EXPERIMENTS TO QUANTIFY POTENTIAL RELEASES AND CONSEQUENCES FROM SABOTAGE ATTACK ON SPENT FUEL CASKS

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ABSTRACT

On behalf of the German Federal Ministry of Environment, Nature Conservation and Nuclear Safety (BMU) an experimental program was performed in 1992 to quantify the potential release from a CASTOR type spent fuel cask following attack by a conical shaped charge. Salient features of these experiments were:

- a very close approximation of real conditions by using a cask which was in all essential aspects identical to a real CASTOR cask;
- the cask was loaded with 9 fuel elements filled with depleted uranium pellets as surrogate material instead of irradiated spent fuel; the fuel elements being internally pressurised to simulate conditions after burn-up;
- the airborne release of material through the penetration channel of the shaped charge jet was retained in an aerosol chamber and directly analysed by applying a specially developed in-situ classification with respect to the amount and aerodynamic particle size distribution of the ejected dust up to an aerodynamic diameter of 100 µm.

The main features and results of the experiments will be reviewed. The transfer of the results obtained with depleted UO_2 as surrogate material to the conditions of a cask with spent fuel is discussed. On this basis potential airborne releases of radioactive material can be estimated for a real spent fuel cask and resulting radiation exposures be calculated. An advanced atmospheric dispersion model in connection with statistical data on atmospheric dispersion conditions is applied to derive probability distributions of ground-level air concentration, depositions levels and resulting potential radiation exposures of persons.

1 INTRODUCTION

Of increasing public concern, especially in connection with shipments of spent fuel elements and high radioactive wastes, are potential consequences from conceivable sabotage actions. For the competent authorities aspects of physical protection during transport and storage of such materials have been of concern for a long time. Consequently various kinds of investigations have been performed in this area in different countries. The present contribution to this topic reports about experiments to investigate the radiological threat from conical shaped charge attack of a modern monolithic spent fuel cask which have been performed on behalf of the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) in the early 90^{th} of the last century. Major parts of the experimental approach and of the extrapolation of the results to real spent fuel casks have already been published at a specialized conference /INM 94/.

The fundamental aspects of the experimental approach and the derived source term from shaped charge attack onto a modern monolithic (CASTOR type) spent fuel cask assuming high burn-up spent fuel are presented. In addition, probability distributions of potential radiological consequences have been calculated by applying an advanced atmospheric dispersion and deposition model suited for near ground-level and short term releases of particulate materials in the size range of interest (< 100 µm) in connection with statistical data on atmospheric dispersion conditions.

Transport and interim storage of spent fuel elements in dry transport and storage casks is an important part of the nuclear fuel cycle. The geometry of the whole cask and of the inner free volume is in general adapted to take up certain types and numbers of spent fuel elements. In all cases the casks have a very strong construction of walls and lid(s) and the total weight sometimes can exceed 100 tons. Main reasons for the large wall thickness which is typically in the range around 35 cm for monolithic casks are the high degree of shielding needed to reduce penetrating radiation from radioactive decay and to have a very high mechanical stability to effectively protect the spent fuel and to avoid any significant release of radioactive matter in possible accidents during transport and storage. At the same time these characteristics of the casks also give a very high degree of protection of the spent fuel against many conceivable malevolent actions.

Some anti-tank weapons which are available in the military domain and which could be handled by one or few individuals could possibly locally breach the wall of a spent fuel cask, lead to some destruction of spent fuel elements and result in a release of radioactive matter through the penetration hole. In order to estimate potential radiological consequences of such sabotage attacks and to judge to what extent protective measures are required it is important to have quantitative data on possible releases in such circumstances. Experimental investigations in this domain have been performed before, notably in research centers in the USA in the early 80th /YOS 01a/, but it was the opinion that additional experiments with different experimental approach and measurement techniques could lead to improved source term data for sabotage attack on spent fuel casks. It was anticipated that an experimental approach using a close to 1:1 scale of a typical modern cask and fuel element configuration (but with depleted UO_2 as surrogate material) would have the advantage of fewer extrapolating steps to determine the source term for a conceivable real sabotage attack with a shaped charge on a cask with spent fuel.

In the context of assessments of potential radiological consequences from shaped charge attack on a spent fuel cask during shipment or in an interim storage facility which were required by the German Federal Ministry of Environment, Nature Protection and Reactor Safety (BMU) an experimental program was suggested and specified by GRS. The company Dornier, Friedrichshafen, was responsible for the organization and conduction of the whole project. The Fraunhofer Institute for Toxicology and Aerosol Research (FhG-ITA), Hanover, designed and carried out the aerosol measurements and GRS had the function of a scientific advisor. The experiments were carried out in the Centre d'Étude de Gramat (CEG) in France in 1992. This is a research facility where missiles which include depleted uranium are tested for military purposes. The whole project was carried out on behalf of BMU.

2 EXPERIMENTAL APPROACH

The ideal experiment to determine and to characterize the release from shaped charge attack of a spent fuel cask would be performed with a real cask and real spent fuel. This is , of course, hardly practical for obvious reasons. Such an experiment would have the advantage that the interesting quantities and data could be measured directly if the methods to characterize the released radioactive material were adequate. Properties of the release which are of interest in this case are:

- activities of radionuclides released as gases,
- activities of radionuclides released as particulate matter,
- activity size distribution of released aerosol particles.

The information on activity size distribution is important for further assessment of resulting potential radiation exposure of individuals or of contamination of ground and other surfaces from atmospheric dispersion of the radioactive cloud. Only particles with aerodynamic equivalent diameters AED < 10 µm are considered to be respirable and to contribute to radiation exposure via inhalation. For other exposure pathways such as groundshine the deposition velocity which depends on the aerodynamic diameter influences the level of ground contamination from dry or wet deposition.

It was the aim to design the experimental approach in such a way that real conditions are simulated as closely as possible in order to reduce the number and degree of extrapolating steps which are necessary to derive the source term for a real cask with spent fuel. This resulted in the following experimental configuration:

- A monolithic Castor IIa type cask was used having the identical dimensions of a real spent fuel cask except that the length was of 1/3 scale.
- The cask was filled with 9 fuel elements of PWR type (17 x 17 array). The fuel elements were shortened to fit into the cask cavity with fuel basket. As surrogate for spent fuel the fuel rods were filled with pellets of depleted UO_2 (DUO_2). The rods were pressurized to an internal gas pressure of 40 bar to simulate conditions after burn-up.
- A sampling chamber was attached on the side wall of the cask where the shaped charge jet penetrated to collect the total release out of the penetration channel. In order to avoid any losses of released materials the sampling chamber was equipped with a fast closing slide valve triggered by the detonating charge.
- An upward directed airflow with a velocity of 30 cm/s which was homogenized over the full cross section of the sampling chamber by passing through a metal frit served as gravitational separator: Particles with settling velocities exceeding 30 cm/s were deposited on the metal frit by gravitational settling, whereas aerosol particles with deposition velocities below 30 cm/s, equivalent to particle sizes below about 100 µm AED, remained in the air stream and were transported to different aerosol measurement devices.
- In order to classify aerosol particles according to aerodynamic equivalent diameter the main air stream first passed a specially constructed coarse particle impactor in which particles in the size range 12.5 - 100 µm deposited on three stages (12.5 - 25 µm, 25 - 50 µm, 50 - 100 µm AED). Particles below 12.5 µm remained airborne and were either deposited on aerosol filters or transported with a fraction of the air stream to a fine particle impactor with 5 stages covering the size range below 12.5 µm. In parallel to the main air stream a sampling tube connected at the upper end of the sampling chamber led air to additional fine particle impactors with 8 and 10 stages and to an aerosol photometer to record the time dependence of the release. The main aerosol measuring instruments were put in operation 30 s before ignition of the shaped charge. The fast closing slide valve of the sampling chamber closed within 7 ms to fully contain and collect any release of particulate matter from the cask.
- The masses of dust samples which were collected on different impactor stages, filters or which deposited on inner surfaces of the sampling chamber or on the metal frit were determined by

weighing. The characteristic gamma radiation emitted from UO_2 material was used to differentiate between the released masses of UO_2 and of other structural material from the cask, fuel element basket or cladding.

- DUO_2 was used as surrogate for spent fuel from light water reactors. This has several advantages: sintered UO_2 pellets have a well defined production process and essentially the same material properties as spent fuel except for effects introduced by high neutron flux, high temperatures and fission product generation in the course of the burn-up process. In independent laboratory measurements using hot-cell techniques, as have been performed in the USA and are currently planned /YOS 01b/, differences in dust production behavior of spent fuel compared to fresh fuel and possibly enhanced release behavior of some more volatile fission products can be determined.

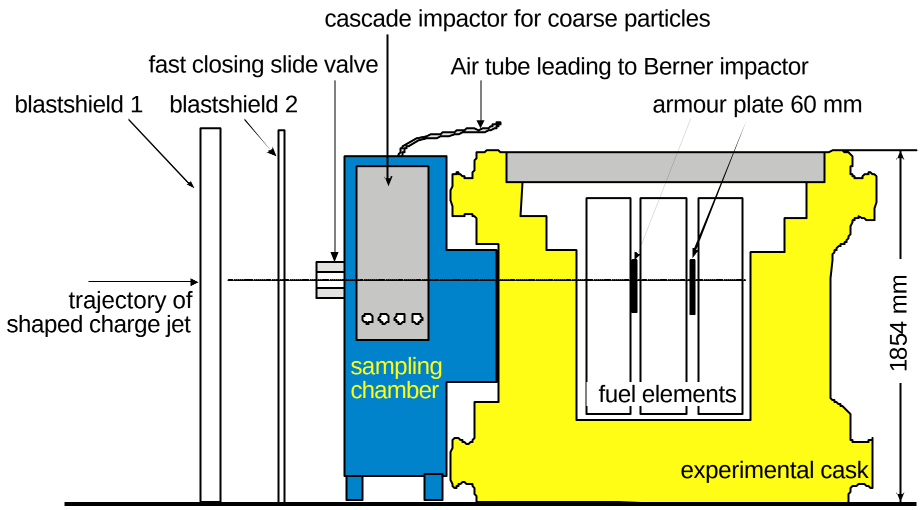

Fig. 1: Side view of experimental set-up

3 EXPERIMENTAL SET-UP

The principle experimental configuration is shown as side view in Fig. 1. The cask has original lateral dimensions of a CASTOR type spent fuel cask (CASTOR IIa) except in length (vertical direction in Fig. 1) which is of 1/3 scale. Accordingly the fuel elements placed inside the fuel basket in a 3 x 3 array were shortened in length but otherwise of original dimensions. From left to right are shown: the position where the shaped charge was triggered, a first and second blast shield, the sampling chamber including a cascade impactor for coarse particles, sampling lines to different aerosol measuring instruments and a fast closing slide valve, and the experimental cask.

The lid on top of the cask was not of original design but was adapted to the experimental needs. It had feedthroughs and flanges to measure the time dependence of the internal pressure build-up after a shot and to be able to produce sub-atmospheric pressure levels inside the cask as applied for interim storage in Germany and sometimes also for transport.

4 EXPERIMENTAL PROGRAM AND RESULTS

A penetrating shaped charge jet creates a channel through the front cask wall and can damage fuel elements on its further way inside the cask until its kinetic energy has been consumed. In this way fuel rods may be breached and affected fuel pellets can be pulverized to some extent. The action of the jet itself, associated ingression of hot detonation gases and in addition depressurization of damaged fuel rods result in an overpressure inside the cask. This will lead to a short term release of gases and dust particles through the penetration channel. In real conditions some of the released gases and dust particles resulting from damaged fuel rods and pulverized spent fuel pellets will be radioactive. The source term from the cask will be made up of some fission gases and, more important, of aerosol particles containing fission products, activation products, uranium and other actinides.

The main and essential part of the experimental program was conducted in the following way:

- The experimental cask was filled with 9 fuel elements in a 3 by 3 configuration and then closed on top by the lid. This allowed three different shaped charge shots to be fired onto the cask in such a way that each time one row of three undamaged fuel elements were in line with the shaped charge jet.
- The dust materials which were released through the penetration channel and deposited on different sampling media were collected for further analysis after each shot. The penetration channel of the shaped charge jet through the cask wall was sealed with suitable material. The sampling chamber and the aerosol instruments were prepared for the following shot.
- After a total of three conical shaped charge shots the lid of the cask was removed, fuel elements were removed and the damage to the cask and to fuel elements assessed.
- For the third and last shaped charge shot the internal pressure inside the experimental cask was reduced to 0.8 bar in order to determine the effect of initial below atmospheric pressure on the release from the cask. A pressure of 0.8 bar is an upper limit for conditions during interim storage of spent fuel casks in Germany.
- Dust samples collected on the different sampling media were weighed and later analyzed in the laboratory. This included especially a distinction between the uranium component of the release and other materials by gamma spectrometry. A calibration factor relating the intensity of characteristic gamma radiation to the DUO_2-mass of a sample was used for this.
- As a precaution two armor-plates of 60 mm thickness were inserted into empty spaces of the fuel basket structure because the penetration potential of the shaped charge jet was not known well enough for this special experimental configuration. Without going into detail here the experimental results indicate that the introduction of this additional material inside the cask had no important effect on the measured release from the cask.

The experiments combined the quite rough environment of a shaped charge detonation with a rather delicate experimental set-up including aerosol instruments to collect and analyze the total material release from the breached cask. In the course of three pre-test shots the equipment and its performance had been tested and improved in such a way that the main experiments could be conducted without serious problems.

The main experimental results concerning the released uranium masses are summarized in Table 1. In addition to the data given in Table 1 particle size distributions have been measured for the size range below 12.5 µm. The release of particulate matter from the breached cask is dominantly a short term release. Less than 1% of the total release of fine (< 12.5 µm) particles was registered after 30 s. The first two shots with atmospheric pressure inside of the experimental cask gave reproducible results of 1 g of released uranium mass in the size range < 12.5 µm and of about 2.6 g in the size range between 12.5 µm and 100 µm. A sub-atmospheric pressure of 0.8 bar inside the cask had a noticeable effect on the amount of released particulate matter: The released uranium mass in the particle size range < 12.5 µm was 0.4 g and about 0.3 g between 12.5 µm and 100 µm. From the visual inspection of the damage of spent fuel elements by the shaped charge jet after opening the cask it could be concluded that the release of uranium dust through the entrance channel of the shaped charge jet is dominated by the first fuel element in a row of three.

Table 1: Uranium mass release [g]

aerodyn. diameter AED [µm]	pressure inside cask normal	0.8 bar
< 12.5	1.0	0.4
12.5 - 25	0.7	0.1
25 - 50	1.0	0.1
50 - 100	0.9	0.1

5 ESTIMATION OF SOURCE TERM

In order to estimate potential radiological consequences from a shaped charge attack on a spent fuel cask the experimental findings with DUO_2 as surrogate material have to be used to derive the source term for spent fuel. From the experiments the masses of released uranium dust are known. Two effects can influence the extrapolation to spent fuel: The process of partial pulverization of fuel pellets by the action of the shaped charge jet can differ to some extent between unirradiated UO_2 and burned-up fuel. The spent fuel contains uranium, other actinides and fission products. For some more volatile elements the interaction of the shaped charge jet with penetrated spent fuel can result in an enhanced release in the fine particle range (< 12.5 µm) compared to the release of non-volatile elements such as uranium and other actinides. This effect is interpreted to result from evaporation processes and consecutive attachment to the large number of generated fine dust particles.

Experimental results given in /SAN 83/ indicate that the dust production from spent fuel and from fresh fuel by the interaction with a shaped charge jet is comparable. This could be the result of two counter-acting effects: On the one hand, irradiated fuel pellets have a reduced compressive strength due to fissures, cracks and other structural effects induced during operation in the reactor core. This could enhance particulate production from shaped charge interaction. On the other hand, a reduced material strength reduces the lateral propagation of shaped charge induced stress, thereby leading to less particulate production. The other effect, enhanced release of some potentially more volatile fission product elements compared to the release of uranium, other actinides and non-volatile fission products is taken into account by applying enhancement factors for particles in the respirable size range. The following enhancement factors for particles below 12.5 µm AED have been conservatively determined based on experimental findings /ALV 81, SCH 82/ when deriving a source term from shaped charge attack on a spent fuel cask:

Cs, Te, I 50	Ce, Sr, Y, Ba, Pr, Pm, Sm 5	Eu....................... 3
Ru, Rh, Sb 10		Others 1

For the derivation of a source term which is representative of a modern CASTOR type monolithic cask and for higher burn-up conditions the radionuclide inventory per g of spent fuel was calculated for a burn-up of 55 GWd/tUO_2 and a cooling period of 5 years. This data in connection with the above given element-specific enhancement factors was used to calculate the radionuclide-specific activities released after shaped charge attack of a spent fuel cask. The source term includes released activities of relevant radionuclides as function of the aerodynamic diameter size range corresponding to the experimental results given in Table 1. In addition for radioactive noble gases (Kr 85) and H 3 it was conservatively assumed that from fuel pins which lose their internal gas pressure by the action of the shaped charge there would be a 100% release. On average 20% of all fuel pins of one row of 3 fuel elements were found to be breached in this sense.

6 RADIOLOGICAL CONSEQUENCES

On the basis of the source term derived from the experiments calculations of potential radiation exposures of individuals in the vicinity of a breached spent fuel cask have been made. From the experimental findings it could be concluded that the action of the shaped charge leads to an almost instantaneous release of radioactive material through the penetration channel. The released airborne material will be entrained in the highly turbulent surrounding air and hot explosion gases which result from the explosion of the conical shaped charge very close to the spent fuel cask. An atmospheric dispersion model was therefore applied which is capable of adequately simulating the following boundary conditions:

- Near ground-level release of gaseous and particulate material in the size range up to 100 µm
- Short term release within a few seconds following the detonation
- An initial configuration of released airborne material which is approximated by a rectangular column of 10 m by 10 m cross-section and 20 m height homogeneously filled with the released airborne material with given particle size distribution.

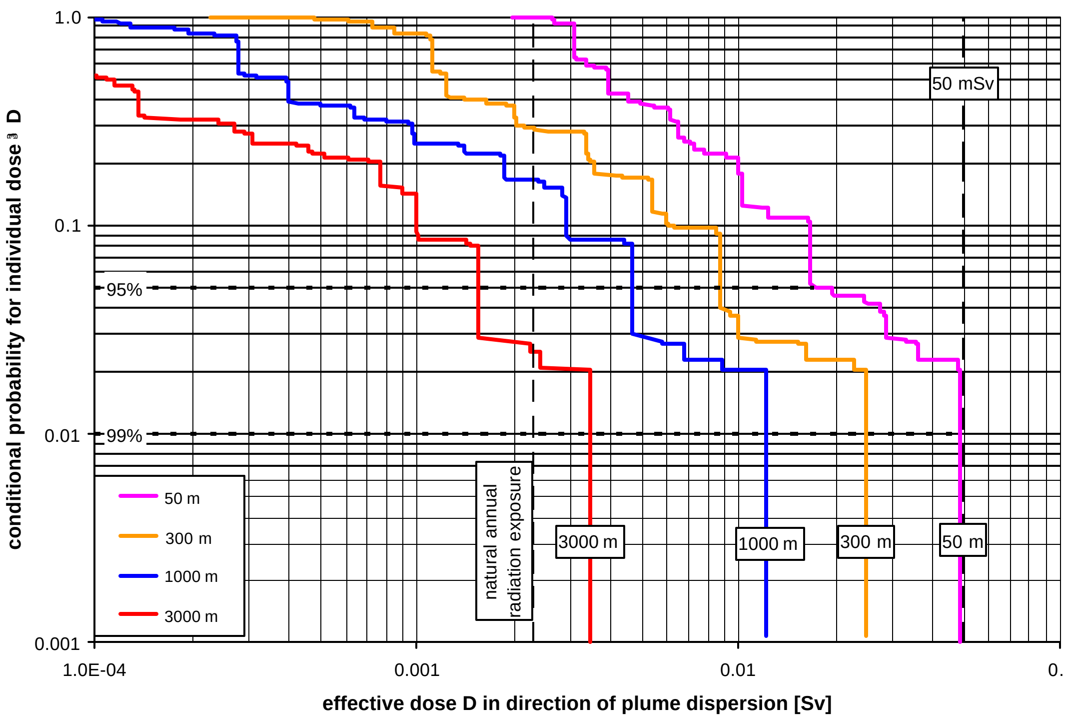

Fig. 2: CCFD of inhalation dose - particles AED < 12 µm (adult, ICRP 72 dose coefficients)

The applied atmospheric dispersion model LASAT /JAN 00/ is a Monte-Carlo type particle model and utilizes modern turbulence parameters for the calculation of short term dispersion and deposition processes in the atmospheric boundary layer /KER 00/. It has recently been officially proposed by the Society of German Engineers /VDI 00/ as atmospheric dispersion tool for industrial applications.

Quite elaborate dispersion and deposition calculations have been performed for a multitude of atmospheric dispersion conditions taking into account four particle size intervals < 12.5 µm, 12.5 – 25 µm, 25 – 50 µm and 50 – 100 µm AED. These results were then used to derive cumulative complementary frequency distributions (CCFD) of ground-level air concentrations and deposition levels in downwind direction from the location of a release and resulting effective doses from inhalation and ground-shine taking into account the broad spectrum of atmospheric dispersions conditions and their respective frequency of occurrence. Weather data typical for large parts of Germany and more or less flat terrain have been used for this purpose.

As one of the results a cumulative complementary frequency distribution of potential effective dose from inhalation is shown in Fig. 2. The probability, conditional that a release occurred, of certain effective doses of a person residing at a given distance in downwind direction from the location of a release can be read from the curves. The results show that close by (50 m) and more so for larger distances even for rare and unfavorable weather conditions inhalation doses which are dominated by released actinides, e.g. Pu-isotopes, remain below a dose of 50 mSv.

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