PRA on Mixed Foreign Substances into Core of Japanese Prototype FBR

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Abstract: Fuel subassemblies (FSAs) of fast breeder reactors (FBRs) are densely arranged and have high power densities. Therefore, the local fault (LF) has been considered as one of the possible initiating events of severe accidents. According to the LF evaluation under the condition of one sub-channel flow blockage in the analyses of design basis accident (DBA) for the Japanese prototype FBR (Monju), it was confirmed that the pin failures were limited locally without severe core damage. In addition, local flow blockage (LB) of 66% central planar in the subassembly was historically investigated as one of the beyond-DBA. However, it became clear that these deterministic analyses were not based on a realistic assumption by experimental studies. Therefore, PRA on LF which was initiated from LB was performed reflecting the state-of-the-art knowledge in this study. As the result, damage propagation from LF caused by LB in Monju can be negligible compared with the core damage due to ATWS or PLOHS in the viewpoint of both probability and consequence.

Keywords: Local Fault; Fast Breeder Reactor; Local Flow Blockage; Core Damage Frequency

I. Introduction

Local fault (LF) accidents have been considered as one of the possible causes of core-disruptive accidents or severe accidents in fast breeder reactors (FBRs) due to the generally densely arranged fuel pins in the fuel subassemblies (FSAs). Therefore, safety evaluations have been performed on LF for the licensing of the Japanese prototype FBR assuming local flow blockage (LB) and local overheat of fuel element (OHFE) as representative phenomena (Ref. 1). A planar and impermeable blockage of 66% of total flow area in the FSA for LB and improper overpower of 200% for OHFE were assumed as hypothetical initiating events. These conservative evaluations revealed that fuel pin damage would be limited within a restricted area of the reactor core. However, the initiating events and their magnitudes for LF vary widely, and the flow of event branches in a number of steps in the detections of abnormality. Thus, drawing up of event tree (ET) and its branching probabilities are necessary to overview the LF. The quantitative evaluations of core damage frequency (CDF) for the LF are required to compare with the other accident sequences in order to decide the representative accident sequence of the severe accidents. Therefore, probabilistic risk assessments (PRAs) of the LF caused by the LB were performed for Japanese Prototype FBR “Monju” in this study. Although the PRAs of LF have been performed in many countries for FBRs (Refs. 2-7), following points were focused and advanced in this study.

- The frequency of initiating event which causes LB was newly calculated based on the operating experiences of FBRs in the world until now.
- Fault tree analysis considering human error and failure of equipment was conducted based on the emergency response which is the predetermined action of human and equipment for the alarm described in the operating manual.
- The branching probabilities were decided in the PRA of the LF caused by the LB considering the new knowledge obtained from the experimental research about the formation mechanism of the LB (Ref. 8).

As a result, comparisons were enabled by the PRA of the LF caused by the LB for Monju with that of the ATWS, PLOHS and the LF caused by the adventitious fuel pin failure (Ref. 9).

II. Initiating event

The initiating event for LB is defined as abnormal flow reduction in a single subassembly of the reactor core by mixing with foreign substances into the subassembly. The frequency of initiating event for LB was evaluated in three steps which are described in Section II.A, II.B and II.C

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II.A Frequency of mixing with foreign substances into the subassembly

Mixing with foreign substances into the subassembly is caused by mixing with foreign substances into the primary system including reactor core. It may difficult to detect completely all the instances related to the former (i.e., mixing into the subassembly) because very small substances cause no change in core parameters such as flow rate, temperature, etc., but it is possible to survey the causal abnormal event associated with the latter (i.e., mixing into the primary system) because it is easy to detect the causal event such as air leak due to failure of a certain component. Therefore, at the first step, we focus on mixing with foreign substances into the primary system, which might flow into subassembly, we surveyed operating experiences of ten reactors: i.e., Joyo, Rapsodie, PFR, Phenix, S-Phenix, BN-600, BN-300, KNK-II, EBR-II and FFTF. The result is shown in column B in Table I. There are 9 instances of mixing with foreign substances into the primary system which might be mixed into the subassembly. Then 6 of them were judged as not applicable to Japanese Prototype FBR “Monju”.

Two of the remained 3 instances (i.e., mixture of oil-sodium reaction products, and aerial mixture to a cover gas system) were counted conservatively because these types of failure and human error are common and an effort to prevent them is taken but they could not be eliminated. Although these two might cause anomaly not only in a specific subassembly but in a whole core, we can evaluate only the severest subassembly in terms of event progression and detection of anomaly as an initiating event for LB.

The other case was conservatively accounted for the possibility of mixing loose parts which is used in the fabrication stage into the primary system in this study. However, in Japanese Prototype FBR “Monju”, rubber plug is not attached to the subassembly so that a total instantaneous blockage in the subassembly cannot occur due to the same cause.

Frequency of mixing with foreign substances into the primary system was calculated as 3.02×10^{-2}[Ry^{-1}] which corresponds to 2.14×10^{-2}[Ry^{-1}] for calendar time at Monju as shown in Table I. In this paper, we assumed this numerical value as the frequency of mixing with foreign substances into the subassembly.

Table I. Frequency of mixing with foreign substances into the primary system

	A	B	C	D	E
	Operation period	Experience number of mixing with foreign substances	Case number applicable to Monju	Frequency of mixing with foreign substances	Frequency for calendar time at Monju
(1)JOYO	8.1	1	0		
(2)Rapsodie	16	1	0		
(3)PFR	4.97	1	1		
(4)Phenix	14.39	4	0		
(5)S-Phenix	1.44	2	2		
(6)BN-600	25.7	0	0		
(7)BN-350	3.61	0	0		
(8)KNK-II	2.21	0	0		
(9)EBR-II	17.1	0	0		
(10)FFTF	5.9	0	0		
ΣAi [Ry: reactor year]	99.42				
ΣCi [times]			3		
ΣAi /ΣCi [Ry^{-1}]				3.02E-02	
ΣAi /ΣCi ×0.71[Ry^{-1}]					2.14E-02

II.A.1 Joyo (Experimental Reactor (ER), Japan)

The operation period is 8.1 reactor years (Ref. 10).The Upper Core Structure was damaged due to the disconnecting the irradiation test subassembly MARICO-2 (Material Testing Irradiation Rig with Temperature Control) in November, 2007. In-vessel observation revealed that 6 pins to connect the handling head and the wrapper tube joint of the MARICO-2 were disconnected (Ref. 11). However, this case is not applicable to Monju due to the uniqueness of the initiating incident for this experimental reactor.

II.A.2 Rapsodie (ER, France)

The operation period was 16 reactor years. The subassembly, Capricorn 1b, failed during the power increase to 20 percent of full power detected by DND, acoustic, TC, and other signals. The cause was attributed to the dislocation of a templug holder; two pins failed and released small amount of fuel (5g) into the sodium (Refs. 12 and 13). This case also is not applicable to Monju for as well as Joyo.

II.A.3 PFR (Prototype Reactor (PR), United Kingdom)

The operation period was 4.97 reactor years according to the database of Power Reactor Information System (PRIS**)** from IAEA (Ref. 14). At the end of 1991, PFR was shut down since 29 June when the reactor was manually tripped for overheating of the top bearing of primary sodium pump 2 (PSP 2). The cause of the overheat was considered to be the spill from the filter on PSP 2 valve due to high pressure difference from the blocking by oil-sodium reaction products. It is also considered that partial blockage of the pump casing overflow pipe led to the problem (Ref. 15). This case is counted as one time during operation period which is applicable to Monju.

II.A.4 Phenix (PR, France)

The operation period was 14.39 reactor years according to the PRIS database (Ref. 14). In the summer of 1989, three emergency shut-downs were activated by negative reactivity signals. An analysis of three events revealed that six purging systems subassemblies located in the diagrid were blocked by impurities (Ref. 16). Corrective measures were taken in order to avoid the presumed phenomena which would induce the emergency shut-downs. Nevertheless, similar event occurred again in September, 1990 (Ref. 15). Thus, this case should not be counted taking into account the uncertain cause.

II.A.5 Super Phenix (Demonstration Reactor (DR), France)

The operation period was 1.44 reactor years according to the PRIS database (Ref. 14). Two events occurred during the period. In June-July 1990 there was an air leak into an auxiliary circuit which caused extensive contamination of the primary sodium (Ref. 15). During the start-up of the reactor it was noted that a newly set-up subassembly was heated up slightly more than the neighbouring subassemblies because a rubber plug was left within the subassembly after an unusual fabrication (Ref. 16).

II.A.6 BN600 (PR, Russia)

The operation period has been 25.7 reactor years according to the PRIS database (Ref. 14). The event of mixing with foreign substances could not be confirmed from the published report (Ref. 15)

II.A.7 BN350 (PR, Kazakhstan)

The operation period was 3.61 reactor years according to the PRIS database (Ref. 14). Unfortunately, data in the Soviet age have not been taken over in this database. The event of mixing with foreign substances could not be confirmed from the published report (Ref. 15)

II.A.8 KNK-II (ER, Germany)

The operation period which can be confirmed from the plant history (Ref. 2) is 2.21 reactor years according to the PRIS database (Ref. 14). The event of mixing with foreign substances could not be confirmed from the report (Ref. 2).

II.A.9 EBR-II (ER, United States of America)

The operation period was 17.1 reactor years according to the database of CORDS developed with JAEA (Ref. 17). LF evaluation was performed in 1994 for the safety evaluation of the Power Reactor Innovative Small Module (PRISM) based on the EBR-II experience (Ref. 18). However, there are no reference data about the occurrence of mixing with foreign substance in the report.

II.A.10 FFTF (ER, United States of America)

The operation period was 5.9 reactor years according to the database of CORDS developed with JAEA (Ref. 17). LF evaluation was performed in 1994 for the safety evaluation of PRISM based on the FFTF experience (Ref. 18). However, there are no reference data about the mixing with foreign substance in the report.

II.B The probability of the blockage by the mixed foreign substances in subassembly

As the foreign substances, four items namely, loose part (Metal), reaction products of sodium (aerial mixture to a cover gas system and breakdown of sodium cold trap), sticker and rubber material (failure of the sticker structure of the cover gas boundary or misplacing the rubber material used in the fabrication stage) and oil (breakdown of dynamic component) are considered according to the past study[8)].

However, the counter measures which are committed in licencing document of Monju (Ref. 1) are taken to prevent the LB accidents as follows.

- Material selecting, design, manufacturing, setting, testing, and inspecting of a fuel element are conducted based on each standard and quality control, and construction operation are performed sufficiently.
- The purity in the primary system is maintained under the appropriate management.
- The inlet of subassembly has a lot of holes as shown in Fig.1 to prevent the simultaneous blockage to keep the coolant flow.

Because of these counter measures, most possible foreign substances which can mix into the FSAs are considered to be metal particles with small diameters.

Then, the branching probability about the blockage by the metal small particle was determined using a rank table as shown in Table II.

Occurrence of LF caused by LB had not been reported in an actual plant except the accident in Enrico Fermi Reactor which had no design measurement in the early stage of FBR development. Then, the scale of blockage is indefinite when it happens in plant. However, it has been studied experimentally for practical use of FBR to date (Ref. 8). As a result of the blockage experiment, it was concluded as follows.

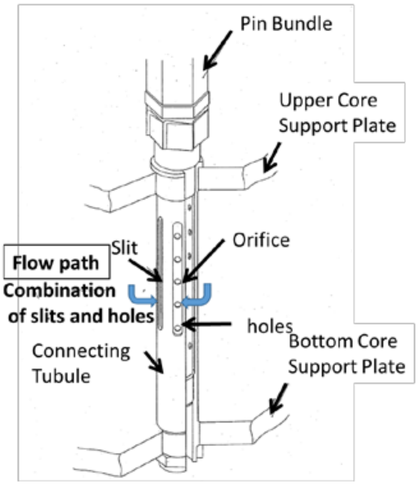

Fig.1. Inlet of subassembly

Table II. Branch probability ranks (Identical to Table 6 in Ref. 7)

Probabilistic rank	Qualitative representation	Representative value	Range of application
1	Indeterminate	0.5	0.7〜0.3
2	Unlikely	0.2	0.3〜0.1
	Likely	0.8	0.7〜0.9
3	Highly Unlikely	0.05	0.1〜0.01
	Highly Likely	0.95	0.9〜0.99
4	Extremely Unlikely	<0.01	<0.01
	Extremely Likely	>0.99	>0.99
5	Impossible	ε	ε
	Certain	1-ε	1-ε

- The behaviour of a foreign particle depends heavily on the particle size. The particles of limited diameter range can contribute to form the blockage in the wire-wrapped fuel pin bundle as described in Fig. 2.
- It is quite unrealistic to consider the blockage which covers the adjoining subchannels, a six-subchannel blockage surrounding a pin for example. No mechanism was found for the propagation of

subchannel blockage to adjoining subchannels. Then, the blockage of multiple subchannels takes the pattern depicted in Fig. 3 due to the geometrical relationship between the spacer wire and the fuel pins.

－Almost all the blockages consist of the particles larger than the diameter of the spacer wire, because a smaller particle can easily bypass the blocked location. Therefore, the final blockage would be highly porous. Cooling is reasonably expected due to the coolant flow through the porosity.

－In the extremely conservative test, blockage or accumulation of the particles formed at the inlet part of the bundle with all the other subchannel pattern as shown in Fig.4. Each accumulation in a subchannel mostly consists of a few particles not including the particles smaller than SWD, and the maximum blockage length is about 10mm.

From these knowledges, even if assuming possible size and amount of the foreign substances mixing into the subassembly in the realistic situation the possibility of the mixed foreign substances which can be trapped by a wire is highly unlikely corresponding to the probabilistic rank “3” in Table II**.** Therefore, the occurrence probability of this branch (S) is judged as 0.05.

Furthermore, even if assuming the foreign substances with the size almost adjusted to be trapped by wire mixing into the subassembly, the possibility of forming large scale blockage is extremely unlikely corresponding to the probabilistic rank “4” in Table II. Therefore, the occurrence probability of this branch (L) is judged as 0.01.

Then, the branch probabilities of blockage occurrence for small scale (a) and large scale (b) were calculated as follows when the foreign substances mixed into the primary system.

(a) Small scale blockage:

$S \times (1-L)=0.05 \times (1-0.01)=0.0495$

(b) Large scale blockage:

$S \times L=0.05 \times 0.01=0.0005$

II.C Frequency of initiating event

By combining the results of II.A and II.B, the frequency of “small scale blockage” and “large scale blockage” as the initiating events were evaluated as follows.

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(a) Small scale blockage:

$2.14 \times 10^{-2} \times 0.0495=1.06 \times 10^{-3}$

(b) Large scale blockage:

$2.14 \times 10^{-2} \times 0.0005=1.07 \times 10^{-5}$

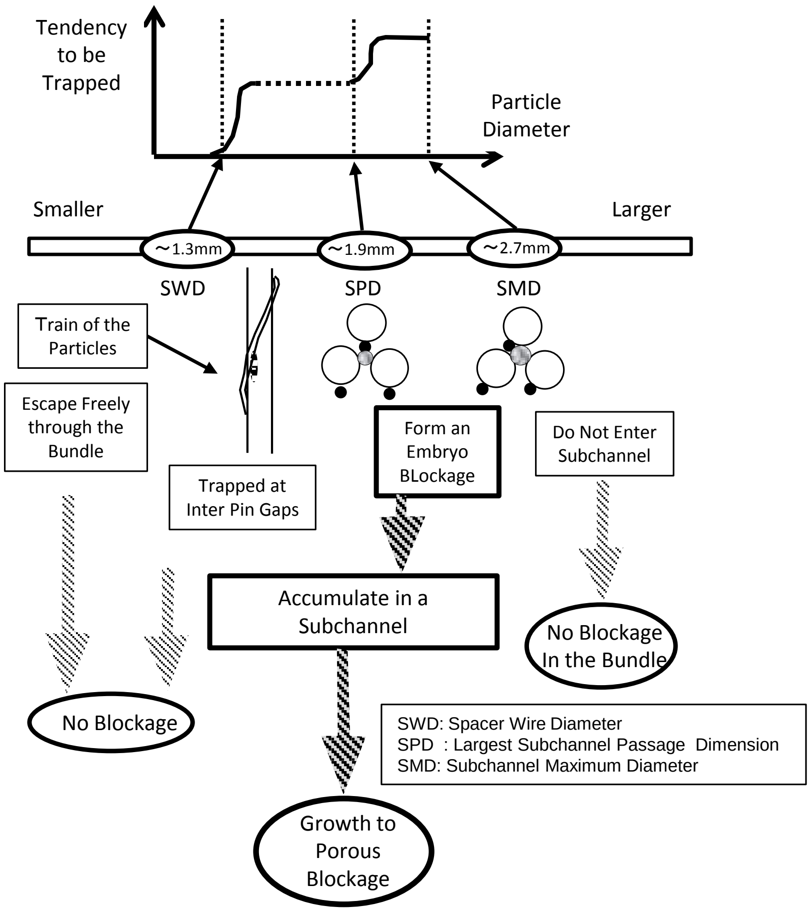

Fig. 2. Effect of particle sizes on blockage formation
(Identical to Fig.4 in Ref. 6)

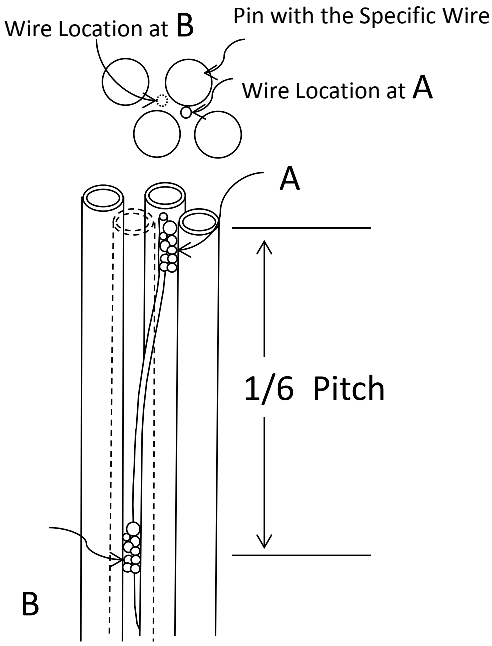

Fig. 3. Geometrical relationship among wire, pins and blockages (Identical to Fig.6 in Ref. 6)

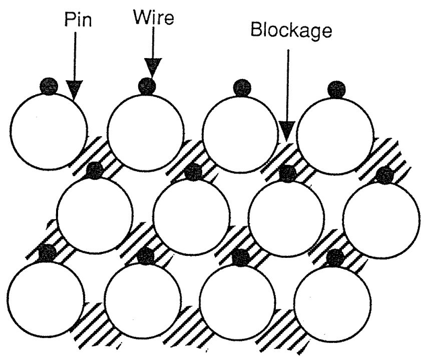

Fig. 4. Blockage pattern
(Identical to Fig.7 in Ref. 6)

III. Event tree analysis(ETA) for failure propagation from LB

III.A Headings of Event tree (ET)

The main flow after fuel pin failure in the operation procedure, alert and reactor trip level of detectors of fuel pin failure are shown in Table III and Fig.5 respectively. These relations are essentially same as the case of adventitious fuel pin failure (Ref. 7).

Table III. Alert and reactor trip level of detectors for fuel pin failure in Monju (Identical to Table 5 in Ref. 7)

Name of alert or reactor trip	Alert or reactor trip threshold
Alert of high count rate at the precipitators in CG method	FP gas release (0.01% of one fuel pin)
Alert of very high count rate at the precipitators in CG method	Fuel pin failure (0.01% of total fuel pins)
Alert of high count rate at the NaI counter in CG method	Fuel pin failure (0.02% of total fuel pins)
Alert of high count rate at DNDs in DN method	Breached cladding area (over 200mm^2)
Alert from TC at the outlet of sub-assembly	More than 66% of flow blockage within one sub-assembly
Reactor trip at DNDs in DN method	Breached cladding area (over 5,000mm^2)

FP gas is not released unless the cladding fails, even if LB occurs by the foreign substances which mix into the core. Then, the precipitators of CG method cannot detect the abnormally caused LB, and the operation continues normally without shutdown until the fuel exchanges.

The operators doubt the possibility of fuel failure, if the precipitators of CG method detect the abnormality with alert level. After the fuel pin failure and subsequent FP gas release detection at the precipitators in CG method, manual reactor shutdown will be initiated if the cladding defect size exceeds 200 mm^2 which is the alert threshold in DN method.

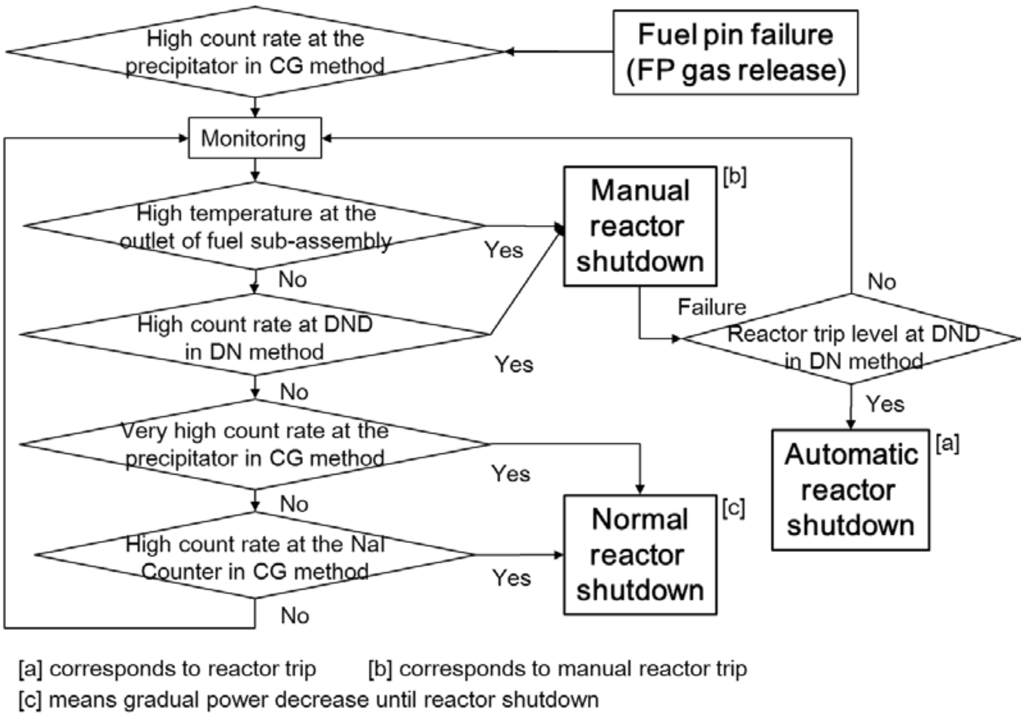

Fig. 5. Main operation procedures after fuel pin failure in Monju (Identical to Figure 2 in Ref. 7)

Normal reactor shutdown will be initiated after the detection of 0.01 % of total driver fuel pin failures at the precipitators in CG method and after the detection of 0.02 % of total driver fuel pin failures at the NaI detectors in CG method. More than 3 or 6 fuel pin failures are necessary for normal reactor shutdown by precipitators or NaI detectors respectively because the number of driver fuel pin in the core is 33,462 in Monju.

Furthermore, automatic reactor shutdown will be initiated if the cladding defect size exceeds 5,000 mm^2 which corresponds to the reactor trip level in DN method.

If the automatic shutdown fails, there is a pass of manual shutdown by operators recognizing the abnormality from the alert threshold of TC at the outlet of subassembly.

In these sequences except the automatic reactor shutdown by DN signals, human factor significantly contributes to the consequence. Then, the difference of propagation rate in the early stage of LF phenomena with the case causes adventitious fuel pin failure. They depend on the initiating scale of blockage described in section II.B.

III.B Main ET for LF caused LB and Fault tree Analysis

As described in Section II.C, two initiating events depending on the blockage scale were assumed. Main ET was developed for those two initiating events; i.e., small scale blockage and large scale blockage as shown in Fig.6. The ET reflects the operation procedure after the fuel pin failure and the latest knowledge on experiments and analyses. Although the quantification of branch probabilities for phenomenological headings ((2), (4), (7), (9), (11), and (12)) were determined through the engineering judgment based on the knowledge on experiments and analyses, it was standardized using Table II in order to keep consistency in this ETA.

Each branch probability is described below in each case of the blockage scale.

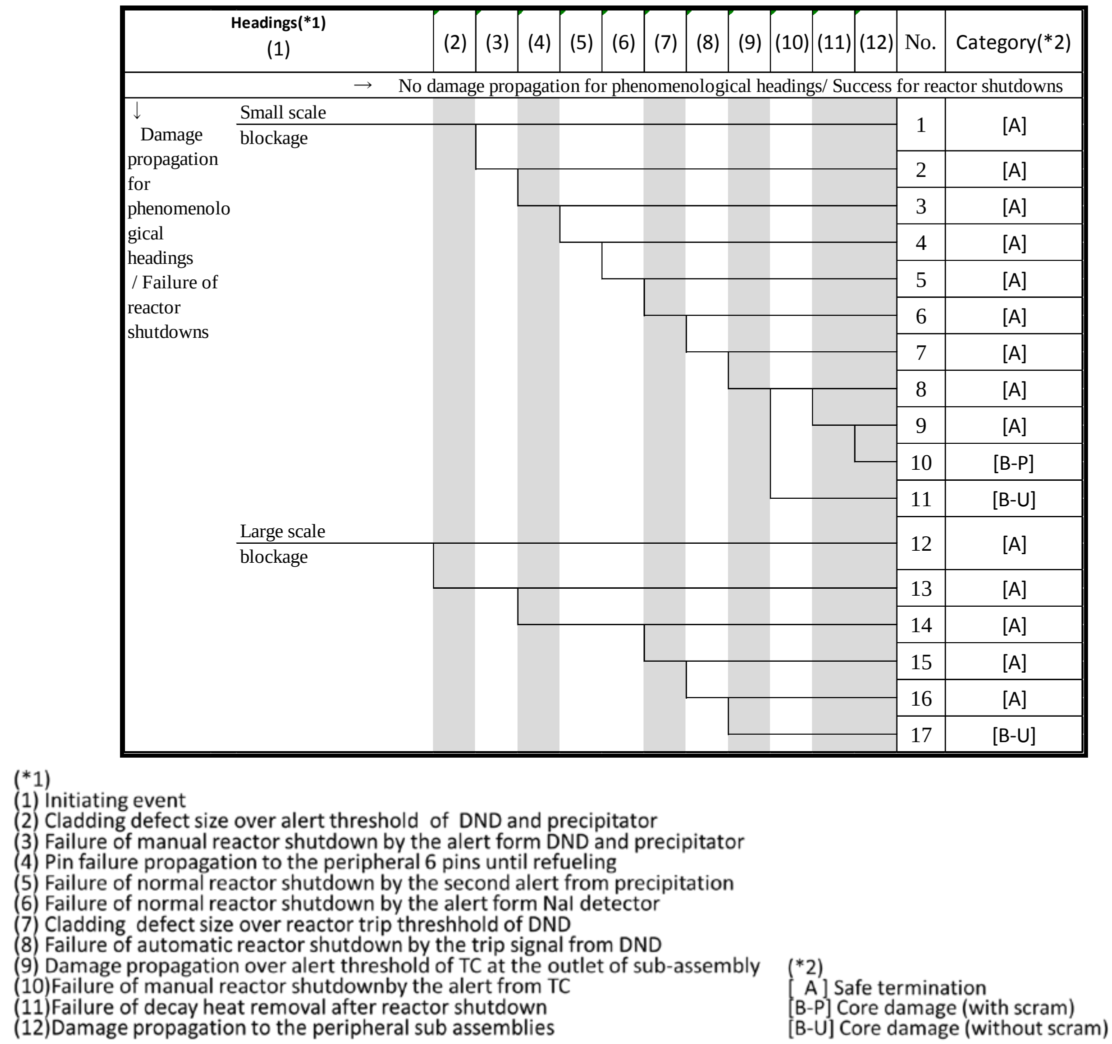

Fig. 6. Main ET for LF caused by LB

III.B 1 Small scale blockage (a)

(2)Cladding defect size over alert threshold of DND and precipitator, (4) Pin failure propagation to the peripheral 6 pins until refueling, (7) Cladding defect size over reactor trip threshold of DND, and (9) Damage propagation over alert threshold of TC at the outlet of sub-assembly

It is hard to assume the propagation of failure because the temperature rising rate is slow (Ref. 7). However, the probabilities are 0.5 conservatively because they cannot be denied completely by the existence of blockage.

(3) Failure of manual reactor shutdown by the alert form DND and precipitator, (5) Failure of normal reactor shutdown by the second alert from precipitation, (6) Failure of normal reactor shutdown by the alert form NaI detector, (8) Failure of automatic reactor shutdown by the trip signal from DND, and (10) Failure of manual reactor shutdown by the alert from TC

These probabilities are calculated by FTA as shown in Table IV. This method is as well as the case of adventitious fuel pin failure (Ref. 7).

(11) Failure of decay heat removal after reactor shutdown, and (12) Damage propagation to the peripheral sub-assemblies

These probabilities can refer to the value of the case of adventitious fuel pin failure (Ref. 7).The probabilities are 0.2 and 0.8 for (11) and (12)

III.B 2 Large scale blockage (b)

(2)Cladding defect size over alert threshold of DND and precipitator, (4) Pin failure propagation to the peripheral 6 pins until refueling, (7) Cladding defect size over reactor trip threshold of DND, and (9) Damage propagation over alert threshold of TC at the outlet of sub-assembly

These probabilities are same as small scale blockage of 0.5. The flow path in subassembly is kept even if the large scale blockage occurs from the knowledge of blockage experiments (Ref. 6).

(3) Failure of manual reactor shutdown by the alert form DND and precipitator, (5) Failure of normal reactor shutdown by the second alert from precipitation, (6) Failure of normal reactor shutdown by the alert form NaI detector, (8) Failure of automatic reactor shutdown by the trip signal from DND, and (10) Failure of manual reactor shutdown by the alert from TC

The manual shutdown cannot be expected in case of large scale blockage, because the progress speed of the phenomena would be fast. Other probabilities are fundamentally same as the small scale blockage.

(11) Failure of decay heat removal after the reactor shutdown, and (12) Damage propagation to the peripheral sub-assemblies

These probabilities are same as the small scale blockage of 0.2 and 0.8 for (11) and (12).

Table IV. Results of FTA

Headings					Probability
Support and common systems for frontline systems	I	Unavailability of support systems (power supply) for manual reactor shutdown			2E-06
	II	Unavailability of common system for manual reactor shutdown by the alert from precipitators or NaI detectors (Ar gas sampling line)			8E-04
	III	Unavailability of common component for precipitators (3 signal line and calibration error)			4E-04
	IV	Unavailability of common component for precipitators (2 signal line)			2E-08
	V	Common cause failure and calibration error in DN method for manual and automatic shutdown			4E-04
	VI	Unavailability of common system in DN method for manual and automatic shutdown (detectors, control circuits, and power supply for A loop)			3E-06
	VII	Unavailability of support system in DN method for manual and automatic shutdown (power supply for B loop)			2E-06
	VIII	Unavailability of support system in DN method for manual and automatic shutdown (power supply for C loop)			2E-06
	IX	Failures of components necessary only for manual shutdown			3E-06
	X	Failures of components for reactor shutdown (reactor trip breakers and control rods)			6E-08
Main event tree headings (Frontline systems)	(3)	Failure of manual reactor shutdown by the alert from DNDs and precipitators	(3)-2	Failures of DN detectors	1 out of 2:8E-07 2 out of 2:6E-13
			(3)-3	Cognitive and decision error against alert	4E-04
	(5)	Failure of normal reactor shutdown by the second alert from precipitators	(5)-2	Cognitive and decision error against alert	4E-04
	(6)	Failure of normal rector shutdown by the alert from NaI detectors	(6)-1	Failures of NaI detectors	1E-06
			(6)-2	Cognitive and decision error against alert	8E-04
	(8)	Failure of automatic reactor shutdown by the trip signal from DNDs	(8)-1	Failures of DN detectors	1 out of 2:8E-07 2 out of 2:6E-13
	(10)	Failure of manual reactor shutdown by the alert from TC	(10)-1	Failures of components related to alert signal lines	1E-03
			(10)-2	Cognitive and decision error against alert	4E-04

Note: 2E-06 means 2×10^{-6}.

IV. Results and discussions

Table V show the analysis results of the frequency of core damage induced from LB in this study and the associated studies. Our results indicate about one tenth smaller value compared with the past study (ref. 5) on the frequency of damage propagation to 37 subassemblies induced from flow blockage. The difference comes from the following improvements in the analysis:

(1) Reflecting the investigation result of FBR operating history in the world and experimental knowledge for the mechanism of the blockage in the subassembly to the initiating event frequency of LB,
(2) Considering the human factor based on the emergency operating procedure of Monju, and
(3) Conducting FTA which considers functional dependency among the systems and components in Monju.

From the detailed comparison, there is no significant difference between our results and the past work (ref. 5) in the occurrence frequency of the large scale blockage which can cause cladding breach. Therefore the difference of the core damage frequency (CDF) between the two would be mainly due to the above improvements of (2) and (3).

These improvements were fundamentally same as the work of PRA on the the adventitious fuel pin failure (ref. 7). The initiating event frequency of LF caused by LB described in section II.C was much smaller than that of the adventitious fuel pin failure as shown in Table VI. However, the CDF when the local blockage occurs was much larger than that when the LF is caused by the fuel-element-failure propagation from adventitious-fuel-pin failure (FEFPA) as shown in Table V.

Table V also shows the CDF of the anticipated transient without scram (ATWS) and protected loss of heat sink (PLOHS) in Monju (ref. 17). The frequency of damage propagation to the peripheral subassembly without or with scram was smaller than CDFs of ATWS and PLOHS. Furthermore, the consequence of whole core accident from LF caused by LB without or with scram was not greater than that of ATWS or PLOHS because almost all the subassembly will be damaged at ATWS or PLOHS. Therefore, damage propagation from LF caused LB can be negligible compared with the core damage due to ATWS or PLOHS in the viewpoint of both probability and consequence.

Table V. CDF from LB compared with those from FEFPA, ATWS and PLOHS

		Without scram (/ry)	With scram (failure of decay heat removal) (/ry)
CDF from LB (This work)		**∼2.7×10^{-10}**	**∼3.2×10^{-12}**
(Past work by JNES) Damage propagation more than 37 SA	(ref 5)	(1.59×10^{-9})	
CDF from FEFPA	(ref.7)	∼9.6×10^{-13}	∼7.3×10^{-13}
CDF from ATWS and PLOHS	(ref.17)	~3×10^{-8} in ATWS	~5×10^{-8} in PLOHS

Table VI. Frequency of the initiating events of LF

Initiating event		Frequency (/ry)
Adventitious fuel pin failure	(ref.6, 7)	2.4
Small scale blockage		1.06×10^{-3}
Large scale blockage		1.07×10^{-5}

V. Conclusions

Frequency of damage propagation to the peripheral subassemblies was quantified as 2.8×10^{-10} [Ry^{-1}] in Monju based on the ETA. Therefore, frequency of whole core damage was much smaller than this value due to the other detection and reactor shutdown systems after the damage propagation to the peripheral subassemblies. It was clarified in this study that damage propagation from LF caused by LB in Monju can be negligible compared with the core damage due to ATWS or PLOHS in the viewpoint of both probability and consequence.

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