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Study on the Detection of the Criticality Accident Alarm Systems and Area Monitors

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Criticality Accident Alarm Systems (CASs) are important for the rapid evacuation and the reduction of the operators' exposure. Though some methods shown in ANSI/ANS-8.3 etc., the relation between fissions and dose were evaluated for some source materials and shields under criticality accident. The connection of the criticality calculation for the decision of the source spectrum and the shielding calculation for the evaluation of the dose at the detectors were executed. MCNP4C and ENDF/B-VI cross-section library were used for criticality calculation and ANISN and DLC-23E cross-section library were used for shielding calculation. As the sources of the criticality accident, the uranyl nitrate solution, plutonium nitrate solution, and PuO_2 powder were considered. The concrete and iron were considered for the shielding material of the facilities. The distance from the accident points to the detectors of CAS was constant for simplification. The possibility of the detection of the CAS and area monitors was studied numerically. The effectiveness of area monitors for the detection of the slow excursion was also evaluated numerically.

KEYWORDS: Criticality Accident, Criticality Accident Alarm System (CAS), Area Monitor Detection, MCNP4, ANISN

1. Introduction

Criticality Accident Alarm Systems (CAS) are important for the rapid evacuation and the reduction of the operators' exposure. The examples of the detector placement are shown in ANSI/ANS-8.3(1) Appendix B and the closely handling cases (ex. glove box etc.) were considered. When the nuclear materials are treated in the cell, it is also necessary to consider the placement of CAS for the facilities design. The simple equations, which were originated by the criticality accidents or experiments, have been used for the decision of the placement. The detection of the CAS, however, depends on the neutron/gamma-ray (n/γ) ratio, the energy spectrum etc. It is also related to the physical and chemical conditions of the nuclear materials and the shielding material of the facility.

ICRP recommendation(2) says that dose limit for the workers, should be 20mSv/year (averaged by 5 year) for radiation protection. The detection of a prompt criticality accident is generally easier than a slow excursion by CAS. When a slow excursion occurs, operators may expose more than 20mSv before the CAS have detected it.

The report (3) indicated that the accident, which integrated doses may excess to 200mGy at 2m from the source, may not be detected by criticality accident alarm detectors. If the detection level is set lower, CAS will be able to detect the slow excursion. It is problem that single failure caused by noises etc. appears many times on normal operation.

On the other hand, DOE Order 420.1A(4) said "To aid in protecting workers against the consequences of slow criticality accidents in facilities where analysis has shown that slow criticality accidents are credible, CASs should be supplemented by warning devices such as audible personnel dosimeters (e.g., pocket chirpers/flashers, or their equivalents), area radiation monitors, area dosimeters, or integrating CASs."

There are usually many area monitors in the nuclear facilities and the possibility of the detection of the slow delayed criticality accident is likely. The supports of the neutron or gamma-ray area monitors were also considered about its effectiveness for detection of the slow excursion.

In this report, the effectiveness of area monitors for the detection of the slow excursion was studied numerically.

2. Purpose

The purpose of this study were as follows;

(1) The possibility of the detecton by CASs for various condition was studied numerially, without large radiation exposure. The detection absorbed dose for the directly operation was 200mGy at 2m from source according to ANSI/ANS-8.3 and the dose with shield was 20 mSv at the outside surface of the shield.

(2) The effectiveness of the detection by area monitor

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for slow excursion was studied numerically. The detection dose for slow excursion was 20mSv at 2m from source or at the outside surface of the shield.

3. Evaluation Method

The connection of the criticality calculation for the decision of the leakage spectrum and the ratio, and the shielding calculation for the evaluation of the dose at the detectors were executed. MCNP4C(5) and ENDF/B-VI cross-section library were used for criticality calculation and ANISN(6) and DLC-23E(7) cross-section library were used for shielding calculation. Calculation flow is shown in Fig.1.

This evaluation method was compared with the Nuclear Criticality Slide Rule(8) about prompt neutron and gamma-ray and the results were corresponded(9).

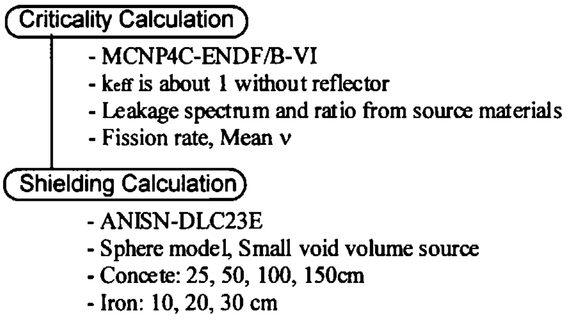

Fig.1 Calculation Flow

3.1 Criticality Calculation for Source Spectrum and Strength

As the sources of the criticality accident, the uranyl nitrate solution (enrichment: 4%, 1000L, 540.0gU/L), 30L plutonium nitrate solution [1] (^{239}Pu: ^{240}Pu = 95: 5, 40.0gPu/L), 300L plutonium nitrate solution [2] (^{239}Pu: ^{240}Pu = 95: 5, 11.0gPu/L) and PuO_2 powder (11.46 g/cm^3, 28.2 kgPu, 0.0 water content) were considered. k_{eff} of each case is about 1 without reflector.

In MCNP criticality calculation, tallies were normalized by one fission neutron. Mean ν of each source was evaluated in Table 1. The source strength for 1 fission was given as follows;

Source Strength for 1 fission=F1 Tally value * Mean ν

Table 1 Mean ν for Each Source

Criticality source System	Mean ν
Uranyl Nitrate Solution	2.44
Pu Nitrate Solution [1]	2.88
Pu Nitrate Solution [2]	2.87
PuO_2 Powder	3.13

For the evaluation of the detection of the CAS and Area monitor, the only prompt neutron and gamma, which were obtained by criticality calculation, were considered. The evaluation of the radiation exposure, prompt neutron, prompt gamma, and the gamma from short-lived fission products(10) were considered.

3.2 Shielding Calculation

The calculation model is one dimensional sphere model and the outside of the shield 5m from source center. The source was set in the small void region. The cross section libraries are DLC23E.

3.2.1 Shielding Materials

The concrete (25cm, 50cm, 100cm and 150 cm) and iron (10cm, 20cm and 30cm) were considered for the shielding material of the facilities. Concrete density was 2.3 g/cm^3 and iron's was 7.87 g/cm^3 (11).

3.2.2 Dose Conversion Factors

Three conversion factors were considered as follows;

(1) The dose for average soft tissue of adult in ICRU 33(12), (13) was applied to the detector of CAS and radiation dose when rapid fission spike.

(2) The effective dose, AP (Anterior-Posterior) direction to the Anthropomorphic Phantom, in ICRP pub.74(14) was applied to the dose for personnel for slow excursion and outside of shields. This conversion factor has been adopted by the Japanese law.

(3) The 1cm depth equivalent dose(15) was applied to the area monitor because of its response function.

4. Results and Precondition for the Study

The evaluation results are shown in Table 3 to 5 (unmodereted system) and 6 to 9 (solution systems), under the precondition as below;

(1) The position of CAS was 10 m from the source center and its detection level was set in 2.0 mGy/h. In this report the gamma rate meter was only considered.

(2) The positions of area monitor were 10 and 20 m from source center and the alarm set to trip 50 μSv/h.

(3) About the radiation exposure for personnel, tissue dose was 200 mGy at the 2m from source center. The effective dose was 20 mSv for the outside surface of the shield (at 5m) for fission spike of a criticality accident or a slow excursion.

(4) the shielding condition of CAS, area monitor and radiation exposure were same.

(5) The dose evaluation point for the directly

operation was 2m from source center. The dose evaluation point with shield was at 5m from source center, *i.e.* the outside surface of the shielding materials.

(6) Minimum dose for detection considered in this report shown in Table 2.

Table 2 Minimum dose for detection

	Fission Spike		Slow Excursion	
	Without Shield*1	With Shield*2	Without Shield*1	With Shield*2
Unmoderated System	200 mGy	20 mSv	-	-
Moderated System	200 mGy	20 mSv	20 mSv	20 mSv

*1 at 2m *2 At 5m, the outside surface of shield

(7) In this report, three solution source were considered, for the effect of self-shielding of source materials and mean ν, the dose of 30 L plutonium nitrate solution [1] systems were the largest and 1000L uranyl nitrate solution systems were the smallest. In this study, the 30L plutonium nitrate solution [1] resutls applied to the fissions estimation for the dose, and 1000L uranyl nitrate solution results applied to the fission rate estimation for the detection CASs and area monitors.

4.1 Fission Spike for Unmoderated System

The evaluation results are shown in Table 3 to 5 (unmodereted system).

For ummoderated System, it is assumed the fission spike was within 0.5 [s](16).

4.2 Fission Spike for moderated system

The evaluation results are shown in Table 6 to 9 (solution systems).

The spike peak power was estimated by the equation of report (17) for moderated system.

There were the relation between F [fissions] and P [fissions/sec] as follows;

$$(\omega/2)\cdot F\ [\text{fissions}]=P[\text{fissions/sec}]$$

ω was Inverse Period. F [fissions] was the magnitute of minimum criticality accident for detection by the dose evaluation. The ω was 0.1 as conservative value referred to CRAC experiments(18). In addition, minimum fission rates of 30L plutonium nitrate solution estimated from Nomura's formula was estimated 2.46E+14 [fissions/sec] for ω = 0.1.

On the other hand, in Table 3, the spike peak power for 200 mGy at 2m and ω = 0.1 was 7.7E+13 [fissions/sec]. Therefore, the spike peak power was conservative.

4.3 Slow Excursion for modarated System

As a slow excursion, doubling time was 18 [s] and fission rate became 10 times for 60 seconds(16). the integral of the fissions from *t* to *t*+60 [s] was 0.9 times the fissions of the detection dose for the consideration of exposure before *t* [s]. The example for the 1.5E+15 fissions was shown in Fig. 2.

If this magnitude were equivalent 200 mGy, 5.7E+12 fissions/sec at *t* [s] should be detected for reducing the personnels radiation exposure.

Slow excursion was considered for only moderated systems.

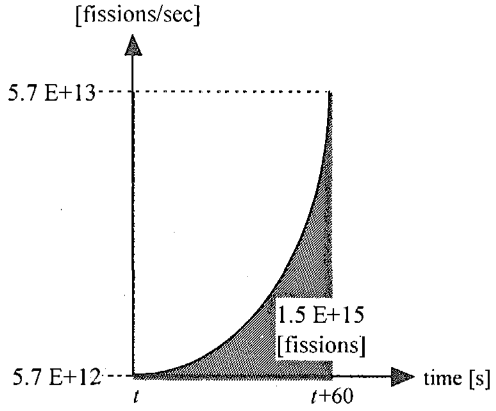

Fig. 2 Relation of the total fission and fissions rate for the slow excursion (example)

5. Conclusion

5.1 Unmoderated System

The unmoderated system of the condition in this report was PuO_2 powder. From Table 3 to 5, CAS was able to detect criticality accident for every case.

5.2 Moderated Sysyem for Fission Spike

From Table 6 and 9, CAS was able to detect criticality accident for no shield and concrete shield. For iron shield, in Table 9, was difficult to detect as expected.

5.3 Moderated Sysyem for Slow Excursion

From table 7 to 9, CAS was not able to detect criticality accident at *t* [s] and area monitors are effective. Both neutron and gamma area monitors for no shield or concrete shield were effective. The effectiveness of neutron area monitors for iron shield were evaluated numerically. After the alarm of area monitor turn on, personnel evacuated within 1 minute, they have less than 20 mSv radiation exposure.

These considerations will be able to be applied to the design of nuclear fuel cycle facilities although actual facilities' conditions (the distance from the accident points to the detectors, shielding thickness etc.) are more complex, and expect to more rational design.

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Table 3 Unmoderated System (PuO_2) without Shield

	200mGy at 2m from source center	**200mGy, 0.5 [s] Spike Peak Power**	**Detectable[*1] fissions/sec by CAS at 10m**	Detectable fissions/sec by Area Monitor at 10m[*2]		Detectable fissions/sec by Area Monitor at 20m[*2]	
	[fissions]	**[fissions/sec]**	**[fissions/sec]**	Neutron [fissions/sec]	Gamma-ray [fissions/sec]	Neutron [fissions/sec]	Gamma-ray [fissions/sec]
No shield	1.6E+15	**3.1E+15**	**1.9E+12**	2.5E+08	4.5E+10	9.6E+08	1.8E+11

*1 Detection level 2.0 mGy/h, *2 the values of area monitor for reference

Table 4 Unmoderated System (PuO_2) with Concrete Shield

Concrete Thickness	20mSv at 5m[*1] from source center	**20mSv, 0.5 [s] Spike Peak Power**	**Detectable[*2] fissions/sec by CAS at 10m**	Detectable fissions/sec by Area Monitor at 10m[*3]		Detectable fissions/sec by Area Monitor at 20m[*3]	
[cm]	[fissions]	**[fissions/sec]**	**[fissions/sec]**	Neutron [fissions/sec]	Gamma-ray [fissions/sec]	Neutron [fissions/sec]	Gamma-ray [fissions/sec]
25.0	3.0E+14	**6.1E+14**	**1.8E+12**	1.2E+09	4.3E+10	4.8E+09	1.8E+11
50.0	2.0E+15	**4.1E+15**	**3.1E+12**	8.6E+09	7.6E+10	3.5E+10	3.2E+11
100.0	8.5E+16	**1.7E+17**	**3.6E+13**	4.7E+11	8.8E+11	1.9E+12	3.6E+12
150.0	3.1E+18	**6.1E+18**	**6.8E+14**	2.7E+13	1.7E+13	1.1E+14	6.9E+13

*1 The outside surface of the shield, *2 Detection level: 2.0 mGy/h, *3 the values of area monitor for reference

Table 5 Unmoderated System (PuO_2) with Iron Shield

Iron Thickness	20mSv at 5m*1 from source center	**20mSv, 0.5 [s] Spike Peak Power**	**Detectable*2 fissions/sec by CAS at 10m**	Detectable fissions/sec by Area Monitor at 10m*3		Detectable fissions/sec by Area Monitor at 20m*3	
[cm]	[fissions]	**[fissions/sec]**	**[fissions/sec]**	Neutron [fissions/sec]	Gamma-ray [fissions/sec]	Neutron [fissions/sec]	Gamma-ray [fissions/sec]
10.0	1.0E+14	**2.0E+14**	**6.2E+12**	3.4E+08	1.5E+11	1.4E+09	6.2E+11
20.0	1.8E+14	**3.5E+14**	**1.1E+13**	5.8E+08	2.7E+11	2.3E+09	1.1E+12
30.0	3.3E+14	**6.5E+14**	**1.6E+13**	1.0E+09	4.0E+11	4.1E+09	1.7E+12

*1 The outside surface of the shield, *2 Detection level: 2.0 mGy/h, *3 the values of area monitor for reference

Table 6 Moderated System without Shield, for Fission Spike

	200mGy at 2m from source center*1	**200mGy, ω=0.1 Spike Peak Power*1**	20mSv, for slow excursion at *t**2	**Detectable*3 fissions/sec by CAS at 10m**	Detectable fissions/sec by Area Monitor at 10m		Detectable fissions/sec By Area Monitor at 20m	
	[fissions]	**[fissions/sec]**	[fissions/sec]	**[fissions/sec]**	Neutron [fissions/sec]	Gamma-ray [fissions/sec]	Neutron [fissions/sec]	Gamma-ray [fissions/sec]
No shield	1.5E+15	**7.7E+13**	-	**1.6E+12**	4.6E+09	3.8E+10	3.8E+10	1.5E+11

*1 The minimum number of fission during the first peak power of 30 [L] was estimated 4.92E+15[fissions], and minimum fission rates for ω=0.1 was estimated 2.46E+14 [fissions/s] with the Nomura's formula.
*2 *t* was shown in Fig 4.1, *3 Detection level 2.0 mGy/h

Table 7 Moderated System without Shield, for Slow Excursion

	20mSv, at 2m from source center	20mSv, ω=0.1 Spike Peak Power	**20mSv, for slow excursion at *t**1**	***Detectable*2 fissions/sec by CAS at 10m***	**Detectable fissions/sec by Area Monitor at 10m**		**Detectable fissions/sec by Area Monitor at 20m**	
	[fissions]	[fissions/sec]	**[fissions/sec]**	***[fissions/sec]***	**Neutron [fissions/sec]**	**Gamma-ray [fissions/sec]**	**Neutron [fissions/sec]**	**Gamma-ray [fissions/sec]**
No shield	3.4E+13	-	**1.3E+11**	*1.6E+12*	**4.6E+09**	**3.8E+10**	**1.8E+10**	**1.5E+11**

*1 *t* was shown in Fig4.1, *2 Detection level: 2.0 mGy/h

Table 8 Moderated System with Concrete Shield

Concrete Thickness	20mSv, at 5m*1 from source center	**20mSv, ω=0.1 Spike Peak Power**	**20mSv, for slow excursion at *t**2**	**Detectable*3 fissions/sec by CAS at 10m**	**Detectable fissions/sec by Area Monitor at 10m**		**Detectable fissions/sec by Area Monitor at 20m**	
[cm]	[fissions]	**[fissions/sec]**	**[fissions/sec]**	**[fissions/sec]**	**Neutron [fissions/sec]**	**Gamma-ray [fissions/sec]**	**Neutron [fissions/sec]**	**Gamma-ray [fissions/sec]**
25.0	7.2E+14	**3.6E+13**	**2.7E+12**	**6.8E+12**	**2.1E+10**	**1.6E+11**	**8.5E+10**	**6.7E+11**
50.0	4.6E+15	**2.3E+14**	**1.8E+13**	**2.6E+13**	**1.5E+11**	**6.3E+11**	**6.0E+11**	**2.6E+12**
100.0	1.9E+17	**1.9E+15**	**7.1E+14**	**4.6E+14**	**7.8E+12**	**1.1E+13**	**3.2E+13**	**4.6E+13**
150.0	6.5E+18	**3.3E+17**	**2.5E+16**	**9.2E+15**	**4.3E+14**	**2.2E+14**	**1.7E+15**	**9.3E+14**

*1 The outside surface of the shield, *2 *t* was shown in Fig4.1, *3 Detection level: 2.0 mGy/h

Table 9 Moderated System with Iron Shield

Iron Thickness	20mSv, at 5m*1 from source center	**20mSv, ω=0.1 Spike Peak Power**	**20mSv, for slow excursion at *t**2**	**Detectable*3 fissions/sec by CAS at 10m**	**Detectable fissions/sec by Area Monitor at 10m**		**Detectable fissions/sec by Area Monitor at 20m**	
[cm]	[fissions]	**[fissions/sec]**	**[fissions/sec]**	**[fissions/sec]**	**Neutron [fissions/sec]**	**Gamma-ray [fissions/sec]**	**Neutron [fissions/sec]**	**Gamma-ray [fissions/sec]**
10.0	2.7E+14	**1.3E+13**	**1.0E+12**	**1.5E+13**	**6.4E+09**	**3.6E+11**	**2.6E+10**	**1.5E+12**
20.0	4.9E+14	**2.4E+13**	**1.9E+12**	**9.3E+13**	**1.1E+10**	**2.2E+12**	**4.4E+10**	**9.4E+12**
30.0	9.0E+14	**4.5E+13**	**3.4E+12**	**2.4E+14**	**2.0E+10**	**5.9E+12**	**7.9E+10**	**2.5E+13**

*1 The outside surface of the shield, *2 *t* was shown in Fig4.1, *3 Detection level: 2.0 mGy/h

SPECIAL SESSION

POST IRRADIATION EXAMINATION

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