Proceedings of the 17th International Symposium on the
Packaging and Transportation of Radioactive Materials
PATRAM 2013
August 18-23, 2013, San Francisco, CA, USA

EVALUATION OF RADIOLOGICAL CONSEQUENCES DUE TO SABOTAGE DURING NUCLEAR MATERIAL TRANSPORTATION

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ABSTRACT

To clarify level of unacceptable radiological consequences due to sabotage, new concept to define physical protection measures appeared in revised recommendation for nuclear material protection, INFCIRC/225/Rev.5, radiological consequences caused by sabotage during nuclear material transport were evaluated using plume model based on hypothetical scenario for release of radioactive materials. Evaluations were carried out for principal packages used for transport of nuclear material and wastes from nuclear plants. Evaluated maximum cumulative dose for 24 hours at 15 m from transport cask was approximately 4 mSv. The evaluated results shown in this paper are expected be used as base data in consideration of additional physical protection measures taking into account the new IAEA physical protection recommendation. In this study, radiological consequences due to sabotage during maritime transport of radioactive materials were also demonstrated and the results indicated that radiological consequences are lower than 1 mSv, dose limit for general public in normal condition.

INTRODUCTION

In 2011, IAEA developed and issued Nuclear Security Series No.13 (NSS No.13), “Nuclear security recommendations of physical protection of nuclear material and nuclear facilities (INFCIRC/225/Rev.5)” [1]. In NSS No.13, a concept that all risks should be taken into account to define physical protection measures was implemented. According to the concept shown in Figure 1 [2], it is required to define additional physical protection measures if the radiological consequence due to sabotage results in unacceptable. To apply the concept to the domestic regulations regarding physical protection measures, it is required to discuss radiological consequences raised by sabotage with realistic assumptions and a level of unacceptable radiological consequence.

Discussions on the level of unacceptable radiological consequence could refer to the IAEA safety guides and ICRP recommendations those were used to determine the evacuation zone or the emergency evacuation preparation zone surrounding the Fukushima No.1 nuclear power plant. The value of 50 mSv assigned as a level for emergency evacuation immediately after an accident could be one of reference values.

In this paper, radiological consequences due to sabotage during nuclear material transport were evaluated by using atmospheric dispersion simulation with plume model. Packages considered were spent fuel, low level radioactive waste, high level radioactive waste, TRU waste, uranium fresh fuel, and MOX fuel. In this study, radiological consequences due to sabotage during especially for maritime transport of radioactive materials focused on crew exposure and ocean dispersion are also discussed.

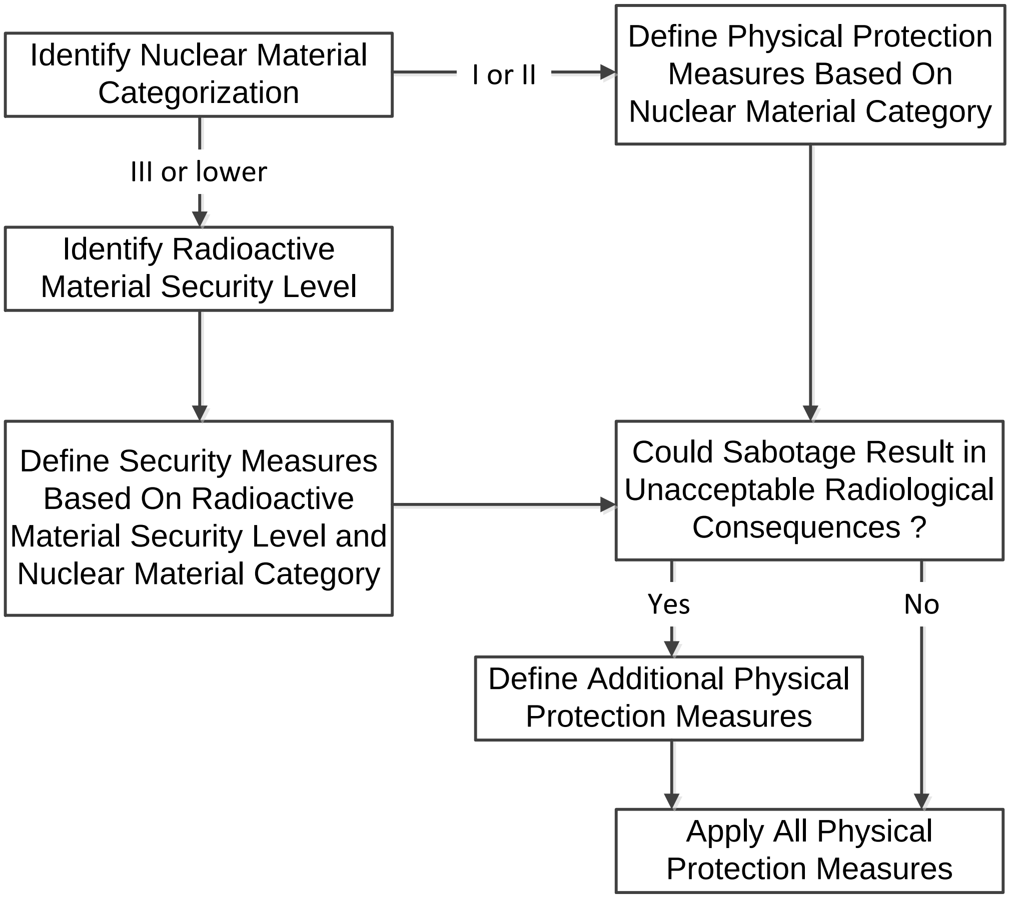

Figure 1. Flow chart for defining physical protection measures to take into account for all risks [2]

EVALUATION OF RADIOLOGICAL CONSEQUENCES

Assumption for release of Radioactive Materials due to Sabotage

Although various scenarios are possible to be considered as sabotage, amounts of release of radioactive materials from various types of transport casks were assumed by results of existing researches for impact analyses due to severe accident condition beyond conditions for tests for demonstrating ability to withstand accident conditions of transport.

Bundesanstalt für Materialforschung und –prüfung (BAM), Germany, conducted impact experiment for CASTOR THTR/AVR spent fuel cask by using explosion of LPG rail tank car [3]. The CASTOR cask was positioned beside the LPG tank as to suffer maximum damage due to the explosion. Mechanical and thermal impacts directly loaded on to the CASTOR cask resulted in moving the cask 7 m from the original position. After the impact test, helium leak measurements of the lids metal seals were conducted and the measured result of leak rate for the primary lid was less than 4.5 $\times 10^{-10}$ $Pa \cdot m^3 \cdot s^{-1}$. The measured leak rate was good enough lower than the specified maximum leakage rate of 10^{-8} $Pa \cdot m^3 \cdot s^{-1}$ for the accident conditions of transport. Even for extreme accident condition, it was confirmed that integrity of the transport cask could be maintained.

Russian Federal Nuclear Center was carried out numerical estimation of cask resistance to explosion of 50 kg of TNT placed at external lid of dual purpose cask TP-117 [4]. The simulation results indicated that the cask body destruction in zone of lids location did not occur and the cask kept its tightness.

According to the results of impact experiment and simulations in references [3, 4], it can be said that type-B packages has enough integrity for terrorists attack using explosives generally considerable sabotage scenarios. In this study, release of radioactive materials, however, considered to be released in the case of terrorists attack with acceptable release rate for type-B packages for accident conditions, 10 A_2/week for Kr-85 and A_2/week for all other radionuclides, as a worst case scenario. For package of uranium fresh fuel, it was assumed that all contents would be released because A_2 value was infinity for Uranium.

Conditions for evaluation of radiological consequences

For evaluation of radiological consequences due to release of radioactive material was carried out using the plume model. Conditions of atmospheric dispersion simulations are as follows.

- ✓ Among the contents of packages, inhalation rate were assumed to be 100 % for noble gas and 5 % for other nuclei contributed to internal exposure considering user guide of RADCAT [5], which is an input generator for risk analyses tool for radioactive material transport, RADTRAN [6].
- ✓ Particle size of 95 % of other nuclei was assumed to be 10 μm. This means that these nuclei are only contributed to external exposure because particles with diameter larger than 10 μm are difficult to be inhaled.
- ✓ These assumptions are more conservative than possible inhalation rate of 6×10^{-5} to 5×10^{-5} which were derived from measurement of inhalation rate from spent fuel caused by high energy density explosives conducted at Sandia National Laboratories, SNL [7] and Gesellschaft für Anlagen- und Reaktorsicherheit mbH, GRS [8]. These data with collection [9] were used for environmental impact assessment of transport to Yucca Mountain [10].
- ✓ Wind speed was chosen as 3 m/s because the wind speed is generally highest frequency of appearance. Atmospheric instability F was used for conservative estimation.
- ✓ Radiological consequences were estimated as function of distance from packages and cumulative exposure dose for 24 hours considering evacuation time.

Evaluated results of radiological consequences

Based on the above mentioned evaluation conditions, change of exposure dose as function of distance from packages for spent fuel, high level radioactive waste (HLW), low level radioactive waste, TRU waste (CSD-B and CSD-C), fresh uranium fuel, MOX fuel. Evaluated results are shown in Figure 2. Current Japanese guidance for nuclear energy disaster prevention regarding transport prescribes that separation distance between packages and general public should be 15 m. Considering the separation distance of 15 m, cumulative dose for 24 hours at 15 m from packages were evaluated and shown in Table 1. As shown in Table 1, maximum cumulative dose for 24 hours was 4.1 mSv for CSD-B. These facts indicats that radiological consequences due to sabotage would not exceed 50 mSv that prescribed in GS-R-2 [11] for preventing high exposure at initial stage after occurrence of accident involving radioactive material. The present results are consistent with a report of SPIEZ laboratory that radiological consequence due to dirty bomb would be 10 mSv/h at center of explosion [12].

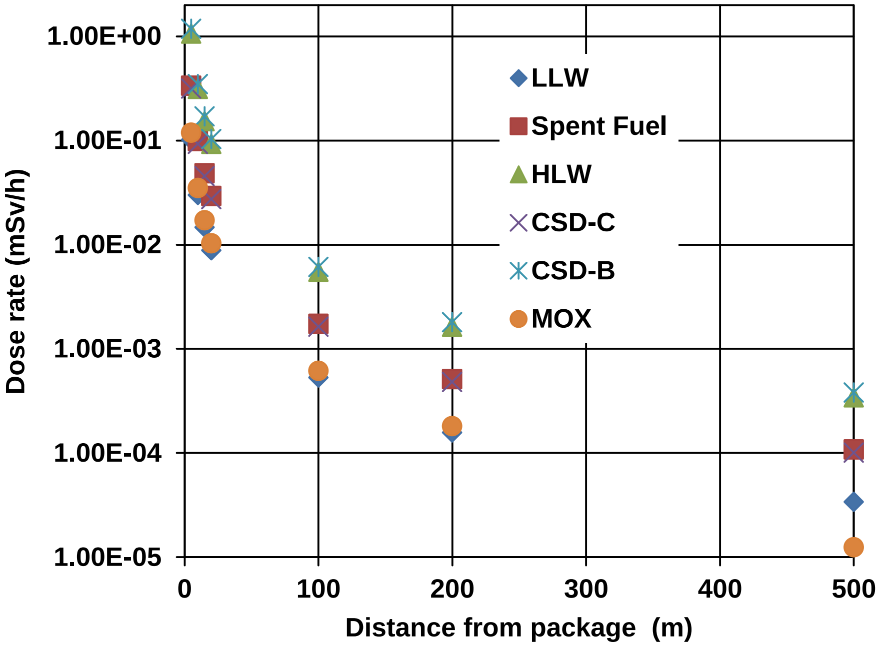

Figure 2. Evaluated radiological consequences due to hypothetical release of radioactive materials from various packages. Results for fresh fuel package are not shown in the figure because evaluated dose rate were order of magnitude of 10^{-5} mSv/h or less than 10^{-5} mSv/h.

Table 1. Estimated cumulative exposure dose for 24 hours at 15 m from packages due to hypothetical release of radioactive materials from various packages.

	Total (mSv)	Internal Exposure (mSv)	External Exposure	
			β - ray (mSv)	γ - ray (mSv)
LLW	3.5×10^{-1}	3.5×10^{-1}	1.1×10^{-4}	5.3×10^{-4}
Spent Fuel	1.2	1.2	2.7×10^{-5}	1.5×10^{-4}
HLW	3.7	3.7	9.7×10^{-5}	6.5×10^{-4}
CSD-C	1.1	1.1	6.2×10^{-6}	2.9×10^{-5}
CSD-B	4.1	4.1	2.7×10^{-5}	8.7×10^{-5}
U Fresh Fuel	6.9×10^{-6}	6.9×10^{-6}	2.5×10^{-8}	7.8×10^{-8}
MOX	4.1×10^{-1}	4.1×10^{-1}	3.8×10^{-7}	1.2×10^{-6}

Evaluation of radiological consequences during maritime transportation

In this study, evaluation of radiological consequences during maritime transportation was also carried out taking into account peculiarity of maritime transport.

Source term was assumed as 10 A_2/week for Kr-85 and A_2/week for all other radionuclides, they were same as worst case scenario for above mentioned evaluation. For package of uranium fresh fuel, it was assumed that all contents would be released from the package because A_2 value was unlimited for low enrichment uranium.

For estimation of radiological consequences inside transport vessel, structures of vessel were neglected in the plume model calculation because it is not realistic to model all structures of vessel in detail, such as shielding wall, wall of accommodation area. On the other hand, walls of vessel are expected to be a barrier for dispersion of radioactive material. Taking into account the barrier effect, it was assumed that 10 % of released radioactive materials from package in cargo hold were contributed to exposure for crew in the accommodation area of the vessel. This assumption is also applied to estimation of amount of radioactive materials released from building of waste management facility of nuclear fuel reprocessing plant in case of a hypothetical incident [13].

Conditions for calculation of plume model are almost same as above mentioned consequence evaluation except for the followings:

- ✓ wind speed of 1 m/s was used as more conservative condition,
- ✓ and cumulative dose for 48 hours were evaluated considering that more evacuation time would be necessary compared with land incident.

Calculated cumulative exposure dose for 48 hours for crew member in accommodation area are shown in Table 2. Maximum cumulative dose for 48 hours was 2.8×10^{-3} mSv for CSD-B. Cumulative dose for spent fuel, low level radioactive waste and CSD-C are in comparative level; order of magnitude of 10×10^{-4} mSv. These results indicated that radiological consequence caused by release of radioactive material inside vessel were significantly low compared with dose limit for general public for normal operations, 1 mSv/y.

Table 2. Estimated cumulative exposure dose for 48 hours in accommodation area in transport vessel due to hypothetical release of radioactive materials from various packages.

	Total (mSv)	Internal Exposure (mSv)	External Exposure	
			β - ray (mSv)	γ - ray (mSv)
LLW	2.5×10^{-4}	2.5×10^{-4}	3.7×10^{-8}	5.1×10^{-7}
Spent Fuel	8.3×10^{-4}	8.3×10^{-4}	9.1×10^{-9}	1.4×10^{-7}
HLW	2.6×10^{-3}	2.6×10^{-3}	3.4×10^{-8}	6.3×10^{-7}
CSD-C	7.7×10^{-4}	7.7×10^{-4}	2.1×10^{-9}	2.7×10^{-8}
CSD-B	2.8×10^{-3}	2.8×10^{-3}	9.1×10^{-8}	8.3×10^{-7}
U Fresh Fuel	8.2×10^{-11}	–	8.3×10^{-12}	7.4×10^{-11}

In this study, radiological consequence caused by ocean dispersion of radioactive material from sunken packages in ocean was also estimated. Estimations were made for packages of TRU waste, high level radioactive waste and spent fuel.

Amount of release of radioactive material from package in hypothetical sabotage incident was evaluated as follows,

- ✓ contents of package was leached into sea water infiltrated package through tight seal broken at the time of submergence,
- ✓ and leached radioactive materials were dispersed into ocean through gap of tight seal.

Concentration of radioactive materials were calculated by solving an advective diffusion equation shown as follows,

$$\frac{\partial C_i}{\partial t} + \vec{u} \cdot \nabla C_i = \frac{\partial}{\partial x}\left(D_x \frac{\partial C_i}{\partial x} \right) + \frac{\partial}{\partial y}\left(D_y \frac{\partial C_i}{\partial y} \right) + \frac{\partial}{\partial z}\left(D_z \frac{\partial C_i}{\partial z} \right) - K_d \rho_s w_s \frac{\partial C_i}{\partial z} - \lambda C_i$$

C_i: concentration of radioactive materials (q/m^3), x, y, z: geographical coordinates (m), t: time (s), u, v, w: advective velocity (m/s), D_x, D_y, D_z: diffusion coefficient (m^2/s), K_d: distribution coefficient of radionuclide (m^3/g), λ: radioactive decay constant (1/s), ρ_s: concentration of suspended material (g/m^3). For the calculation of concentration of radioactive materials, flow filed of ocean current for east coast of Japan was represented by MASSCON (MASs CONsistent flow) model [14, 15] based on JCOPE data [16].

For estimation of radiological consequences, effective dose conversion factors were used for various exposure routes, including external exposure and internal exposure. These conversion factors have been used for safety assessment of a nuclear fuel reprocessing plant in Japan. Estimated results of radiological consequences are shown in Table 3. As shown in Table 3, estimated effective exposure doses are low compared with dose limit for general public for normal operations, 1 mSv/y.

Table 3. Estimated external effective dose and 50 years committed effective dose caused by hypothetical release of radioactive materials from various packages into ocean.

	Total external effective dose (mSv)	50 years committed effective dose (mSv)
Spent Fuel	1.7×10^{-40}	1.4×10^{-17}
HLW	8.8×10^{-3}	1.3×10^{-1}
CSD-C	1.2×10^{-42}	9.3×10^{-20}
CSD-B	2.2×10^{-39}	1.8×10^{-16}

CONCLUSIONS

In this study, radiological consequences are evaluated for sabotage incident for various types of packages using plume model. It was found that cumulative dose for 24 hours at 15 m from packages are varied 6.9×10^{-6} to 4.1 mSv depends on contents of packages and the exposure dose are considerably lower than 50 mSv that prescribed in GS-R-2 for preventing high exposure at initial stage after occurrence of accident. Radiological consequences were also evaluated for sabotage incident during maritime transport and cumulative exposure dose for 48 hours in accommodation area and exposure due to marine work and inhalation of marine products were evaluated by plume model and ocean dispersion model. The estimated radiological consequences were also considerably low compared to 1 mSv, annual dose limit for general public. The evaluated results shown in this paper are expected be used as base data in consideration of additional physical protection measures taking into account the new IAEA physical protection recommendation.

ACKNOWLEDGMENTS

This research was supported by Maritime Bureau, Ministry of Land, Infrastructure, Transport and Tourism, Japan.

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