DEVELOPMENT OF NUMERICAL METHODS FOR VULNERABILITY ASSESMENTS

Anna-Lena Becker, Christopher Ole Gerber, Mark Pelzer
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH
Cologne, Germany
E-Mail: Anna-Lena.Becker@grs.de
Ole.Gerber@grs.de

ABSTRACT

The protection against the release of radioactive material through sabotage is one of the primary objectives of the state´s nuclear security regime. Among other things this also applies to transports of such radioactive materials, which is why the state should specify which transports require protection against sabotage because of the potentially caused unacceptable radiological consequences. The potential radiological consequences of a successful act of sabotage can be determined by a quantitative estimate as part of a vulnerability assessment for a transport. In Germany a nuclear transport is classified into a security category that combines threats against unauthorized removal and sabotage, so the assessment of the potential consequences is part of this classification. The potential radiological consequences of sabotage are calculated by using both analytical and numerical tools, and these calculations are based on established and verified methods of calculating release and dispersion processes. In order to develop such methods for potential sabotage scenarios and release processes, both an experimental basis and a development of numerical models are essential. Within the scope of two research projects, the German expert and research association for nuclear safety and security GRS investigates release processes caused by the impact of a shaped charge in the form of a two-phase (particle loaded) discontinuous free jet, which is emitted from a package. The goal of our research activities is to analyze whether numerical simulations using CFD (Computational Fluid Dynamics) software enables an improvement of the accuracy and flexibility of the calculation methods. The outflow behavior of a discontinuous free jet is considered in the simulations, systematically evaluated, and then compared to experimental data collected in the course of one of the research projects. It is shown that a good data basis could be created based on experiments and that the results of the simulations to date can reproduce them well. An application of these methods in future vulnerability assessments is discussed.

1. INTRODUCTION

Each year there are approximately 400 transports of nuclear material in Germany [1]. One of the primary objectives of the state´s nuclear security regime for transports is to protect the nuclear material against unauthorized removal and sabotage. The transports are therefore classified in different categories. In terms of the risk of unauthorized removal the material to be transported is categorized into one of the three categories according to the Convention on the Physical Protection of Nuclear Material (CPPNM) [3]. Most transports fall into Category III, while a few are sorted into Category I and II with respect to unauthorized removal. For unauthorized removal, the categorization is based on a simple evaluation scheme. The categorization with respect to sabotage instead requires a more detailed examination in form of a vulnerability assessment, which in Germany is carried out with analytical and numerical models and tools. These models and tools are created and improved based on experimental data, which is an ongoing process.

The following section 2 describes the German security regime for transports with a focus on sabotage and a look at the international recommendations on this subject is given in section 3. This will explain why vulnerability assessments are necessary and what the basis for such assessments are. The research projects building on this basis take a closer look at the effects of anti-tank weapons, which may be of interest in considerations. The outflow from a package as a result of such an impact is investigated and recorded with experiments, which are described in section 4, and simulations based on them, which are described in section 5. Finally, Section 6 provides an overview of the research conducted and an outlook for possible future applications of the results.

2. GERMAN SECURITY REGIME FOR TRANSPORT

The Atomic Energy Act (AtG) is the legal basis of the German security regime for the transport of nuclear material. The AtG states in § 4 para. 2 “A license shall be granted provided that […] the necessary protection has been provided against disruptive action or other interference by third parties” [2]. There are three main security objectives, which have been defined to ensure this protection and have to be fulfilled by the operator. These three main security objectives according to § 42 AtG [2] are:

- Protection against sabotage: Prevention of hazards to life and health as result of considerable direct radiation or the release of a substantial quantity of radioactive material.
- Protection against unauthorized removal: Prevention of a single or repeated unauthorized removal of nuclear material in quantities that are sufficient for the direct manufacture of a critical assembly without reprocessing and enrichment.
- Protection against release after unauthorized removal: Prevention of a single or repeated unauthorized removal of nuclear material in quantities that are sufficient for hazards to life and health as a result of considerable direct radiation or the release of a substantial quantity of radioactive material at a different location.

In the following, the focus is on protection against sabotage. In general, a categorization regarding the risk of sabotage must be carried out for each nuclear transport. In such a categorization, it is examined whether, with the boundary conditions laid down in the Design Basis Threat (DBT), an exceedance of the specified dose limit with unacceptable radiological consequences is to be expected. The DBT defines the adversaries, tools, and scenarios against which the licensee must provide adequate protection. Based on the DBT, a vulnerability assessment is performed in which the possible consequences of sabotage are determined. If, under the assumptions to be made, an exceedance of the defined dose limit is to be expected and thus a significant release cannot be ruled out, the transport is designated as "relevant with regard to a possible release of radioactive substances by sabotage” and increased security measures must be implemented.

3. INTERNATIONAL RECOMMENDATIONS

The previously described German approach is in good agreement with the nuclear security recommendation IAEA NSS 13 [4] and the implementing guide IAEA NSS 26-G [5] of the International Atomic Energy Agency (IAEA), which give recommendations, guidance and implementation suggestions on the risk and assessment of sabotage. IAEA NSS 13 emphasizes the importance of implementing protection requirements that correspond to the potential radiological consequences, based on the graded approach to physical protection. Therefore, in order to identify the necessary protection requirements, it is crucial to determine the potential radiological consequences of sabotage using the DBT. This can be achieved through a vulnerability assessment, as elaborated in IAEA NSS 26-G.

IAEA NSS 26-G suggests that a quantitative estimate of the potential radiological consequences of sabotage based on the DBT may involve using theoretical and numerical tools to evaluate the impact of weapons that an adversary could use on packages containing nuclear material. The IAEA recommends using experimental data to obtain the most accurate results possible.

Based on the assessment, it should be determined whether existing measures and barriers can prevent sabotage or what the extent of potential radiological damage would be. If the assessment reveals potential unacceptable radiological consequences, countermeasures such as additional barriers, providing a sufficient delay, or preventing access to the package should be implemented, according to IAEA NSS 26-G. Furthermore, the amount of radioactive material that could be released by an act of sabotage and the activity of various radionuclides in that material, including those released in respirable form, should be assessed. This estimate can be used as a source term to calculate possible doses to individuals in the vicinity of the shipment in the event of sabotage. Based on this information, it should be determined whether the radiological consequences of sabotage are unacceptable according to the State's definition.

4. EXPERIMENTS

Apart from the actual specifications in the DBT for a vulnerability assessment, it is of great interest for current and future developments under which assumptions and scenarios a significant release due to sabotage could be expected. Therefore, both established and new weapon types and tools and their mode of action must be understood, and their effects made quantifiable to the extent possible. A relevant development is constant advancement and spread of weapons with ever greater penetration depths and ever better precision. For example, anti-tank weapons using the shaped-charge principle could be used to violate the integrity of heavy packages and thus cause the release of radioactive materials. The impact of such a weapon should therefore be understood in order to assess possible consequences.

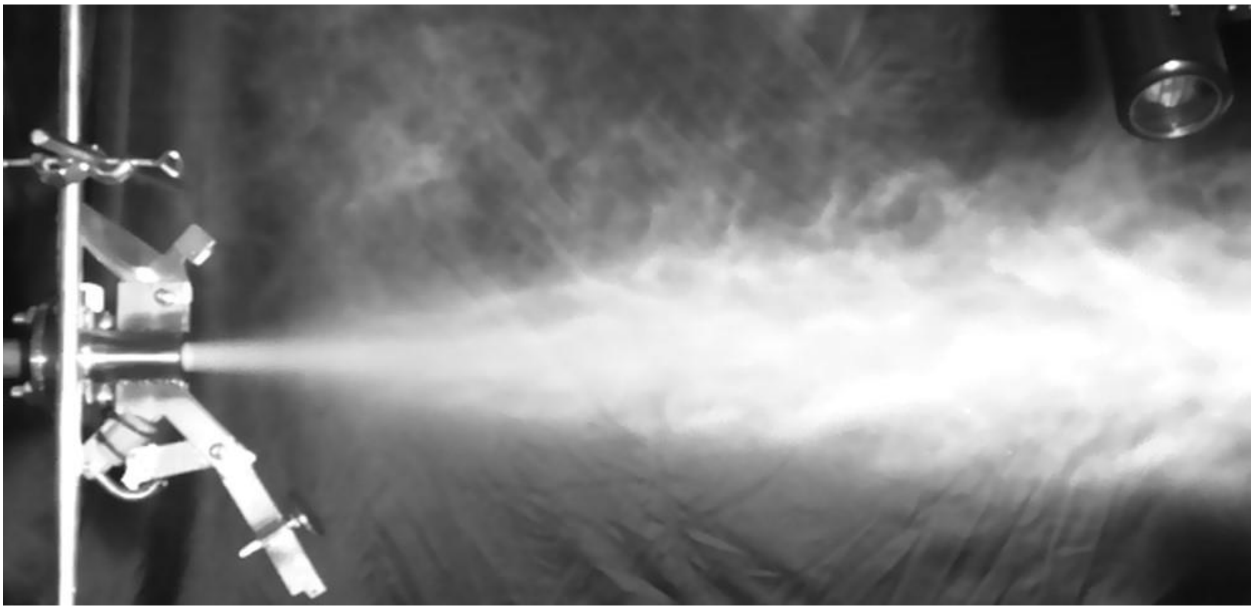

Fig. 1 Image of an emerging two-phase (particle loaded) free jet taken during the experiments

The impact of an anti-tank weapons on a package is a highly dynamic process. In order to understand these processes and to make them quantifiable so that possible radiological consequences of a release can be derived from them, experimental data have already been collected. However, further experiments are necessary to be able to create analytical and numerical models based on this data.

An essential process to be understood during the impact of an anti-tank weapon is the outflow of the filling gas, loaded with radioactive particles because of the impact, from the damaged package into the open environment. In this case, the radioactive particles were generated by the partial destruction of the inventory and the container gas may reach an overpressure with respect to the environment due to the heat release as a result of the impact, which leads to an outflow process. Such an outflow process through a relatively small hole, as produced by an anti-tank weapon, can be described by the physical phenomenon of a free jet. An example of such a free jet is shown in Fig. 1.

The physics of a stationary gas free jet is known in principle in the literature, but the phenomenon described above is a transient two-phase (particle-loaded) free jet. The decay of the overpressure is very fast, and the particles can have a large contribution to the energy and momentum of the free jet. No physical models or experimental data can be found in the literature for such a free jet. Therefore, in order to create a numerical model to perform a simulation describing a transient two-phase (particle loaded) free jet, it is first necessary to create through experiments the necessary experimental basis for later optimization and validation of such a model. The establishment of such a basis and a basic understanding of the properties of a transient two-phase (particle loaded) free jet were established by experiments.

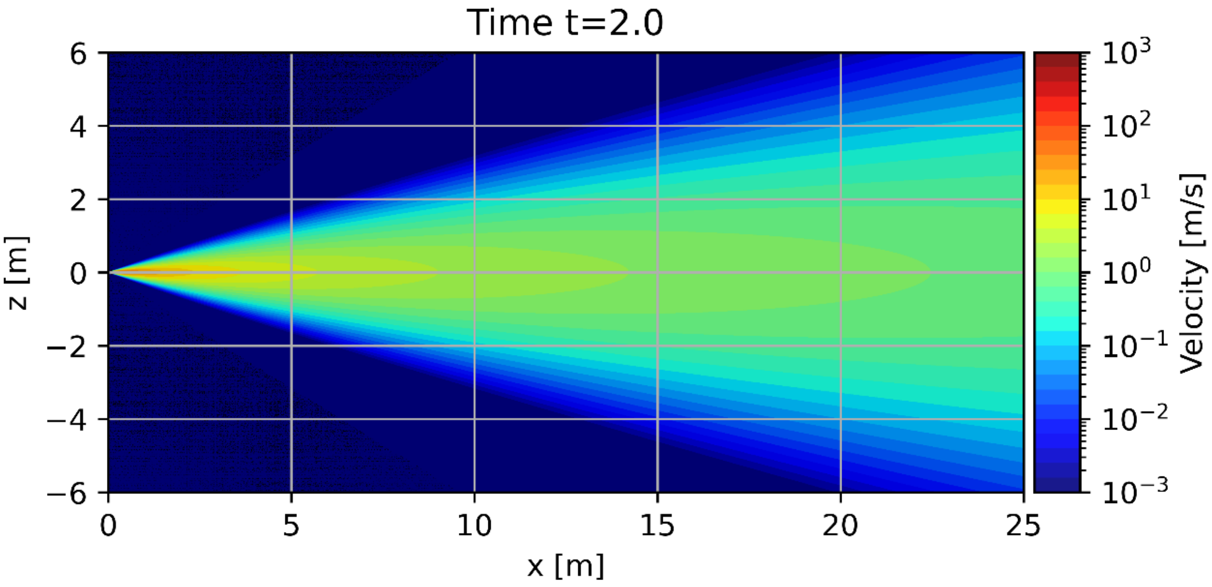

Fig. 2 Exemplary representation of an analytical model for the velocity field developed from experimental data

A transient particle-loaded free jet was investigated experimentally. For this purpose, measurement facilities were set up in the laboratories of the Technical University (TU) Dortmund together with the Chair of Fluid Mechanics of the Faculty of Bio- and Chemical Engineering and tests were carried out by varying the test parameters. A total of over 300 individual tests were carried out with five variations of the test parameters using different measurement techniques, which allow both quantitative and qualitative evaluation. A Phase-Doppler-Anemometer was used to determine the velocity and particle diameter of particles at different measurement positions. The results of the experiments allow statements to be made on the outflow behaviour, the velocity field, and the influence of the particles on a transient multiphase free jet. Analytical models, as exemplified in Fig. 2, were developed on the basis of the experimental data, with which the time-dependent and particle size-dependent propagation of the particle loaded free jet can be calculated. This work enables optimisation and validation of numerical models.

The results of the experiments are comparable with literature values. Furthermore, the results provide a data basis of processes that have not been investigated so far. Accordingly, simulations can be developed based on these experiments. This is explained in more detail in the following section.

5. SIMULATIONS

The aim of the research projects described in this paper is to be able to simulate and calculate the effects of sabotage scenarios as generically as possible for different transport configurations. As a first step, an experimental basis was developed for this purpose. The next step is to use this as a basis for designing a numerical simulation that can be used to reproduce the results of the experiments. For these simulations ANSYS FLUENT, a commercial software tool for CFD, is used.

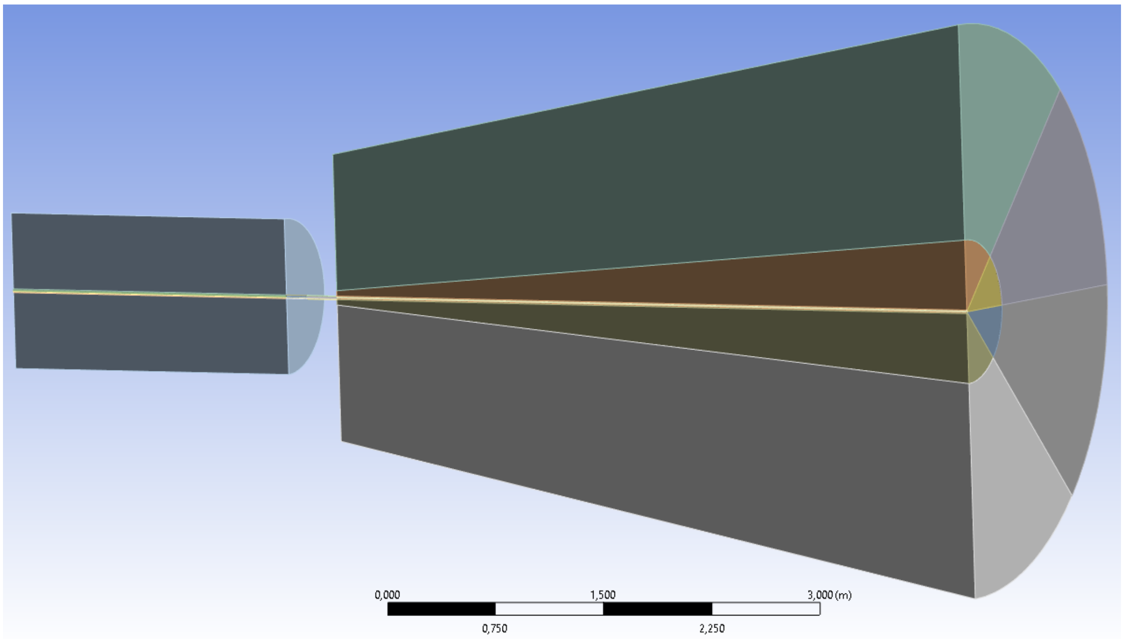

Fig. 3 Layout for the simulations; left: container, middle: pipe, right: distribution area

To achieve this objective, a CFD simulation was devised that includes a geometry, a mesh, and physical models. First, a layout was created that was similar to the one used for the experiments. The layout (see Fig. 3) consists of a vessel filled with overpressure and a distribution area with a pipe connecting these two. Subsequently, the vessel was substituted with an inlet boundary condition, where the pressure is controlled by means of a function, thereby reducing the computational effort required for the simulation.

The initial simulations were conducted under the assumption that the container was filled with air and an overpressure of 50 bar. The velocity of the free jet after 1 second goes up to roughly 80 m/s. The highest velocity for the free jet is right at the beginning and goes up to about 250 m/s.

In a next step, a container filled with helium was examined. The overpressure remained at 50 bars. The result after 0.5 seconds is shown in Fig. 4. The computations conducted on the helium showcase a considerably higher free jet velocity in comparison to that of air. After 0.5 seconds, the velocity increases to about 500 m/s, while the highest velocity right at the beginning of the free jet is about 650 m/s.

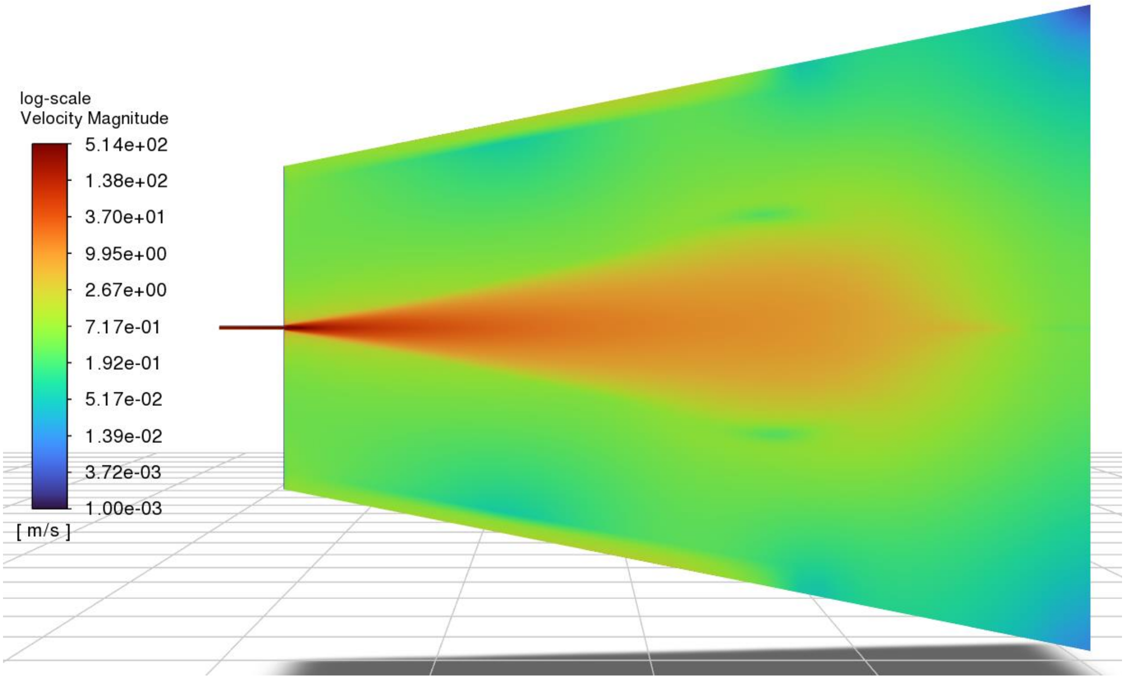

Fig. 4 Exemplary velocity results of a CFD simulation of a particle-loaded helium free jet with an initial overpressure of 50 bar after 0.5 seconds

The next step was to extend the simulation to a second phase and introduce particles into the free jet. For this purpose, an injection was created in the center of the tube. For each time step, a defined number of particles is injected into the tube, resulting in a specific loading of the free jet with these particles. The particles are defined with a diameter spectrum of something between 2 and 130 micrometers. An example of a particle free jet generated with helium after 0.5 seconds is shown in Fig. 5. The number of released particles at this time is about 4.8 million. At this stage of formation, different behaviour of the various diameters is already apparent. Smaller particles are clearly more conspicuous at the outer edge of the unconfined beam, while their larger counterparts have already gravitated toward the centre and are moving further away from the exit point.

The simulations for this project and their evaluation are still ongoing. Among other things, the speed of the free jet and especially its decay over the distance to the outlet of the pipe is analyzed. Subsequently, parameter studies to determine various effects, will be carried out. One step along this way is for example to analyze the effect of a cover over the container with a small pinhole on the resulting free jet.

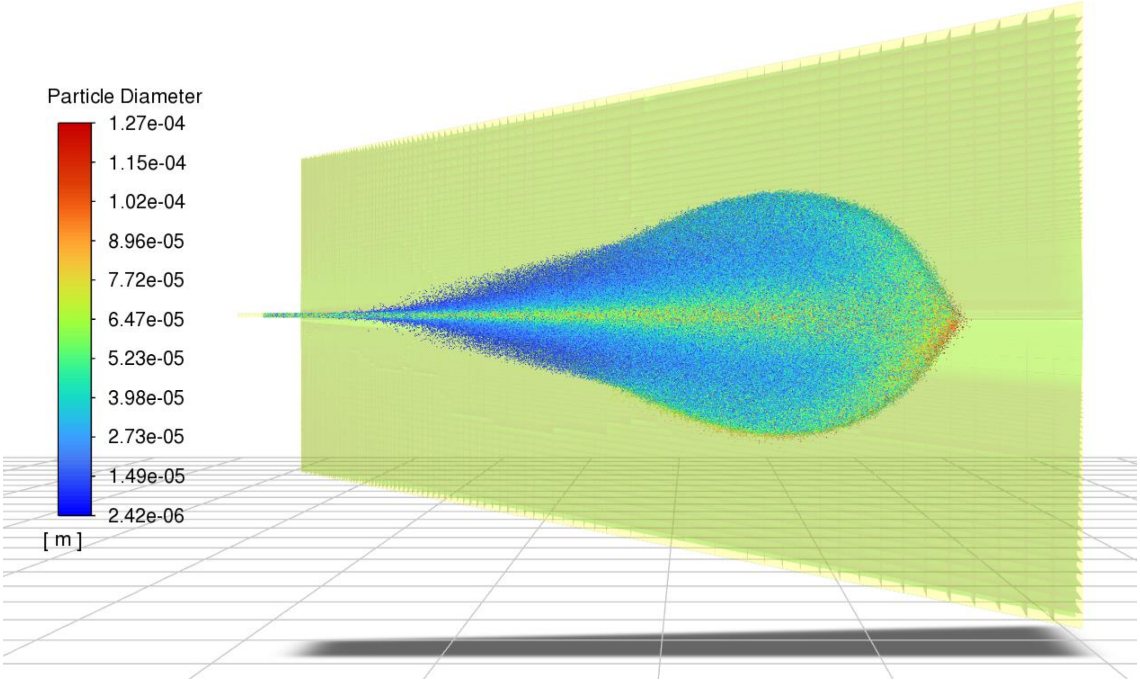

Fig. 5 Spatial particle distribution of a two-phase (particle loaded) helium free jet after 0.5 seconds. The initial overpressure is 50 bars, and the particles have diameters in the range of about 2 to 130 micrometers

6. CONCLUSION AND OUTLOOK

Within the framework of these projects, experiments on the (particle loaded) free jet were successfully carried out in the laboratory and CFD simulations were set up on this basis. To assess the fidelity of the simulations, a preliminary step entailed comparing them against experimental findings. The outcomes of this comparative analysis evince a favourable concurrence between the simulated and experimental data. Particularly, the velocity decay slope of the unconfined jet, as a function of its distance from the pipe, exhibited a comparable trend across both the experimental and simulated domains. Subsequently, the ensuing stage encompasses the variation of parameters, leading to a broader overview of diverse scenarios. Further simulations, coupled with a deeper analysis of the outcomes, and a more detailed comparison of the findings with experimental results, constitute the impending course of action in the near future.

The goal of these investigations is that in future, such simulations can be applied to specific transport configurations incorporating multiple parameters, allowing for a more sophisticated assessment of the potential radiological consequences that may ensue. Based on this, possible structural and technical security measures can then be evaluated and applied more effectively.

REFERENCES

[1] FEDERAL OFFICE FOR THE SAFETY OF NUCLEAR WASTE MANAGEMENT (BASE), Current transport licenses / Gültige Beförderungsgenehmigungen nach § 4 Atomgesetz bzw. §§ 27 und 29 StrlSchG, 31.03.2023

[2] FEDERAL OFFICE FOR RADIATION PROTECTION (BFS), Act on the Peaceful Utilisation of Atomic Energy and the Protection against its Hazards (Atomic Energy Act), Edition 12/22, 2022a

[3] INTERNATIONAL ATOMIC ENERGY AGENCY (IAEA), The Convention on the Physical Protection of Nuclear Material (CPPNM), May 1980

[4] INTERNATIONAL ATOMIC ENERGY AGENCY (IAEA), Nuclear Security Recommendations on Physical Protection of Nuclear Material and Nuclear Facilities, Nuclear Security Series No. 13, INFCIRC/155/Revision 5, 2011
[5] INTERNATIONAL ATOMIC ENERGY AGENCY (IAEA), Security of Nuclear in Transport, Nuclear Security Series No. 26-G, 2015