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Short communication

Calculation and usage of containment monitor radiation readings during PWR accidents

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Abstract

A computer code named CALCON for calculation of containment monitor radiation readings is introduced. The validity of the code was verified by comparison with data given in IAEA technical documents. The contribution of isotopes to containment readings under conditions of core melt, gap release and normal coolant release were investigated. The conclusions were that the radiation reading in containment is mainly from iodine and noble gases when sprays are off, and the radiation reading is mainly from noble gases when sprays are on, and during the beginning hours when radionuclides are released into containment, the monitor readings will decrease rapidly. Curves of containment radiation readings versus shutdown time for DAYA BAY nuclear power plant were calculated using CALCON.

Keywords: Containment radiation levels; Core damage assessment; EAL

1. Introduction

Deterministic health effects can be prevented by taking protective actions before or shortly after a major release. These immediate actions must be based on plant condition. Core damage assessment and accident classification are both important procedures for determining protective actions for the public and controlling dose to emergency workers for accidents at a nuclear reactor. To estimate core damage based on containment radiation levels is an important and widely used procedure. Containment radiation levels are also very important instrument readings for accident classification.

Assessment of core damage based on containment radiation levels should use plant conditions such as representative (unshielded) containment monitor readings, time of readings after release into containment, and containment spray status. Core condition was estimated from the increase above normal background radiation levels in containment by using figures or tables precalculated. Different figures or tables should be used according to containment types [1]. For giving a sample, normalized monitor readings of a nuclear power plant used by IAEA were listed in Table 1. A typical PWR with thermal power level of 3000 MW, unshielded containment monitor, a containment volume of 10^5 m^3 and a uniform mixture of 100% release of fission products were assumed in Table 1. Containment radiation reading indicates the release of reactor coolant to the containment. In the process of developing emergency action levels (EAL), site-specific readings indicating release in different core conditions were used [2].

In order to calculate site-specific containment radiation readings of different core conditions, spray status and shut down times in a PWR, a computer code named **CAL**culation of containment radiation levels to core **CON**ditions (CALCON) was developed. In order to verify the validity of CALCON, the containment radiation readings of a PWR with thermal power level of 3000 MW, unshielded containment monitor, a containment volume of 10^5 m^3 and a uniform mixture of 100% release of fission product were calculated. Times after shutdown of 1 and 24 h were used. Core conditions of core melt, gap release and normal coolant release were considered. The containment spray statuses were also considered. The validity of the code was proved by comparison of results between CALCON and the IAEA technical document. The importance of individual elements to in-containment radioactive readings was compared in different core conditions. The curves of site-specific containment radiation readings ver-

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Table 1
PWR core damage vs. containment monitor radiation levels

Level of core damage	Dose rate (mGy/h)[a]			
	No spray or pool time after shutdown		With spray or pool removal[b] time after shutdown	
	1 h	24 h	1 h	24 h
Core melt	5E+06	2E+06	2E+06	2E+05
Gap release	1E+06	5E+05	5E+05	5E+04
Normal coolant	1E+01	5E+00	5E+00	2E+00

Source: Ref. [1].
[a] Above normal background.
[b] Spray or pool has removed the non-noble gases to where they cannot be "seen" by monitors.

sus shutdown time in DAYA BAY nuclear power plant were calculated.

2. The expressions used in calculation of dose rate

Assume that there was a source S_0 in point A, and a detector was placed in point P, and the distance between A and P was α. If there was no medium between the source and detector, the gamma photons received by detector with solid angle of dA are [3]:

$$\frac{S_0(\mathrm{d}A/a^2)}{4\pi} \quad (1)$$

Radiation is weakened following absorption in the medium. When build-up is considered, the γ photons arriving at the detector (N) can be calculated using the following expression:

$$N = S_0 \frac{\mathrm{d}A}{4\pi a^2} B\,\mathrm{e}^{-\mu a} \quad (2)$$

where B is the buildup factor; μ is the linear attenuation coefficient, in m^{-1}.

The definition of the effective flux of gamma rays at point P is N/dA, therefore, the general expressions for the effective flux of gamma rays at a point r from source dispersed in air is:

$$\Phi(r) = \int_E \int_V \frac{f(E)C(r)B(\mu|\vec{r} - \vec{r}'|)}{4\pi(\vec{r} - \vec{r}')^2} \exp[-\mu|\vec{r} - \vec{r}'|]\,\mathrm{d}V\,\mathrm{d}E \quad (3)$$

where $C(r)$ is the concentration of the isotope being considered, in Bq/m^3; $f(E)$ is the branching ratio to the specified energy.

Since the integrals could not in practice be evaluated precisely, approximate methods were used. Columniation coordinates (r, θ, z) centred on the centre line of the containment were employed. The detector lied at point (r', θ', z'). The following expression was used in CALCON in order to calculate the dose rate of gamma rays from the source in containment air:

$$\mathrm{CD}(t) = \sum_{\mathrm{KE}} \sum_{(r,\theta,z)} E_0(n, \mathrm{KE})\,\mathrm{FE}(n, \mathrm{KE})\,\mu_{0a} \times \exp(-\mu R)\,B(E_0)\,C(n, t)\,\frac{r\,\mathrm{d}r\,\mathrm{d}\theta\,\mathrm{d}z}{4\pi R^2} \quad (4)$$

where CD(t) is the dose rate from isotope in containment air in shutdown time t, in Gy; KE the serial number of photon produced by decay of isotope n; $E_0(n, \mathrm{KE})$ the energy of photon KE emitted by isotope n, in J; FE(n, KE) the branching ratio of photon KE in nuclide n; μ_{0a} the absorption coefficient in standard air; R the distance from the emission point (r, θ, z) to the detector (r', θ', z'), in m; $C(n, t)$ is the air active concentration of isotope n in containment at shutdown time t, in Bq/m^3.

The distance R was calculated using the following expression:

$$R = \sqrt{(z - z')^2 + (r\cos\theta - r'\cos\theta')^2 + (r\sin\theta - r'\sin\theta')^2} \quad (5)$$

The dose rate of gamma rays from isotopes absorbed on the containment wall was calculated using the following expression.

$$\mathrm{CDA}(t) = \sum_{\mathrm{KE}} \sum_{s} E_0(n, \mathrm{KE})\,\mathrm{FE}(n, \mathrm{KE})\,\mu_{0a} \times \exp(-\mu R)\,B(E_0)\,\mathrm{CA}(n, t)\,\frac{\mathrm{d}s}{4\pi R^2} \quad (6)$$

CDA(t) the dose rate of gamma rays from isotopes absorbed onto the containment wall in shutdown time t, in Gy; CA(n, t) surface activity concentration of isotope n on the containment wall at shutdown time t, in Bq/m^2.

3. Assumptions used in CALCON

The following assumptions were used in CALCON:

(1) Prompt release into the containment of the fission products in the normal coolant, gap, or from core melt;
(2) Uniform mixing in the containment;
(3) The readings are above normal operating background levels in the containment;
(4) Unshielded monitor;
(5) Sprays are assumed to remove non-nobles to a location where the monitor cannot see them;
(6) When sprays are on, natural processes for reducing of particulate/aerosol are ignored;
(7) The isotopes are uniformly absorbed onto the containment wall;
(8) The decays of isotopes are considered in the calculation of the concentration of isotopes in containment air and the surface of the containment wall.

4. The parameters used in CALCON

The amount of fission products assumed to be released is approximately the mean value calculated for a range of core damage accidents. From the definition of Ref. [1], the core damage states used were defined as:

Leakage of normal coolant following a steam generator tube rupture (SGTR) accident that does not involve core damage.

A gap release assumes that the core is damaged and all fuel pins have failed, releasing the gaseous fission products contained in the fuel pin gap.

A core melt release assumes that the entire core has melted, releasing a mixture of isotopes believed to the representative for most core melt accidents.

The source terms used in CALCON were calculated using the methodology described in Ref. [4]. In order to calculate the in-containment source term, the following steps were used:

(1) Estimate the amount of fission products in the core;
(2) Estimate the fraction of the fission product inventory released from the core for a normal coolant, gap release or core melt;
(3) Estimate the fission product inventory released from the core that is removed in the containment.

The following expression was used to estimate the in-containment source term:

$$\text{Source term}_{\text{in}} = \text{FPI}_i \, \text{CRF}_i \prod_{j=1}^{N} \text{RDF}_{(i,j)} \tag{7}$$

where FPI_i is isotope inventory, CRF_i amount of isotope i released out of core/core inventory of isotope i, $\text{RDF}_{(i,j)}$ fraction of the isotope i activity in containment following reduction mechanism j, N the reduction mechanisms acted on the way to the containment.

The following parameters were used in CALCON:

(1) The isotopes included in CALCON contained all isotopes listed in Ref. [1];
(2) The fission product inventories were from Ref. [5];
(3) Photon energy, emission probability and half-life of isotopes were from Ref. [6];
(4) The linear attenuation coefficients and the absorption coefficients in standard air were from Ref. [7], the coefficients of interspace energies were using Newton's three points insert methods;
(5) The Build-up factor B was calculated using methods from Ref. [8]:

$$B(E_0) = 1 + \mu R + \frac{(\mu R)^2}{7E_0^{2.4}} \quad E_0 \geq 0.5\,\text{MeV} \tag{8}$$

$$B(E_0) = 1 + 1.1\mu R + (\mu R)^2 \quad E_0 < 0.5\,\text{MeV} \tag{9}$$

(6) The reduction factors of natural process and sprays of particulate/aerosol were from Ref. [4].

5. Results and discussion

In order to verify the validity of CALCON, the containment radiation readings of a typical PWR were calculated. The results of CALCON and data in Ref. [1] were compared in Table 2. Most of the results were consistent with each other. The main differences result from the data of sprays and natural reduction factors.

Contributions of isotopes to the containment monitor radiation reading during normal coolant release, gap release and core melt of a typical PWR [9] were also calculated by CALCON. It was concluded from the results that when sprays are off the radioactive reading in containment is mainly from iodine and noble gas, when sprays are on the radioactive reading is mainly from noble gas. For giving an example, contributions of isotopes to the containment monitor radiation reading in 24 h shutdown time were given out in Table 3.

For DAYA BAY nuclear power plant, the thermal power is 2905 MW, free containment volume is 49 400 m^3, and the inner diameter of the containment is 37 m. There are two monitors in the containment. The locations of the radiation monitor are 11.8 and 15 m away from the center line of the containment, and they are both in the level of 21.5 m above the bottom of the containment; the equipment floor is in the level of 20 m above the bottom. Therefore, the monitor locates 1.5 m above the free containment volume floor. From previous calculations [10,11], the locations of the monitor did not affect the readings very much. The calculations were made assuming the monitor was located 13.5 m away from the center line and at the level of

Table 2
Comparison between results calculated by CALCON and data in Ref. [1]

Core conditions	Spray	Shutdown time (h)	Source	
			IAEA-TECDOC-955 (mGy h^{-1})	CALCON (mGy h^{-1})
Normal coolant	Off	1	10	7
	On	1	5	4
	Off	24	5	3
	On	24	2	2
Gap release	Off	1	1E+06	0.5E+06
	On	1	5E+05	0.8E+05
	Off	24	5E+05	10E+05
	On	24	5E+04	0.9E+04
Core melt	Off	1	5E+06	5E+06
	On	1	2E+06	2E+06
	Off	24	2E+06	1E+06
	On	24	2E+05	20E+05

Table 3
Contributions of isotopes to containment readings in 24 h shutdown

Isotope	Spray off (%)			Spray on (%)		
	Normal coolant	Gap release	Core melt	Normal coolant	Gap release	Core melt
Noble gas						
Kr-87		2				
Kr-88		9			2	2
Xe-131m	45			64		3
Xe-133	21	2	13	29	82	80
Xe-133						3
Xe-135	4			5	8	8
Iodine						
I-131	3	4	19		2	
I-132		21				
I-133	7	13	29		3	
I-134		21				
I-135	5	24	10			
Ru-106	3					
Te-131			3			
Te-132			6			
Cs-134			5			
Cs-136			2			
Ba-140			2			
La-140	5					
Others	7	4	11	2	3	4

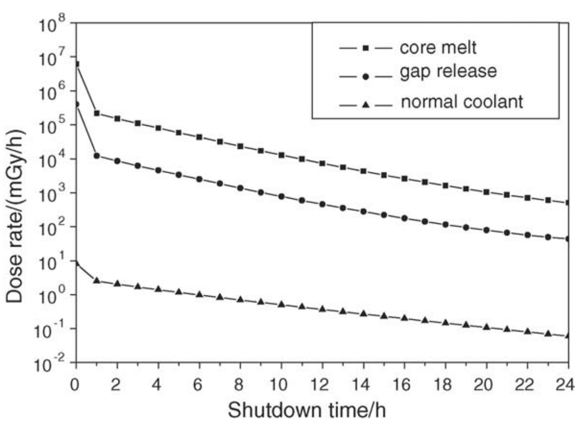

Fig. 1. Curves of containment radiation readings vs. shutdown time in DAYA BAY with sprays.

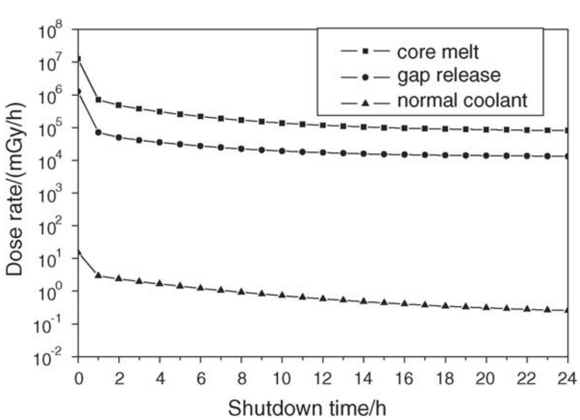

Fig. 2. Curves of containment radiation readings vs. shutdown time in DAYA BAY without sprays.

1.5 m above the free containment volume floor. The curves of containment radiation readings versus shutdown time of containment reading in DAYA BAY nuclear power plant were given in Figs. 1 and 2.

6. Conclusion

CALCON is a valid and useful tool for calculating containment monitor radiation reading of PWR in core conditions of core melt, gap release and normal coolant.

When sprays are off, the radiation reading in containment is mainly from iodine and noble gases. When sprays are on, the radiation reading is mainly from noble gases.

During the beginning hours when radionuclides are released into containment, the monitor readings will decrease rapidly. Sprays in containment will accelerate the decreases.

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