-level wastes are designed to sustain a series of tests to demonstrate their ability to withstand normal conditions of transport, consisting of a water spray, a free drop, a stacking test and a puncture test to reproduce the kind of treatment packages may be subjected to in transport.

Packages for fissile materials

Industrial and Type A packages may be designed for fissile materials, notably enriched uranium oxide powder and fresh fuel, and they are then designated Type IF and Type AF. Special criticality safety assessments are required for these packages both in isolation and in arrays. Tests are specified appropriate to the duty and design of the package.

Packages for uranium hexafluoride

Hex is a volatile solid which can give off toxic products on reaction with moist air. Natural and depleted Hex is of low activity and is transported in large 48” diameter steel cylinders holding some 12 tonnes. These are subjected to a pressure test which they must withstand without leakage and unacceptable stress according to the ISO standard 7195. The cylinders must also meet free drop, stacking and puncture tests and also a thermal test at 800ºC for 30 minutes.

In addition, packages for enriched Hex (which are smaller, typically 30” in diameter) are subjected to criticality safety assessment.

Test requirements for Type B packages

The detailed requirements for the high duty Type B packages used for the transport of some nuclear fuel cycle materials, notably spent fuel and VHLW, are set out in the IAEA Regulations and tests are specified to ensure the integrity of the package in accidents such as crashes involving high impacts, long duration fires or after submergence.

Impact tests for Type B packages

The IAEA impact tests include a requirement for Type B packages to survive a 9 metre drop test onto a flat unyielding, i.e. a rigid surface, without giving rise to a significant release of radioactivity. This drop test is very severe because in an impact with an unyielding surface all the kinetic energy of the falling package has to be absorbed by the package in the deformation and damage it sustains. The objects which a package could impact in real-life situations, such as concrete roads, bridge abutments and piers, will yield to some extent and therefore a proportion of the energy of the moving package can be absorbed by the object. The 9 metre drop test onto an unyielding surface is therefore relevant to impacts into real-life objects as a result of a high speed crash.

Impacts onto an unyielding surface

Ammerman (2) carried out finite element calculations for impacts onto unyielding, rigid surfaces to determine the response of spent fuel transport casks as part of the study (3) initiated by the US Nuclear Regulatory Commission to examine the risks associated with the transport of spent fuel. The analyses were carried out using programmes developed by Sandia in the USA (4).

Whereas an unyielding surface is a hypothetical concept not encountered in real life, the results showed that for a monolithic steel rail cask used for transporting spent nuclear fuel even at impact velocities onto the hypothetical unyielding surface of 60 miles per hour (26.8 metres/second), which is twice the impact velocity of the IAEA 9 metre drop test, the deformation was such that leakage from the cask would be prevented.

Impacts onto real objects

In impacts with real-life objects, which yield to some extent (5, 6), the kinetic energy of the package on impact is shared between the package and the object. If the object is much weaker than the package, the object will absorb most of the energy.

The partitioning of the impact energy between a spent fuel cask and real objects can be used to obtain impact speeds that would cause the same damage as impacts onto a rigid surface. This comparison is the key to relating the IAEA drop test to real-life accident scenarios. A number of independent analyses, both theoretical and experimental, have been successfully carried out.

Impact studies on spent fuel transport casks

Spent fuel transport is becoming an increasingly important international operation and one which gives rise to public concern in some quarters. The same is true for VHLW transport and the equipment used for these two operations is similar.

Ammerman (7), in his early work, showed that for a cask with an impact limiter, the speed onto a hard soil to give the same forces on the cask would have to be twice that of the 9 metre drop test onto an unyielding surface, that is 26.8 metres/second (60 miles per hour) rather than 13.4 metres/second (30 miles per hour). Without an impact limiter the speed of 26.8 metres/second onto hard soil would be equivalent to only 1.74 metres/second onto an unyielding surface which shows the value of impact limiters.

The later study by Ammerman (2) showed that equivalent velocities for a monolithic steel spent fuel rail cask without an impact limiter on real-life objects would be at least three times the velocity for impact on an unyielding surface. For example at 30 miles per hour (13.4 metres/second), which is the speed corresponding to a 9 metre drop, the equivalent speed for an end-on collision onto hard soil or a concrete slab would be more than 150 miles per hour.

Other impact studies on Type B packages for the transport of spent fuel by Tso and Farina (9), Vallée *et al* (10) and Ito *et al* (11) show that casks will maintain their integrity in transport accidents which can be realistically envisaged and these are less severe than the IAEA 9 metre regulatory drop test.

Impacts in plutonium dioxide transport

Vallee (10) also studied the impact behaviour of containers for the transport of plutonium dioxide powder under the same conditions as for the study on spent fuel casks for a range of real objects and configurations. The results again showed that the container maintained its integrity and real transport accidents would be less severe than the regulatory 9 metre drop test.

Impacts in uranium hexafluoride transport

Shirai *et al* (12) carried out experimental drop tests on a 48Y-cylinder, used for the transport of Hex, onto an essentially unyielding surface and also onto soft and hard soils. Acceleration measurements were taken at various points on the cylinder to allow the impact force to be estimated. A 9 metre drop onto the unyielding surface gave a maximum acceleration of 203g whereas for a 14 metre drop onto a hard soil the maximum was 138g. This work provided a method to estimate the relationship between the drop height for real objects and the equivalent drop height onto an unyielding surface.

Impact tests for Type C packages for air transport

For the transport of high hazard radioactive material, such as plutonium by air, a special type of package was specified in the IAEA Regulations, TS-R-1. Such packages have to withstand the relevant tests specified for Type A and B packages, and in addition an enhanced impact test of 90 metre/second onto an unyielding surface, compared with 13 metre/second which is equivalent to the 9 metre drop test. In addition, Type C packages must withstand an enhanced thermal test of a fully engulfing fire of 800ºC for 60 minutes, instead of 30 minutes.

Garg (16) has compared the severity of the impact test for Type C packages for radioactive materials with the test requirements for flight data recorders which are designed to ensure that a recorder will survive an air crash. No packages designed specifically to meet Type C requirements were available but Garg carried out Type C tests on a Type B package used to transport radioactive sources. The results showed that whereas a Type C package would survive flight data recorder test requirements a flight data recorder may not survive the Type C test requirement. This gives confidence that the robustness of Type C packages should be adequate to survive an air crash.

Shapovalov *et al* (18) carried out tests on packages for fresh nuclear fuel to determine their performance under Type C test conditions for air transport. A container designed to carry VVER fuel elements was propelled on a rocket track into an unyielding surface at the speed of 90 metre/second specified for the Type C impact test. The container was deformed but containment of the fuel was maintained. The work also allowed computational techniques for the design of containers for air transport to be developed and validated.

Fire tests for Type B packages

Fire also is a consideration in the transport of nuclear fuel cycle materials since it increases the potential for release of radioactive material to the environment. For this reason, the IAEA Regulations specify that the packages for the more radioactive nuclear fuel cycle materials must be able to withstand fires. The IAEA thermal test specifies that Type B packages for the more radioactive nuclear fuel cycle materials must be able to withstand a fully engulfing fire of 800ºC for 30 minutes without significant release of activity.

Spent fuel transport

Several studies, for example by Ju *et al* (14), have been carried out to investigate the ability of nuclear fuel cycle packages to withstand long duration fully engulfing fires, which could be caused by the rupture of an oil or gas pipeline, or fires resulting from a train crash involving highly inflammable cargoes such as gasoline. The probabilities of such events have been estimated by Koski *et al* (15). Koski *et al* (13) also carried out an analytical study on various spent fuel cask designs to assess their response to fires. The analysis included a 1000ºC fire lasting for 11 hours, conditions far exceeding the regulatory test requirement. The results provided data for the times at which cask seal failure or rod burst could occur. The results indicated that for a fire at 800ºC it would take over 1 hour for the internal temperature to reach 350ºC, the temperature at which elastomeric seals degrade, and about 5 hours to reach 750ºC, at which the spent fuel rods could fail.

In the work of Ito (11), a spent fuel cask was subjected to a regulatory fire test at 800ºC for 30 minutes and an analysis was carried out to determine the response to a realistically severe fire accident resulting from a collision with a tanker truck. The results showed that the cask would remain sound and the conditions generated in the regulatory test would be more severe than in the realistic accident.

Water immersion

The immersion test specified in the IAEA Regulations is mainly designed to ensure safety in the event of accidents at sea. Type B packages for the more radioactive materials have to undergo an immersion test equivalent to a water depth of 15 metres for 8 hours without loss of shielding or significant release of radioactivity. In addition, packages for spent fuel (and VHLW) are subjected to immersion for 1 hour at 200 metres and the containment system must not rupture.

Spent fuel and vitrified high-level waste transport

The IAEA carried out a research project in 2001 (17) to determine whether the current IAEA Regulations were adequate to cover accidents at sea, taking account of the probabilities of accidents and their consequences. The sea transport of spent fuel and VHLW were the focus of the study.

Potential accident scenarios, probabilities and severities were established using historical data sources of marine accidents. Ship collisions and fires are infrequent events. Fires and collisions were covered separately, as well as combined fire and collision events.

From a fire test on a cargo ship combined with modelling work it was concluded that even if a ship fire reaches a hold where spent fuel or VHLW packages are stowed, the cask would not fail and release significant quantities of radioactivity. For such a release a hot long-duration fire well in excess of the regulatory thermal test would be needed with the massive casks used to transport these materials.

For collisions, extensive analytical work on the structural behaviour of ships, and spent fuel and VHLW casks was carried out. It was concluded that ship collisions are unlikely to damage the casks because the collision forces would be relieved by the collapse of the ship structures and not by the casks. The forces on the cask would be less than the forces imposed by the 9 metre drop test.

If the cask were to sink due to the sinking of the ship or by being pushed through the side by a collision, it was concluded that recovery would be likely if this occurred on the continental shelf. If the cask were not to be recovered, the rate of release of radioactive material into the sea would be very slow since the containment of the cask would be unlikely to have been lost, and both spent fuel and VHLW are very refractory. Dilution by large quantities of sea water of any material dissolved would be very great. The radiation doses received by people who consume marine foods affected by the accident would be negligible.

The probabilities of fires and collisions at sea are low and the radiation doses that might result would be significantly less than the natural background, therefore the risks posed by the transport of spent fuel and VHLW by sea are very small. The same would apply to other nuclear fuel cycle materials, the activity of which is much less.

Comparison of recorded road and rail accidents with the regulatory tests for spent fuel casks

The US Department of Energy recently commissioned a detailed study of severe accidents that have occurred in the USA over the past 20 years. The accidents did not involve radioactive materials.

Accident reports for twelve very severe road and rail accidents involving high impacts, fires, explosions or water immersion were studied to determine how the conditions generated in theses accidents compare with regulatory tests and how such conditions would have affected spent fuel transport casks (19).

Some of these accidents involved impacts such as high speed train derailments and the collapse of bridges and viaducts, which resulted in road vehicles falling onto concrete roads or plunging into rivers. The impacts which a spent fuel cask would have experienced in these accidents were much less severe than in the regulatory 9 metre drop test. Where submergence occurred there would have been no water ingress to the flask and recovery would have been possible.

Some accidents involved fires, such as one in which a liquid propane tanker collided with a bridge support in a road crash. Other accidents studied included hazardous chemicals The conclusion was that such accidents would not have resulted in significant damage to a near-by spent fuel transport cask.

Transport accidents resulting in explosions were also considered. One such accident occurred when a road vehicle carrying ten explosive devices was involved in a collision. It was concluded that a spent fuel cask loaded onto an adjacent truck would not have failed.

Conclusions

The IAEA Regulations for the Safety of the Transport of Radioactive Materials, TS-R-1, which includes nuclear fuel cycle materials, specify design and operating criteria and appropriate tests for packages to ensure safety under both normal and accident conditions.

Type B packages, which are used for the more highly radioactive materials, notably spent nuclear fuel and VHLW, require a demonstration of the successful performance of the package in both impact tests relevant to crashes, thermal tests which simulate fires and water immersion tests.

The IAEA impact tests include a requirement for Type B packages to survive a 9 metre drop test onto a flat unyielding surface without giving rise to a significant release of radioactivity. This drop test is very severe and is relevant to impacts onto real-life objects at high speeds. Fire also is a concern in the transport of nuclear fuel cycle materials since it increases the potential for release of radioactive material to the environment and for this reason the IAEA Regulations specify that the packages for the more radioactive nuclear fuel cycle materials should be able to withstand a fully engulfing fire of 800ºC for 30 minutes. Analytical studies and experimental tests have shown that Type B packages, notably for spent fuel and VHLW, can withstand such conditions without significant release of radioactivity.

The probabilities of fires and collisions at sea are low and studies have shown that the radiation doses that might result would be significantly less than the natural background. The risks posed by the transport of spent fuel and VHLW by sea are therefore very small. The same conclusion applies to other nuclear fuel cycle materials, the activity of which is much less.

Spent fuel transport has received particular attention. Analysis of some very severe high impact, fire and submergence accidents, not involving nuclear fuel cycle materials, which have occurred in the USA over the past 20 years has shown that such accidents would not have caused significant damage to spent fuel transport casks had they been involved.

There is, therefore, a large body of evidence to demonstrate that the IAEA tests are severe tests which cover all the situations which can be realistically envisaged in the transport of spent fuel, VHLW and other fuel cycle materials. Proposals for more severe tests, which have little technical justification, should therefore be treated with caution since this could result in a loss of public confidence in the current regulations and the ratcheting up of design requirements which could not be justified on quantitative safety grounds.

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