ICANS-XV
15th Meeting of the International Collaboration on Advanced Neutron Source
November 6-9, 2000
Tsukuba, Japan

23.12

Safety Concept for Spallation Target System - JAERI/KEK Joint Project -

K. Kobayashi*, M. Kaminaga, K. Haga, H. Kinoshita and R. Hino

Japan Atomic Energy Research Institute, Tokai 319-1195, Japan
*E-mail: kobayashi@cat.tokai.jaeri.go.jp

Abstract

A MW-class mercury target of the spallation target generates much larger amounts of radioactive nuclides than existing spallation neutron sources. To estimate the maximum level of public exposure under the guillotine break of mercury pipelines that is one of the major accidents of the target system, the hazard analyses were carried out by using a transportation model which considers heat transmission of mercury decay heat, diffusion of evaporated radioactive nuclides, etc. In the analyses, mercury, iodine, bromine and noble gas were selected as the effective source term because of their high vapor pressures and activation levels. From the preliminary analytical results obtained under the conservative conditions of 2 m/s of the air velocity around the mercury leakage area, the maximum level of the public exposure was approximately 5.8×10^{-3} mSv. This level is negligible in comparison with the 1mSv one-year natural radiation exposure.

1. Introduction

In the joint project (JAERI/KEK) of spallation neutron source, a spallation neutron source coupled with a MW-class pulsed proton beam was planed to supply high-intensity neutron beams to life and material sciences (1). A mercury target system working as the spallation neutron source has been designed at the Japan Atomic Energy Research Institute since 1997 (2). The mercury target produces much larger amounts of radioactive nuclides by spallation reaction than those in the existing spallation neutron source. Almost all these nuclides are considered to exist in mercury in the form of mercury compounds.

Since mercury including these nuclides, namely the radioactive mercury is prospected to have large hazard potential, safety analyses are needed to ensure the safety to the public, the workers and the environment. In the safety analyses, postulated events that are initiated at the target system by equipment failure, natural phenomena and human error has to be considered (3).

In this study, the source term in the radioactive mercury and the maximum public exposure in relation with mercury transportation were estimated under a major accidental event in order to clarify safety concept of the spallation target system.

2. Safety Design Concept of Spallation Target System

2.1 Safety Design Concept

The safety concept of the spallation target system is roughly categorized as normal and abnormal operation modes as shown in Fig. 1. Basic safety concepts in each operation mode are as follows.

(1) Normal Operation Mode

On the basis of the as low as reasonably achievable (ALARA) concept, designs of equipment are considered very carefully for protection of radiation and confinement of radioactive nuclides. Moreover, safety is improved to promote the skills in the operation, maintenance and quality controls, for decreasing human factors. As a result, we expect the worker exposure to be negligible small.

(2) Abnormal Operation Mode

The concept of defense-in-depth is applied to ensure the safety at the accident. This concept consists of three stages: (1) To prevent abnormal event occurrence, (2) To prevent abnormal events escalating into accident, (3) To minimize accidental effects for the public. The concept demands quality assurance, conservative design margins for some transient events and successive physical barriers for protection against the release of radioactive nuclides. In addition to these demands, the spallation target system requires some recovery functions from the accidents.

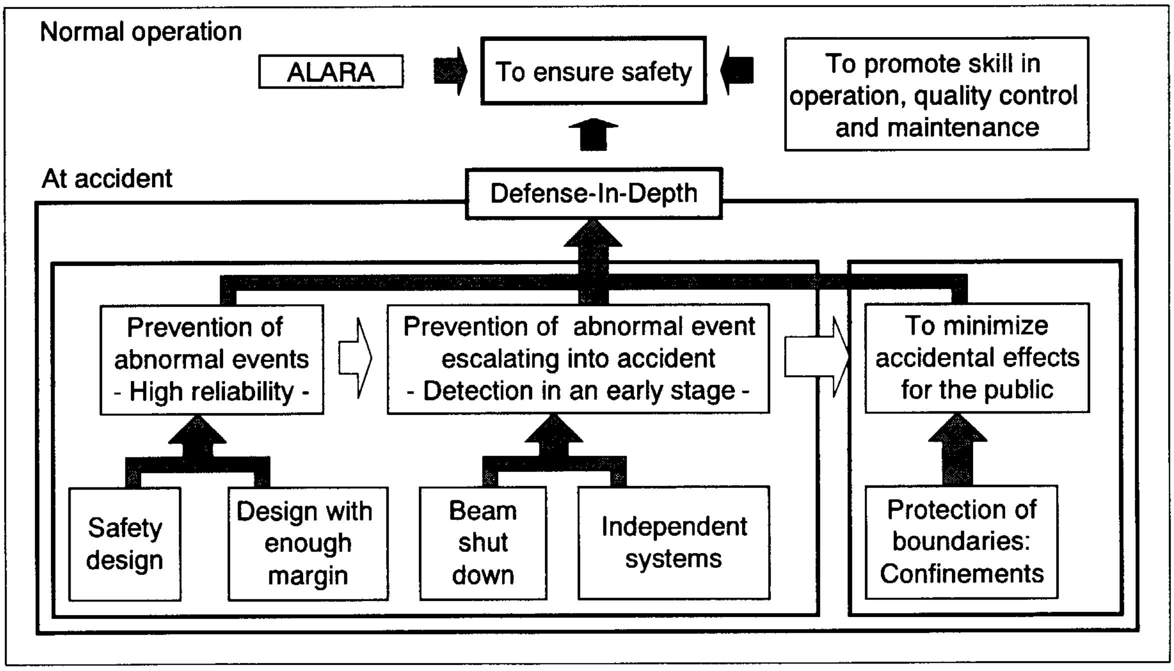

Fig. 1 Safety Concept of Spallation Target System (JAERI/KEK Joint Project)

2.2 Hazard Potential for Spallation Target System

The spallation target system contains the radioactive nuclides in mercury, cooling water and structural materials. Inventories of the radioactive nuclides, especially mercury, are used as the source term in order to estimate the hazard potential.

The accidental potentialities of the spallation target system were roughly categorized as the following three items as shown in Fig. 2.

(1) Mercury boundary breakage

Activated mercury exists in the target vessel and the mercury flow loop consisting of pumps, surge tanks, heat exchangers and pipelines. In the source term estimation, it would be more serious in the case of break of the mercury flow pipe, because the mercury inventory in the mercury flow loop is about 40 times larger than that in the target vessel. So we must estimate the maximum public exposure in the case of abnormal events brought about mercury release.

(2) Decay heat

Although activated mercury produces decay heat, effect of decay heat to equipment is very small, because the maximum heat density in mercury is small about 0.001 watt/cm^3 due to large amount of mercury volume. It seems that decay heat has little possibility to cause the accident.

(3) Fire and explosion

Hydrogen circulates cryogenic moderator vessels, hydrogen pipeline, etc. If the hydrogen leaks to the helium vessel in the case of the moderator vessel rapture, the helium vessel where helium gas is filled up can prevent the events of fire and explosion. Then, the proton beam injection is also stopped by an emergency control system.

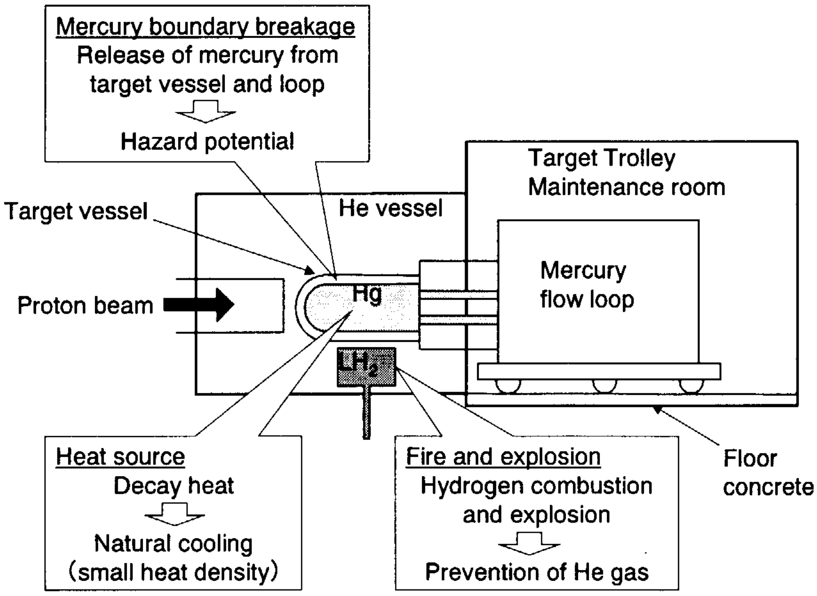

Fig.2 Accidental Potentialities of the Spallation Target System
(JAERI/KEK Joint Project)

From these conditions, the event of mercury boundary breakage was selected as a major accident. Especially, the event of the guillotine break of the mercury pipeline would cause the harshest situation without working a collection system, because almost all the mercury in the target vessel and the mercury pipelines flows out to the target trolley maintenance room. Then, the spilled mercury behaves as the source term.

3. Preliminary Estimation of Source Term

3.1 Nominal Case

Since the source term depends principally on the behavior of the spilled mercury, we assumed the typical scenario of the spilled mercury release from the target trolley maintenance room to the atmosphere. This scenario contains the mercury transportation processes as shown in Fig. 3: evaporation and dispersion atmosphere, capture by a filter and release from a stack. In the conceptual design of the spallation target system, almost all the spilled mercury collects to a dump tank, so that the amount of the remainder of mercury is expected to be small on the floor in the target trolley maintenance room. However, to estimate source term conservatively, we assumed that mercury of 2 m^3 containing in the mercury loop is browed out over the half area of the target trolley maintenance room, 3.5 m wide and 15.75 m long. Table 1 shows major analytical parameters as the nominal case. These parameters have high safety margins in the source term analyses for the following reasons:

(1) We assumed that the accident would be occurred at the end of operation time, i.e., in order to maximize the inventories of radioactive nuclides and the decay heat under a 30-year continuous injection of the 1MW proton beam into mercury target, and

(2) the initial temperature of the mercury was assumed to be 150 °C which is almost same as the maximum mercury temperature in the target vessel; average mercury temperature in the target vessel is below 100 °C under the 1 MW proton beam operation.

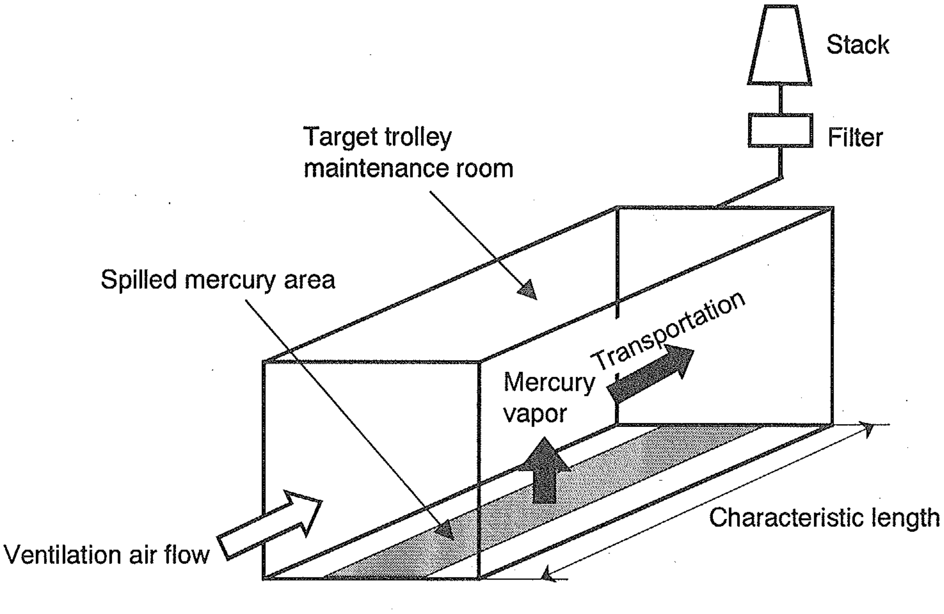

Fig. 3 Release Concept of radioactive Mercury at the Accident

Table 1 Major analytical parameters of nominal case for source term

	Specifications
Accelerator	
- Energy	3 GeV
- Power	1 MW
Spallation target system	
- Target material	Mercury
- Total volume of target material	2 m3
- Operation period	30 years
- Length of target trolley maintenance room	15.75 m
- Wide of target trolley maintenance room	7 m
- Initial temperature of floor concrete	20 °C
- Filter efficiency for mercury	95 percents
- Filter efficiency for noble gas	0 percents

3.2 Radioactive Nuclide

To select nuclides for the source term, we must consider the hazard potential which is defined as the ratio of the radioactivity to annual limit of intake for inhalation. Figure 4 shows radioactive nuclides of 1 % contribution to total hazard potential of inhalation after 30 years operation of 1MW power. Gd-148, Hf-172, Hf-178m, Ir-192m, Au-195 and Hg-203 are shown in this figure. As for the nuclides of 0.1 % contribution to total hazard potential, Eu-154, Os-185, Hg-195 and Hg-197, are also listed. These are non and semi volatile elements. The contribution of these nuclides to the total hazard potential was 97.5 % just after the

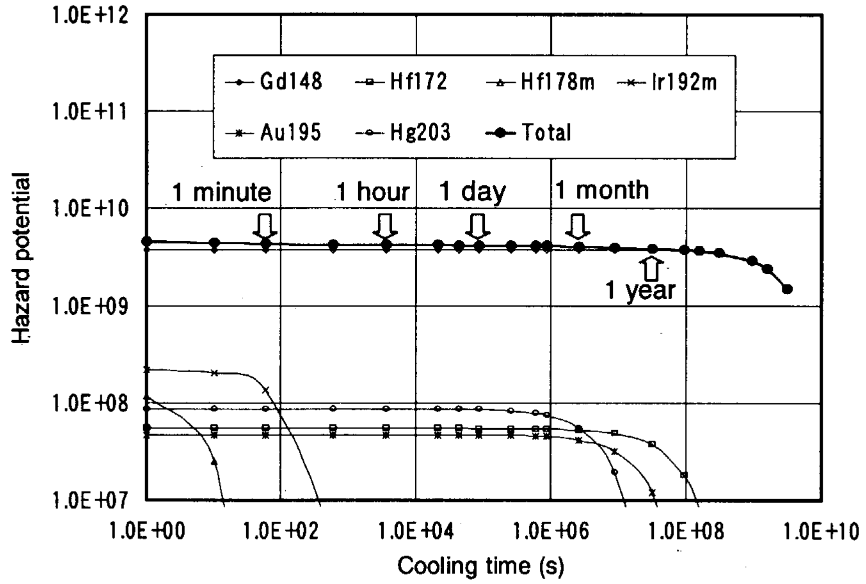

Fig. 4 Radioactive nuclides of one percent contribution to total hazard potential of inhalation after mercury target operation of 1MW power for 30 years

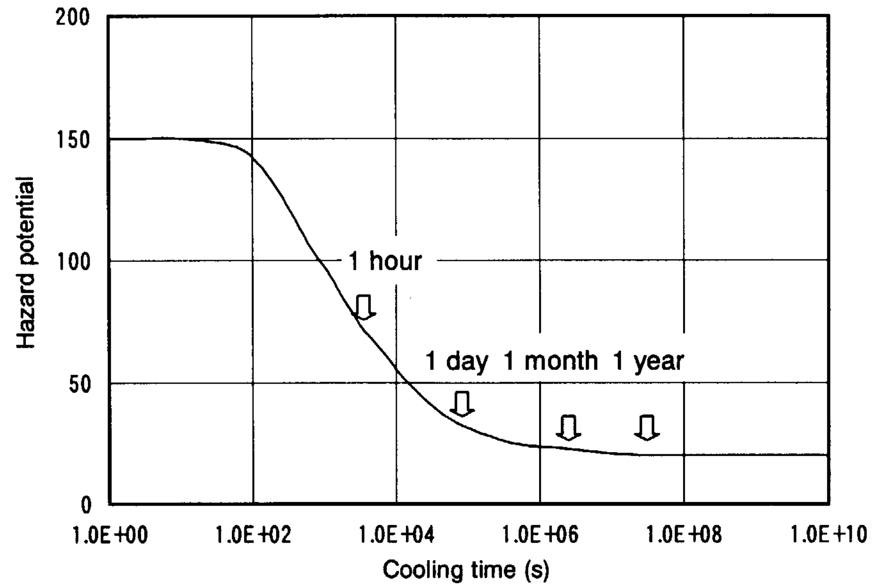

Fig. 5 Relationship between the maximum temperature on mercury surface and the cooling time

accident. The remainder of 2.5 % was mainly contributed by the noble gas (Ar, Kr, Xe), volatile elements (Br, I) and shot-lived radioactive nuclides.

3.3 Temperature of Spilled Mercury

It is important to examine the spilled mercury temperature in respect of source term analyses, because the vapor pressure of mercury is strongly affected by the temperature. Temperature of the spilled mercury decreases with increasing cooling time owing to the heat transmission to the floor concrete and ventilation air. The temperature change of the spilled mercury was calculated with the STAR-CD code. Figure 5 shows the relationship between the maximum temperature on the mercury surface and the cooling time which means the time after the pipe rupture. As seen in the figure, the mercury temperature goes down to the initial temperature of the floor concrete, 32 °C, after one day.

3.4 Evaporation and Transportation Models for Mercury

The spilled mercury vapor is transported by the ventilation air flow to the filter. The amount of transported activated mercury, M_{Hg}, was assumed by using the following equation $^{(4)}$:

$$M_{Hg} = -D_{air\text{-}Hg}\left(\frac{\partial \rho_0}{\partial y}\right)_{y=0} \approx \alpha_D(\rho_0 - \rho_\infty) < \alpha_D \times \rho_0 \qquad (1)$$

where $D_{air\text{-}Hg}$: Binary diffusion coefficient between air and mercury vapor

α_D: Mass transfer coefficient

ρ_0: Equilibrium mercury concentration on spilled mercury surface

ρ_∞: Mercury concentration of bulk ventilation air flow.

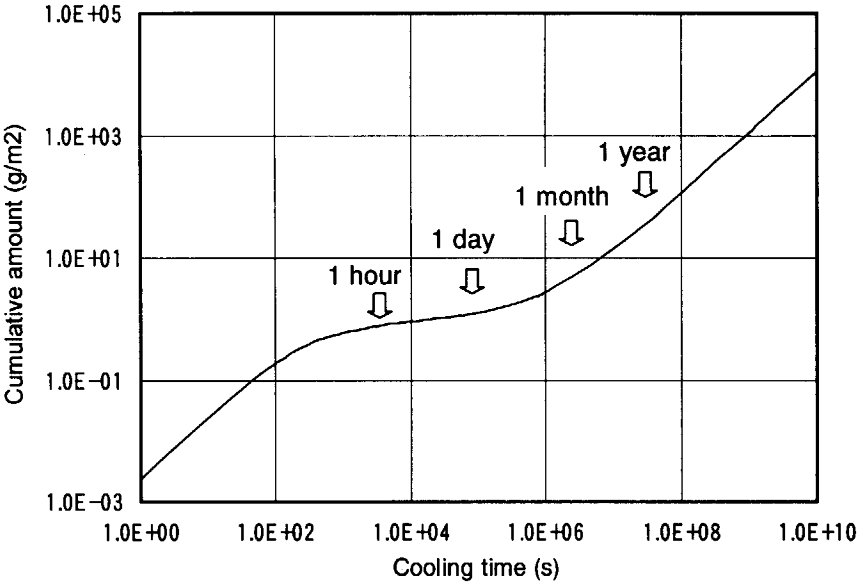

Fig. 6 Relationship between cumulative amount of evaporated mercury and the cooling time

The mass transfer coefficient is expressed as the following equations:

laminar flow:

$$\alpha_D = \frac{0.664 \times Re^{\frac{1}{2}} Sc^{\frac{1}{3}} D_{air\text{-}Hg}}{L} \tag{2}$$

turbulent flow:

$$\alpha_D = \frac{0.037 \times Re^{\frac{4}{5}} Sc^{\frac{1}{3}} D_{air\text{-}hg}}{L} \tag{3}$$

where Re: Reynolds number

Sc: Schmidt number

L: Characteristic length of the ventilation air flow (see in Fig. 3).

On the other hand, assuming that the mercury vapor behaves as the ideal gas, a equilibrium concentration of mercury can be expressed as

$$\rho_0 = \frac{P_{Hg}}{RT} \tag{4}$$

where P_{Hg}: vapor pressure of mercury

R: gas constant

T: mercury temperature.

Figure 6 shows the relationship between the cumulative amount of evaporated mercury and cooling time. As seen in the figure, the amounts of evaporated mercury after a day and a month were small about 1.25 g/m^2 and 5.03 g/m^2, respectively.

Table 2 Comparison of typical atmospheric dispersion factor to evaluate public exposure for research reactors in Japan

Research Reactor (Japan)	Height of stack m	Atmospheric dispersion factor χ/Q h/m^3
JRR-3	40	2.2×10^{-9}
HTTR	0	1.2×10^{-7}
	80	1.0×10^{-9}
STACY	0	7.3×10^{-8}
TRACY	50	4.2×10^{-9}
MONJU	0	3.0×10^{-8}

3.5 Filter Efficiency

We assumed that almost amount of the evaporation mercury would be collected at a filter. Ninety-five percents of the filter efficiency was assumed to all nuclides except noble gas, which is generally used in the safety analyses for research reactors in Japan.

3.6 Dispersion Factor of the Atmosphere

The dispersion factor of the atmosphere depends mainly on a climate and a height of stack. Table 2 shows the dispersion factor used for the safety analyses of the typical research reactors in Japan. On the basis of the values shown in the table, 1.0×10^{-7} h/m^3 of the dispersion factor was selected in order to obtain a conservative estimation value for the public exposure.

3.7 Release Rate of Radioactive Nuclides

Radioactive nuclides, which contribute to the total hazard potential, can be categorized into four forms as mentioned in 3.2; (1) gaseous elements such as noble gas (Ar, Kr and Xe), (2) volatile elements (Br, I), (3) semi-volatile element (Hg) and (4) non-volatile elements (Eu, Gd, Hf, Os, Ir and Au). Since solubility of above-mentioned elements in mercury is not clear, we assumed that all the elements are solved in mercury. This assumption would be conservative, i.e., noble gas would be eliminated with a purge gas circulation system in operation of the spallation target system. Figure 7 shows the relationship between the temperature and the vapor pressures except the noble gas. As seen in the figure, since the vapor pressure of the non-volatile element such as Eu, Gd, Hf, Os, Ir and Au are much smaller than that of mercury (less than 10^{13}), such non-volatile would have almost no effect to the source term. We assumed that the volatile elements, semi-volatile elements and noble gas except non-volatile elements would be released with the evaporation of the mercury as the first step of the public exposure estimation.

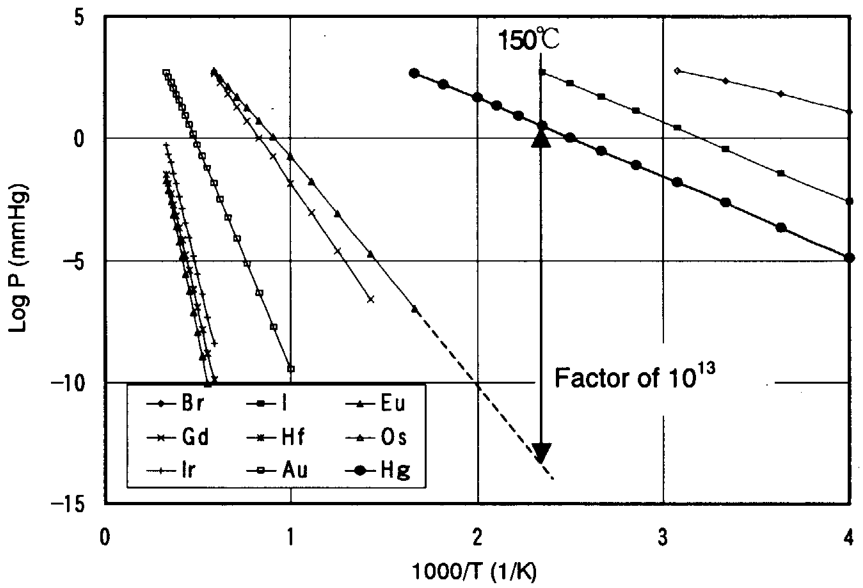

Fig. 7 Vapor pressure of elements for large contribution to total hazard potential

Table 3 Analytical cases and their major parameters for estimation of the public exposure

Case No.	Spilled Mercury				Air velocity (m/s)	Remarks
	Length (m)	Width (m)	Depth (m)	Initial Temp. (℃)		
1	15.75	7.0	0.018	150	0.02	
2	15.75	7.0	0.018	150	0.20	
3	15.75	7.0	0.018	150	2.00	
4	15.75	3.5	0.036	150	0.02	Nominal case
5	15.75	3.5	0.036	150	0.20	
6	15.75	3.5	0.036	150	2.00	
7	15.75	1.75	0.072	150	0.02	
8	15.75	1.75	0.072	150	0.20	
9	15.75	1.75	0.072	150	2.00	
10	15.75	0.875	0.144	150	0.02	
11	15.75	0.875	0.144	150	0.20	
12	15.75	0.875	0.144	150	2.00	

3.8 Public Exposure

Mercury evaporation rate especially depends on the condition of the spilled mercury area and velocity of the ventilation air flow. In order to estimate the maximum public exposure with having high safety margin, parameter survey was carried out. Table 3 gives analytical conditions. Figure 8 shows analytical

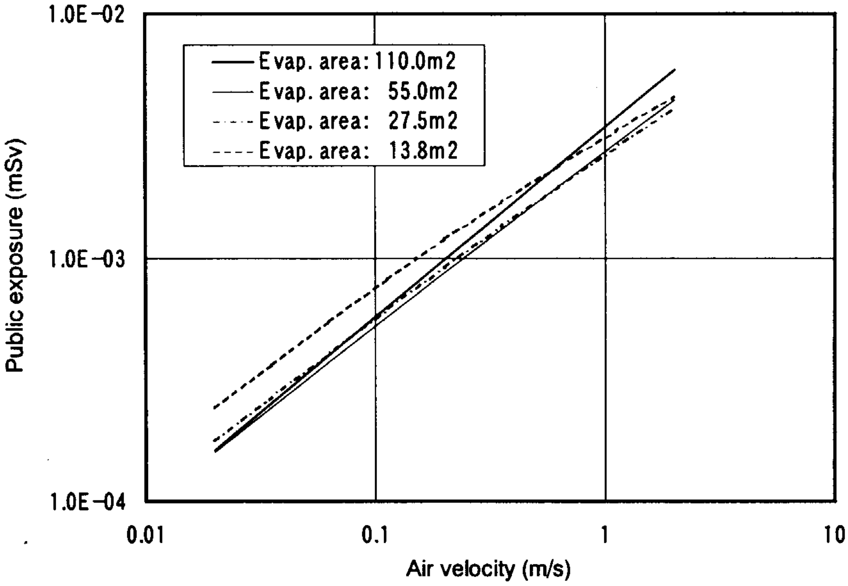

Fig. 8 Parameter survey results of public exposure

results of the public exposure for 10 days. As seen in the figure, effects of the evaporation areas of mercury changed from 13.8 to 110 m^2 to the public exposure is small under the same velocity. The maximum public exposure was 5.8×10^{-3} mSv/year. This value was obtained under the conservative conditions: (1) mercury evaporation area is 110 m^2 which is the total area of target trolley maintenance room, (2) average velocity of ventilation air flow is 2 m/s. This exposure is negligible small in comparison with the 1mSv one-year natural radiation exposure.

4. Concluding Remarks

The public exposure was estimated by using a mercury transportation model under the guillotine break of the mercury pipeline. Though conservative analytical conditions and parameters were used, the maximum public exposure was only 5.8×10^{-3} mSv under 110 m^2 of the spilled mercury area and 2 m/s of the ventilation air flow, which is negligible small in comparison with the 1 mSv one-year natural radiation exposure.

Reference

[1] The Joint Project Team of JAERI and KEK, "The Joint Project for High-Intensity Proton Accelerators", JAERI-Tech 99-056 (1999).

[2] Design Group of Research Complex for Neutron Science, "Proposal of the Research Complex for the Neutron Science (The First Plan)", JAERI-Tech 99-030 (1999), [in Japanese].

[3] Jack Edwards, "Safety in High-Power Accelerator Applications: The Accelerator Production of Tritium Example", AccApp 98, P94 (1998).

[4] Kaneyasu Nishikawa and Yasunobu Fujita, "Dennetsugaku", Rikougakusha, (1982) [in Japanese].