Evaluation method of core damage fraction of Mark-I containment vessel

■ 1. Introduction

The reactor core of Unit 2 could be cooled until about 09:00 on March 14, 2011, because the RCIC continued to operate despite the loss of DC power due to the earthquake. Therefore, the CAMS, which measures the dose rate inside the containment vessel, was restored on the morning of the same day, and it was possible to capture the dose rate behavior in the containment vessel before and after the core damage. The relationship between the measured values and the accident progression has been set as Issue No. 2-12 and has been discussed in Attachment 2-10 as the sharp increase in CAMS measurements on March 15 of Unit 2, and in Attachment 2-11 as the FP migration behavior estimated from CAMS measurements on March 14 and 15 of Unit 2.

Based on the results of these studies and other results related to the accident progression in Unit 2, it is estimated that Unit 2 experienced almost 100% core damage, as was the case in Units 1 and 3. On the other hand, at the time of the accident, the CAMS measurements were also used to evaluate the core damage fraction. For example, the core damage fraction for Unit 2 announced on April 27, 2011, was 35%, which was evaluated based on the degree of core damage estimated from the accident progression and the methodology to evaluate core damage by using CAMS measurements established before the accident. The core damage fraction (Figure 1), which was evaluated based on the CAMS measurements, appears to have differed significantly from the degree of core damage estimated from the accident progression. (In the same publication, core damage fractions of Unit 1 and Unit 3 were evaluated at 55% and 30%, respectively.) In addition, as a common trend in Units 1 to 3, it can be observed that the S/C measurements are much smaller than the CAMS measurements for D/W, except for the measurements before core damage in Unit 2, as shown in Figure 2.

At the time of the 2011 accident, CAMS dosimetry was considered to be an important parameter for severe accident management because it was used to determine the application of severe accident operating procedures and to evaluate the core damage fraction. Therefore, in this document, the actual accident progress as described above and CAMS measurements are used to discuss the factors that appear to show different trends.

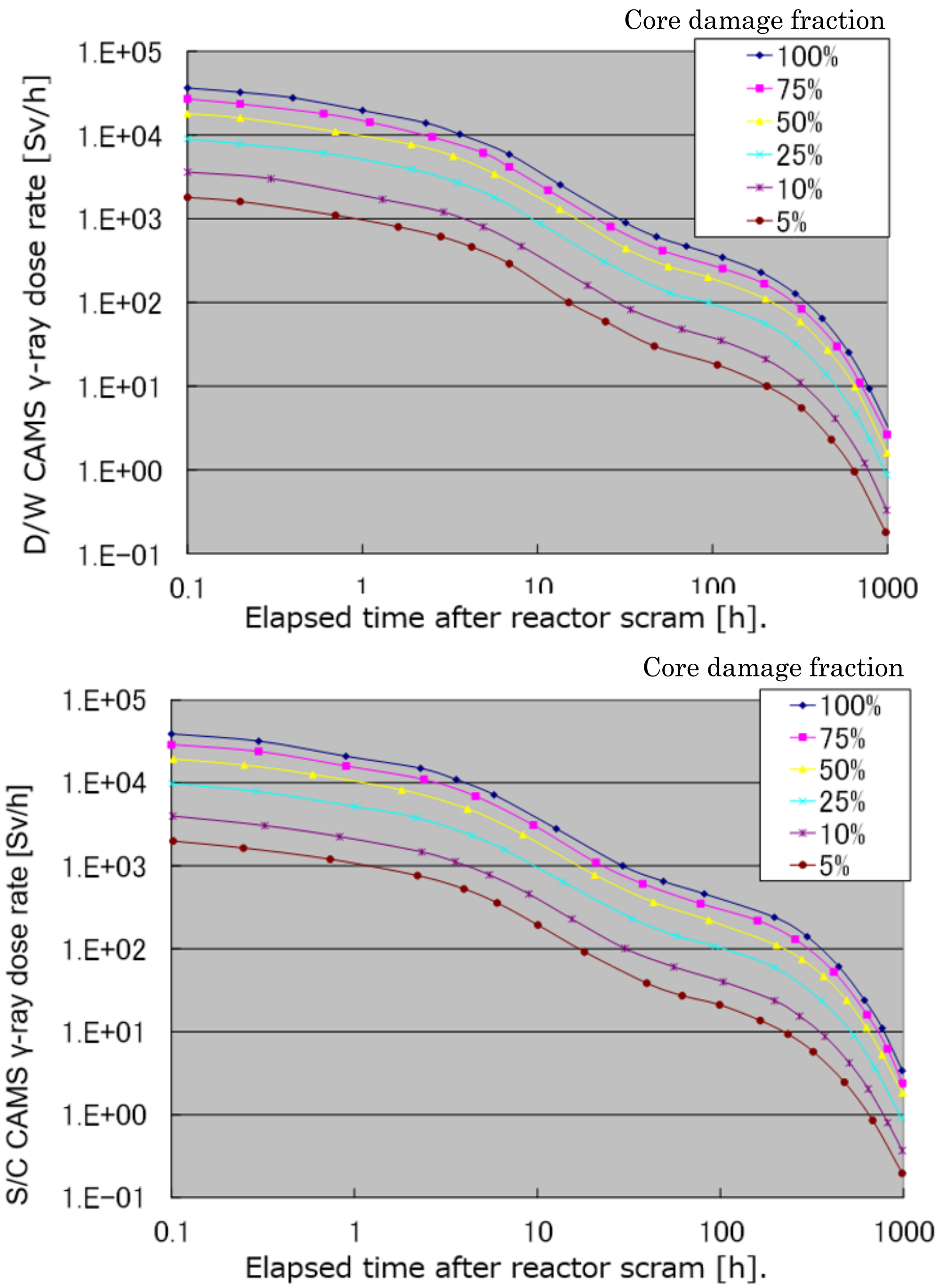
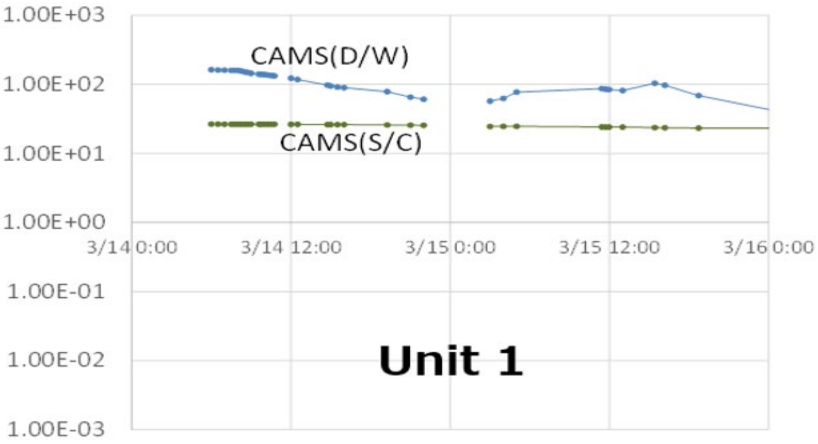
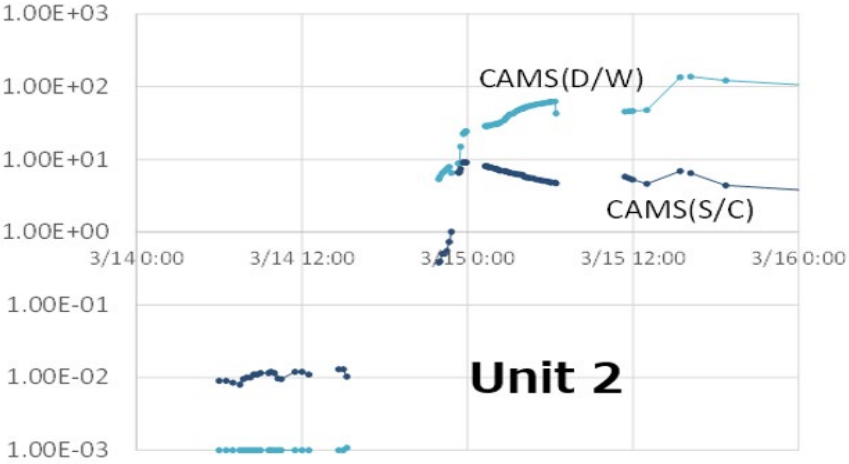


Figure 1 Map of core damage fraction for Unit 2 (common to BWR4)
(Upper) Relationship between elapsed time after scram and D/W CAMS measurements and core damage fraction
(Lower) Relationship between elapsed time after scram and S/C CAMS measurements and core damage fraction

Dose rate unit: Sv/h





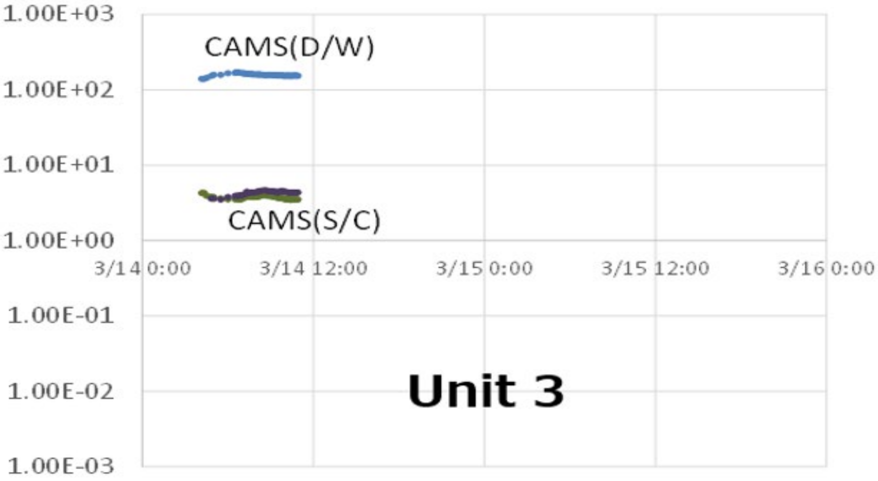


Figure 2　CAMS dose rate measurements for Units 1 to 3

■ 2. Relationship between CAMS dose rate measurements and core damage fraction

The relationship between CAMS dose rate measurements and core damage fraction shown in Figure 1 was developed prior to the accident, assuming an accident progression in which a fuel rod is damaged and the radioactive materials trapped inside it migrated into the containment vessel. The dose rate in the containment vessel at that time was used to estimate the radioactive materials released from the fuel rods. Although noble gases, iodine, cesium, etc. are considered as radioactive materials released from fuel rods at the time of fuel failure, from the viewpoint of conservatively judging core damage, it has been assumed that only noble gases were released and core damage was evaluated using a lower dose rate.

Since the amounts of radioactive materials decrease with time due to decay, the relationship between the dose rate measured by CAMS and the core damage fraction is determined in a time-dependent manner so that the later the time after the scram, the larger the core damage fraction for the same dose rate.

The dose rate can be calculated as the amount of radiation from surrounding radioactive materials reaching a certain point. In making this relationship diagram, a hemisphere with a volume equivalent to the free space volume of the D/W and S/C is assumed, and the dose rate is obtained by calculating the dose rate when the measurement point is placed at the center of the sphere. This is the so-called hemispheric model, which has been commonly used in dose rate calculations for a long time.

■ 3. Relationship between dose rates measured during the accident and evaluated values of core damage fraction

Figure 3 shows the measured CAMS values for D/W and S/C in Unit 2 measured from March 14 to March 16. As mentioned above, except for the dose rate measurements from around 12:00 to 16:00 on March 14, before the core damage, the dose rate measurements of the S/C from the night of March 14, which is considered to be after the core damage occurred, are all about one order of magnitude lower than the CAMS dose rate measurements for the D/W.

In terms of the accident progression of Unit 2, the core was damaged before the reactor vessel was damaged, radioactive materials initially released from the fuel rods were discharged into the S/C via the SRVs, and some of them migrated to the D/W as well. Along with the accident progression, large amounts of radioactive materials were then transferred to the D/W due to direct release of radioactive materials from the reactor vessel to the D/W as a result of the reactor vessel failure. Therefore, it is expected from the characteristics of the accident progression that the dose rate of the S/C first increases and then the dose rate of the D/W reverses during core damage and core melt, but in the actual measured values, the measured dose rates of the S/C were consistently lower than those for the D/W.

Figure 4 shows the location of the D/W and S/C CAMS dose rate detectors in Unit 2; the D/W detector was installed in the penetration where it measured dose rates in the immediate vicinity, not inside the containment vessel. The S/C detectors, on the other hand, were not directly installed in the doughnut-shaped S/C, but were fixed to the wall of the torus room where the S/C was installed. However, the measured dose rate used to evaluate the core damage fraction was set after conducting a calculation to determine what dose rate would be obtained in a situation where a hemisphere with the same volume as the free space volume of the S/C existed directly above the dose rate detector and was filled with noble gases, as shown on the right side of Figure 5. Moreover, under the actual conditions, noble gases filled the upper area of the doughnut-shaped S/C, and the radiation emitted from them was partially shielded by the D/W and other structures, which, together with the fact that the S/C was located a little further away, resulted in actual measured dose rates that were likely to have been smaller than the dose rates in Figure 3 used to assess the core damage rate.

In Attachment 2-11, the distribution of radioactive materials in the S/C is estimated by Monte Carlo calculations that consider the geometry of the CAMS installation location, etc., in relation to the dose rate measured by the CAMS. The measured value of 9.1 Sv/h at 23:54 on March 14, which corresponds to approximately 80 hours after the earthquake, is the sum of the contributions from the following three sources.

① Noble gas FPs migrate directly to the gas phase of the S/C and become a source of radiation.

② Volatile FPs such as iodine and cesium are mostly trapped in water and become a source of radiation in water.

③ Some of the volatile FPs in the gas phase adhere to the inner surface of the S/C and become a source of radiation.

However, according to the evaluation in Attachment 2-11, the contribution from noble gases, the source of radiation in (1), was estimated to be 1.2Sv/h, even if the contribution from the rare gases was estimated to be more. On the other hand, in the evaluation of the core damage rate, considering 100% total release, the radiation from the noble gas component alone was about 460 Sv/h after 81.8 hours and 240 Sv/h even after 197.4 hours. Compared to their purpose of evaluating the core damage rate, the location of the dose rate detectors in the CAMS and the inconsistency of the evaluation method with the actual situation resulted in a significant underestimation of the degree of core damage.

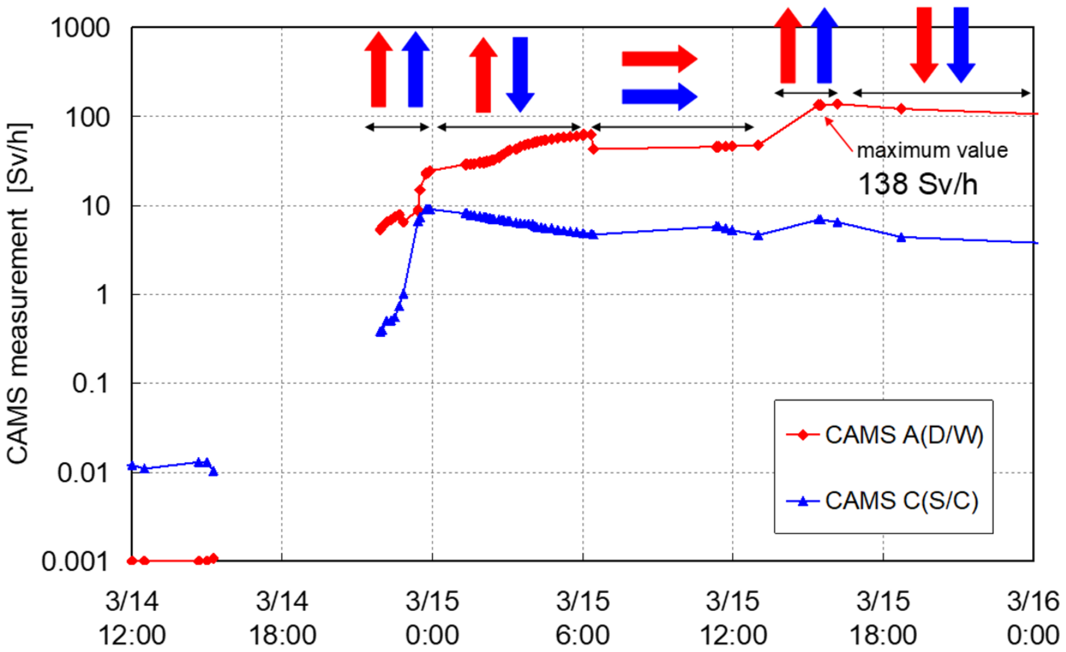


Figure 3 Dose measurements by CAMS installed in D/W and S/C

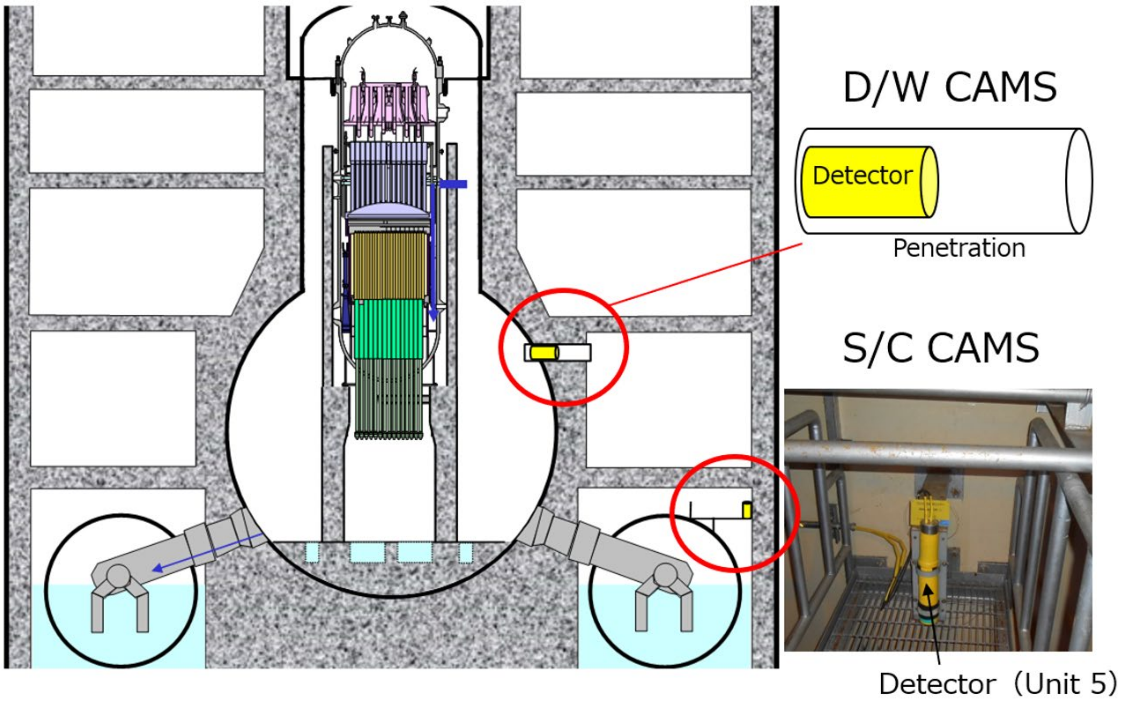


Figure 4 Installation of dose rate detectors in CAMS for D/W and S/C

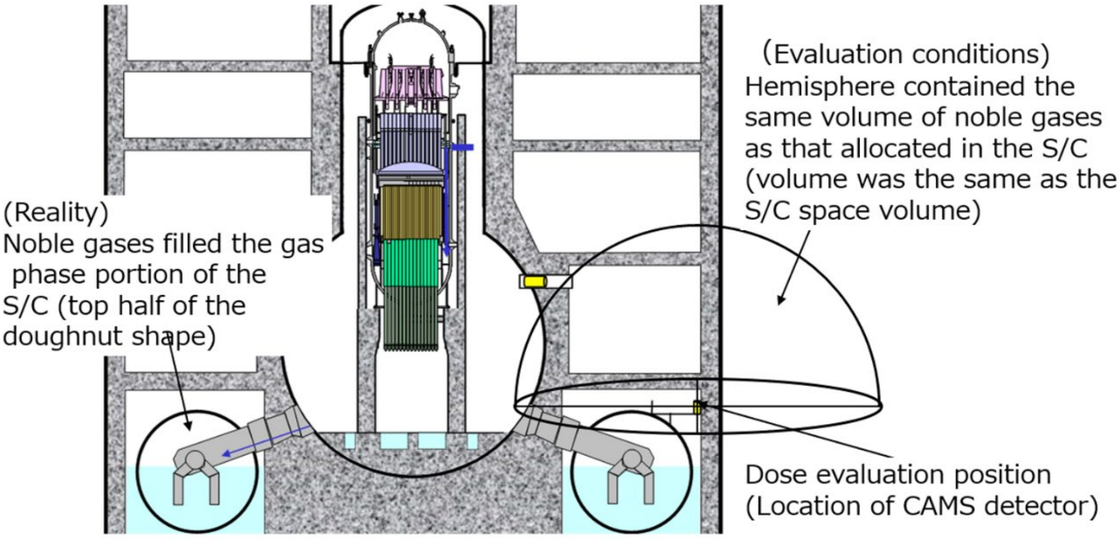


Figure 5 Differences between actual and assessed CAMS dose rate measurements

■ 4. Summary

Since there were inconsistencies in the relationship between the measured dose rates of the CAMS in the S/C measured at the time of the accident and the evaluated values of core damage fraction using those dose rates, a retrospective review of the evaluation method was conducted. Comparison of the evaluation method for core damage fraction developed prior to the accident and the location of the dose rate detectors actually installed showed that plants with the Mark-I containment vessel, such as Unit 2, tended to have a higher possibility of evaluating the core damage fraction on the non-maintenance side (i.e., with a smaller damage ratio).

■ 5. Relationship to safety measures at the Kashiwazaki-Kariwa Nuclear Power Station (NPS)

Based on the relationship between the measured CAMS dose rate and the core damage fraction for the Mark-I containment vessel shown in Figure 1 (hereinafter referred to as the "evaluation map"), the evaluation of the core damage fraction using the CAMS dose rate tends to underestimate the core damage fraction, which is assumed to be due to the geometry of the Mark-I containment vessel and the location of the CAMS detector. This is due to the fact that the geometry of the Mark-I containment vessel and the location of the CAMS detector are not properly reflected. Therefore, it is necessary to properly account for attenuation due to shielding and distance between the source and the CAMS detector when estimating core conditions from CAMS dose rates.

The Kashiwazaki-Kariwa NPS operating procedures use an evaluation map to determine core damage, and it is believed that this is an appropriate approach for determining core damage for the following reasons.

- The CAMS detectors in Units 6 and 7 of the Kashiwazaki-Kariwa NPS are installed in the containment vessel penetration area for both D/W and S/C (Figure 6).
- The dose rate used as a criterion for determining core damage is conservatively low to avoid delay in judgment.
- The dose rate increases significantly in a short time period at the time of core damage, so the influence of the uncertainty of the core damage determination curve on the determination time of core damage is small.

Previously, the core damage fraction was not used to determine the operational actions to be taken by the operators. In addition, the manuals referred to by organizations that provide technical support to operators during accidents (technical support organizations) previously stipulated that the core damage fraction should be calculated using an evaluation map, but this practice has now been discontinued.

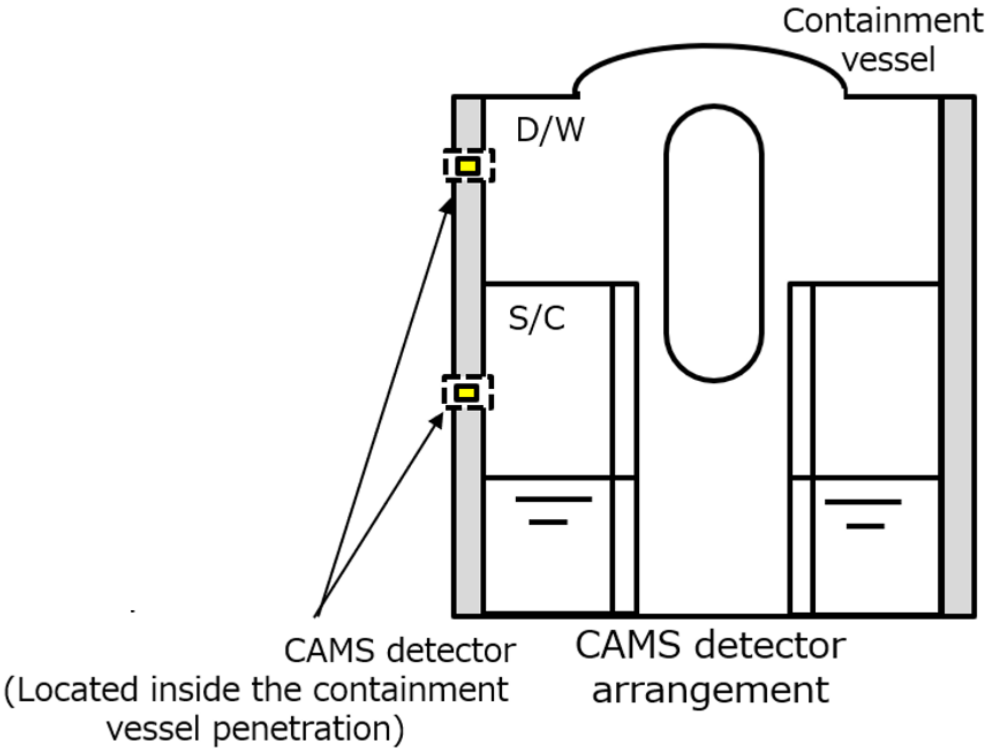


Figure 6　CAMS detector arrangement