Numerical Quantification of Effectiveness in the Countermeasure against Severe Accident

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ABSTRACT

In March 11, 2011, the Fukushima Dai-ichi nuclear power plant accident was occurred because of the Tohoku-Taiheiyou-Oki Earthquake. After the accident new safety standard for nuclear power station was established by Nuclear Regulation Authority (NRA), Japan. In the standard, an importance of the Defense in Depth (DiD) and a necessity of countermeasure against severe accident (SAs) are notified clearly. But these countermeasures against SAs listed in the new standard are not clear how effective to the accident.

In the paper, organizing a correspondence between SAs and the countermeasure, a quantification of the effectiveness of the countermeasure based on a level 1.5 probabilistic risk assessment (level 2 PRA without source term evaluation) and the consideration of them in accordance with the concept of the DiD have been carried out for the purpose of quantitative assessment of effectiveness in the countermeasure.

As concerns the correspondence, failure modes of a containment vessel are classified into several categories and the relationship between the categories and articles in the new standard are discussed. Then the countermeasure are chosen based on the articles in a certain severe accident condition and are coupled with the event tree (ET) of the containment vessel failure as well as the effectiveness and the contribution of each article toward each failure mode. In the analysis, a large-break loss of coolant accident (large-break LOCA) is selected as an initiating event. Then the change of the conditional containment failure probability (ΔCCFP) is evaluated with/without the countermeasures and the effectiveness of each countermeasure is discussed based on ΔCCFP.

KEYWORDS

Severe Accident, new Standard for nuclear power station, countermeasure, level 1.5 PRA

1. INTRODUCTION

In March 11, 2011, the Tohoku-Taiheiyo-Oki Earthquake occurred, and an Severe Accident (SA), in which radioactive materials leaked out off-site and many people was evacuated from the contamination area, was happened in the Fukushima Dai-ichi nuclear power plant mainly caused by a flooding due to the Tsunami attack.

After the accident, it was reported that the regulatory framework must take much care an importance of Defense in Depth (DiD), diversity and flexibility of safety measures, and an importance of countermeasures against SA including a consideration for internal and external events [1].

In July 2013, a new safety standard for nuclear power station was established by Nuclear Regulation Authority [2], Japan that came into being to enhance a safety of nuclear power station in the right of hard-learned lessons from the accident. In the standard, an importance of the DiD concept, a necessity of countermeasure against SAs and examples of equipment and functions for the countermeasure are notified in addition to the previous standard.

From the viewpoint of effectiveness of each countermeasure against SAs, a quantitative assessment is importance. In this paper, the effectiveness of each countermeasure described in new standard is investigated based on a probabilistic risk assessment (PRA). For this purpose, the influence of the countermeasures on the failure probability of each branch is added to an event tree of a containment vessel failure that is applied in level 2 PRA and the effectiveness of the countermeasure is quantified by a change of a conditional containment failure probability (ΔCCFP).

2. CONTAINMENT FAILURE EVENT TREE WITH COUNTERMEASURES

For the quantitative assessment of the effectiveness of countermeasures against SA, we use the event tree of containment vessel failure that is applied in level 2 PRA. Firstly, the countermeasures are selected and classified based on the new standard as shown in Table 1. Then those are coupled with the event tree.

Table 1. List of Countermeasures against SA [2]

No.	Article	Detail	Category
I	44	Facilities to start auxiliary feed water system and stop a steam turbine	D
II	45	Portable battery	D
III	46	Portable compressor	B
IV	47	Nitrogen cylinder	D
V	48	Main steam relief valve	A
VI	49	Containment vessel spray alternative facilities	A
VII	50	Filter vent facilities	B
VIII	51	Pressure hose and pump truck	A
IX	52	Hydrogen concentration control facilities	C
X	53	Hydrogen discharge facilities	C
XI	54	Pump truck for spent fuel storage tank	A
XII	55	Drainage facilities to building	D
XIII	56	Pump to take from alternative water sources	D
XIV	57	Alternative power source	D

2.1. Countermeasures in new standard

With regard to the new standard Countermeasures against SA are described at Articles 44 to 57. In the present study, those are classified into four categories taking into account their function in the following.

A. Facilities to cool a reactor

B. Facilities to depressurize a reactor
C. Facilities to control hydrogen gas
D. Facilities to aid other facilities

Table 1 summarizes the countermeasures and their categories.

2.2. Event tree of containment vessel failure with countermeasures

In this paper, the same event tree of vessel failure with the previous study carried out by Japanese Nuclear Safety Organization (JNES) [3] is applied. A large break LOCA is selected as an initiating event for the event tree. Table 2 shows all heading of the event tree.

In each heading, correspondent countermeasures are considered based on their function shown in Table 1. Furthermore, the countermeasures are divided into two types as; measures for prevention (C1) and for mitigation (C2). For example, valves such as an isolation valve must be closed in E3 heading (Containment isolation failure). Therefore, preparations for closing valves are selected as a countermeasure. When containment vessel is to be isolated, each valve of pipe is closed. When main steam isolation valve is closed, main steam turbine should be stopped. Facilities to start auxiliary feed water system and stop a steam turbine (I), portable battery (II), and nitrogen cylinder (IV) are selected as a prevention type (C1) countermeasure.

Table 3 summarizes heading and correspondent countermeasures and an example of the coupling of the event tree and the countermeasures are pictured in Fig. 1

Table 2. Headings and their failure probability [3]

Accident Headings		Failure Probability
E1	Reactor Building Breakage	0.00
E2	All Steam Generators Breakage	0.00
E3	Containment Isolation Failure	2.40E-02
E4	ISLOCA	0.00
E5	Phreatic Explosion in Reactor Vessel	3.00E-08
E6	Containment Overpressure Failure prior to Core Damage	0.00
E7	LOCA	
E8	Air Return Fan	1.00E+00
E9	Hydrogen Combustion prior to Reactor Failure	9.00E-05
E10	Debris Drifting	1.00E-04
E11	Coolant in Reactor Cavity	9.00E-01
E12	Phreatic Explosion outside Reactor Vessel	4.50E-04
E13	Containment Atmosphere Direct Heating	4.00E-23
E14	Debris Direct Attack	8.30E-03
E15	Air Return Fan	1.00E+00
E16	Hydrogen Combustion at Reactor Failure	8.10E-01
E17	Air Return Fan	1.00E+00
E18	Hydrogen Combustion in the accident late	9.00E-02
E19	Containment Overpressure Failure	9.90E-01
E20	Base mat Erosion	6.80E-01
E21	Containment Penetration Overheating Failure	1.00E-02

Table 3. Headings and correspondent Countermeasures (1/3) [2]

E1	Heading	Reactor Building Breakage	
	Consideration	No reactor building breakage is considered in large break LCOA.	
	Countermeasures		
E2	Heading	All Steam Generators Breakage	
	Consideration	Same with E1.	
	Countermeasures		
E3	Heading	Containment Isolation Failure	
	Consideration	To isolate containment, blind flanges and isolation valve are must be closed when an accident occurred.	
	Countermeasures	(C1)	D(I,II,IV) (For operating the isolation valves)
		(C2)	
E4	Heading	ISLOCA	
	Consideration	Same with E1	
	Countermeasures		
E5	Heading	Phreatic Explosion in Reactor Vessel	
	Consideration	In-vessel steam explosion is difficult to prevent. In-vessel steam explosion is mitigate to inject near saturated water in the reactor vessel.	
	Countermeasures	(C1)	A(VIII) (To inject water into the reactor vessel) D(XIII) (To ensure the injecting)
		(C2)	
E6	Heading	Containment Overpressure Failure prior to Core Damage	
	Consideration	Same with E1.	
	Countermeasures		
E7			
E8	Heading	Air Return Fan	
	Consideration	Air return fan is in containment vessel, so it may be broken due to heat from core. This breakage is very difficult to avoid, so no countermeasure is selected.	
	Countermeasures		
E9	Heading	Hydrogen Combustion prior to Reactor Failure	
	Consideration	Hydrogen gas might be produced because of fuel and water. Hydrogen gas is should be removed.	
	Countermeasures	(C1)	C(IV,X) (To reduce Hydrogen gas density in containment)
		(C2)	
E10	Heading	Debris Drifting	
	Consideration	Debris drifting is momentary, so it is very difficult to stop this event and no countermeasure is selected.	
	Countermeasures		

Table 3. Headings and correspondent Countermeasures (2/3) [2]

E11	Heading	Coolant in Reactor Cavity	
	Consideration	If there is not enough water in a reactor cavity, it may be difficult to cool containment atmosphere. At that situation, enough water should be supply from outside.	
	Countermeasures	(C1)	
		(C2)	A(XI)（To pour water to a reactor cavity） D(XIII,XIV)（To aid the facility）
E12	Heading	Phreatic Explosion outside Reactor Vessel	
	Consideration	Phreatic Explosion might be occurred in containment vessel due to falling heat debris to water. To stop explosion, molten core must be cool.	
	Countermeasures	(C1)	A(VIII)（To cool molten core） D(XIII)（To ensure the coolant）
		(C2)	
E13	Heading	Containment Atmosphere Direct Heating	
	Consideration	Containment atmosphere might be overheated by debris, so containment vessel might be broken. To avoid this, containment must be depressurized.	
	Countermeasures	(C1)	B(III,VII)（To depressurize containment vessel） D(XIV)（To aid filter vent facilities）
		(C2)	
E14	Heading	Debris Direct Attack	
	Consideration	It is very difficult to remove attached debris from inside wall of containment, so no countermeasure is selected.	
	Countermeasures		
E15	Heading	Air Return Fan	
	Consideration	Same with E8.	
	Countermeasures		
E16	Heading	Hydrogen Combustion at Reactor Failure	
	Consideration	Hydrogen gas might be produced. Hydrogen gas is should be removed.	
	Countermeasures	(C1)	C(IX,X) (To reduce Hydrogen gas density in containment)
		(C2)	

Table 3. Headings and correspondent Countermeasures (3/3) [2]

E17	Heading		Air Return Fan
	Consideration		Same with E8.
	Countermeasures		
E18	Heading		Hydrogen Combustion in the accident late
	Consideration		Same with E16
	Countermeasures	(C1)	C(IX,X)（To reduce Hydrogen gas density in containment）
		(C2)	
E19	Heading		Containment Overpressure Failure
	Consideration		If containment vessel pressure rises abnormally, to cool containment atmosphere by natural convection, auxiliary feed water system must start.
	Countermeasures	(C1)	B(III,VII)（To depressurize containment vessel） D(I,XIV)（To start auxiliary feed water system）
		(C2)	
E20	Heading		Base mat Erosion
	Consideration		When cavity water is not enough, base mat might be eroded. To stop this, enough water must be injected into cavity.
	Countermeasures	(C1)	A(VIII)（To inject water into cavity） D(XIII,XIV)（To aid pouring water）
		(C2)	
E21	Heading		Containment Penetration Overheating Failure
	Consideration		If containment atmosphere is overheated, a weak point in containment penetration might be broken due to heat.
	Countermeasures	(C1)	A(V,VI)（To cool containment atmosphere） D(XIII,XIV)（To aid facilities）
		(C2)	

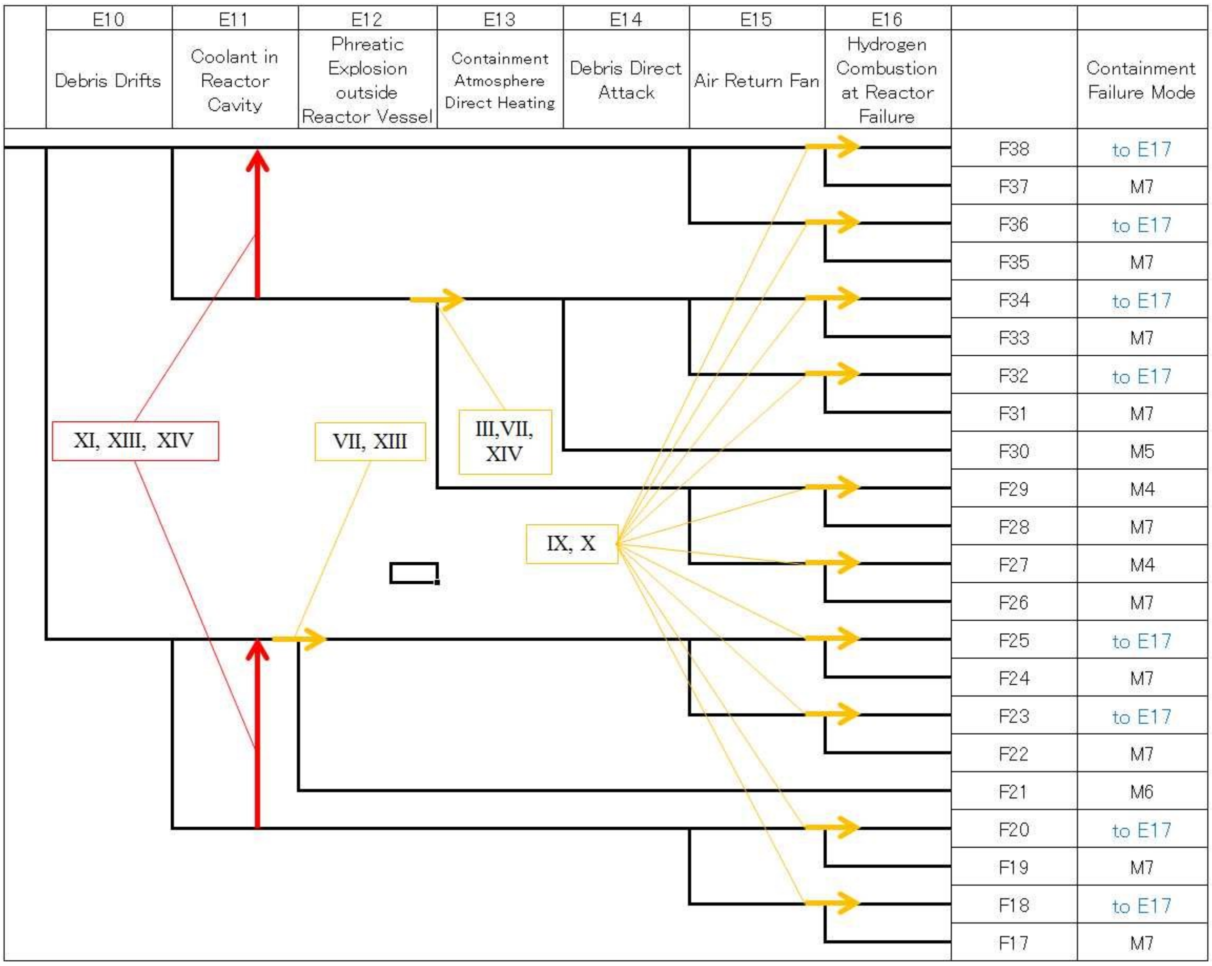

Fig. 1 Event tree of containment vessel failure [2]

3. QUANTITATIVE ASSESSMENT OF EFFECTIVENESS OF COUNTERMEASURES AGAINST SA BASED ON CONTAINMENT FAILURE MODE

In the assessment, a conditional containment failure probability (CCFP), in which all countermeasures are taken into consideration under the condition of the initiating event (large break LOCA) occurrence, is investigated. Then it is assumed that all countermeasures except a target one are successful and CCFP is evaluated again in order to investigate the efficiency of the target countermeasure.

3.1. Analytical condition

With regard to the failure probability of each branch at the event tree, the same values with the previous study [3] are used. On the other hand, a failure probability of each countermeasure in the event tree is calculated in the following.

Firstly, a failure probability of each countermeasure (I to XIV in Table 4) are divided into two types as; easy operation (failure probability: 0.1) and a little bit difficult operation (0.25) as shown in Table 4 by taking into account such as a portability and a complicacy of handling. Since a combination of countermeasures is considered as the countermeasure in the event tree (Table 3), the following equation is applied to calculated the failure probability. Table 5 summarizes the failure probability of the present countermeasures.

$$P_f = 1 - \prod_{k=1}^{n}(1 - P_{fk}) \tag{1}$$

Here, n means the number of the countermeasures applied in each branch shown in Table 4.

Table 4. Failure probabilities of each countermeasure

I	Facilities to start auxiliary feed water system and stop a steam turbine	0.1
II	Portable battery	0.1
III	Portable compressor	0.25
IV	Nitrogen cylinder	0.1
V	Main steam relief valve	0.25
VI	Containment vessel spray alternative facilities	0.25
VII	Filter vent facilities	0.25
VIII	Pressure hose and pump truck	0.25
IX	Hydrogen concentration control facilities	0.25
X	Hydrogen discharge facilities	0.25
XI	pump truck for spent fuel storage tank	0.25
XII	Drainage facilities to building	0.1
XIII	Pump to take from alternative water sources	0.1
XIV	Alternative power source	0.1

Table 5. Failure probabilities of countermeasures in event tree

	(C1)		(C2)	
	Facilities	Probability	Facilities	Probability
E3	I,II,IV	0.271	-	-
E5	VIII,XIII	0.325	-	-
E9	IX,X	0.438	-	-
E11	-	-	XI,XIII,XIV	0.393
E12	VIII,XIII	0.325	-	-
E13	III,VII,XIV	0.495	-	-
E16	IX,X	0.438	-	-
E18	IX,X	0.438	-	-
E19	I,III,VII,XIV	0.494	-	-
E20	VIII,XIII,XIV	0.393	-	-
E21	V,VI,XIII,XIV	0.544	-	-

3.2. Assessment of countermeasures based on containment failure modes

Analytical results are classified into 7 failure modes as in Table 6. Table7 shows the comparison of CCFP between no countermeasure and all countermeasure cases. When no countermeasure is considered, the failure mode of “Hydrogen Combustion (M7)” is the most dominant mode and the conditional probability of no containment failure (or no fission product release) becomes quite small (5.0×10^{-4}). On the contrary, CCFP of M7 reduces to around half if all countermeasures are considered. Besides, CCFPs of some failure modes such as “Static Containment Failure with Overheating and Overpressure (M1)” and “Base Mat Erosion (M3)” increase. The probability of no containment failure increases to 2.3×10^{-1} and it is demonstrated that the efficiency of countermeasures can be quantified with the present method.

Figure 2 shows the efficiency of each countermeasure in M7. In the following figures, “all” means that all countermeasures are available, whereas the focused countermeasure is unavailable in “I” to “XIV”. As in Fig. 2, countermeasures of “Hydrogen concentration control facilities (IX)” and “Hydrogen discharge facilities (X)” are most important against M7 failure mode and other countermeasures are negligible in terms of CCFP.

The efficiency of each countermeasure in M1 is pictured in Fig. 3. It is concluded that the countermeasures “Portable compressor (III)”, “Filter vent facilities (VII)” and “Alternative power source (XIV)” have high efficiency against the M1 failure mode. It is noted that CCFP without countermeasure IX or X reduces rather than that in all countermeasures case (“all”). This is attributed the fact that some scenarios of M7 shifts to M1 by avoiding hydrogen combustion as seen in Table 7.

Figure 4 shows the influence of countermeasure on the conditional probability of no containment failure. “no” in Fig. 4 means no countermeasure is available. It is demonstrated that the most significant countermeasures are III, VII and XIV, which almost correspond to those against the M1 failure mode, in case of “large break LOCA” initiating event. The efficiency of the countermeasures of IX and X is rather small than that of III, VII and XIV because those countermeasures have contribution to shift failure mode although they are quite effective in the most dominant failure mode.

It is noted that some of countermeasures have almost no influence on the conditional probability as in Fig. 4. Those countermeasures will be efficient for the other initiating events.

Table 6. Containment failure modes

Classified Containment Failure Mode	
M1	Static Containment Failure with Overheating and Overpressure
M2	Containment Vessel Bypass
M3	Base mat Erosion
M4	Containment Atmosphere Direct Heating
M5	Debris Direct Attack
M6	Phreatic Explosion
M7	Hydrogen Combustion

Table 7. Comparison of CCFP

Mode	No countermeasure	All countermeasure
M7	8.012E-01	3.762E-01
M1	1.658E-01	3.015E-01
M2	2.400E-02	6.504E-03
M5	7.289E-03	2.912E-03
M3	1.139E-03	8.382E-02
M6	3.367E-08	1.908E-08
M4	6.675E-24	4.474E-24

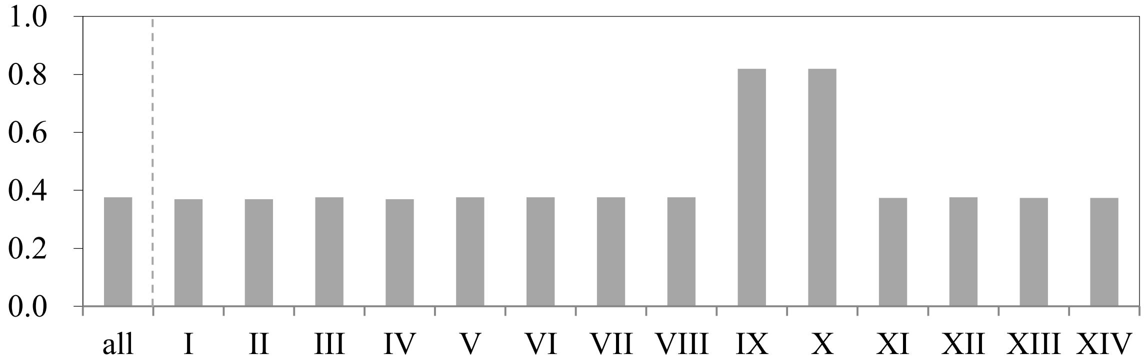

Fig. 2 CCFP of M7

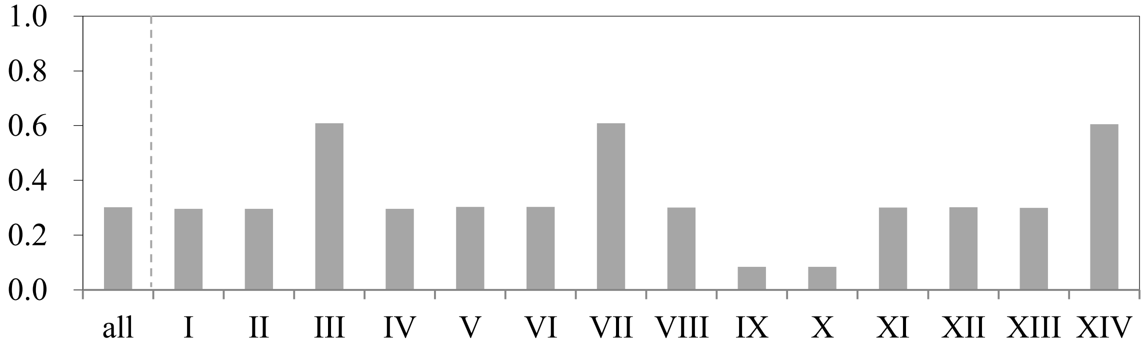

Fig. 3 CCFP of M1

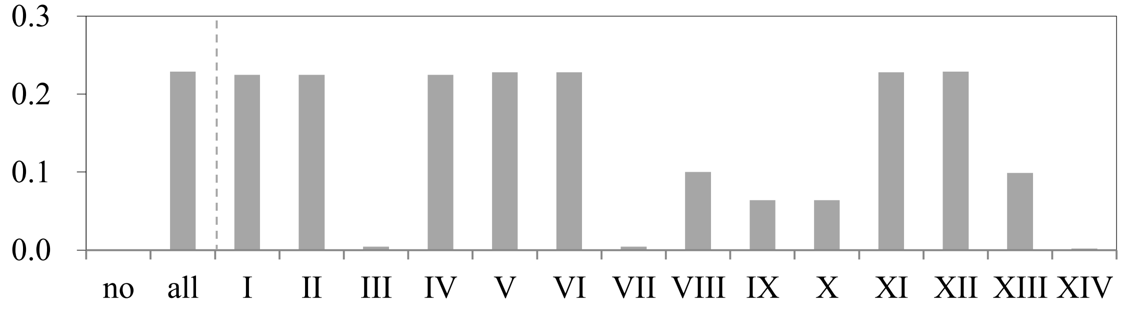

Fig. 4 Conditional Probability of No Containment Failure

4. CONCLUSIONS

In this paper, the purpose is to assess quantitatively effectiveness of the countermeasures against SA. To do this, the event tree of containment vessel failure was created and countermeasures against SA were selected from the new safety standard. After that, the failure probabilities of countermeasures against SA of each heading in the event tree were calculated. And then, CCFP of each of the classified containment failure modes was calculated. And the relationship between the countermeasures against SA and each of the accidents was analyzed. Thereby, it was confirmed that countermeasure against SA has effectiveness by comparison of CCFP between no countermeasure and all countermeasure cases. And it was found that the failure mode of "Hydrogen Combustion (M7)" is the most dominant mode, and hydrogen concentration control facilities and hydrogen discharge facilities have very high efficiency against this failure mode.

In the paper, one method to assess quantitatively effectiveness of countermeasures against SA was devised. The objective in this analysis was one accident, but others also can be analyzed in the same method.

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