BEHAVIOR OF TRANSPORT CASKS UNDER EXPLOSIVE LOADING

B. Autrusson, D. Brochard, F. Delmaire-Sizes, A. Nicaud
IPSN/DSMR/SATE B.P. 6 92265 Fontenay-aux-Roses Cedex (France)
F. Gil CS-SI 16 av. Gallilée 92350 Le Plessis Robinson (France)
J.M. Guérin, P.Y. Chaffard, F. Chaigneau
CEA-DAM Ile de France B.P. 12 91380 Bruyères le Chatel (France)

ABSTRACT

The behavior of the casks used for shipping nuclear material must be assessed for a set of various normal and accidental situations. Though not explicitly required by French regulations, the security of the casks must be studied from the viewpoint of the loads imposed by an explosion such as induced by aggression involving a large amount of explosive.

In order to evaluate the consequences of such aggression in terms of damage to the cask and radiological release into the environment, IPSN has launched a program including experiments and the development of numerical models concerning a cask used for the shipment of PuO_2 powder. Experiments were carried out using simplified reduced-scale mock-ups representing a multi-layered cylindrical cask, and allowed evaluating the influence of the reduction ratios and the type of explosive. These experiments showed that the inner cylinder containing the PuO_2 powder remains intact Numerical 2D models, employing two orthogonal planes representing the cross section of the device comprised by the explosive and the cask, were developed to understand the physical phenomena occurring during the interaction between the shock wave and the cask.

This approach, combining tests and numerical models, allows limiting the need for costly experiments, since these models can be extrapolated over the corresponding range of validity, to cover casks having similar geometry or to different loads (amount and type of explosive). Moreover, IPSN has proposed a multiyear program whereby the approach may be extended to various kinds of casks and aggression types.

INTRODUCTION

The behavior of the casks used for the shipment of nuclear material must be assessed for a set of various normal and accidental situations. Though not explicitly required by French regulations, the cask security must be studied in the context of the potential loads resulting from aggression (terrorism) involving a large amount of explosive or conical shaped charges. As there is no legal framework allowing the competent authority to require the evaluation of cask behavior in such situations, the Institut de Protection et de Sûreté Nucléaire (IPSN), in order to provide the Authority with elements of appreciation, has, for the last ten years conducted, analyses based on both experimentation and numerical modeling, for various types of casks and loads (ref. [1] and [2]).

The purpose of this paper is first to summarize the background to these studies, then offer a detailed presentation of the methodology (i.e. experimentation and numerical modeling) employed for evaluating the behavior of a cask used for the shipment of PuO2 powder. Finally, IPSN proposes a multiyear program aiming to extend this approach to different types of casks and aggression.

BACKGROUND

For nuclear facilities, French regulations state that the consequences of aggression (i.e. terrorism) intended to generate a safety hazard and/or radiological releases into the environment must be assessed. Concerning the casks used for the shipment of nuclear material, there is no precise legal framework allowing the authorities to require studies in this field. Nevertheless, as the potential for such aggression exists, and considering the number of shipments organized each year, IPSN decided roughly 10 years ago to undertaker studies on the most commonly used casks, in order to provide the Authority with data to evaluate the consequences of such aggression.

The design of the casks, based on safety considerations, on one hand, and the various physical protection devices installed in vehicles to protect the nuclear material against theft and diversion (these devices avoid or at least make very difficult any action at the contact of the cask itself), on the other hand, contribute to enhance the cask's resistance against terrorism acts. The approach proposed by IPSN aims to determine the level of aggression against which the cask is protected. The threats considered in these studies have been chosen in order to provide the nuclear material with a similar level of protection in a facility or during shipment. The considered threat is an external threat presented by a small group of people having efficient tools, weapons, perforating charges and a large amount of explosive. In view of the structure of the casks, IPSN has decided to concentrate its efforts on aggression performed with perforating weapons (bullets, conical shaped charges and other devices) and with a large amount of explosive. The casks considered for these studies were chosen on the basis of their frequency of use and the sensitivity of the nuclear materials transported.

Initial studies were mainly experimental and aimed at checking the integrity of the cask. In 1996, IPSN initiated a program concerning a cask, (called FS47), used for the shipment of PuO_2 powder, subjected to detonation loads from a large amount of explosive. This program included both experiments on mock-ups, and the development of numerical models. The purpose of such an approach was first to identify and understand the physical phenomena involved, then perform parametric studies in order to determine the most severe configurations and to allow extrapolation towards models of casks having similar geometry. The FS47 study will be presented in the following paragraphs.

In 2000, IPSN proposed, to the competent authority, to extend this approach for three casks used for the transport of fresh and irradiated fuel assemblies (UO_2 and MOX) in a multiyear program. Simultaneously, in countries involved in the shipment of nuclear materials, the behavior of casks in a sabotage context became a concern, mainly for the shipment of irradiated fuel. An international collaborative project is being organized on this topic (see ref [5]).

BEHAVIOR OF THE FS47 CASK SUBJECTED TO DETONATION OF A LARGE AMOUNT OF EXPLOSIVE

Description of the container

The FS47 cask is constituted of two concentric steel cylinders; the metallic cans containing the radioactive material are inserted in the inner steel cylinder. The voids separating the two cylinders are filled with a mixture of plaster and a boron compound acting as a neutron shield. Radial copper blades joined to a copper cylinder are inserted in the plaster, allowing for heat removal. Several containers are shipped upright simultaneously in the same truck.

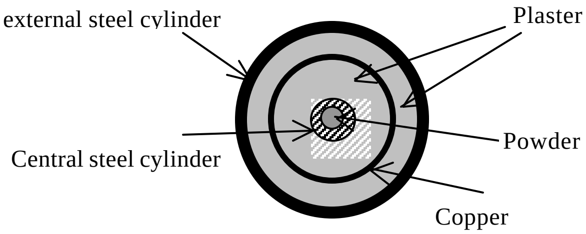
Features of the study

It is assumed that a large amount of explosive (several hundred kilograms) is detonated very close to the truck. The difficulty of evaluating the consequences of such an aggression arises from several causes: firstly, the geometry of the cask itself and the behavior, at high strain rate, of the various materials, also the presence of the truck wall, and the geometry of the explosive source. The size of the explosive charge, which is small in comparison with the truck dimensions but of the same order of size as the cask. Since the distance between the explosive and the container is too small, a simple relationship between the pressure in air and the energy of the explosion cannot be used. But, as there is no close contact between the explosive and the container, the influence of the equation of state associated with the detonation products may be important (ref. [3]).

Considering the complexity of the problem, IPSN proposed to perform tests on simplified reduced-scale mock-ups in order to limit the quantity of explosive used as well as the cost of the experiments, and simultaneously develop numerical models.

Description of cask mock-ups

From the outside inward, the mock-ups (fig. 1) comprise a steel outer protective shell, an outer plaster layer, a copper cylinder which is a part of the heat removal system, an inner plaster layer, and a central steel cylinder which is the main barrier against potential dispersion of the contained radioactive material. The central cylinder thickness was increased to take account of the can inertia. A powder (sand) represents the radioactive material.



Outer diameter : 611 mm
Height : 2050 mm

Figure 1 Mock-up simulating the cask (full scale)

Layer	Thickness (mm)
External steel cylinder	8
External plaster	38
Copper shell	3
Inner plaster	160
Central steel cylinder	34.7

Table 1 : Dimension of the full scale mock-up

Definition of experimental process

Since the cask shape is cylindrical, it was decided to work with a cylindrical explosive device with its axis parallel to the cask axis (height = 2 x diameter). The charge is located 640 mm (full scale) from the mock-up (distance between the outer surfaces of the two cylinders). The explosive is primed in the center of its bottom face. The trailer walls are simulated by a two-layer aluminum sheet.

Concerning the size of the mock-ups, two reduction ratios (λ) are employed: λ=0.43 (40 Kg of explosive) and λ=0.2 (4 Kg of explosive). The higher value is chosen to comply with the limit regarding the maximal authorized mass of explosive in the facility, and the lower one for obtaining sufficient thickness in the metal layers. The use of two reduction ratios allows verifying the scaling laws.

Five experiments were carried out. The first (λ=0.43) was aimed at testing the instrumentation. Thereafter, two experiments were carried out for each reduction ratio and two types of explosives having very different strength characteristics, namely octogen (HMX) and nitromethane. Generally, two cask mock-ups (one left open for the installation of measurement devices and one closed containing very few devices) were set installed for each experiment (see fig. 2).

Instrumentation

The following measurement devices were installed for the tests:

- a frame camera for recording the interaction between the shock wave and the mock-ups,
- polymer and ferroelectric gauges for characterizing shock-wave propagation around and through the mock-ups,
- quartz sensors and PVDF gauges (for λ=0.43 mock-ups only) installed on a heavy horizontal measurement support for characterizing shock-wave propagation in air (fig. 3),
- Laser Doppler Interferometry heads for estimating the velocity of the inside surface of the central cylinder (when an open mock-up was used),

Figure 2 : Test arrangement for test N°4 with nitromethane

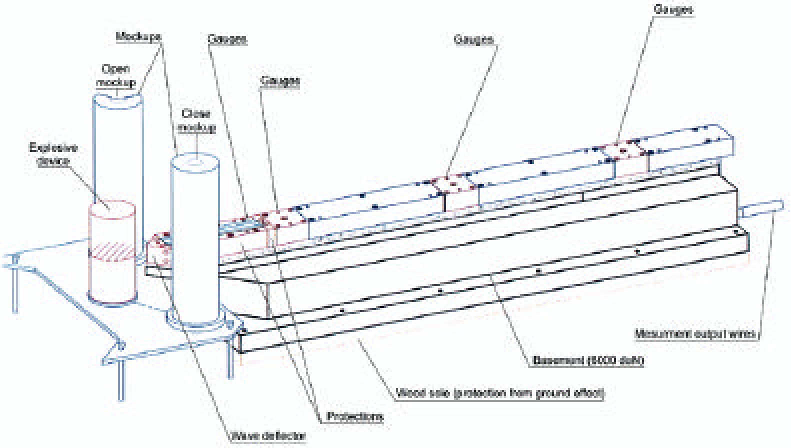


Figure 3 : Schematic view of experiment

Figure 4 : Frame camera records

Experimental results

Frame camera records

The detonation wave propagates spherically from the ignition point until it reaches the sides of the aluminum can containing the explosive, which expands and quickly breaks, letting the detonation products move ahead of the fragments. A shock wave propagates in air just in front of the detonation products; its presence is revealed by ionization of the air. The presence of the wall (fig. 4) does not modify the shape of the detonation-product expansion envelope, but induces a delay due to the piercing phase.

Shock wave propagation in the mock-ups

The propagation is symmetrical with respect to the generating line of the mock-up external shell closest to the explosive device. Moreover, the time needed for the wave to reach the inner cylinder after its first interaction with the external shell varies very slightly between 50 µs and 60 µs depending on the level (fig. 5) for (λ=0.43, HMX), and is equal to 22 µs for λ=0.2 with the same explosive and 50µs for λ=0.43 and nitromethane. Figure 6 shows the comparison of the radial propagation (expressed at scale 0.2) obtained for both reduction ratios. It allows the conclusion that the scaling laws are well respected. The presence of the wall induces a delay (of approximately 16 µs for λ=0.43 and HMX) in attack of the external shell of the mock-up, but its influence on the shock propagation velocity and the maximal pressure remains limited.

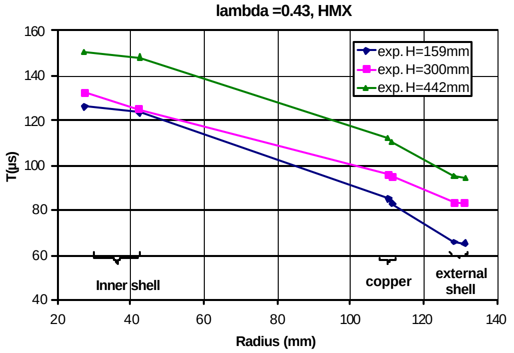


Figure 5 : Radial propagation of the shock wave in the mock-up (l =0.43, nitromethane)

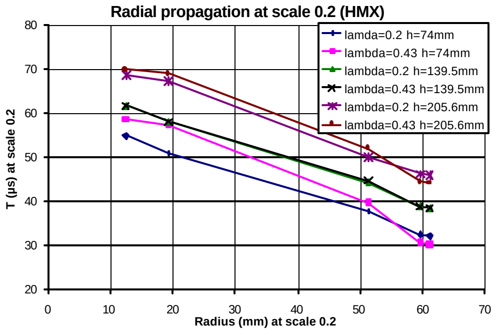


Figure 6 : Radial Propagation at scale 0.2 (HMX)

Figure 7 : copper shell

Figure 8 : Inner Cylinder

Recovery of the mock-up fragments

The external shell is seriously damaged. For the copper shell, only the part facing the explosive is torn. The central pipe was recovered intact. The bottom weld and the top cap were intact, the cap screws being slightly loosened. The sand filling remained inside the pipe, showing that no leakage had occurred. Deformations of the central pipes after all tests were measured; and were higher for λ = 0.2 than for λ = 0.43 and naturally for HMX than for nitromethane (fig. 7and 8).

Numerical models

Regarding numerical simulation, efforts were focused on three experiments representative of the entire series: tests 1 (λ=0.43) and 3 (λ=0.2) with HMX, and test 4 (λ=0.43) with nitromethane.

Principle

Calculations were performed using the HESIONE computer code developed by CEA/DAM. These calculations required two stages: first, a Eulerian solver to simulate the detonation and expansion of the detonation products and their interaction with the mock-up (assumed to be clamped), then a lagrangian solver to determine the cask response; for this second stage the pressure field on the external shell obtained during the previous stage was applied to the same shell.

Though the geometry of the system is 3D, development of 3D models remains difficult as they would require refined discretization, especially in the neighborhood of the wavefront. An alternate approach consists in making two kinds of 2D models:

- **longitudinal calculations**: the calculation plane passes through the axes of revolution of both the cask and the explosive device. The eulerian model is axisymmetric, the axis of revolution being the axis of the explosive device, and the lagrangian model is a planar model neglecting the cylindrical stiffness of the shell. The explosive cylinder is primed at the center of its bottom face;
- **transverse calculations**: the calculation plane is perpendicular to the axes of both the explosive device and the mock-up (the same geometrical model is used for both eulerian and lagrangian calculations). These results were used to assess the integrity of the structure through a ductility criterion determined for each material. The explosive cylinder was primed at its center (as opposed to the “progressive” priming of the experiments).

Material constitutive laws

The mechanical behavior of the various materials was modeled as followed (ref. [4]): the air by an equation of state of the ideal gas type; the explosives by an equation of state of the Jones-Wilkins-Lee type; the metals (steel, copper and stainless steel) using an equation of state of the Mie-Grüneisen type and an elastoplastic behavior law of the Steinberg-Cochran-Guinan type; the plaster by an equation of state of the Mie-Grüneisen type and a perfectly plastic elastic behavior law with a very low plasticity threshold. The sand contained in the inner cylinder was modeled by an equation of state of the Mie-Grüneisen type.

Results

Radial propagation through the mock-up: The agreement on the arrival time of the shock wave, in all cases, is fairly good as the maximal discrepancy is equal to 15.5 µs (λ=0.43, HMX) on the inner cylinder (see fig.9).

Change of pressure as a function of time on the external shell: the pressure development presents the characteristic shape of a shock wave (fig. 10). Measured maximum values are coherent with calculated values (10% discrepancy).

Structural integrity: As plaster is a porous material with a low level of resistance, only the integrity of the metal shells was analyzed. The external steel shell and the copper shell rupture on and around the 0° generating line (that closest to the explosive device). The central stainless-steel cylinder would not rupture: the maximum equivalent plastic deformation does not exceed 14% whereas the ductility threshold is close to 32% (fig. 11); this result is in agreement with the fact that the inner cylinder remains intact after the tests.

Inner cylinder deformation curve: It can be seen that the curve (fig. 12) showing deformation of the inner cylinder is logically more pronounced for HMX than for nitromethane, which is consistent with the amounts of energy released by these explosives. Calculations lead to the same qualitative behavior; nevertheless, comparison of the deformation contours obtained by experimentation show significant discrepancies (related to the limitations of 2-D planar numerical modeling).

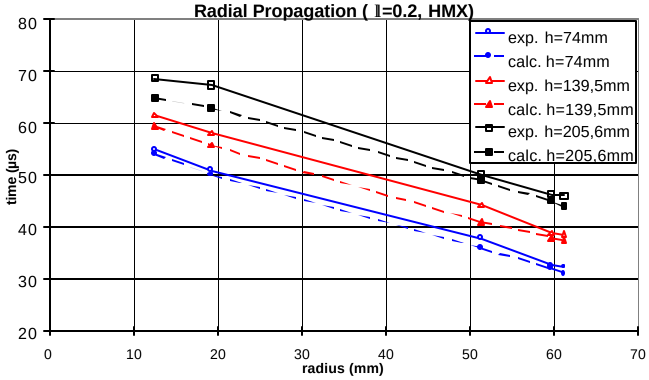


Figure 9 : Radial Propagation
(l=0.2, HMX)

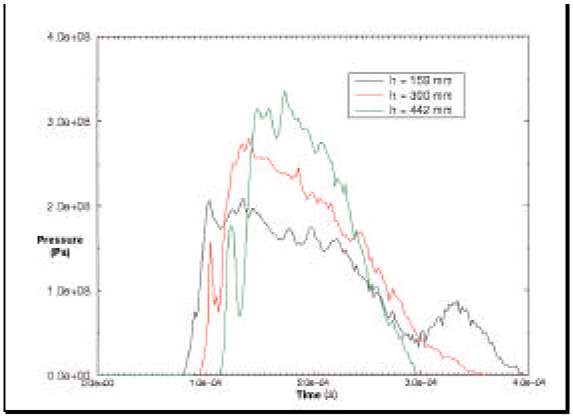


Figure 10 : Pressure on the external shell
(l=0.43, nitromethane)

Further studies

These numerical models will be used to investigate the potentially severest configurations (shape and position of the explosive device). This approach allows limiting the number of costly experiments, the latter then being necessary only to analyze very specific configurations or evaluate the behavior of certain components difficult to process using numerical models.

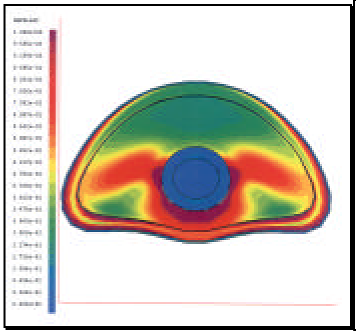


figure 11 : Structural integrity (l=0.43, HMX)

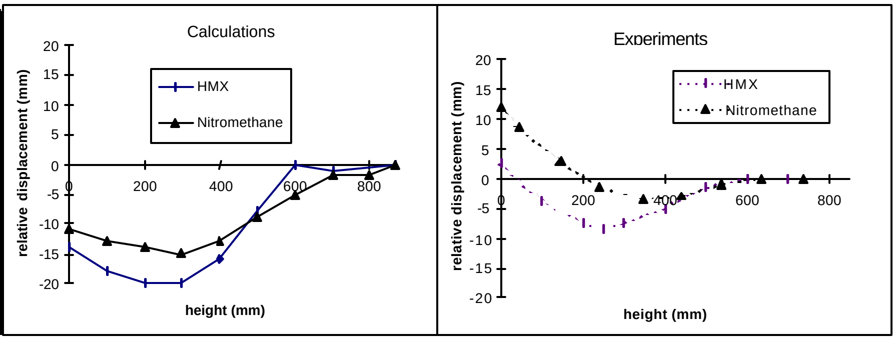


Figure 12 : Inner cylinder deformation curve (l=0.43)

MULTIYEAR PROGRAM

This program aims to evaluate the behavior of nuclear-material shipping casks subjected to terrorist action, from the viewpoint of mechanical damage to the cask and release of radioactive material into the environment, in order to estimate the radiological consequences for populations. As for the FS47 cask, this program will be based on a joint approach combining experiments on reduced-scale mock-ups and the development of numerical models, the models being used for evaluating cask behavior in configurations differing from those tested (different cask geometry, materials, types of aggression), yet sufficiently close to remain within the validity range of the models. The program is scheduled to last five years. The weapons considered in the initial stage are armor-piercing munitions (bullets, conical shaped charges) and detonation of a large amount of explosive.

On the basis of their frequency of use in shipment and the representiveness of the various casks likely to be employed, four casks have been selected,. as follows:

- the FS47 cask, described previously,
- a cask used for the shipment of irradiated spent PWR fuel assemblies
- a cask used for the shipment of fresh PWR fuel assemblies,
- a cask used for the shipment of MOX fuel assemblies.

In all these experiments, nuclear material will be replaced by surrogate material. An international collaborative program (ref. [5]) is being organized by the USA, Germany, France, the UK and Canada. The aim is to asses the consequences of sabotage against spent fuel casks and the first technical project will be to compare the release obtained with surrogate material versus real spent fuel.

Concerning the development of numerical models, the main difficulties will be first to determine the mechanical properties of the various materials used in the manufacturing of casks. This aspect may lead to additional elementary tests to characterize these materials. The second difficulty is related to the size of the models that can be reasonably accepted: for the FS47 cask, it was necessary to consider 2-D models. This problem will remain for the other casks, and especially for those carrying fuel assemblies (interaction between a shock wave or a jet of liquid metal and a fuel assembly).

CONCLUSION

This paper presents the context in which, in France, the behavior of nuclear-material shipment casks against terrorism is assessed. As there is no strict legal requirement allowing the competent authority to impose the needed studies on operators, IPSN has for the last ten years undertaken experiments and theoretical studies in order to provide the authority with data allowing the consequences of such aggression to be evaluated. An example of such a study is presented, namely the FS47 cask. Finally, IPSN has proposed a multiyear program, based on the same approach, to assess the behavior of four casks used for nuclear-material shipment, subjected to loads from armor-piercing bullets, conical shape charges and detonation of a large amount of explosive. This program could be extended in the future to casks used for shipment of highly radioactive sources. Furthermore, the international collaborative effort shows that this issue is becoming a concern for all countries fielding nuclear industries, and it will be useful to compare choices in the field of aggression against those taken by our partners, thereby allowing checks of their relevance and integrality.

REFERENCES

[1] F. Delmaire-Sizes, B. Autrusson, A. Nicaud, D. Brochard, F. Gil J.M. Guérin, P.Y. Chaffard, Behavior of transport casks under explosive loading: Numerical models, , Atlanta PVP 2001

[2] A. Nicaud, F. Delmaire-Sizes, O. Kadouch, M. Gibert, J. Aveillé, J.M. Guérin, P.Y. Chaffard, B. Landeau, Behavior of multi-layered cylinders under explosive loading, Boston PVP 1999.

[3] W.E. Baker, P.A. Cox, P.S. Westine, J.J. Kulesz, R.A. Strehlow, Elsevier, Explosion hazards and evaluation, 1983.

[4] Ammann & Whitney, Structures to resist the effects of accidental explosions, 1987.

[5] H. Richard Yoshimura, M. G.Vigil, A. Kapoor, J. R. Davis, F. I. Young, G. Pretzsch, F. Lange, D. Brochard, B. Autrusson, R. E. Luna, International Initiatives in Transportation Sabotage Investigations, PATRAM 2001