Study on the limits of confinement leakage rates of pool-type sodium-cooled fast reactor

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Abstract. Pool-type sodium-cooled fast reactor primary vessel and confinement or containment is used as barrier of containing radioactive material. Based on the design data of CEFR and the system characteristics of demonstrated fast reactor, the confinement leaking model in normal operating condition and accident conditions is established in this paper. In the accident condition, the reactor's total amounts of radioactive material were calculated by ORIGEN2. The released fraction of fission products from fuel elements to primary sodium (FC factors) is used to calculate the amounts of radioactive gas from reactor core to primary sodium, and the released fraction of fission products from primary sodium to cover gas region (FS factors) is used to calculate the amounts of radioactive gas from primary sodium to covering gas. The calculation model mentioned before calculated the amounts of radioactive gas from covering gas to containment and from containment to environment. Finally, the proposed upper limits of containment leakage rate and main vessel leakage rate were brought forward.

Key Words: SFR; Containment; Severe accident

1. Introduction

Pool-type sodium-cooled fast reactor primary vessel and confinement or containment is used as barrier of containing radioactive material[1]. In normal operating condition, hermetic breakage may be occurred in fuel element, and radioactive material would release from cladding gap of fuel element to primary sodium. Therefore, the radioactive material constitutes the main source term in normal operating condition. Based on the design data of China experimental fast reactor (CEFR) and the system characteristics of demonstrated fast reactor (CFR600), the confinement leaking model in normal operating and accident conditions were established. Routes of gas leaking at the top of the reactor core, the release of covering gas, reactor pit ventilation and ionization chamber ventilation were considered in the normal operating condition.

If some reactivity input into reactor core, this occasion may expand to an accident[2]. The reason of accident is that the heat caused by reactor core is not matched with the removal heat of the coolant. Eventually, overheat may induce to the melt of reactor core. At the early period of a severe accident, reactor core releases some volatile and non-volatile fission product and noble gas to primary sodium. All of the noble gas will be released to the cover gas of SFR shortly, and some of volatile and non-volatile fission product will be released to cover gas in a long period. Large rotatable plug and small rotatable plug, which are arranged to handle fuel assemblies, may have some leakage rates. Consequently, some radioactive material will be released to containment of sodium fast reactor. Due to the leakage of containment, airborne radioactive material will be released to environment. In order to minimize the hazard of the public and occupation, the dose of radioactive material impacting to the public should be below the limits of related regulations in normal operating state and severe accident. By now, the mitigated influence of confinement of CFR600 to the transportation of airborne radioactive materials is not analysed by a computer code. The paper investigated the confinement design of fast reactor of Russia, France, Japan, America and India, and the domestic and international research of release of airborne radioactive material[23456]. The leak model of airborne radioactive confinement of normal operation and accident condition is established in this paper. The calculation methods of generation, release and transport of airborne radioactive material is put forward in this paper. Meanwhile, the methods could analyse the process of radioactive material generated, released and transported from reactor core to cover gas area, containment and environment. The paper mainly researched a large pool-type sodium cooled fast reactor(1500MWt,600MWe),because an 600MWe fast reactor is designing and constructing in China, and this work is a part of the design of 600MWe fast reactor. The amount of airborne radioactive material entering environment can be obtained by changing the leakage rate of primary vessel and containment. The amounts of released radioactive material should not exceed the requirement of Regulations for environmental radiation protection of nuclear power plant.

2. Methods and modeling

2.1 Calculation methods

In normal operating condition, hermetic breakage of fuel rod is the main source of radioactive material. Hermetic breakage of fuel rods depends on the manufacturing level of nuclear fuel elements. The breakage probability of nuclear fuel elements is assumed to 0.1% on the calculation of source term in normal operating condition[7]. In accident condition, the fraction of radioactive material released depends on a lot of factors, such as the fraction of reactor core melt, the amount of fission product in primary sodium, the distribution of nuclear fuel in reactor core and so on. In a lot of related examples that used a conservative release value in accident condition, same methods were adopted to calculate the transportation of various radioactive nuclides. Fission products and fissile could divide into four steps, including the step from reactor core to primary sodium, the step from primary sodium to cover gas area, the step from cover gas area to containment, and the step from containment to environment. ORIGEN2 code can be used to calculate the total amount of radioactive material of fission products and minor actinides[7]. The output of ORIGEN2 code can be used to calculate the amount of radioactive material from reactor core transported to environment. The GASDOSE code developed by China Institute of Atomic Energy, which is a radioactive material diffusing code in air, could be used to calculate the impact of radioactive material released and transported from reactor to the public. The leakage rates of containment and main vessel could influence the amount of radioactive material released from reactor core to environment.

2.2 Leak model of confinement in normal operating condition

In normal operating condition, as showed in the fig.1, pool-type sodium-cooled fast reactor's total amounts of radioactive material were calculated by ORIGEN2, and the amounts of airborne radioactive material through 4 routes entering environment were calculated. The 4 routes include the leak of primary loop, the ventilation of reactor pit, the release of reactor cover gas and the ventilation of spent fuel transfer barrel. According to experience of CEFR[8], the amount of radioactive material released from SFR is mainly from the leak of primary loop. In this paper, we focus on the modelling of this route.

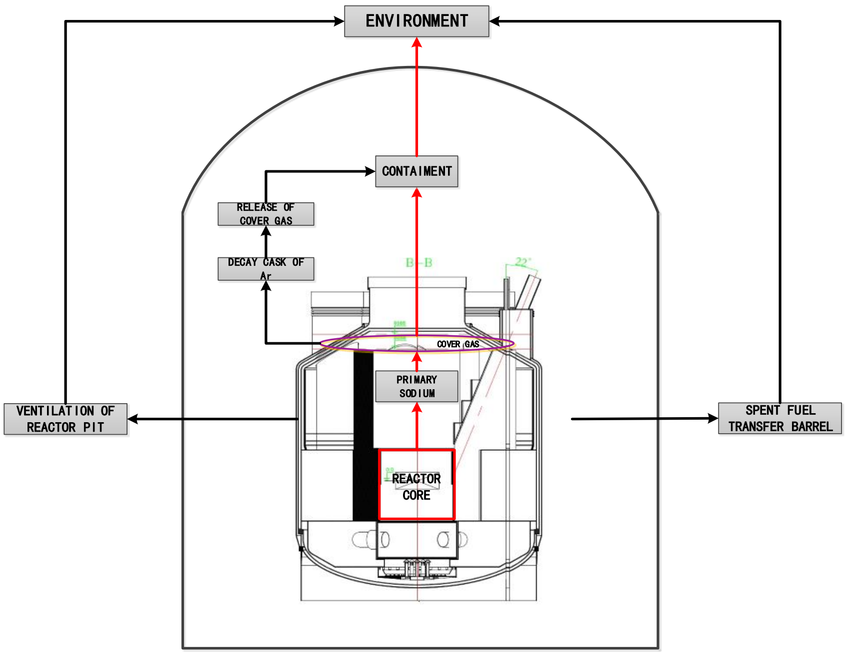


FIG. 1 The schematic of radioactive gas release route in the operating state

Radioactive gas is mainly released by the leakage of cover gas at the normal operation of sodium-cooled fast reactor. After airborne fission product released from defected fuel to primary coolant, airborne fission product will be detained in sodium and then released to cover gas region. Fission product released to cover gas region may include fission gas and volatile fission product.

The transportation mechanism of fission gas is described assuming:

a. Fission product will be accumulated in fuel elements, and entered into the gas area and crevasse of fuel elements.

b. Fission product will be released to primary coolant via fuel cladding cracks, and then released to reactor cover gas region.

This progress will evolve with given rates. According to final safety analysis report of CEFR, as to those isotopes with not too long half-life, gaseous fission product in reactor cover gas will be calculated based on following equation:

$$A=\frac{3.2\times10^{8}\cdot N\cdot\eta\cdot\alpha_{fy}}{V_{TP}}\times\frac{\lambda_{ph}\cdot\lambda_{hn}\cdot\lambda_{gT}\cdot\lambda}{(\lambda_{ph}+\lambda)(\lambda_{hn}+\lambda)(\lambda_{gT}+\lambda)(\lambda_{yT}+\lambda)} \tag{1}$$

Where:

A=the radioactivity of fission products released to cover gas region per liter, Bq/l.

$3.2\times10^{8}\times N$= the production rate of fission product.

N = reactor thermal power, W.

η=fraction of failed fuel.

α_{fy}=isotope yield fraction.

Vtp=the volume of reactor cover gas region, l.

λ_{pn}=escape fraction from failed fuel elements to cracks, s^{-1}.

λ_{hn}=escape fraction from cracks to primary sodium, s^{-1}.

λ_{gT}= the leakage constant of fission product from reactor cover gas to the outside of reactor vessel, s^{-1}.

λ= the decay constant of a nuclide, s^{-1}.

Some volatile fission product could be released from primary sodium to cover gas region via steam or aerosol. The amount entered into cover gas of ^{131}I,^{133}I,^{135}I,^{134}Cs and^{137}Cs could be calculated by following equation:

$$A_i = A_i^T L_i \frac{\gamma_c}{\gamma_T} \tag{2}$$

Where:

A_i= the activity of nuclide *i* in reactor cover gas region per liter, Bq/l.

A_i^T= the activity of nuclide *i* in primary sodium per liter, Bq/l.

γ_T= the density of primary sodium at the reactor core outlet's temperature, g/l.

γ_C= the density of supersaturating steam of sodium, g/l.

L_i= the relative of volatility of nuclide i to primary sodium.

In normal operating condition, the amount of fission product from reactor core to cover gas can be calculate by equation (1) and (2). Meanwhile, the model of fission product release from reactor core is established. Airborne radioactive material is released from reactor cover gas region to the atmosphere of containment via leak of primary vessel. The amount of radioactive material *i* released from cover gas region to containment is equal to the activity of nuclide *i* in reactor cover gas region per liter multiply the leakage rate of primary vessel, which unit is liter/day.

2.3 Leak model of confinement in accident condition

In the accident condition, we conservatively assume that the sodium-cooled fast reactor core is melt down entirely. The release process of fission product from reactor core is assumed to be followings in accident condition:

a. As the fast reactor melt down, all fission gas, most alkali metals and halogen, some alkaline-earth metals, and little lanthanides could be released to primary sodium from nuclear fuel.

b. As for the radioactive nuclides released to primary sodium, all fission gas could be released to cover gas region. Thanks to the steam of sodium, other radioactive nuclides may be present in cover gas region.

c. Some aerosols could be released from cover gas region to the atmosphere of containment via reactor rotating plugs.

d. Airborne fission products could be released from the atmosphere of containment to environment by given leakage rates.

As showed in the fig.2, fission product could be released from fuel to environment. The ORIGEN2 calculation codes[9] were used to calculate the reactor's total amounts of radioactive material. The amounts of radioactive gas from reactor core to primary sodium were calculated by FC factors, and the amounts of radioactive gas from primary sodium to covering gas were calculated by FS factors.

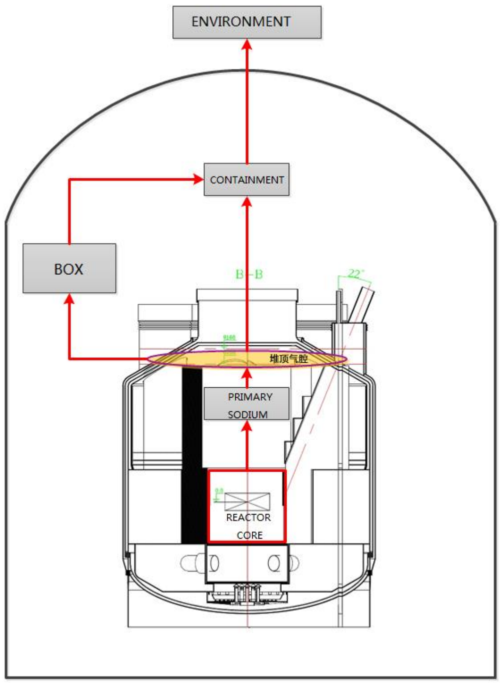


FIG.2 The schematic of radioactive gas release route in the accident state

There are two types of airborne fission product from primary sodium to reactor cover gas region: decay and the leakage from cover gas region to the atmosphere of containment. The activity of cover gas region were calculated by the following equation:

$$A_g = \mathrm{A} \times \mathrm{FC} \times \mathrm{FS} \times e^{-(\lambda+\lambda_g)t} \tag{3}$$

Where:

A_g= the activity of reactor cover gas region, Bq.

FC= the released fraction of fission products from fuel elements to primary sodium.

FS= the released fraction of fission products from primary sodium to cover gas region.

A= the total amount of radioactive material calculated by ORIGEN2, Bq.

λ= the decay constant of a nuclide, s^{-1}.

λ_g= the leakage rate from reactor cover gas region to the atmosphere of containment, s^{-1}.

After the reactor core melts, the temperature of primary sodium could be raised. On one hand, the pressure of reactor cover gas region could be risen to a level, which can let the protect system of super pressure open. Airborne fission products could be released into box room and be detained in the room. On the detaining period, airborne fission products could be leaked from box room to containment. On the other hand, fission gas and other volatile fission products could be leaked from reactor cover gas region to the atmosphere of containment via given leakage rates. At last, some fission gas and other volatile fission products could be leaked from containment to environment. The radioactive activity of nuclide i could be changed according to the equation (4). The change amounts of radioactive activity in the containment are equal to the amount of radioactive activity entering into the containment subtracted by the decay amount by itself and the amount of radioactive activity released from containment to environment.

$$\frac{dA_c}{dt} = A_g \times \lambda_g - A_c(\lambda + \lambda_c) \tag{4}$$

The radioactive activity A_c of different nuclides in the containment could be calculated by the equation (3) and (4). λ_c is the leakage rate from containment to environment. The answer of radioactive activity A_c can be calculated by the following equation(5).

$$A_c = \mathrm{A} \times \mathrm{FC} \times \mathrm{FS} \times \left\{ \frac{\mathrm{e}^{-(\lambda+\lambda_c)-(\lambda_g-\lambda_c)}}{\lambda_c-\lambda_g} + \frac{\mathrm{e}^{-(\lambda+\lambda_c)}}{\lambda_c-\lambda_g} \right\} \tag{5}$$

The total amounts released from containment to environment, A_{out},are equal to the integral amount of the radioactive activity multiplied by the leaked amount from containment to environment. In the time from t_0 to t_1, the radioactive activity A_c can be calculated by the following equation(6).

$$A_{out} = \int_{t_0}^{t_1} A_c \times \lambda_c dt \tag{6}$$

In the time from t_0 to t_1, the total amounts released from containment to environment A_{out} could be calculated by the following equation(7).the equation (7) is calculated by the equation (5) and (6).

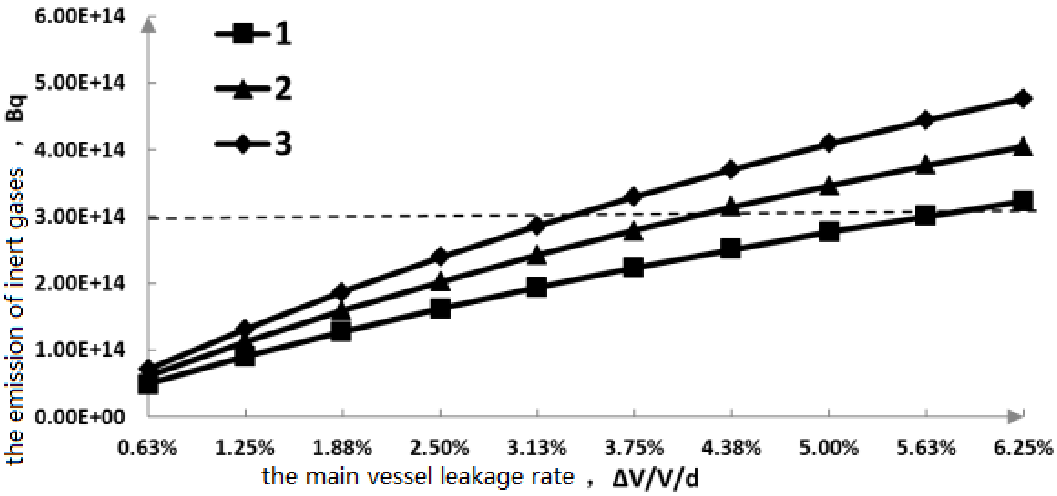
$$A_{out} = A \times FC \times FS \times \left\{ \frac{-\frac{e^{-(\lambda+\lambda_g)t_0} - e^{-(\lambda+\lambda_g)t_1}}{\lambda+\lambda_g} + \frac{e^{-(\lambda+\lambda_c)t_0} - e^{-(\lambda+\lambda_c)t_1}}{\lambda+\lambda_c}}{\lambda_g-\lambda_c} \right\} \tag{7}$$

Meanwhile, the calculation of released amount includes the deposition factor in the containment, which is calculated be the CONTAIN-LMR codes. The impact of the radioactive material released from the reactor to the public were calculated by the GASDOSE code, which was put forward by CIAE. The CONTAIN-LMR codes is used to calculate the released amount of radioactive material released to the air, which is the input data of GASDOSE code. The output data of GASDOSE code is radioactive dose of the public.

3. Results and discussion

3.1 The impact of different confinement leakage rate to the emission of inert gases in normal operation

On the basis of the primary analysis of the emissions, we found that iodine, particles (half-life≥8d),C-14 and tritium could far below the regulated value of GB6249-2011[10]regulations for environmental radiation protection of nuclear power plant. Nevertheless, the emission of inert gases is near the regulated value of 3×10^{14}Bq/a (1500MWt).



1- The inert gases release amount when the containment is 3%ΔV/V/d.
2- The inert gases release amount when the containment is 4%ΔV/V/d.
3- The inert gases release amount when the containment is 5%ΔV/V/d.

FIG.3 Variation of amount of inert gases release vs. main vessel leakage rate

The variation of inert gases should be changed as the main vessel leakage rate. From the fig.3, if the inert gases release amount below 3×10^{14}Bq/y, when the containment is 3%ΔV/V/d, the main vessel leakage rate should be below 5.63%ΔV/V/d; when the containment is 4%ΔV/V/d, the main vessel leakage rate should be below 4.38%ΔV/V/d; when the containment is 5%ΔV/V/d, the main vessel leakage rate should be below 3.75%ΔV/V/d.

3.2 The leakage rate calculation of demonstrated fast reactor in accident condition

By changing reactor main vessel leakage rate and containment leakage rate, different total amounts released from containment to environment A_{out} could be calculated. The generation IV sodium-cooled fast reactor should not need emergency responds. In China's regulations, if the public dose above 10mSv, reactor emergency responds should be adopted. When the public dose is 10mSv, the relationship of the main vessel leakage rates and containment leakage rates is descripted by fig.4.One point in this line means that at special main vessel leakage rates and corresponding containment, the leakage rates the contribution of radioactive material to the public is 10mSv.

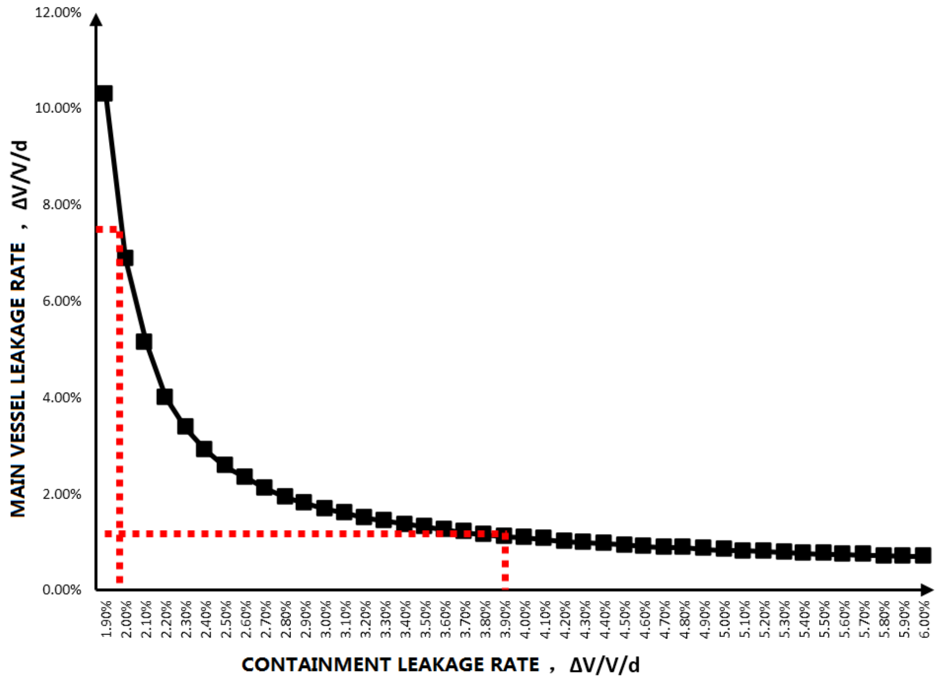


FIG.4 the relationship map of the main vessel leakage rates and containment leakage rates

3.3 The range of main vessel leakage rates and containment leakage rates

In the Final Safety Analysis Report of CEFR, the main vessel leakage rate is 1.14%ΔV/V/d. The size of CFR600’s rotating plugs is bigger than that of CEFR. Hence, the main vessel leakage rate is above 1.14%ΔV/V/d at the same manufacturing level. In the fig.4, the main vessel leakage rate1.14%ΔV/V/d is corresponding to containment leakage rate 3.90%ΔV/V/d. When the containment leakage rate is 3.90%ΔV/V/d, in order to satisfy the inert gases emission, the upper limits of main vessel leakage rate is 0.786%ΔV/V/d. According to the experience of CEFR, the main vessel leakage rate in accident condition is ten times of the main vessel leakage rate in operational condition. When the containment leakage rate is 3.90%ΔV/V/d, the main vessel leakage rate is corresponding to 7.86%ΔV/V/d。Hence, when CFR600’s reactor core was melt down and the public dose is 10mSv, the proposed upper limits of containment leakage rate are range from 1.96%ΔV/V/d to 3.9%ΔV/V/d; the proposed upper limits of main vessel leakage rate are range from 1.14%ΔV/V/d to 7.86%ΔV/V/d.

4. Conclusion

The leak model of airborne fission product in normal operation condition and accident condition is established. The calculation methods of generation, release and transport of airborne radioactive material in sodium-cooled fast reactor is put forward. The proposed upper limits of containment leakage rate are range from 1.96%ΔV/V/d to 3.9%ΔV/V/d; the proposed upper limits of main vessel leakage rate are range from 1.14%ΔV/V/d to 7.86%ΔV/V/d.

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