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CONSEQUENCES OF A NUCLEAR MATERIAL TRANSPORT SABOTAGE: A GENERAL APPROACH FOR THE CASE STUDY OF SABOTAGE PER USE OF AN ARMOR PIERCING WEAPON

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ABSTRACT

In order to predict the consequences of a sabotage act directed against a transport of nuclear material, the present paper is an attempt to put together some components of an approach dedicated to the assessment of the release produced when using a perforating or cutting device to spill out the content of the cask. The category of threat studied here is defined especially with regards to its objective: the objective of sabotage is to instantaneously create a radioactive source term capable of polluting a more or less important area including the vicinity of the target. This definition makes the difference with theft or diversion threats where the material is stolen and taken away from where it has been removed. The work accomplished and reported in this paper is in keeping with the general pattern of the multiyear program of IRSN where the resistance of various casks to various threats is studied.

The paper is structured in two parts. In a first part, we summarize as a whole the question of estimating the release after perforation and give a short review of past studies on the subject. All this work has motivated the development of an approach. The approach developed and used at IRSN is introduced by the statement of a generic problem. Then we identify all the influent parameters which need to be addressed. The most seducing aspect of the approach is the fact that it relies on only six parameters: the five parameters relate to (i) the energy sources capable of moving the material from the inside to the outside, (ii) the cask resistance and (iii) the release mechanisms and physics.

The authors have not included any numerical example in the paper due to the evident sensitivity of such material.

INTRODUCTION

The design of nuclear material shipping casks is in most cases essentially relying on safety considerations and generally converges to very resistant and heavy concepts. Indeed regulations provide a series of well defined usual or accidental situations the cask has to prove its resistance to [1]. Whenever designed to protect from contamination or irradiation (ionizing radiations – neutrons or gammas – emitted by the material inside) or to protect from impacts, fires, deep water pressure coming from outside, or simply to prevent leaks, the walls of a shipping cask are made of one or several materials, like steel, lead, resins, etc. and present thicknesses in the order of magnitude of several tens of centimeters. Based on this statement, one can affirm that most shipping casks offer a good resistance to natural or unattended aggressions – including accidents – as well as to malicious aggressions.

Nevertheless, the assessment of resistance to malicious aggressions is a separated question which needs to be addressed after having defined relevant scenarios for what is to be considered as a realistic malicious act. Even though one might consider accidental sequences as a probable malicious act, the situation is different and the elements for defining a pertinent scenario generally overpass purely technical considerations. Indeed these elements are gathered all together in a so called design basis threat (DBT) [2], the definition of which is done at the state level and is incumbent to the competent authorities relevant on the topic of security. Moreover, the definition varies in time and the DBT considered for transports can be different from the DBT considered for facilities. Although no DBT definition can be given in the present paper due to evident confidentiality issues, people studying the question have understood for a long time that a realistic threat relies on a scenario which differs from a sequence of accidental situations.

Looking at the heavy and resistant concepts of nuclear material shipping casks and thinking of possible threats, one naturally emerges with the idea of considering specific weapons described under the vocable high energy density devices or HEDD. Those weapons designed for military purpose are able to penetrate thick armor walls and defeat some armored tank vehicles. Whether such weapon is relevant or not with one DBT definition or another and for what basic performances is not the point in this paper. The authors have wished to deal with the general question of resistance assessment to HEDDs and how the consequences may be estimated in the case it reaches the material at risk.

To address this central question "How important is the damage caused by an HEDD?" several corollary questions also need to be dealt with: In the case where the basic performances of a given weapon are such that reaching the material at risk cannot be excluded, what amount of material would be swept? In the same case, what amount of material would be driven out from the cask? How is constituted the released source term, i.e. how small are the particles? Etc. One objective of the present paper is to gather most of the corollary questions relevant to the central problem.

MOTIVATION

The major issue with the problem of transport cask sabotage, which has lead to the relatively important literature on the topic, mainly relies on two aspects: on the one hand one cannot perform full scale experiments with actual material and simply measure the consequences, the experiments being too complicated to deal with; on the other hand, the major phenomena governing such a violent and brief interaction were not fully understood at the beginning, making the development of numerical models "from scratch" almost impossible. Adopting a scientific point of view, the problem of expressing the source term after a successful sabotage aggression is one of the best examples of complicated multi physics situations, mixing together high speed dynamics, fragmentation, aerosols and fluid dynamics.

Nevertheless, since the 1980s, several laboratories have been leading studies funded by security authorities and have been publishing results in keeping with the question of the source term produced after a successful sabotage of nuclear material transport. If the resistance to high explosives as a threat is now widely treated with numerical models [3][4][5], the resistance to HEDDs is essentially based on some significant experiments. As reported in Luna et al. [6], several experiments were performed in the U. S. at the beginning of the 1980s, both involving full scale and reduced scale test, and focusing on spent fuel sabotage scenarios[7][8]. The experimental campaigns were performed with actual spent fuel in some cases and surrogate in other cases, generally being depleted Uranium. In the report by Sandoval et al. [8] has been introduced the concept of spent fuel ratio, as a transfer function between the characteristics of the aerosol produced with a surrogate and the aerosol produced with actual spent fuel; in other words, the spent fuel ratio (SFR) is meant to be used to derive realistic predictions from the results obtained after tests performed with mock-ups made with surrogate material instead of spent fuel. At this time, the SFR has been mainly investigated at the Idaho National Engineering and Environmental Laboratory (INEEL) through sub scale experiments in which a single fuel segment was targeted. Later in Europe, Lange et al. [9] reported on experiments conducted in France with the Délégation Générale à l'Armement in Gramat, on mock-ups of a CASTOR cask containing three fuel assemblies in line, filled with depleted Uranium instead of the actual fuel. Due to the presence of several assemblies inside the cask, the results obtained in terms of released material ratio per assembly are slightly different from the results obtained by Sandoval et al. where the cask only contained one fuel bundle. Motivated by the relatively wide uncertainty of the SFR estimation previously obtained [6], a new experimental investigation of the SFR has been started at Sandia National Laboratories reported in Molecke et al. [10], with the support of the international Working Group on Sabotage concerns on Transport and Storage Casks (WGSTSC).

During the same period in France, several comparable studies have been undertaken by different actors, and among them the Institut de Radioprotection et de Sûreté Nucléaire (IRSN). By the end of the 1990's, the organization has notably defined a multiyear program with the objective to cover – in the best manner – the range of casks that are used for transports in France within the nuclear cycle. Several casks containing different kinds of materials have been studied, but very few results were published due to confidentiality restrictions. One objective of the program is the derivation of numerical models that allows transposing results obtained on one cask model to another model. The finality of such a project is to provide the Authority with estimations of quantities likely to be released, in order to prepare the emergency response in case of crisis, as well as simplified models to derive a quick estimation. In addition, the consequences need to be examined with regards to the acceptance threshold, in order to establish if the level of protection needs to be increased for certain transports in the case where the threshold is over passed.

The present paper introduces an approach which summarizes the problem of estimating the source term after a successful sabotage of a cask with an HEDD, as perceived by IRSN and which gathers the experience accumulated. The approach follows several objectives: it can be used (1) as a tool to synthesize past studies and compare them all together, (2) as a guide for starting a new study and taking into account all possible factors, or (3) for deriving a simple computational scheme to obtain a quick approximate answer with simple analytical tools. For that last aspect, this approach is close to the experimental based analytical assessments performed by Luna [11]. The interest here is to introduce not only a list of influent parameters or questions, but also to propose a common glossary. And as a conclusion, we present two synthesis formulas expressing the final source term with respect to the material-at-risk initial quantity and including all the influent parameters.

PROBLEM STATEMENT

In this section, we introduce some definitions useful in order to evaluate the consequences of a sabotage aiming at a nuclear material transport. Those definitions constitute the basis of the approach, as well as a common vocabulary. Fig 1 illustrates the initial problem as stated.

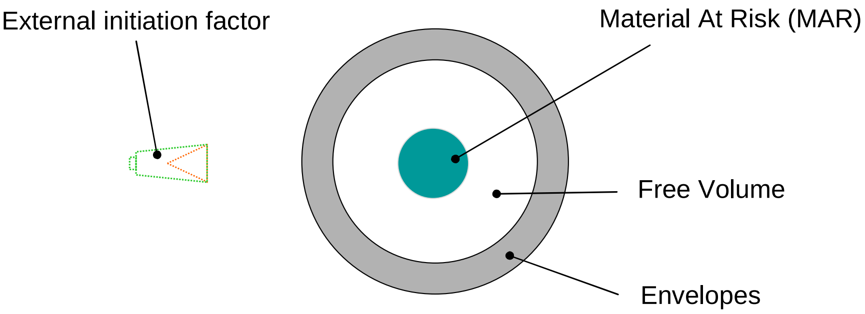


Figure 1. Problem representation

Material-at-risk (MAR)

The material-at-risk is the nuclear material that is transported inside the cask. The material-at-risk is characterized by the total quantity transported, its location inside the cask, the physical-chemical form, the conditioning, the physical state of and the radionuclides composing the matter. As an assumption for this work, the dispersion of material in aerosol form is likely to induce a radiological dose, either par direct inhalation or ingestion.

Vessels

The vessels, essentially the different layers of the cask walls, can be considered as the protection barriers for the material-at-risk from an aggression from the outside. These vessels can be constituted by different materials, and every layer needs to be considered.

External initiation factor

This is the element suspected to be likely to initiate the process of release, by a large, localized and very brief amount of energy delivery. This amount of energy both damages the cask and induces a displacement of the material from the inside to the outside.

HEDDs is the designation under which the external initiation factor is understood in this paper. It is one of the entry data of the problem to be solved. The HEDD characteristics and performances are established in relation with the DBT definition and the threat level to deal with.

Resistance to the aggression

Being given a target, its protection and a sabotage means, evaluating the consequences requires to determine first the resistance offered by the protection with reference to the sabotage means. In the present case, the target is the material-at-risk (MAR); the protection is constituted by everything that surrounds the material in its transport configuration; and the sabotage means is the weapon considered as the external initiation factor.

The resistance concept is directly related to the vulnerability concept, one being the opposite of the latter. The more resistant, the less vulnerable is the target.

Internal aggravation factors

In certain conditions, the material-at-risk is likely to react when the aggression means enters in contact. This is particularly true when the energy amount delivered is very high and concentrated. The reaction or the changes in thermodynamic equilibrium inside the cask — that might result from this local increase of energy — constitute an eventual aggravation factor affecting the damage caused to the cask as well as the importance of release of material to the outside.

ESTIMATING THE SOURCE TERM

Damaged fraction

This is the ratio of initially contained material (MAR) that is affected and damaged by the HEDD. In a simplified manner, if one wants to recover the material left intact after an aggression, only (1-FDAM) x MAR should be available.

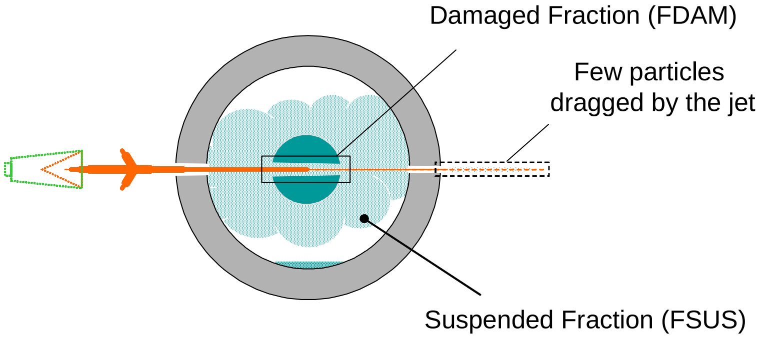


Figure 2. Damaged fraction and suspended material fraction

Suspended material fraction

The momentum transfer from the HEDD to the material induces the formation of dust and pieces of material inside the cask. The heaviest pieces of material, as well as the biggest dust particles, fall directly to the bottom of the cask. Thus heavy material pieces and large particles do not contribute to the source term likely to contaminate outside the cask. In addition, dust forms a cloud which remains in suspension inside the cask in the very next time after the HEDD has penetrated (say not more than 1 second). The amount of material contained in the dust cloud is called the fraction of material in suspension or in aerosol form (FSUS). To calculate this amount of material, one needs to know the amount of damaged material and subtract the quantity deposited at the bottom of the cask. The remaining part divided by the damaged amount of material is the fraction in suspension. This fraction of the damaged material is subject to any air flow or additional momentum transfer, and is to be considered has the source term for external release.

Source term

The source term (ST) is the amount of material likely to pass over the confinement barriers and to be partly or totally released to the environment.

In this approach, the source term is theoretically obtained by $\boxed{ST = MAR \times FDAM \times FSUS}$.

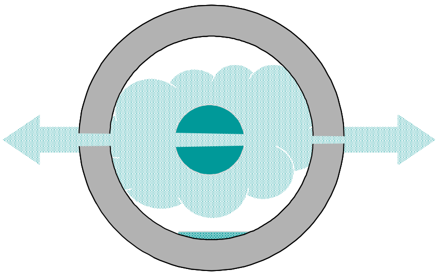


Figure 3. Source term

A very conservative approach for estimating the consequences would be to consider that the source term is constituted by the total amount of material transported (MAR). But generally the source term represents a very much smaller amount of material; say several orders of magnitude lower. This is why assessing the damaged and suspended material fractions is a critical step in the source term assessment.

The source term description ideally comprises a radionuclide inventory, with the relative abundance of every radionuclide, the activity induced, the chemical form and the particle size distribution for the solid part.

The radionuclides to be considered may be an intrinsic part of the material as well as fission products released after the breaking of spent fuel or due to a criticality event. The inventory relating to the source term must include every radionuclide that contributes for some percent to the total activity of the source term. In addition, one needs to take care of the natural decrease of the radionuclides as well as the cooling time, which are influent parameters of the potential source term activity. In the case of spent fuel for instance, the amount of fission product, activation products or actinides in general, are determined from the burn up rate and cooling time.

In some case the list of radionuclides of interest may be extended with the inclusion of those for which the chemical toxicity is likely to have an impact at least as important as the radiological impact itself.

ESTIMATING THE RELEASE

Respirable fraction

Among all the particles in suspension inside or outside the cask, only a certain part can be considered as respirable and thus likely to induce internal contamination to humans. This certain part is named the respirable fraction (FRES).

This fraction is assumed to remain constant once the source term is created. In other words, once the source term has been generated, the particle size distribution in the cloud is not modified. This assumption is of major interest for experiments; Indeed it is easier to characterize the particle size distribution of a source term in a confined space – like the inside of a cask – than trying to characterize the particle size distribution of a release in a wider space – like the vicinity of a cask. Following a conservative assumption, authors consider that the respirable fraction is essentially constituted by the particles with an aerodynamic diameter inferior to 10 µm [9][10].

Reduction factor

The reduction factor (FRED) gathers in one term all the phenomena likely to reduce the amount of radionuclides in the source term before it is released to the atmosphere. The phenomena affecting the reduction factors may be either natural or resulting from mitigation means design. The factor is basically inferior to unity.

On example of reduction of the source term is the adherence of particles to surfaces. In some theories, the electrostatic charge of particles and the global charge of a wall induce electrostatic forces that attract the particles to the wall. In other theories, adherence is attributed to a temperature gradient between a hot aerosol and cold surfaces, this being considered as thermophoresis. By the action of such phenomena with a rather quick kinetic, some particles come and adhere to the walls thus reducing the source term.

It has to be noticed that the reduction factors may vary rapidly with regards to the particle size. For instance mostly the finest particles are attracted to cold surface due to thermophoresis. As a consequence, the reduction factor FRED ideally needs to be expressed as a function of several parameters, the first of which being the aerodynamic diameter.

Released fraction

The released fraction (FREL) is the ratio of the source term that is finally released to the environment. In this approach, the source term is an aerosol constituted of particles and eventually a mix of gases; Thus determining the released fraction essentially relies on determining the importance of the fluid flow from the inside of the cask to the outside, that is induced by the HEDD action. It has to be recalled here that the energy deposited by the HEDD on the target implies a temperature and pressure rise inside the cask, mostly initiating and governing the flow. This has been experimentally observed in [12] notably. So the released fraction is expected to depend essentially on the pressure and temperature inside the cask after the HEDD has stroke and on the gas expansion conditions (adiabatic in most cases).

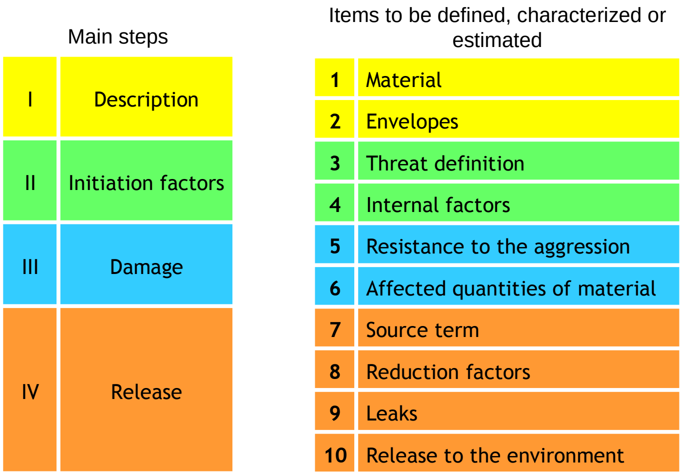
Release to the environment

The amount of material released to the environment (QREL) is deduced from the source term by the following formula: $\boxed{\text{QREL = ST x FRED x FREL}}$
The respirable part of this release (QRES) is simply expressed by $\boxed{\text{QRES = QREL x FRES}}$ or ST x FRES x FRED x FREL .

The result of this calculation is the entry data for a second phase of study, being on one hand the atmospheric or aquatic dispersion study and on the other hand the human and environmental impact evaluation – both are not addressed in the present paper. This implies that the released material is known in terms of constitutive radionuclides, activity, form, etc. In addition, one needs to determine if the release is short-termed or long-termed.

CONCLUSION

The approach developed at IRSN helps to identify all the influent parameters before one begins with a cask vulnerability study. Once this is done, solving the problem means determining all the parameters mentioned above both from experiments, theoretical approaches or numerical simulations. Every parameter has to be determined from very specific experiment, or model, due to the fact that very different physical phenomena may be involved.



Main steps		Items to be defined, characterized or estimated	
I	Description	1	Material
		2	Envelopes
II	Initiation factors	3	Threat definition
		4	Internal factors
III	Damage	5	Resistance to the aggression
		6	Affected quantities of material
IV	Release	7	Source term
		8	Reduction factors
		9	Leaks
		10	Release to the environment

Figure 4. Summary of the approach

The schematic presented on fig. 4 summarizes the ten questions that need to be addressed in the approach. In relation with those questions, four main steps can be identified: Main steps I and II are mainly descriptive and constitute the statement of the problem; Main steps III and IV need the calculation of factors in order to express the final amount of released material as well as all the characteristics needed for the subsequent analyses.

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