Internal Flooding Fragility Experiments using Full-scale Fire Doors to Evaluate Door Failure Water Height and Leakage Flow Rate under Hydrostatic Pressure Loads

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Abstract: The Central Research Institute of Electric Power Industry (CRIEPI) is developing an internal flooding PRA (IF-PRA) guide for nuclear power plants in Japan. One of the questions of interest in the internal-flooding scenario modeling is that of how susceptible to failure structures and components are to the water ingress or spray. In IF-PRA, as doors can be flooding propagation paths, flooding could propagate to adjacent areas through gaps between doors and frames as well as doors opened by static head due to flooding depths. Therefore, it is very important to clarify the characteristics of flooding propagation modeling through doors. CRIEPI has performed hydrostatic pressure tests using one-hour rating fireproof door which is often used in nuclear power plants. In this study, the door which size is about 1.0 m width and 2.1 m height attached to 7.5 m^3 rectangular water tank. By filling the tank with water until door swing to open due to the door latch failure, water height and leakage flow rate were measured. According to the test results, we found that the door failure could be occurred when the static head reached around 1.3 m for forward direction while no failure were occurred for opposite direction. Moreover, the leakage flow rate through the gaps of the door perimeter could be also affected by the direction in which the static head loaded on the door.

1. INTRODUCTION

Internal flooding (IF) could be a major hazard for nuclear power plants (NPPs) since it can cause loss of mitigation functions as well as initiating event. According to the new regulatory requirements for protection against IF events established in response to the Fukushima Daiichi accidents [1], Japanese utilities developed deterministically IF protection measures. IF-PRA is helpful to understand the risk level of NPPs and vulnerabilities against IF events as well as the effectiveness of IF protection measures developed. For a precise IF-PRA, it is so important to identify the zone of influence (ZOI) due to the flooding scenarios considering characteristics of flooding propagation paths. Especially, non-watertight doors which could perform as not only propagation paths but also flooding barriers should be treated precisely in flooding scenarios. Therefore, it is very important to clarify the characteristics of doors on the viewpoint of flooding paths and barriers. CRIEPI has performed hydrostatic pressure tests using one-hour rating fireproof door attached to the rectangular water tank which is often used in NPPs as shown in Fig.1. It is expected that these flooding fragility characteristics of doors will be helpful to precisely identify flooding scenarios in IF-PRA.

Non-watertight doors need to be considered as a flood propagation path in both cases opened and closed since water could leak from the gap of door perimeter even if the door closed. According to the literature [2], practical door failure modeling has been applied as follows.
"In no cases should normal egress and door closure be credited above 3 feet of flood level if the door opens into the area or above 1 foot if the door opens out of the flood area." In other words, this principle means that when the door is loaded with water pressure in the direction in which it normally opens, it should be assumed to open at 1 foot, and when the door is loaded in the direction in which it normally closes, it should be assumed to open at 3 feet. Although this criteria for door failure are very simple and practical, it is necessary to avoid screening the risk important scenarios unexpectedly, such

as the flooding scenario through the openings installed in the high position of the flooding area in order to conduct reliable and realistic IF-PRA.

In this study, in order to develop IF-PRA guide for Japanese NPPs, the water level of door swing to open and leakage flow rate from the gap of closed door perimeter using one-hour rating fireproof non-watertight door under hydrostatic pressure were evaluated.

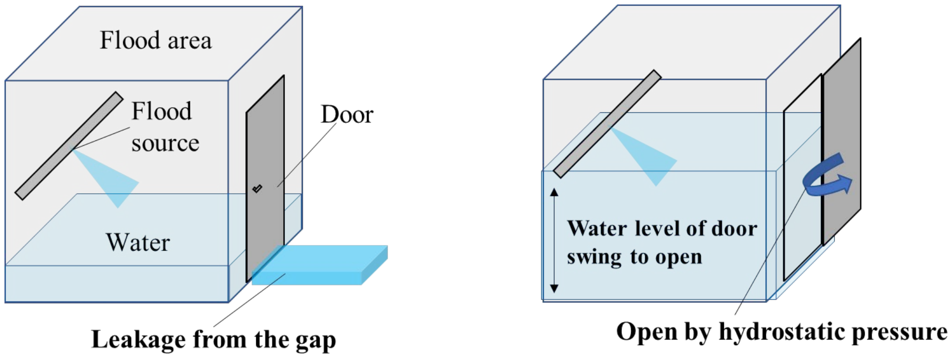


Fig.1 The concept of flood propagation in the presence of doors

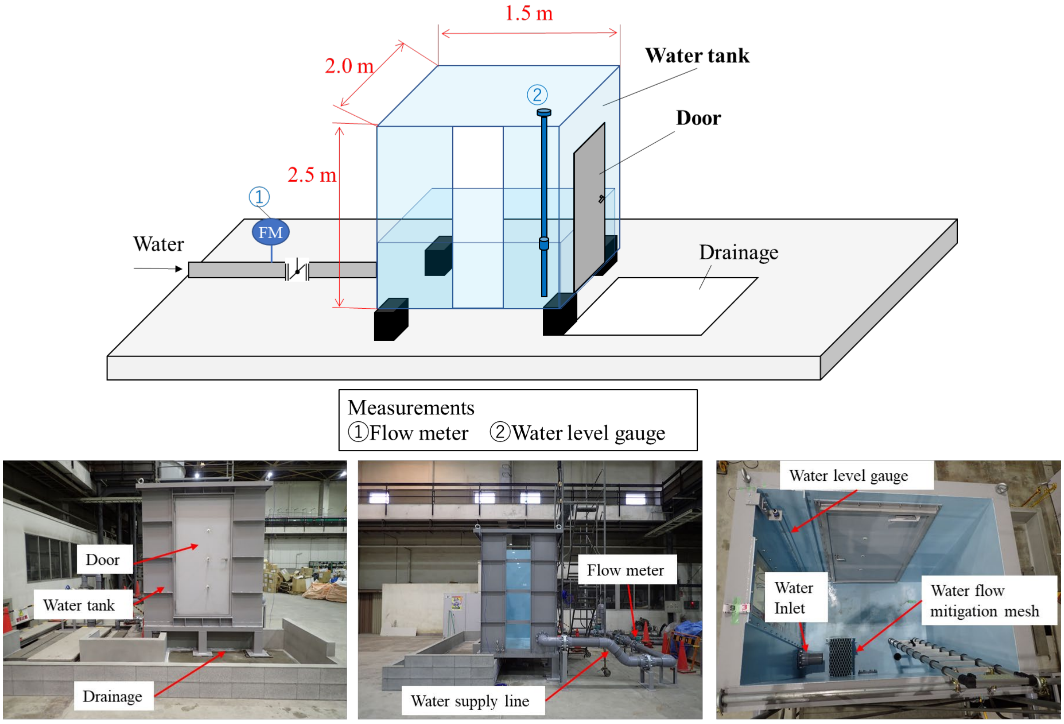
2. TEST CONDITIONS

Hydrostatic pressure test apparatus is shown in Fig.2. Tests were conducted using a test system with a door attached to one side of a water tank with a water supply line. Flow rate of water supply and water level in the tank were measured by flow meter and water level gauge to evaluate the water level of door swing to open and leakage flow rate from the door perimeter.

As shown in Table 1, three series of the hydrostatic pressure tests were conducted using one-hour fireproof door with pressure loading direction (=door installation direction) and swing type of doors as parameters. The door size is about 1.0 m wide for the single swing door and about 0.8 m wide for the doorknob side of the double swing door and 2.1 m height. Water tank has 7.5 m^3 with 2.0 m width, 1.5 m depth and 2.5 m height with about 5.0 m^3/min water supply line. The latch bolts were installed at 1.0 m height from the bottom of the doors and the latch bolt grade was set to III referring Japanese industrial standards JIS A1541-2(2016) [3], which is commonly used in Japanese NPPs. Test series of I and II were conducted using single door, which swings on a double hinge and closed by one latch bolt as shown in Fig.3. The latch bolt has a significant impact on the door failure mode, and in most cases for IF, the door is expected to open when the latch bolt breaks due to hydrostatic pressure. Test I subjected to hydrostatic pressure in the direction the door normally opens, and Test II subjected to static head in the direction the door normally closes as shown in Fig.4. Test series of III were conducted using double swing door. As shown in Table 2, the door gap between door and door flame at the bottom and side were about 2-6 mm. Although the structure of the doorknob side of the double swing door is the same as single swing door, the non-doorknob side has two flash bolts at top and bottom of the door flame. Due to water supply tank capacity, the maximum water level which could be tested was approximately 1.8 m.

Table 1 Test Conditions

Test No.	Type of doors	Swing type	Latch bolt grade*	Size[mm]	Pressure loading direction
Test I	One-hour rating fireproof door	Single	III	W973×D40×H2071	Door opening direction
Test II					Door closing direction
Test III		Double		W1614**×D40×H2071	Door opening direction
*: Based on JIS A1541-2(2016) [3], and installed at 1.0 m from the bottom of the doors **: Width (W) are 807 mm both doorknob side and non-doorknob side					



(Front view) (Side view) (Top view)

Fig.2 Hydrostatic Pressure Test Apparatus

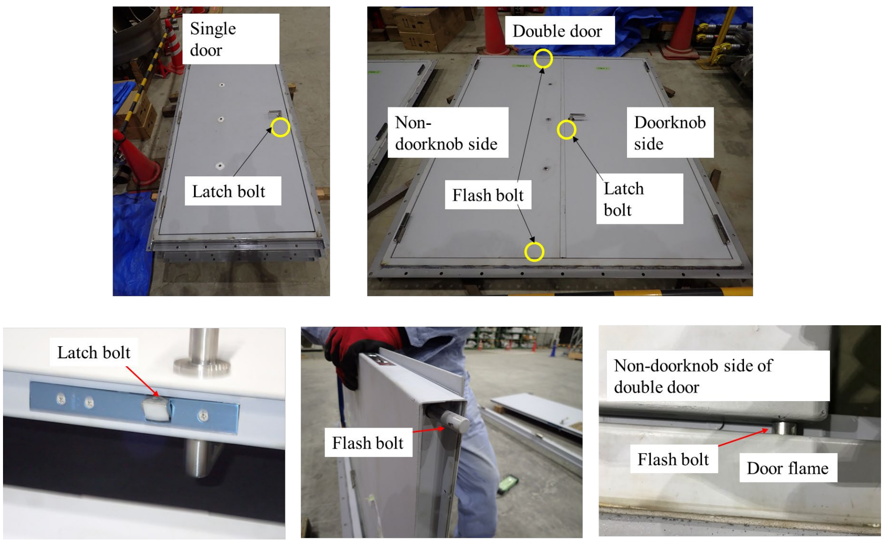


Fig.3 Structure of One-hour Rating Fireproof Doors

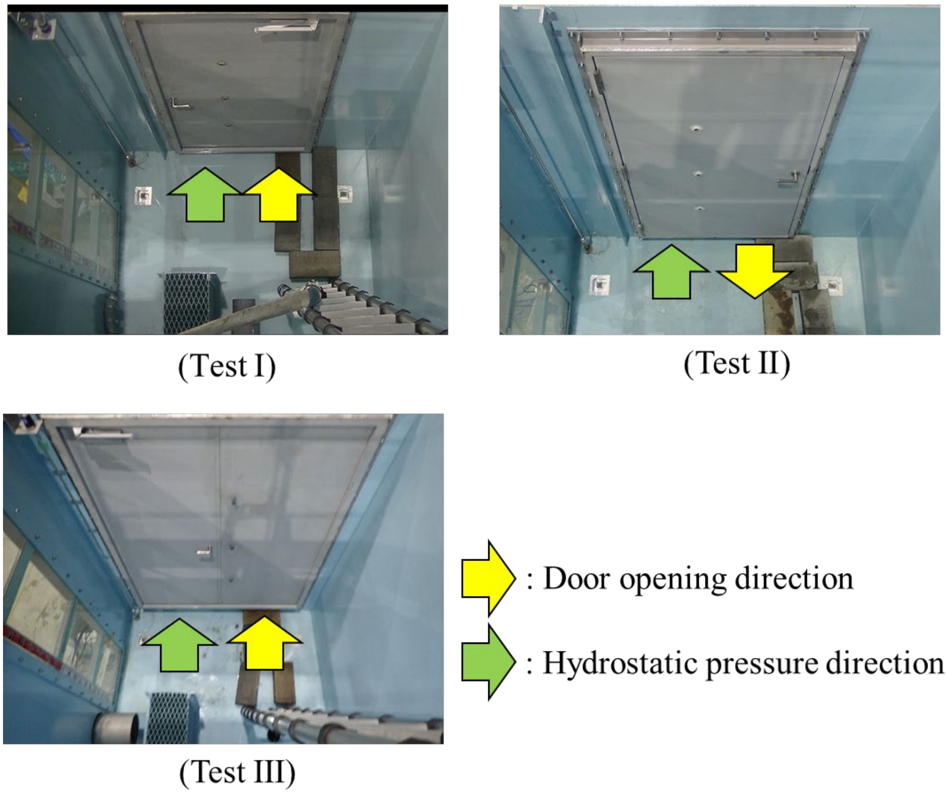
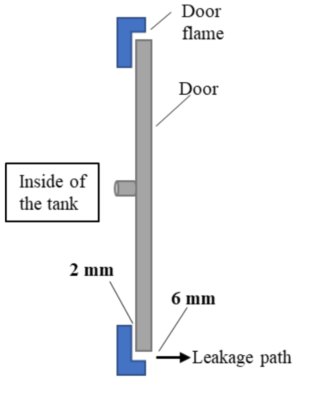
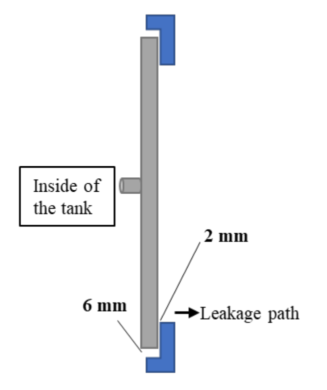
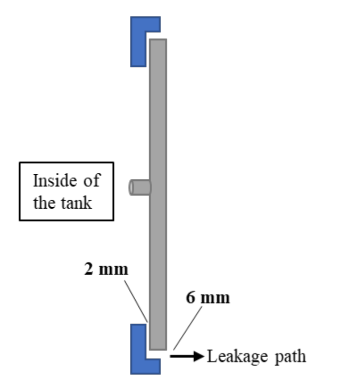
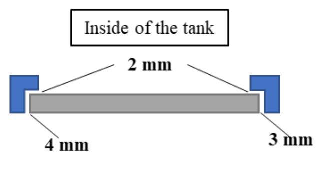
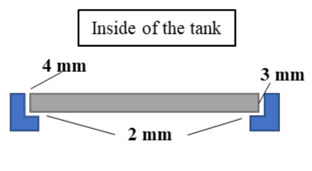
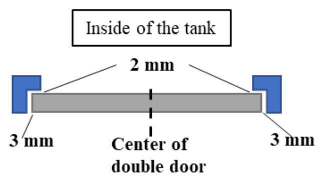


Fig.4 Door installation direction for each test

Table 2 Schematic diagram of the gap between the door and door frame for each test

Test No.	**Test I**	**Test II**	**Test III**
Swing type	**Single**		**Double**
Side view of door gap			
Top view of door gap			

3. TEST RESULTS

3.1 Water Level of Door Swing to Open

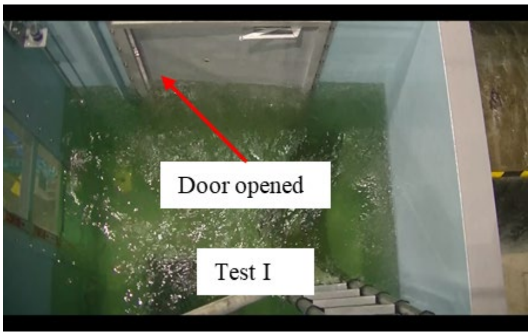
Test results are shown in Table 3. Door opened due to the latch bolt failure when static head acting on doors exceeds around 1.2 m - 1.4 in the Test series of I and Test III as shown in Fig.5. Also, in Test series of III with the double swing door, only the doorknob side of the door opened. On the other hand, the opposite doorknob side of the double swing door did not open because of no significant damage on the flash bolts. In both test series of I and III, the door opening failure mode was the "Damage of latch bolt" as shown in Fig.6. In spite of the difference of door swing type, the doors are damaged at almost the same static head. It suggests that the static heads to damage doors can depend on the strength of the latch bolt, not on the door swing type.

On the other hand, door did not open in the test series of II even in case of the static head of around 1.8 m. It should be noted that the direction of load is reverse to the direction in which door opens in the test series of II. In these tests, as shown in Fig.7, the load could apply only to the door frame in the door closing direction. Hence, latch bolt was not directly affected by the load acting on the door.

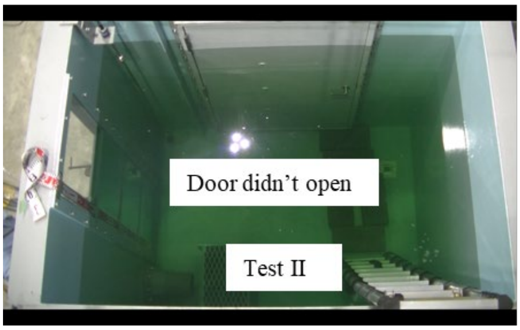
As a result, it can be concluded that the damage criteria of the door in which direction of door opening is the same as load direction can be around 1.3 m. On the other hand, it should be noted that the doors could not damage if the door opening direction and the load directions are opposite.

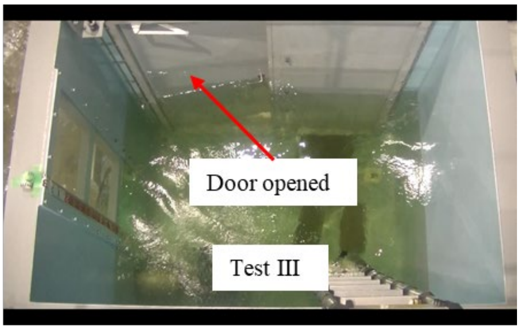
Table 3 Water Level of Door Swing to Open

Test Series	Door Failure Mode	Failure Water Level [m]
Test I	Open due to the Damage of latch bolt	1.33
		1.22
		1.24
		1.32
		1.37
		1.28
		1.19
Test II	Not open	-*2
Test III	Open (only non-doorknob side) due to the Damage of latch bolt	1.40
		1.31
		1.30
*1: Test series of I and II were conducted 7 times, Test series of III were conducted 3times *2: Test series of II were conducted up to a water level of 1.8 m		



(Series of Test I)





(Series of Test II) (Series of Test III)

Fig.5 Top view of the water tank during the tests

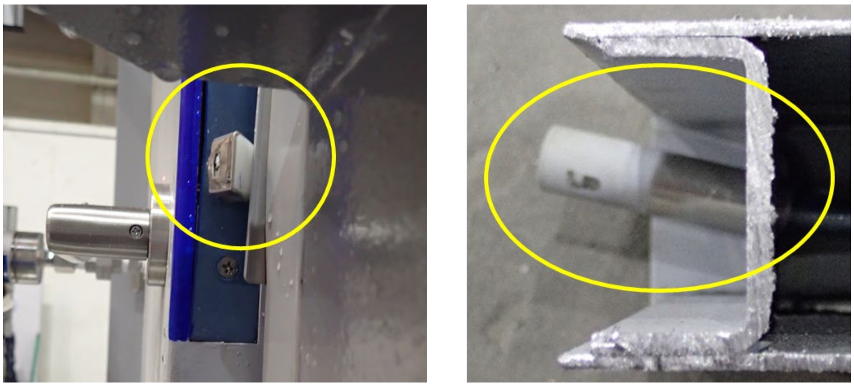


Fig.6. Damage of Latch bolt and flash bolt after tests

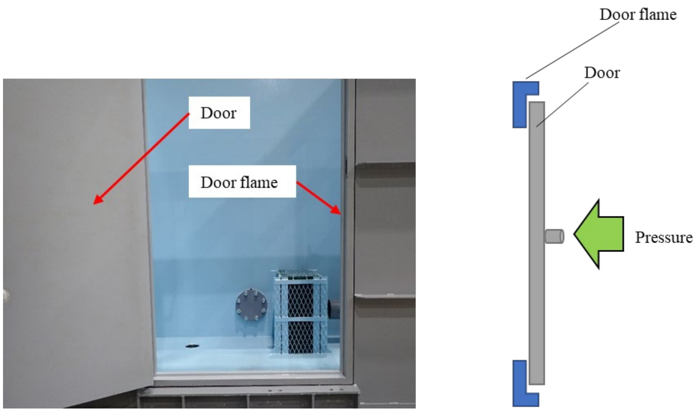


Fig.7 Hydrostatic pressure loaded in the direction of door closing (Test Series of II)

3.2 Leakage Flow Rate from the Gap of the Door

As shown in Fig.8, in all series of tests, water leakage occurred from the sides and bottom of the door. Leakage flow rates during tests are shown in Fig.9. In Tests series of I and III, the leakage flow increased as the water level increased. This could be attributed to the increased gap width between the door and door frame due to static head as shown in Fig.10. In addition, the leakage flow rate was higher in Test series of III than in Test series of I because the door size is larger for the double swing door than the single swing door so the total leakage path area of bottom and side of the door are larger for a double swing door than for a single swing door. On the other hand, in Test series of II, where hydrostatic pressure was applied in the direction of door closes, the leakage flow rate gradually increased up to about 0.5 m of water level and then began to decrease. This could be due to the decrease in the gap distance between the door and the door frame as static head increase.
Therefore, the leakage path and the direction of the load applied to the door have an important role for leakage through door gap. In the future, we expect to develop a correlation formula for leakage flow rates based on test data, which could be used in IF-PRA.

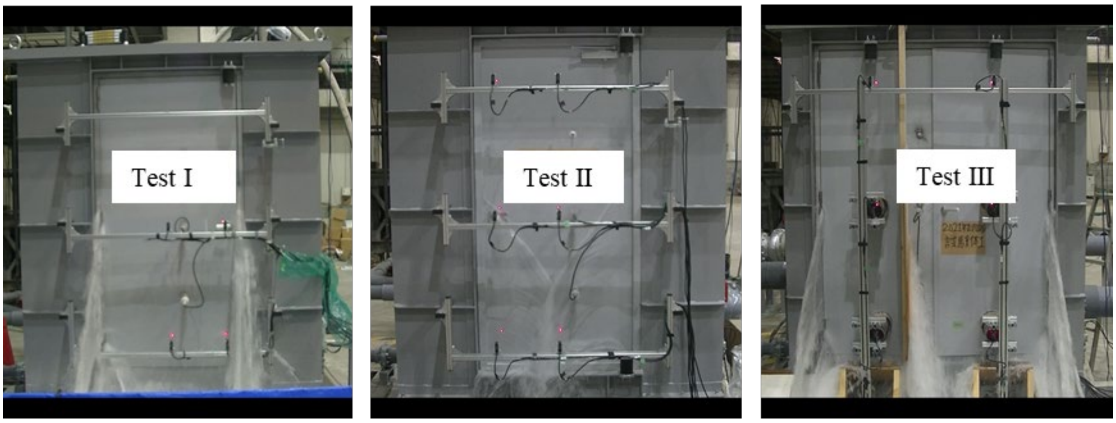


Fig.8. Leakage from door perimeter during tests

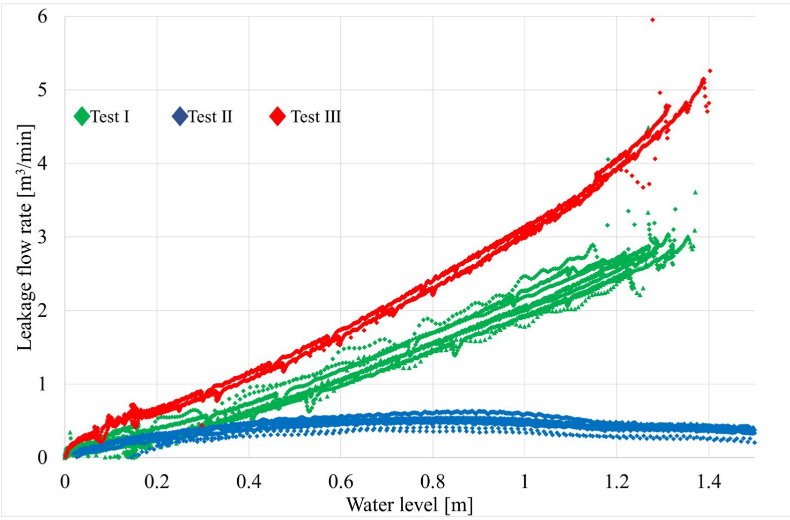


Fig.9 Measured Leakage frow rate during tests

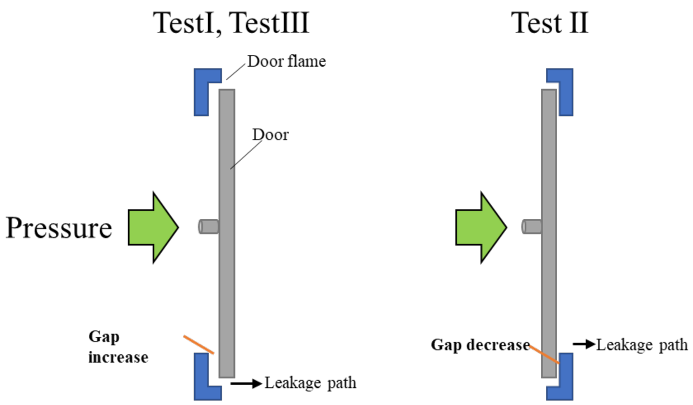


Fig.10 Side view of gaps between door and door frame and leakage paths

3.3 Flooding Fragility Probabilistic Modelling

The approach to use the flooding experimental data is through what are called fragility models. Typically, these fragility model has been simple monotonically increasing functions that give the probability of failure of the door (swing to open) as a function of the flooding severity as measured by a single metric such as the water level. Fig.11 shows the probability of failure of the door as a function of the water level obtained by the Bayesian quantification approach [4]. It is found that the mean value of the water level for a door swing to open was around 1.3 m.

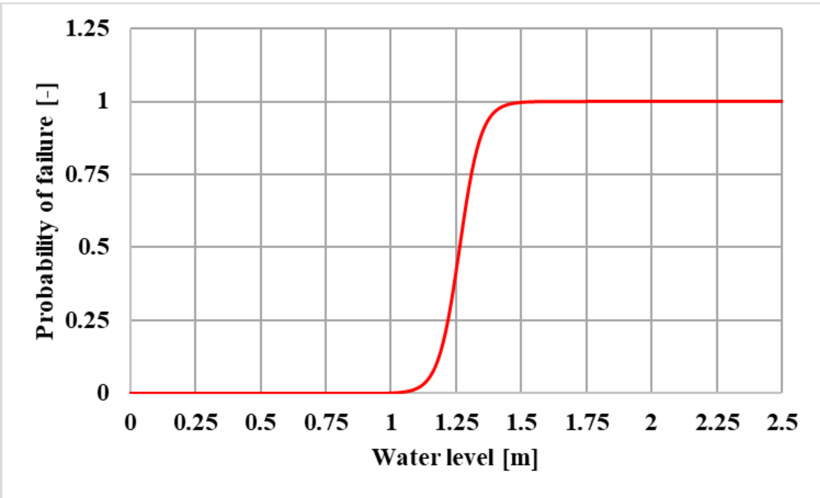


Fig.11 Results of the flooding fragility model for a door swing to open

4. CONCLUSION

To conduct a realistic and reliable IF-PRA, the propagation path of the flooding should be correctly evaluated so that it could avoid screening the risk important scenarios unexpectedly, such as the flooding scenario through the openings installed in the high position of the flooding area. Moreover, to evaluate the propagation path, it is necessary to evaluate the fragility of the door, which is a barrier in the flooding area. Therefore, we evaluated the water level of door swing to open and leakage flow rate of one-hour rating fireproof doors which are non-watertight doors commonly used in Japanese NPPs and obtained the following findings.

(1) Water level of door swing to open

Water level of door swing to open is significantly affected by the direction in which hydrostatic pressure is applied to the door. When hydrostatic pressure is applied in the direction the door opens, the load is applied to the latch bolt, which is a weak part, and the door opens due to damage to latch bolt. On the other hand, when hydrostatic pressure is applied in the direction in which the door is closed, the load could be only applied to the door frame and the latch bolt could not be damaged, so the door does not open. Therefore, the strength of the latch bolt and the direction in which hydrostatic pressure is applied should be considered when setting the water level of door swing to open.

(2) Leakage flow rate from door perimeter

The leakage flow rate is also highly dependent on the direction of hydrostatic pressure applied to the door. When hydrostatic pressure is applied in the direction in which the door opens, the leakage flow rate increases in proportion to the rise in water level. On the other hand, when hydrostatic pressure is applied in the direction of the door closing, the leakage flow rate begins to decrease from a certain water level. Therefore, the direction of the pressure applied to the door should be considered when setting the leakage flow rate from door perimeter.

Acknowledgements
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