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INTERNATIONAL WORKING GROUP FOR SABOTAGE CONCERNS OF TRANSPORT AND STORAGE CASKS

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ABSTRACT

The International Working Group for Sabotage Concerns of Transport and Storage Casks, IWGSTSC, gathers multiple organizations from different countries (For US party DOE, NRC, and Sandia National Laboratories, for German party GRS and Fraunhofer Institut, for the French party IRSN). The goal of the IWGSTSC is to continue cooperation to improve the analytic capabilities, through information sharing and collaborative research and development plus modeling, to understand the potential adverse public health effects and environmental impacts of radiological sabotage directed at or associated with the transport and storage of civilian nuclear material or other civilian radioactive materials. The Parties may also undertake collaborative research and development in other areas of the physical protection of civilian nuclear materials or other radioactive materials.

Since 2000, the International Working Group for Sabotage Concerns of Transport and Storage Casks has conducted an extensive test program for the assessment of the aerosol source term produced in the case of spent fuel transport sabotage by a high energy density device, after having examined several scenarios. The major goal of this program is to produce an accurate estimate of the so called spent fuel ratio in the domain of respirable, aerosol particles produced. All the reports prepared by Sandia National Laboratories have precisely emphasized the important efforts they have made from the beginning and the amount of work already accomplished.

In parallel, the IAEA, assisted by technical experts from different countries, has provided a draft document promised to become guidance for the security of radioactive or nuclear materials during transport. The IAEA document contains general guidance addressed to anyone who intends to implement or improve the security of material transports, but the text is, as of today, limited to rather general recommendations.

Based on all the knowledge accumulated from past experiments and also based on the work done in Vienna at the IAEA, the IWGSTSC members have decided to work on the development of a method for the evaluation of the vulnerability and the source term. So for doing that, joint projects for the research, development, testing, and evaluation of the consequences of the malevolent actions during transport are being pursued and will be described.

INTRODUCTION

The shipments of nuclear material may constitute targets for potential radiological sabotage. Considering the number of shipments carried out every year, this threat is a concern for every country involved in the nuclear industry and must be addressed. Among all shipments, spent nuclear fuel materials are the most sensitive from the point of view of this sabotage threat as such materials have the potential to cause significant radiological consequences if released to the environment. The design of the casks based on safety considerations contributes to enhance their resistance against sabotage attacks. However, attacks using high energy density devices (HEDD), like conical shaped charges, may lead to significant damage to the shipment casks and to the fuel assemblies they contain. Then, aerosolized particles derived from disrupted fuel pellet materials may be released.

Significant prior work has been conducted in the U.S., Germany, and France to assess the potential impacts of hypothetical sabotage events on spent fuel casks, and to develop source terms for aerosol materials created as a result of HEDD impacts. Prior reports (1–3) have provided a good summarization of the various sabotage studies and aerosol experiments that have led to the conduct of the current test program.

The International Working Group for Sabotage Concerns of Transport and Storage Casks, IWGSTSC, gathers multiple organizations from different countries (For US party DOE, NRC, and Sandia National Laboratories, for German party GRS and Fraunhofer Institut, for the French party IRSN). The goal of the IWGSTSC is to continue cooperation to improve the analytic capabilities, through information sharing and collaborative research and development plus modeling, to understand the potential adverse public health effects and environmental impacts of radiological sabotage directed at or associated with the transport and storage of civilian nuclear material or other civilian radioactive materials.

AEROSOL RELEASE - EXPERIMENTAL PROGRAM

The primary goal of the current surrogate/spent fuel aerosol ratio test program is to conduct experiments and supporting analyses to measure the aerosol, primarily respirable particles produced from sabotage by a high-energy density device, HEDD, on spent fuel rods in a transport or storage casks. Previous presentations have presented the progress and details of the program (4-5). The anticipated product of this program is accurate data that verify and significantly extend prior broad estimates of the ratio between the amounts of aerosols generated from actual spent fuel versus surrogate materials when struck by an HEDD. Subsequent more accurate risk analyses could provide a better estimate of the hazards and potentially result in safer and significantly less expensive transportation and storage of the spent nuclear fuel.

The main objectives of the current test program include:

- To provide reliable information for overall radiological consequence assessments for transportation sabotage scenarios, in support of the test and analysis activities of the WGSTSC members;
- To provide technology transfers and support to NRC, DOE, IRSN, GRS, and other vulnerability studies, by providing data and analyses for computer modelling of HEDD attacks against nuclear materials;
- To support participants National Authorities' assessments of the physical protection requirements for nuclear materials in use, storage, and transport.

Aerosol particle testing requires sampling and measurement of the mass and physical characteristics of the aerosol particles produced from (spent fuel or surrogate rod) target-HEDD jet impact, with particle aerodynamic equivalent diameters (AED) up to 100 µm (micrometers). The AED is defined by means of the settling velocity of a unit density sphere, and is equivalent to the particle geometric-diameter times the (particle density)$^{1/2}$. For evaluations of aerosol and radiological consequences, there has always been a special emphasis on respirable particles, commonly defined as 0 to ≤ 10 µm AED in size. Data from the coarser aerosol particles in the ~ 10 to 100 µm AED range, termed the *inhalable* fraction, are of interest primarily for radiological "ground-shine" (dispersion, soil contamination, potential ingestion) consequence estimates. Particles larger than 100 µm are not considered to be aerosols. Multistage aerodynamic particle sizing devices (impactor collectors) are used to classify aerosol particles according to their aerodynamic diameter.

This experimental program is designed to measure several important features of the interaction of a HEDD jet with spent fuel or surrogate material pellets contained within a Zircaloy-4 ™ cladding tube. The source-term data measured includes :

1. The Respirable Fraction, RF. There is special emphasis on the particle respirable fraction produced, defined as the mass of an element (i.e., U, Ce, Zr, Cs, etc.) in respirable particles / mass of that element in the rod volume swept (particulated) by the HEDD. This RF is particularly relevant to (released to the far-field) airborne dispersion and consequence modeling studies. The particle size distribution is also measured for all aerosol particles produced, as a function of chemical element, from 0 to 100 µm AED:

2. The SFR determination is, essentially, the comparison of the respirable, aerosol particle data from irradiated fuel to unirradiated surrogate fuel. These data are obtained in paired experiments using the same apparatus, essentially identical test conditions, and using the same HEDD. The SFR will be calculated from respirable, aerosol particles. The measured SFR values provide a data bridge to previous large-scale surrogate (depleted uranium oxide, DUO_2) cask tests [2, 7] and subsequent consequence assessments [6], etc.. The SFR values permit scaling to other geometries, single fuel rod to rod bundles, by means of supporting modeling studies. The primary test benefit of using the ratio of respirable, aerosol particles for the SFR determination is that it is not necessary to recover and analyze all of the aerosolized materials produced; only the identical portions of aerosol particles from both the spent fuel and surrogate fuel tests must be obtained, analyzed, and compared.

   SFR = [Spent Fuel respirable particle masses] / ["Surrogate" DUO_2 respirable particle masses]

3. The measurement of enhancement of volatile fission product nuclides like cesium and, to a lesser extent, ruthenium, preferentially sorbed onto specific, respirable particle size fractions in the sub-µm to µm size range. This enhanced sorption is expressed as an "Integrated Enrichment Factor," defined as:

   Integrated Enrichment Factor = $RF_{(\text{fission product element})}$ / $RF_{(\text{uranium or cerium pellet material})}$

The current, overall program consists of four linked test phases, to be conducted in a sequential, cost-effective, and safe manner. Individual tests in each phase will use the same type of HEDD, but different test materials, with a similar geometry. Each individual test and test phase helps to "calibrate" or optimize the succeeding test phases, allowing us to fine-tune the test system and individual components, while providing an indication of anticipated system response and results. Successive phase testing allows us to add and evaluate multiple test variables and pellet response to HEDD jets.

Phase 1: The preliminary Phase 1 tests were conducted by Sandia National Laboratories, SNL, and Institut Toxikologie und Experimentelle Medezin Fraunhofer aerosol experts using glass pellets and leaded glass plates as representative brittle materials. Six of these tests were performed in 2002, two with glass pellets contained in a Zircaloy cladding tube, four with leaded glass plates; leaded glass was selected because it has a higher density, closer to that of uranium oxide fuel. These glass brittle materials were impacted by a HEDD jet using the same test apparatus to be described for the Phase 2 tests. This test phase included performance quantifications of the HEDD devices and refinement of the aerosol particle collection apparatus being used. Phase 1 test conduct was completed in 2002.

Phase 2: The more extensive Phase 2 tests used nonradioactive cerium oxide, CeO_2, in sintered ceramic pellets contained within a Zircaloy cladding tube assembly. CeO_2 is an excellent chemical "surrogate" material for both UO_2 fuel material and PuO_2, and a representative ceramic for spent fuel UO_2 pellets. The cerium oxide has a density and melting point similar to those values of uranium dioxide, certainly more similar than those of glass. The Phase 2 surrogate tests allow us to evaluate multiple test variables, pellet and rod responses to HEDD jet impacts, and to fine-tune the experimental setup. The use of cerium oxide pellets is intended to bridge the program from the initial Phase 1 tests with glass, to a lesser number of advanced, slightly radioactive tests with DUO_2 pellets. The Phase 2 tests were initiated in September 2002 and are now completed.
As such, the goal of the overall test program with the surrogate materials is to compare and "calibrate" the subsequent Phase 3 DUO_2 tests and results with the more extensive data obtained from the Phase 2 cerium oxide pellet tests. Nonradioactive volatile fission product (species) enrichment measurements will also be performed.

Phase 3: The Phase 3 tests use slightly radioactive, depleted uranium oxide, DUO_2, pellets in comparable size, new Zircaloy cladding tube test rods; these test rodlets were fabricated in France for testing at Sandia National Laboratories. Phase 3 tests, performed in sealed, explosive-aerosol chambers with multiple aerosol particle measurement apparatus, have been in progress since 2005. Recent progress and results from Phase 3 DUO2 tests will be presented in a separate PATRAM paper.

Phase 4: The Phase 4 tests will use fully radioactive, actual spent fuel pellets in short test rodlets. Two types of spent fuel will be included in the test program. The first is high burnup, ~ 72 GWd/MTU (Gigawatt days per metric tonne of uranium) spent fuel, originating from the H.B. Robinson pressurized water reactor. The second is low(er) burnup, ~ 36 GWd/MTU spent fuel, originating from the Surry pressurized water reactor. Both fuels have been characterized and are being fabricated into test rodlets at Argonne National Laboratory, ANL, for HEDD-impact aerosol testing in the Gamma Irradiation Facility (GIF) at Sandia National Laboratories

The main result of the on going program and, according to the recent experiments reported by Sandia National laboratories [6], a respirable fraction ranging from 1% to 2% was experimentally measured instead of the previously estimated 5% [3]. The following tests of the second part of the Phase 3 and the Phase 4 will refine the value of the respirable fraction.

RELATED TO AEROSOL TESTING

In 2004, after five years of multiple party collaboration as described, the IWGSTSC working group began modeling considerations on the phenomenon of the release of material outside of a cask. Some numerical modeling was performed to simulate the past tests [2, 7], the interaction between the fuel rod and the HEDD jet. The objectives of these simulations were to propose analytical tools in order to interpret or to describe mechanical behaviour of the fuel rod during the impact. This phenomenon was not adequately accessible with the devices dedicated primarily to aerosol quantification. The modelling has permitted us to identify the most influential parameters which govern the aerosol particle release. The results obtained by the modeling simulation have better demonstrated:

- The capability to interpret experimental observations from the past tests
- The prediction of the difference to be observed between sabotage damaged actual spent nuclear fuel or tested surrogate cerium oxide pellet rodlets
- To model a more sophisticated test or real case with multiple fuel bundles in a cask
- To extrapolate to another type of fuel rod (fresh fuel, different burn-up of irradiated fuel, MOX, etc. …)

Moreover, it appears that the results of the present IWGSTSC experimental program gave results of only limited parameters governing the interaction between HED and shipping cask. For a better comprehension of the phenomena attached to a shaped charge jet penetration versus shipping cask, some questions have been discussed during the meetings:

- The driving phenomenon concerning the release of material, e.g., internal pressures, temperatures, hole sizes, etc.
- Knowing the quantity of released material outside of the cask
- Qualification of the volatility of a fission products within spent fuel with regards to a shaped charge passing
- Aerosol transfers and deposition within the cask .

To give a first answer of these questions, it has been decided to define a benchmark to simulate the interaction between a HEDD and a simplified mock-up of shipping cask with simplified models or numerical simulations using a hydrodynamic computer code. The parameters which were studied were the wall penetration (depth and diameter), number of breached pins, pressure and temperature build up, blow down release from the cask, total source term with particle size distribution, source term (mass aerosolized, mass respirable and mass deposited near field). Each parameter was quantified with the range of uncertainty.

One of the key point of this benchmark is to estimate the rank of priority of phenomena/processes and parameters/boundary conditions. First, one collects the estimates on how uncertain parameters and phenomena of the full processes are and the engineering judgement on how important a consideration of this phenomenon or process is. Second, one includes a list of potential parameters or boundary conditions of the planned real scale experiments.

The identification of the main parameters which govern the interaction between a HEDD and a shipping cask is needed to be confident in the order of magnitude release evaluation. It also helps to establish and plan the objectives of a further experimental campaign, if some important omissions of physical phenomenon understanding are identified.

The benchmark results collected to date have allowed us to prioritize the effects versus their importance in terms of radioactive aerosol release outside the cask. After some internal exchanges, the scientific experts have updated the ranking table, and four main phenomena have been identified which could be studied further:

- pressure and the temperature build up inside the cask,
- Aerosol deposition (thermophoresis) within components inside the cask,
- Release from the cask (driven and not driven by blow down),

This approach will help the common, cooperative IWGSTSC experimental program which takes all interests into account and helps to identify future work priorities.

CURRENT AND POSSIBLE FUTURE WORK FOR THE IWGSTSC

The IWGSTSC has initiated and performed a test program for the assessment of the source term produced in the case of spent fuel sabotage by a HEDD. A major objective is to produce an accurate measured value of the spent fuel ratio for the respirable fraction of the aerosol produced. According to the recent experiments reported by Sandia National Laboratories [6, and this PATRAM Conference], a measured spent fuel/surrogate respirable fraction ranging from 1% to 2% could be considered instead of the previously predicted [3], much more conservative 5% value.

IAEA, assisted by technical experts from different countries, has provided a draft document promised to become guidance for security of radioactive or nuclear materials during transport. This general guidance will be dedicated to implement or to improve the security of nuclear materials during transport. The IWGSTSC has provided to the members of the parties some scientific information which is necessary to design the physical protection and the responses force. This IWGSTSC group proposes technical information which are complementary to the IAEA guidance which provide security principles or basic rules to implement security during transport.

So, taking into account fruitful discussions between technical experts during the meetings, the IWGSTC has identified a need for an intermediate approach between high precision dedicated experiments and general guidance, based on

- the knowledge of the past experiments
- the aerosol test results obtained from the IWGSTSC test program on-going at Sandia National Laboratories
- the numerical simulations benchmark discussed herein
- the priorities of ranking parameters tables
- the draft guidance document from the IAEA

This approach should gather the principal techniques and facts on the subjects of sabotage consequences evaluation and become a basis for technical guidance for transport experts.

In summary, the IWGSTSC has defined the scope of future collaborations :

- Informal information exchange,,
- Cooperative joint data interpretations and modelling,
- Common projects,
- Agreements and framework.

In this framework, some topics are still considered as open questions by the group, and need to be investigated in the future. Among them, one finds the scaling of release process question, the influence of target position, the definition of a commonly recognized and accepted approach to cope with the full scale problem, etc.

Information developed in this IWGSTSC program may be used to guide development of future transportation security plans. This program also complements efforts to build and maintain strong collaborative relationships with multiple international partners, to counter potential nuclear sabotage activities. The data obtained will be shared with all participating IWGSTSC partners. These objectives may be expanded in the future as the program progresses.

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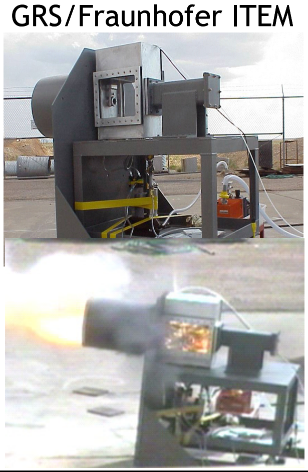
AEROSOL RELEASE - EXPERIMENTAL PROGRAM

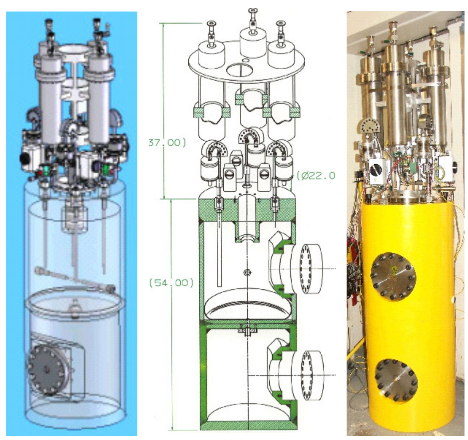
Figure 1

Phase 1	Phase 2	Phase 3	Phase 4
Glass	CeO_2	Depleted UO_2	irradiated UO_2
~ 15 shots	~ 30 shots	6 fuel rods Provided by IRSN	8 fuel rods Provided by ANL
2001-2002	2002-2004	2006	2009

Device designed by GRS/Fraunhofer ITEM



Tweety bird hot cell



Shots in hot cell