IRID

Subsidy Project of Decommissioning and Contaminated Water Management in the FY 2017 Supplementary Budgets

# Advancement of Retrieval Method and System of Fuel Debris and Internal Structures (Development of Technology for Criticality Control in Fuel Debris Retrieval)

## FY2018 Final Report

**July 2019**

**International Research Institute for Nuclear Decommissioning (IRID)**

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# 1. Overall plan
## 1.1 Purpose



[Background]

・ From FY2013 to FY2017, the basic feasibility of elemental technology for criticality control during the retrieval of fuel debris was confirmed as part of a subsidy project of *"Development of fuel debris criticality control technology."* However, in project of *"Advancement of Retrieval Method and System of Fuel Debris and Internal Structures,"* there remain challenges the applicability of the technology for fuel debris retrieval.

[Purpose]

・Study on the on-site applicability of criticality control technology, as part of the conceptual study on the methods and systems for retrieval of fuel debris and internal structures.

(1) Development of technologies for sub-criticality measurement and criticality approach monitoring

(2) Development of re-criticality detection technologies

(3) Development of criticality prevention technologies

(4) Optimization study of ensuring safety of methods and systems (related to criticality control)

・ Promotion of the implementation of criticality control in methods and systems in cooperation with the projects conducted by IRID, such as *"Project of Advancement of Retrieval Method and System of Fuel Debris and Internal Structures."*

# 1.1 Purpose (Processes to which technology development results will be applied)



| Items / FY | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|
| **Main processes on the road-map** | Determining the fuel debris retrieval policy ▲ | | Incorporating the retrieval policy | Determining the retrieval method △ | | Retrieval in first unit △ | |
| **[Development of fuel debris criticality control technology] Project**<br>1. Establishment of criticality evaluation method (criticality evaluation and evaluation of behavior during criticality)<br>2. Development of criticality control technology<br>(1) Criticality approach monitoring technology<br>(2) Re-criticality detection technology<br>(3) Criticality prevention technology<br>Insoluble neutron absorption material<br>Soluble neutron absorption material | Study on criticality scenarios updated with the latest information<br>Criticality control methods and evaluation of each of the debris treatment methods<br>Study on the method: Feasibility test (Verification of principles)<br>Study on advanced systems: Feasibility test<br>Selection of candidate materials, study on the method of application, feasibility test<br>Study on the equipment and impact assessment upon application: Feasibility test | | | Incorporation of development results in the study on methods and equipment | | | |
| **[Advancement of Retrieval Method and System of Fuel Debris and Internal Structures**<br>Development of technology for the establishment of criticality control methods<br>1. Development of technologies for sub-criticality measurement and criticality approach monitoring<br>2. Development of re-criticality detection technologies<br>3. Development of criticality prevention technologies<br>4. Study on optimization related to ensuring safety of methods and systems<br>① Establishment of criticality evaluation and impact assessment methods<br>② Study on criticality control methods | | | | Information on methods and systems | Incorporate in the study on methods and systems | | |
| **[Main relevant projects]**<br>"Development of Technology for Detailed Investigation inside PCV"<br>"Development of Sampling Technology for Retrieval of Fuel Debris and Internal Structures"<br>"Development of Technology for Containing, Transfer and Storage of Fuel Debris" | | | Information on methods and systems | Survey needs<br>Criticality evaluation method | Criticality control methods at each stage<br>Method of rationalizing criticality evaluation using the survey results | | |

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# 1.2 Project Goals (Basic concept of criticality control)

## [Goal of criticality control]

- Prevention of criticality as well as excessive exposure (radiation hazard) of general public and workers, in the eventuality of criticality occurrence.

Evaluation criteria: General public at the site boundary: 5 mSv, Workers: 100 mSv

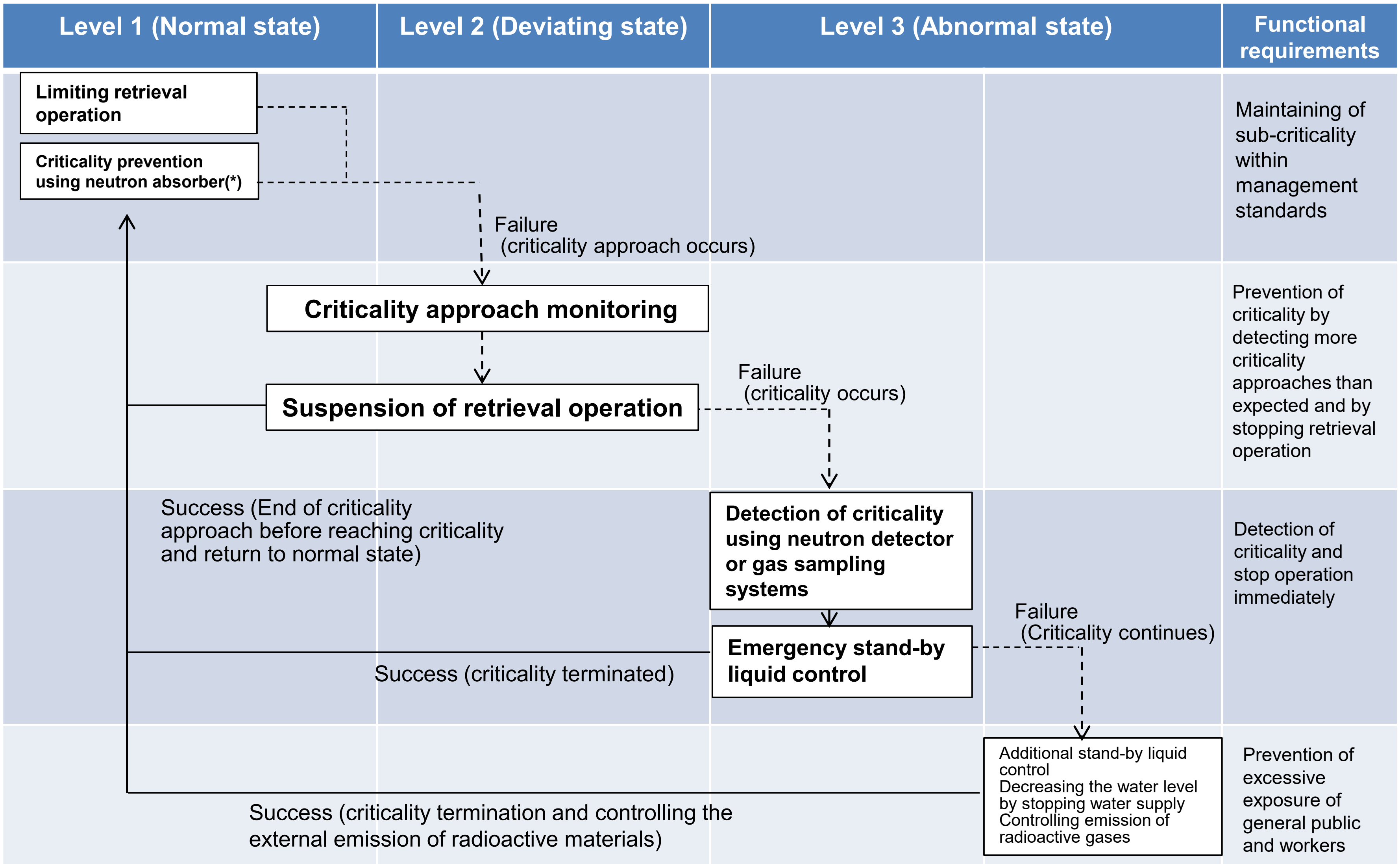
## [Criticality control methods based on defense in depth]

- Safety and functional requirements of methods and systems: See Reference 1
- Level setting review along with the concept of advancement of methods and systems (Occurrence of criticality is classified as level 3)

| Safety requirements | Preventing the generation of abnormal radioactive material due to nuclear reaction | | | |
|---|---|---|---|---|
| Defence in depth | Level 1 | Level 2 | Level 3 | |
| Functional requirements | Maintaining sub-criticality within management standards | Preventing criticality by detecting more criticality approaches than expected and by stopping retrieval operation | Detecting criticality and terminate operation immediately | |
| Status | Normal state (retrieval operation) | Criticality approach state | Supercritical | Criticality continues |
| Specific means (Important points) | ･Limiting the amount of fuel debris being processed<br>･Suspension of operations when criticality approach is observed<br>･Use of neutron absorption material | ･Suspension of operations when criticality approach is detected, collection of processed fuel debris | ･Criticality termination using stand-by liquid control when criticality is detected | ･Criticality termination by other means such as stand-by liquid control, injection of neutron absorber by a portable equipment, decreasing water level, etc.<br>･Controlling emission of radioactive gases |
| Monitoring | ･Neutron flux near the place of retrieval<br>･FP gas concentration in PCV exhaust | | | ･FP gas concentration in PCV exhaust |
| Prevention of escalation to higher levels | ･Terminate criticality approach by suspending operations so that criticality does not escalate to Level 2 | ･Terminate criticality approach by suspending operations so that criticality does not escalate to Level 3 (criticality).<br>･Return to Level 1 by collecting processed fuel debris.<br>･Ensure that excessive increase in environmental exposure does not occur in sub-criticality state (carry out evacuation as necessary based on the area monitor readings) | ･Terminate criticality using stand-by liquid control and return to Level 2 or lower.<br>･Prevent excessive exposure by evacuating the workers from the site. | ･Terminate criticality using additional measures and return to Level 2 or lower. |
| Remarks | Prevention of criticality occurrence, early detection and termination are the major issues in criticality control | | | Confinement of radioactive materials<br>(Ensuring safety as a whole) |

# 1.2 Project Goals (Basic concept of criticality control)

**Criticality control while retrieving fuel debris (In the case of constant use of neutron absorption material)**




* When using absorber (soluble / insoluble)

# 1.3 Details of the study related to on-site applicability of criticality control technology



・The prerequisites for the study are summarized in Reference 17.
・The study on on-site applicability of criticality control was conducted based on the following four perspectives:

① Adopting criticality control in retrieval methods and systems (Figure 1, Reference 4)
- Specifications for criticality approach detection systems that can be mounted on to retrieval equipment
- Method of application and usage of neutron absorption material
- Verifying the effectiveness of criticality control with respect to the system configuration and operating conditions during retrieval

② Demonstration assuming the systems at 1F site
- Feasibility of sub-criticality measurement in complex systems
- Demonstration test plan until the application of criticality approach monitoring systems on actual equipment
- Detector calibration technology for PCV gas radiation monitor advanced systems

③ Latest criticality scenarios and risk evaluations based on the results of internal investigation

④ Criticality control methods in each process until full-scale retrieval (system configuration and conditions)

The next sheet summarizes the correspondence between the perspective of the study and implementation details.

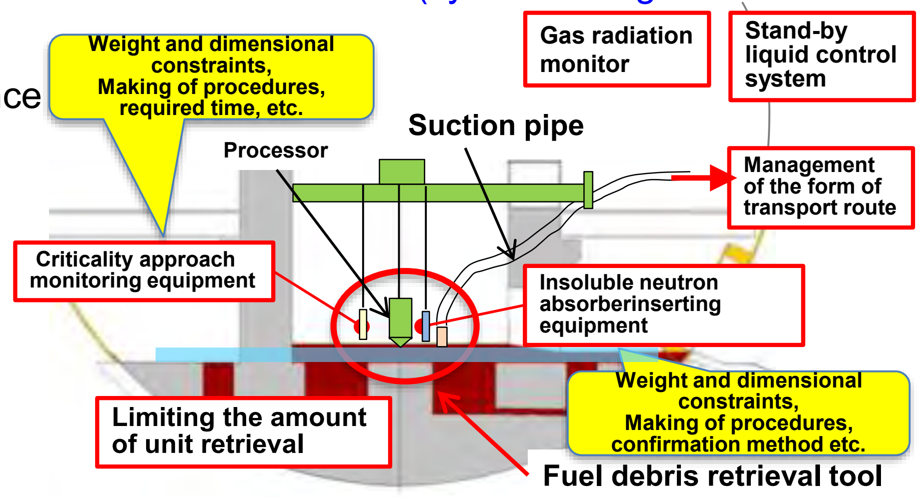



**Figure 1 Example of implementation items for criticality control**

# 1.3 Details of the study related to on-site applicability of criticality control technology



## Selection of implementation details from the perspective of studying the on-site applicability of criticality control

| Perspective of on-site applicability / Implementation details | a) Adopting criticality control with respect to retrieval methods and systems (Figure 1 in previous slide) | b) Demonstration assuming the systems at 1F site | c) Latest criticality scenarios and risk evaluation based on the results of internal investigation | d) ④Criticality control methods in each process up to full-scale retrieval |
|---|---|---|---|---|
| (1) Development of technologies for sub-criticality measurement and criticality approach monitoring | 1) Study on installing neutron detector in retrieval equipment | 2) Verifying the feasibility of sub-criticality measurement methods simulating the complex systems of actual 1F equipment<br>3) Study on the method for verifying the feasibility of instrumentation systems in actual equipment | | |
| (2) Development of re-criticality detection technologies | 1) Study on the method of operation of negative pressure control systems<br>2) Decision on the applicability in detecting localized criticality approach events<br>3) Study on the possibility of installation of neutron detector | Study on the detector calibration method from the items included in 1) | | |
| (3) Development of criticality prevention technologies | 1) Study on the method of dispersing neutron absorber fuel debris and the method of verifying the effects after dispersion<br>2) Study of long-term irradiation effects on canisters, assessment of impact on the number of canisters and the amount of waste | Confirmation test of workability from the items included in 1) | | |
| (4) Study on optimization related to ensuring safety of methods and systems (related to criticality control)<br>① Establishment of criticality evaluation and impact assessment methods | | | 1) Study on criticality scenarios and criticality evaluation<br>2) Advancement of statistical criticality evaluation methods | |
| ② Study on criticality control methods | i-1 Evaluation of criticality control procedures for each retrieval method<br>i-2) Impact assessment of circulating cooling water systems with soluble neutron absorption materials | Confirmation test of the boron concentration impact caused by the elements generated from concrete, from the items included in i-2) | | ii) Study on the criticality control methods for each stage that has gradually increased in scale after debris sampling |

# 1.5 Project Organization



**International Research Institute for Nuclear Decommissioning – IRID (Headquarters)**

○ Supervision of the development of overall plan and integration of technology
○ Supervision of technology management such as progress of technological development etc.

**Advancement of Retrieval Method and System of Fuel Debris and Internal Structures**

**Development of Technology for Detailed Investigation inside PCV**

**Development of Sampling Technology for Retrieval of Fuel Debris and Internal Structures**

### Mitsubishi Heavy Industries, Ltd.

1) Development of technologies for sub-criticality measurement and criticality approach monitoring
2) Development of re-criticality detection technologies
3) Development of criticality prevention technologies
4) Study on optimization related to ensuring safety of methods and systems (related to criticality control)
① Establishment of criticality evaluation and impact assessment methods
② Study on criticality control methods

**MHI NS Engineering Co., Ltd.**
・Assistance in criticality evaluation
・Assistance in analyzing the evaluation of behavior during criticality

**Nuclear Development Corporation**
・Assistance in the study on the usage of soluble neutron absorption materials

**TEPCO SYSTEMS CORPORATION**
・Assistance in the study on criticality control methods

**Research Reactor Institute, Kyoto University**
・ Assistance in testing criticality approach detection

### Toshiba Energy Systems & Solutions Corporation

1) Development of technologies for sub-criticality measurement and criticality approach monitoring
2) Development of re-criticality detection technologies
3) Development of criticality prevention technologies
4) Study on optimization related to ensuring safety of methods and systems (related to criticality control)
① Establishment of criticality evaluation and impact assessment methods
② Study on criticality control methods

**Nuclear Fuel Industries, Ltd.**
・ Criticality prevention technology (Gd particles)
・ Study on improvement of criticality approach monitoring method

**Fuji Chemical Industries Co., Ltd.**
・ Criticality prevention technology (water and glass materials)

**Toshiba Nuclear Engineering Services Corporation**
・Assistance in analyzing the methods of criticality evaluation and impact assessment

**TEPCO SYSTEMS CORPORATION**
・Study on testing the spent fuel storage equipment

**Research Reactor Institute, Kyoto University**
・ Tests for verifying the applicability of criticality approach monitoring systems and insoluble neutron absorption materials in complex systems

### Hitachi-GE Nuclear Energy, Ltd.

1) Development of technologies for sub-criticality measurement and criticality approach monitoring
2) Development of re-criticality detection technologies
3) Development of criticality prevention technologies
4) Study on optimization related to ensuring safety of methods and systems (related to criticality control)
① Establishment of criticality evaluation and impact assessment methods
② Study on criticality control methods

**Hitachi Chemical Company, Ltd.**
・ Assistance in the development of insoluble absorption materials

**Hitachi High-Technologies Corporation**
・Assistance in the development of insoluble neutron absorption materials

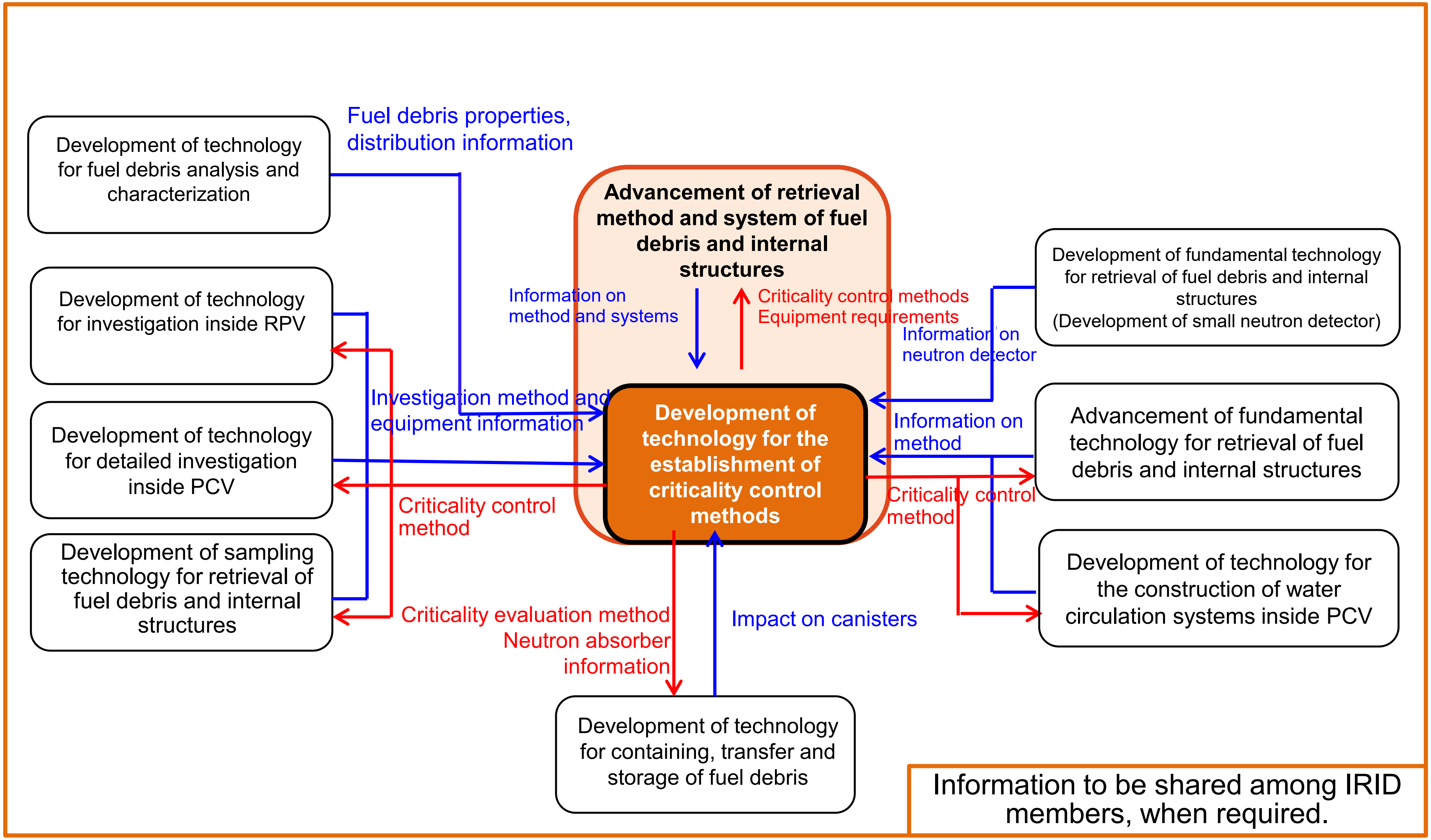
**Hitachi, Ltd.**
・ Experimental study of calibration technology for FP gas radiation monitor (gas sampling system)

**Nice corporation**
・Assistance in statistical criticality evaluation and evaluation of behavior during criticality

**Research Reactor Institute, Kyoto University**
・ Tests for verifying the applicability of criticality approach monitoring systems and insoluble neutron absorption materials in complex systems

Only the major implementation items are listed.

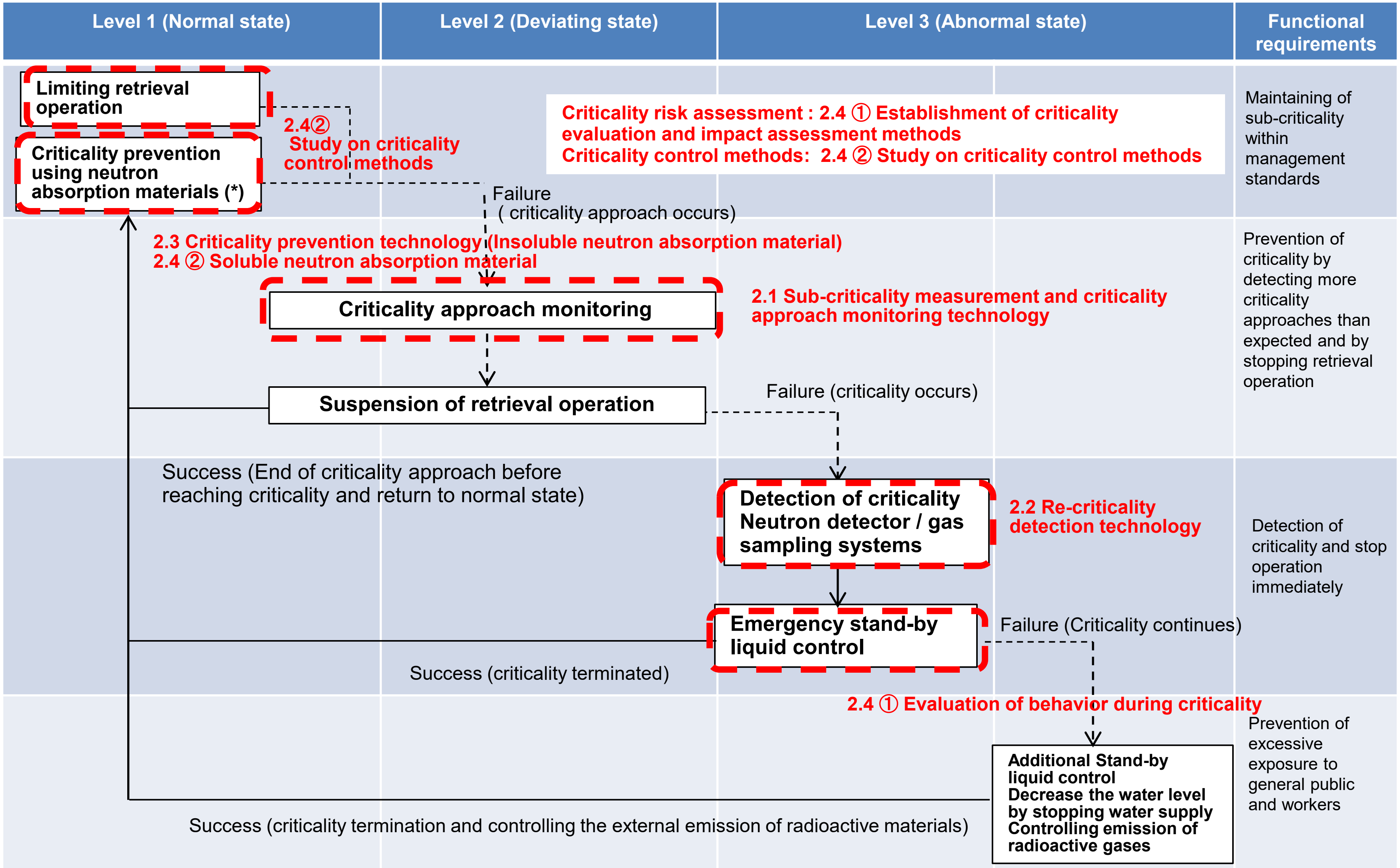
# 1.5 Project Organization (Relations with other research)



# 2. Implementation results



## (Reference) All implementation details (Processes to which elemental technology will be applied)




* When using absorption materials (soluble / insoluble)

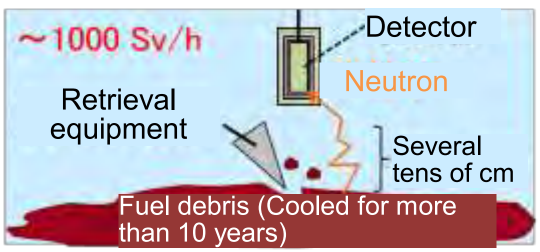
# 2. Implementation results
## 2.1 Development of Technologies for Sub-criticality Measurement and Criticality Approach Monitoring
### Overview

**[Purpose]**

- **Development of systems for measuring sub-criticality and monitoring criticality approach to prevent criticality by detecting criticality approach and suspending the retrieval operations**

**[Overview of systems]**

- **Measuring the localized fluctuation of neutrons caused due to fission, by installing a neutron detector near the debris. (Figure 1)**
- **Estimating sub-criticality by performing reactor noise analysis of neutron fluctuations.**
- **Real-time monitoring for changes in sub-criticality caused by fuel debris retrieval operation using neutron source multiplication method.**



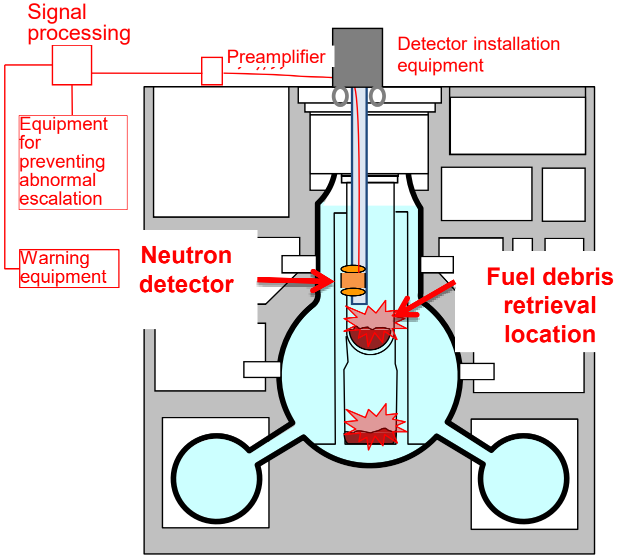
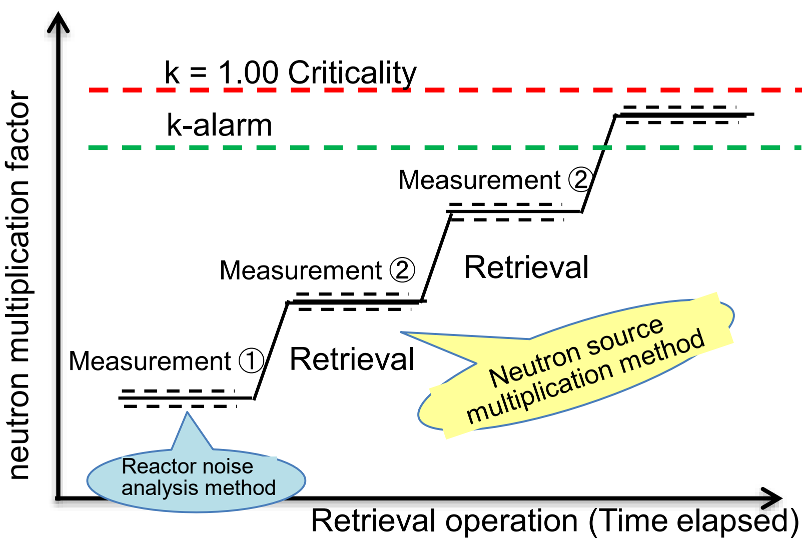



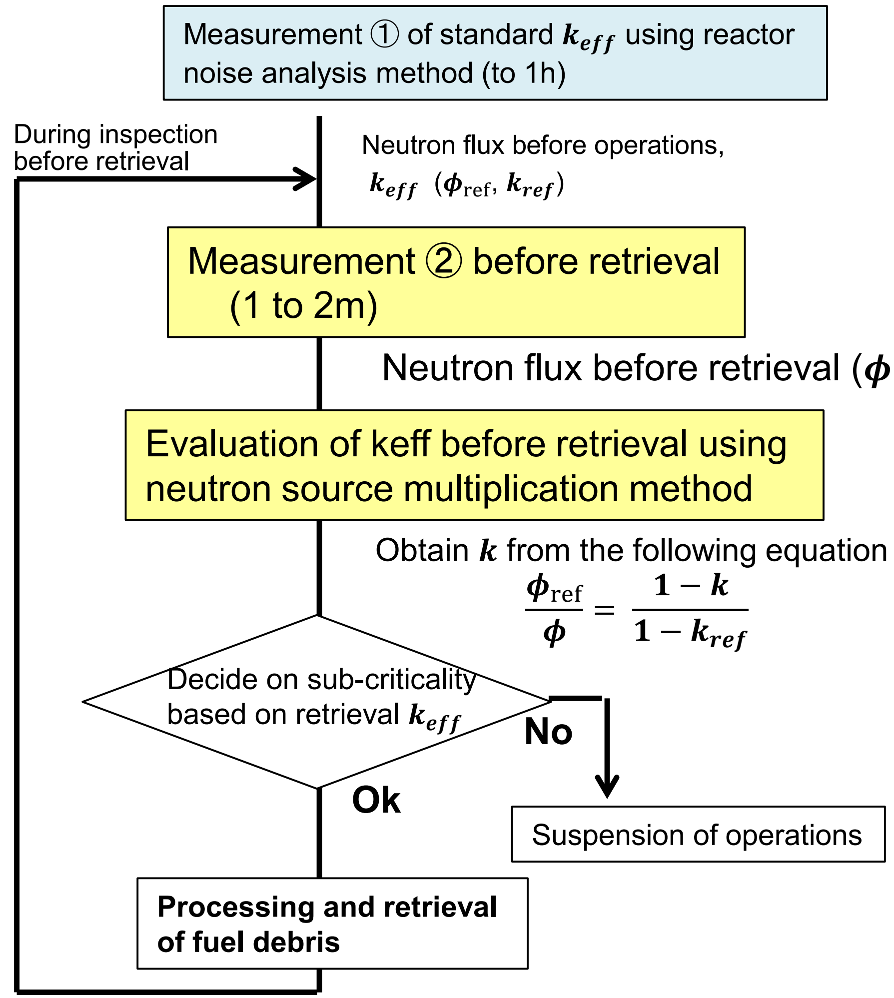

**Figure 1 Overview of sub-criticality measurement and criticality approach monitoring systems**

# 2.1 Development of Technologies for Sub-criticality Measurement and Criticality Approach Monitoring Overview

[Monitoring procedure]

- Measure the standard neutron multiplication factor (keff) using the reactor noise analysis method before starting debris retrieval ①.
- Monitor the neutron counting rate in real time during debris retrieval ②.
- When neutron counting rate changes, evaluate the neutron multiplication factor (keff) using the neutron source multiplication method.
- When the neutron multiplication factor reaches the evaluation criteria, suspend the operations.
- Measure the criteria once again using reactor noise analysis method after reducing the neutron multiplication factor ①.



# 2.1 Development of Technologies for Sub-criticality Measurement and Criticality Approach Monitoring



Details of completed goals (Black) , Details of goals in FY2018 (Blue)

## Table 1 Development results and challenges toward the actual application

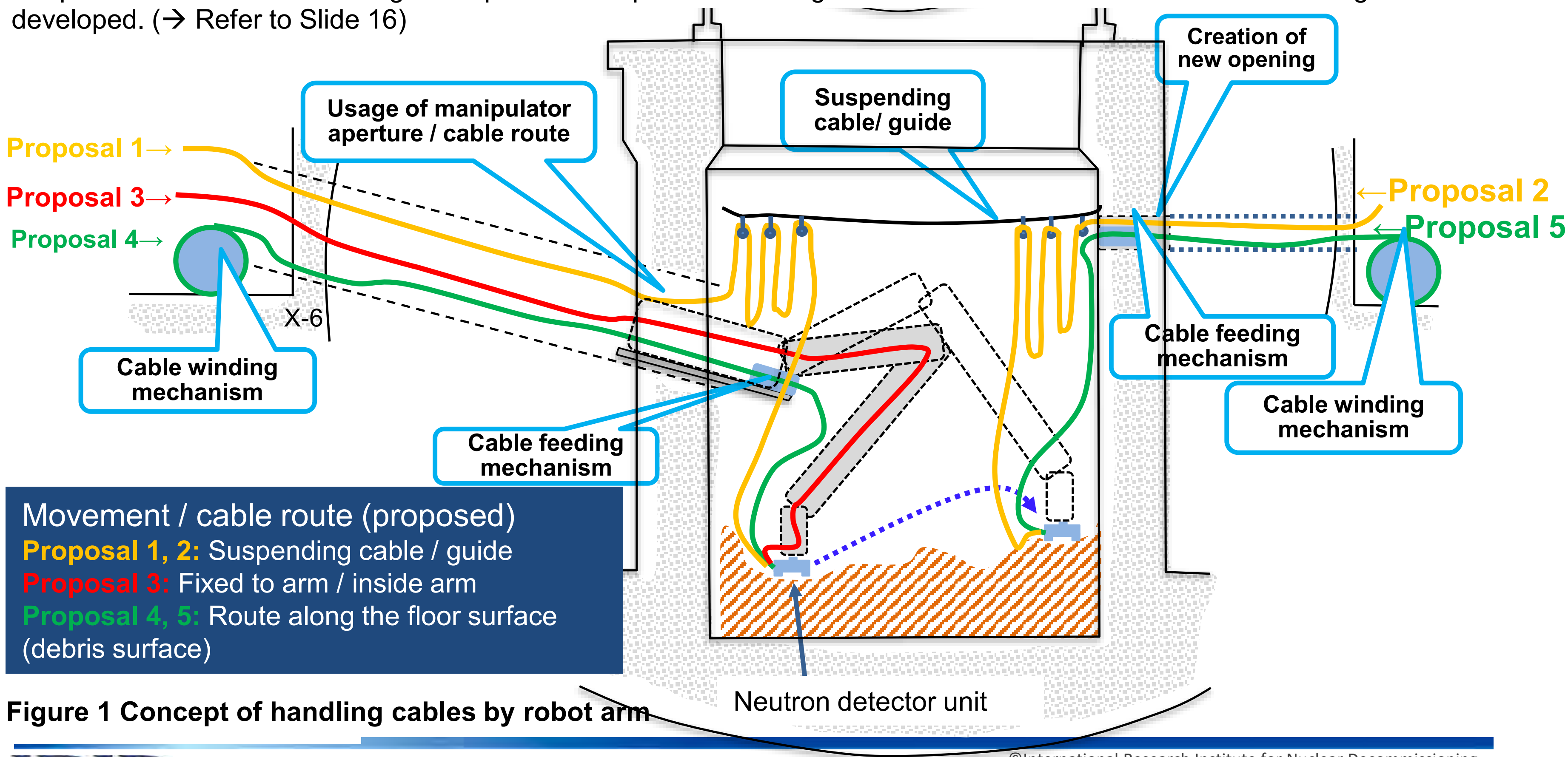
| Final Goal | Goals to be achieved toward the actual application | Status of achievement | Challenges toward the actual application |
|---|---|---|---|
| **Verifying the feasibility of technology (Establishment of technology for sub-criticality measurement)** | ① Establishment of measurement method | Selection of a method combining reactor noise analysis method and neutron source multiplication method (completed)<br>Study on the sensitivity and placement of detector for reducing measurement errors | |
| | ② Development of system specifications | Development of system specifications for detector, measurement circuit, etc. (completed) | |
| | ③ Specifications of neutron detector | Development of neutron detector specifications and selection of detector for prototyping (completed) | |
| | ④ Systems design and prototyping | Prototyping of systems consisting of neutron detector, measurement circuit and PC (used for analysis) to be used for the testing system. | |
| | ⑤ Performance evaluation of prototype | Confirming the performance of neutron detection in high gamma ray environment<br>Confirming the measurement of sub-criticality in simulated homogeneous debris<br>Confirming the performance of sub-criticality measurement under large-scale debris simulated conditions (KUCA test # 3) | Verification test of performance for sub-criticality measurement under simulated conditions of non-homogeneous debris / neutron absorber(KUCA test #4) |
| **Implementation of technology (Incorporation into debris retrieval system)** | ① System configurations and layout design | Organizing the specification items for neutron detector unit for transferring it using robot arm<br>Development of cable handling concepts | Designing / prototyping / elemental test<br>Verification in combination with debris retrieval equipment |
| | ② Countermeasures for electro-magnetic noise | Evaluating the effect of simulated noise, and putting together the countermeasures | Verification in combination with debris retrieval equipment |
| | ③ Development of operation procedures | Evaluating the time required for measurement | Development of procedures for maintenance operations and normal operations carried out in combination with debris retrieval procedures |
| | ④ Simulated demonstration | Analyzing and evaluating the test conditions that can be implemented in spent fuel pool of 2F-4 | Determining the necessity of spent fuel pool test<br>Verification in combination with debris retrieval equipment |

# 2.1 Development of Technologies for Sub-criticality Measurement and Criticality Approach Monitoring

## 1) Study on installing neutron detector in retrieval equipment

[Implementation details]

- The layout design and system configurations for installing criticality approach monitoring systems in debris retrieval systems, were studied.
- Side retrieval method that is more restrictive than the top retrieval method was also studied.
- Cable handling was confirmed as a challenge as the cables become stiffer due to noise prevention measures.
- Proposals on the cable handling concept were compared assuming the installation on the robot arm that is being developed. (→ Refer to Slide 16)




Movement / cable route (proposed)
**Proposal 1, 2:** Suspending cable / guide
**Proposal 3:** Fixed to arm / inside arm
**Proposal 4, 5:** Route along the floor surface (debris surface)

**Figure 1 Concept of handling cables by robot arm**

# 2.1 Development of Technologies for Sub-criticality Measurement and Criticality Approach Monitoring
# 1) Study on installing neutron detector in retrieval equipment



Continued from previous slide

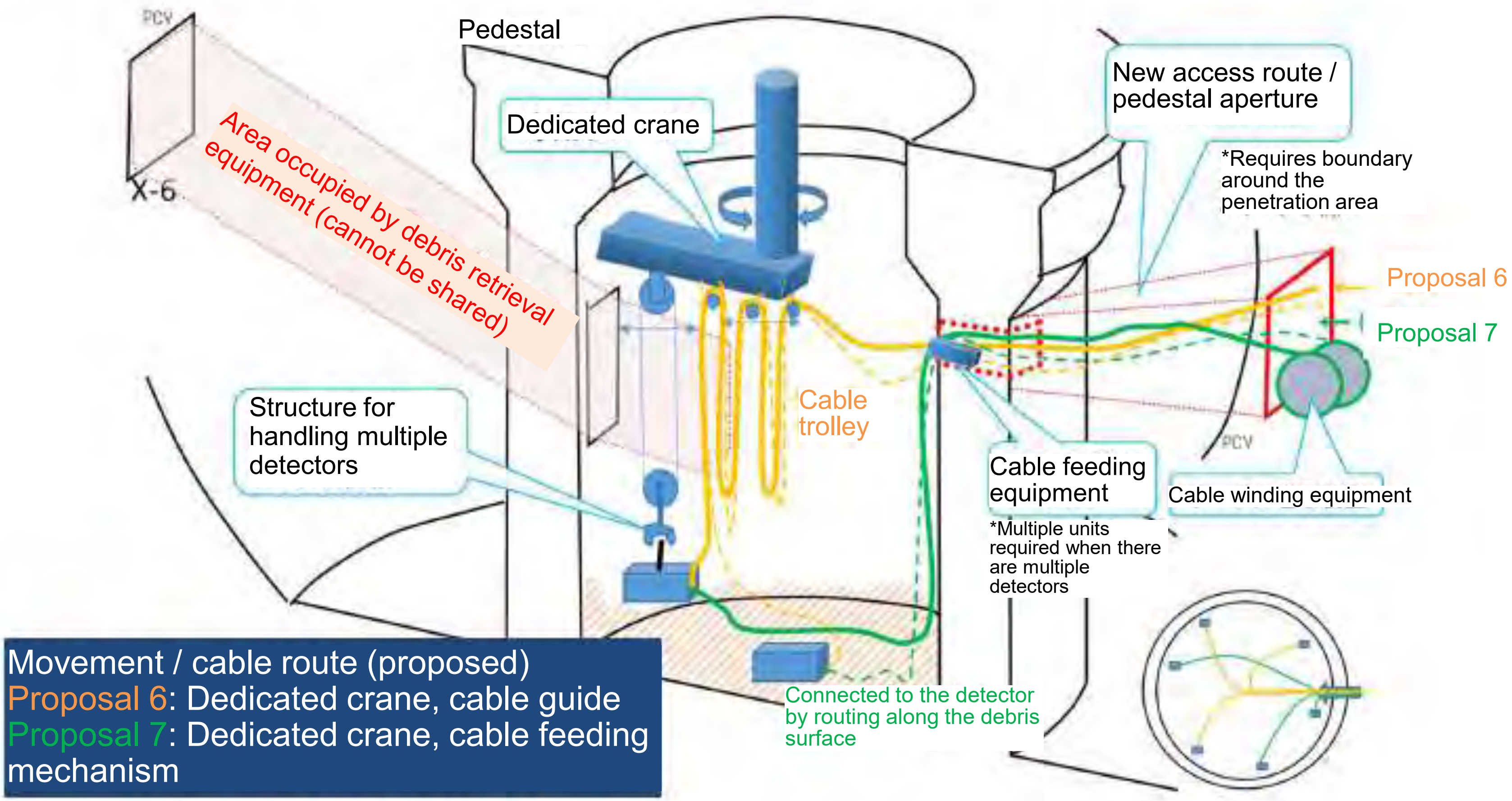



Figure 2 Concept of cable handling using dedicated crane

# 2.1 Development of Technologies for Sub-criticality Measurement and Criticality Approach Monitoring

[Restricted to authorized persons]

## 1) Study on installing neutron detector in retrieval equipment

[Results]

・The proposals for the handling of cables to be installed in debris retrieval equipment were planned and those that were highly feasible were identified.

=> Method with robot arm + cable winding mechanism + cable feeding mechanism

[Challenges toward the actual application]

・Designing, prototyping and elemental testing of detector and ancillary facilities related to cable handling

| Items / operating method (proposed) | | Proposal of using robot arm | | | | | Proposal of using dedicated crane | |
|---|---|---|---|---|---|---|---|---|
| | | Proposal 1 | Proposal 2 | Proposal 3 | Proposal 4 | Proposal 5 | Proposal 6 | Proposal 7 |
| Access | Necessity of new opening | ○ (Not required) | x (Required) | ○ (Not required) | ○ (Not required) | x (Required) | x (Required) | ← |
| Method of moving the detector unit / the standalone detector | Necessity of ancillary facilities for PCV | x (Cable guide) | ← | ○ (Not required) | ○ (Not required) | ← | x (Crane + cable guide) | x (Crane) |
| | Necessity of outer ancillary facilities | ○ (Not required) | ← | ○ (Not required) | ○* (Cable feeding mechanism) | ← | ○ (Not required) | x** (Cable feeding mechanism) |
| | Handling of detector unit / standalone detector | ○ (Possible) | ← | x (Not possible) | ○ (Possible) | ○ (Possible) | ○ (Possible) | ← |
| | Level of operational difficulty | Depends on manipulator | ← | ← | ← | ← | △ (Limited movement) | ← |
| | Positioning accuracy (cm) | Depends on manipulator | ← | ← | ← | ← | △ (Affected by shaking) | ← |
| Cable movement method | Level of operational difficulty | △ (Guide wiring) | ← | ○ (Internal wiring) | △ (Routing) | ← | ○ | △ (Routing) |
| | Presence of damage to cable | ○ (No contact) | ← | x (Multiple bends) | △ (Routing) | ← | ○ | △ (Routing) |

* Installed in debris retrieval system

** Installed at new penetration locations

# 2.1 Development of Technologies for Sub-criticality Measurement and Criticality Approach Monitoring



## 1) Study on installing neutron detector in retrieval equipment

[Implementation details]

・The neutron flux (1/cm²/sec) assumed to be inside the pedestal of Unit 2 was analyzed and evaluated based on the information of the appearance of the sediments observed during internal survey.

**<Evaluation conditions>**

The purpose of this evaluation was to check on the possibility of neutron measurement at the bottom of the pedestal, and to set conditions to reduce the amount of fuel debris at the bottom of the pedestal.

- Estimate the volume of fuel debris deposited at the bottom of the pedestal.
- Assume a small value as the fuel debris density, considering porosity .(1.3 g / cm$^3$)
- Calculate the amount of fuel debris at the bottom of the pedestal based on the density and volume stated above, and assume the rest of it to be at the bottom of RPV. (not directly linked to the current estimation of fuel debris distribution)

- As Unit 2 is estimated to have a large amount of debris at the bottom of RPV in addition to that at the bottom of the pedestal, neutron contribution from above is expected inside the pedestal. (There is considerable uncertainty depending on the debris composition and water conditions)

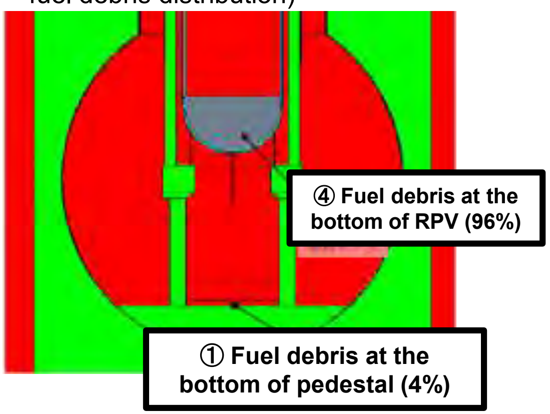



**Figure 1 Neutron flux analysis model**

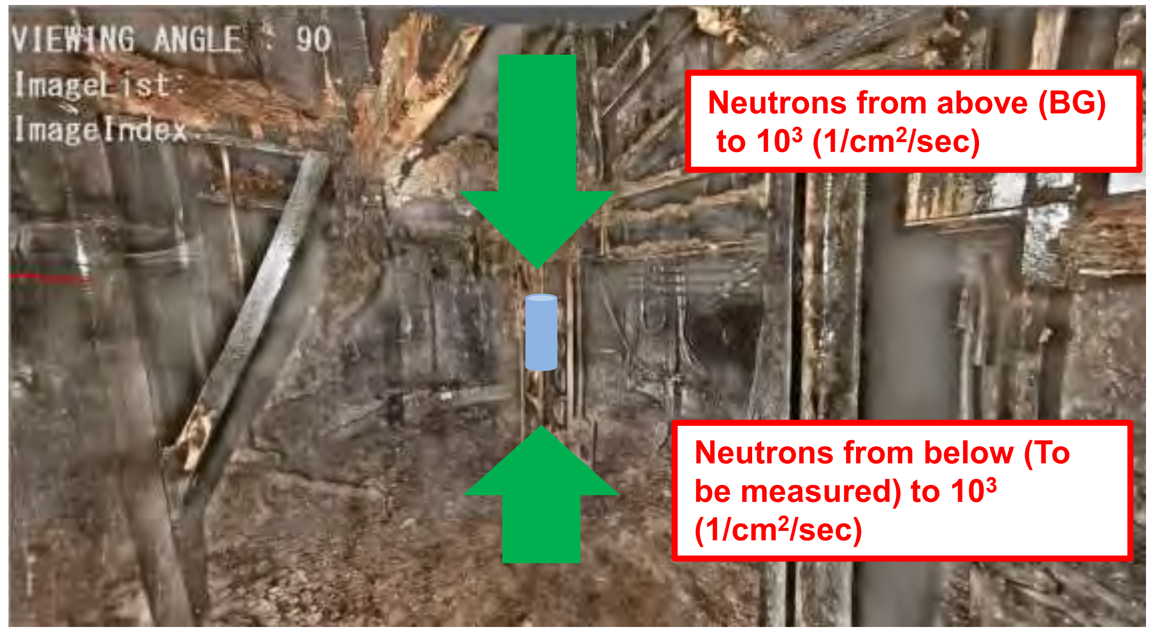



**Figure 2 Image of neutron flux analysis result**

Source: TEPCO Holdings HP

# 2.1 Development of Technologies for Sub-criticality Measurement and Criticality Approach Monitoring

## 1) Study on installing neutron detector in retrieval equipment

[Results]

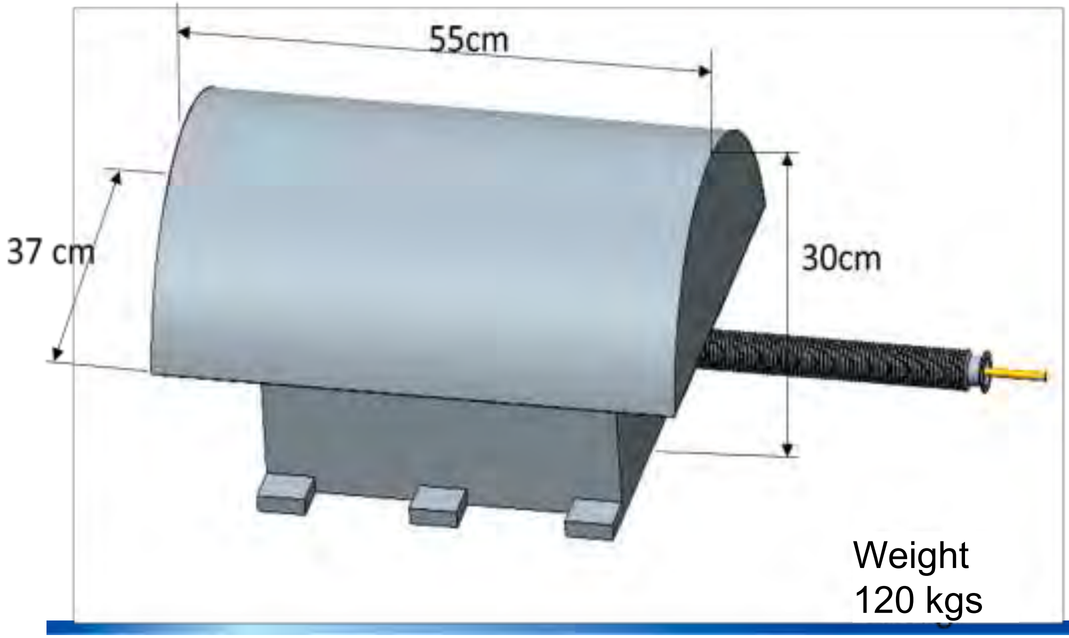
・A structural plan including the shield and moderator for using the neutron detector on site was developed based on the neutron flux assumed in the Unit 2 pedestal, and the size and weight appropriate for on-site use was estimated.

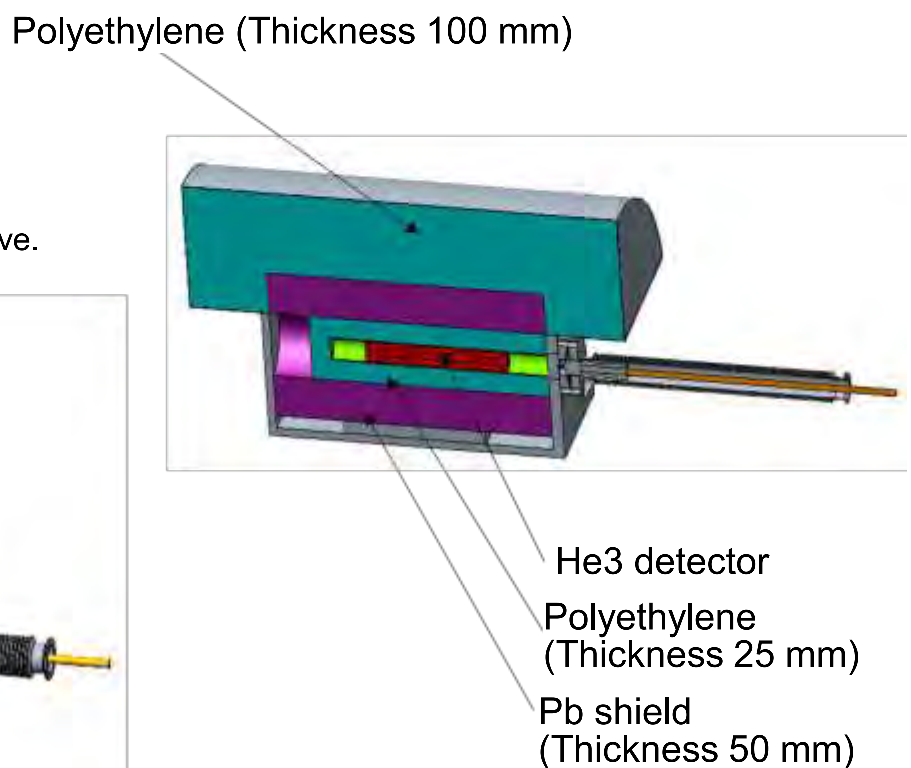
[Challenges toward the actual application]

・Designing, prototyping and elemental testing of neutron detector unit

**Type of He-3 detector where soft cable and connector are directly connected.**

- Consider radiation resistance / water resistance.
- Adopt a structure that cuts B.G neutrons from above.




- The figure shows the case of He-3 detector In addition, a case for B10 detector was also developed.

# 2.1 Development of Technologies for Sub-criticality Measurement and Criticality Approach Monitoring

## 1) Study on installing neutron detector in retrieval equipment

[Implementation details]

・The impact of induced noise on a small B-10 proportional counter that will be affected by the adjacent power cables to be installed was evaluated.

[Results]

・The test results confirmed that the impact was mostly from noise at frequencies between 300 kHz and 400 kHz.

[Challenges toward the actual application]

・Investigation on operational methods such as laying of cables, sequence of retrieval and monitoring.

・Development of signal cables to mitigate the noise effect.

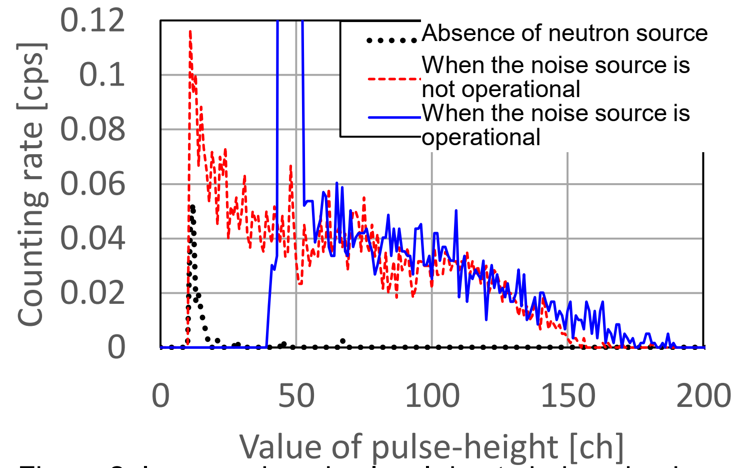



Figure 2. Increase in noise level due to induced noise

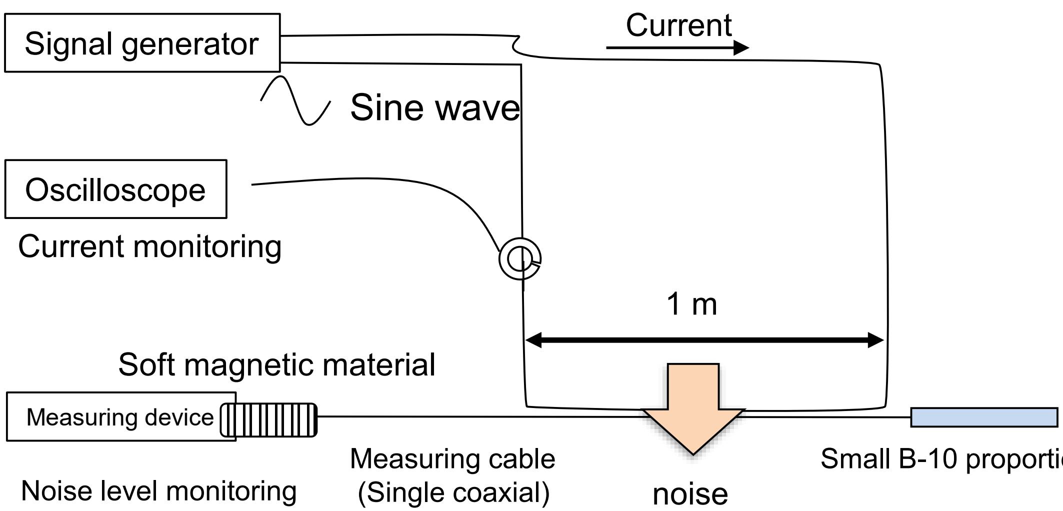



Figure 1. Induced noise impact assessment system

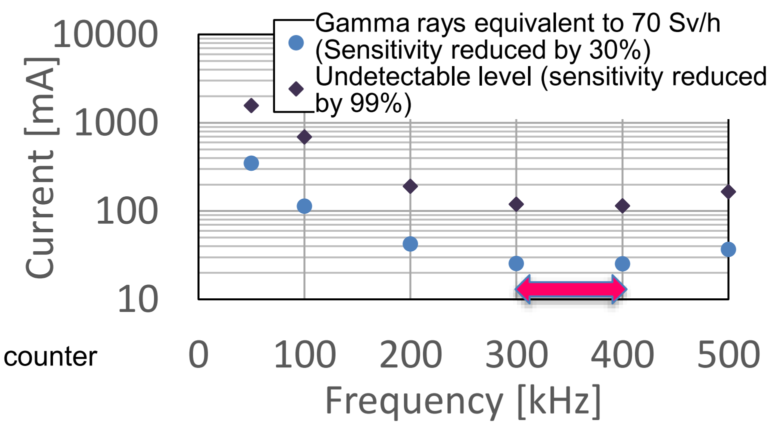



Figure 3. Impact of induced noise on neutron measurement

# 2.1 Development of Technologies for Sub-criticality Measurement and Criticality Approach Monitoring

## 1) Study on installing neutron detector in retrieval equipment

[Implementation details]

- Proposals on countermeasures for electromagnetic noise were consolidated.

[Challenges toward the actual application]

- Confirming the effect of noise countermeasures for cables, etc. by evaluating the impact of noise in combination with debris retrieval equipment.

**Table 1. Proposed countermeasures against electromagnetic noise**

| Proposed countermeasures | | Details |
|---|---|---|
| System | Layout | Control electromagnetic noise by covering the system as entirely as possible with metal. |
| Detector | Shield | Control electromagnetic noise by using a detector unit where the entire detector is covered with metal. |
| Cable | Installation of ferrite core | Control noise by attaching a ferrite core to the cable and increasing the cable impedance based on its magnetization. Continue to make improvements in prototypes that can be easily replaced in the optimal core in accordance with the noise band. |
| | Adoption of new cables | Equipment matching / noise resistance need to be evaluated when using new flexible cables suitable for material handling.<br>Neutron measurement tests at KUCA, NFD, etc. |
| Signal processing device | Circuit board components | Study on improving noise resistance by using components with high noise resistance and adding a noise filter. Evaluation by means of EMC test, etc. |
| Power supply | Adoption of noise-resistant power supply unit | Improve noise resistance by manufacturing a power supply unit that houses the entire built-in power supply unit in a dedicated housing. |

# 2.1 Development of Technologies for Sub-criticality Measurement and Criticality Approach Monitoring

## 1) Study on installing neutron detector in retrieval equipment

[Results]

- The specification items of neutron detector unit required for transfer by robot arm were consolidated.

[Challenges toward the actual application]

- Designing, prototyping and elemental testing of neutron detector unit

**Table 1 Specification items of neutron detector unit required for transfer by robot arm**

| Requirements | | Details |
|---|---|---|
| Measurement requirements | Detector type / number | Is the type of detector / number of detectors such that the detection efficiency required for measurement by Feynman-alpha method can be obtained? |
| | Distance between fuel debris and detector | Can it come close to the distance at which the detection efficiency required for measurement by the Feynman-alpha method can be obtained? |
| Response to environmental conditions | Radiation resistance | Can the frequency of replacement be reduced to about once a year? (1MGy or more (= 100 Gy / h x 365 d / y x 24 h)) |
| | Water resistance and pressure resistance | Does it have water resistance and pressure resistance? (assuming the existing water level in Unit 3 is 6.5 m) |
| | Moisture resistance | Does it have moisture resistance ? (Assuming 100% humidity) |
| Handling by remote control | Connection with arm | Can it be connected to a robot arm, etc.? |
| | Conveyable weight | Can it be carried with a robot arm, etc.? (Should be less than 200 kgs when using an MHI arm) |
| | Conveyable size | Can it be carried with a robot arm, etc.? (Diameter: should be less than 70 cm, and length: should be less than 100 cm, when using an MHI arm) |
| | Decontamination of unit | Can it be decontaminated and brought out? |
| | Calibration of the detector | Can the detector be calibrated? (Requires measurement of neutron source with known strength) |
| | Repair and replacement of parts | Can the parts be repaired or replaced? (Requires manual work) |

# 2.1 Development of Technologies for Sub-criticality Measurement and Criticality Approach Monitoring

## 2) Verifying the feasibility of sub-criticality measurement methods simulating the complex systems of actual 1F equipment

[Implementation details]

- Criticality experiment simulating large-scale non-homogeneous debris state was performed assuming debris in pedestal of Unit 2.
- The sub-criticality measurement performance was confirmed using a neutron detector and a measurement circuit that was prototyped before last year.

[Results]

- Though it was difficult to monitor the entire system for large-scale fuel debris, it was confirmed that localized sub-criticality near the detector could be monitored.

[Challenges toward the actual application]

- Verifying the impact on sub-criticality measurement when using neutron absorber/ when the extent non-homogeneousness of debris is large.

**Kyoto University Critical Assembly (KUCA)**

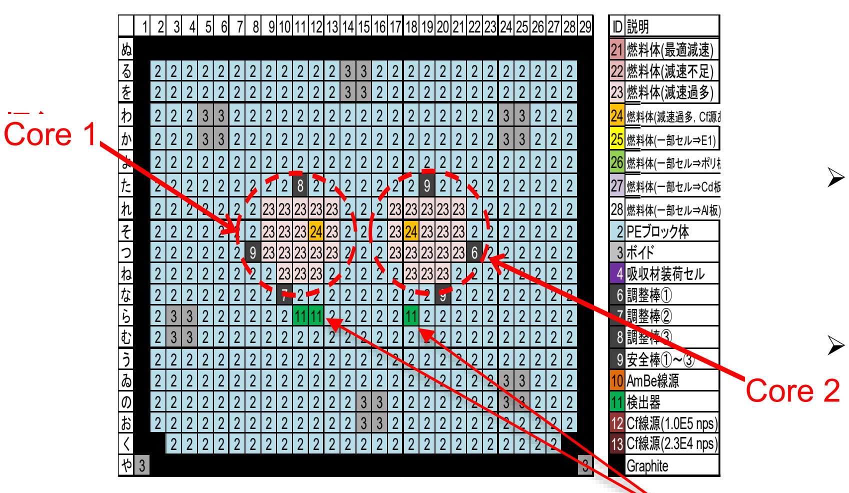
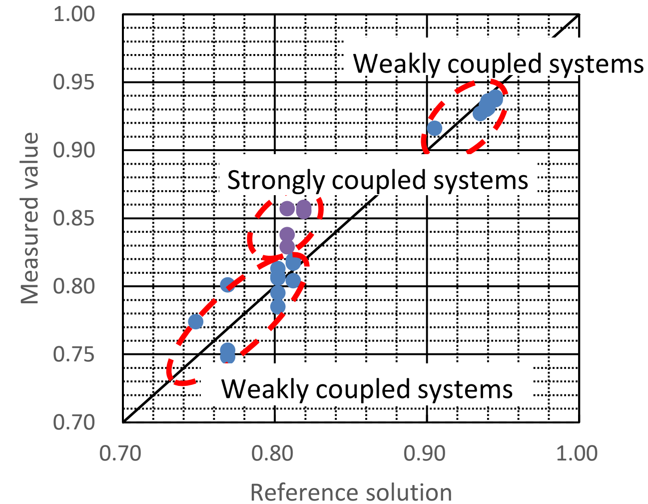



**Figure 1. KUCA test system**

- Focus on eigenvalue intervals that indicate the extent of nuclear coupling as an index to simulate large-scale systems
- Eigenvalue intervals analyzed and evaluated assuming debris in pedestal of Unit 2 $1 \times 10^{-1 \text{ to } -3}$
- Eigenvalue intervals simulated with KUCA 2-core system $1 \times 10^{-1 \text{ to } -2}$




Comparison of measured values and reference solutions (k-local)

**Figure 2. KUCA test results**





* Errors increase when the uncertainty of debris properties is considered (prompt neutron lifetime)

## 2.1 Development of Technologies for Sub-criticality Measurement and Criticality Approach Monitoring

## 2) Verifying the feasibility of sub-criticality measurement methods simulating the complex systems of actual 1F equipment

[Implementation details]

Verifying the feasibility of neutron source multiplication method

- A sub-criticality system using neutron source-encapsulated fuel was built to enhance the debris simulation at KUCA.
- Two detectors were installed to evaluate the positional dependency of detectors.
- Experiments were conducted with continuous monitoring even while refueling the test system.

[Results]

- The results confirmed that criticality approach monitoring can be performed regardless of the detector position, if evaluation error 5% Δk is anticipated in the neutron source multiplication method.

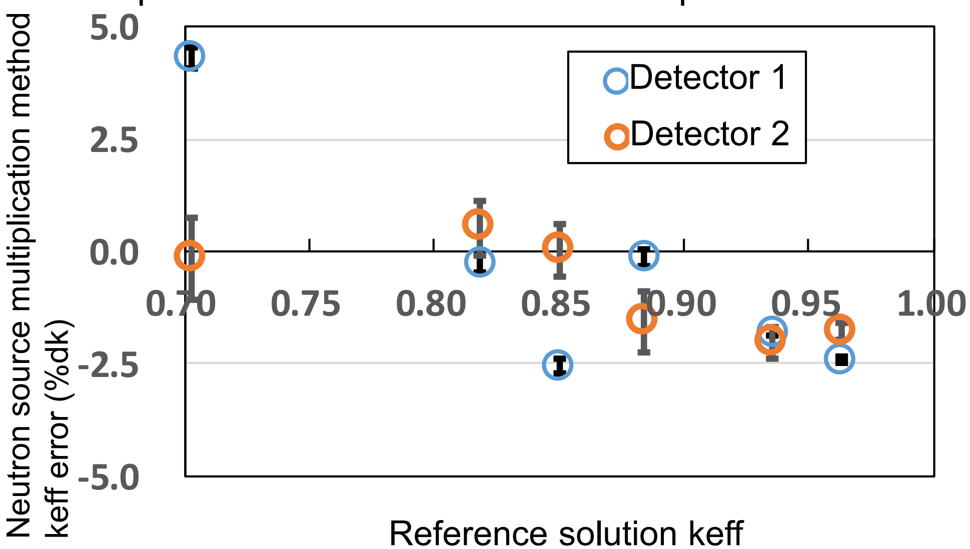



Figure 1. Evaluation error in neutron source multiplication method

① k =0.7

| | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
|---|---|---|---|---|---|---|---|---|---|
| た | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| れ | 2 | 8 | 2 | 2 | 2 | 2 | 2 | 9 | 2 |
| そ | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| つ | 2 | 9 | 2 | 2 | 2 | 2 | 2 | 6 | 2 |
| ね | 2 | 2 | 23 | 29 | 23 | 23 | 29 | 15 | 2 |
| な | 2 | 2 | 7 | 23 | 23 | 23 | 9 | 2 | 2 |
| ら | 2 | 2 | 2 | 2 | 14 | 2 | 2 | 2 | 2 |
| む | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| う | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |

⑫ k =0.95

| | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
|---|---|---|---|---|---|---|---|---|---|
| た | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| れ | 2 | 8 | 2 | 2 | 23 | 2 | 2 | 9 | 2 |
| そ | 2 | 2 | 23 | 23 | 23 | 23 | 23 | 2 | 2 |
| つ | 2 | 9 | 23 | 23 | 23 | 23 | 23 | 6 | 2 |
| ね | 2 | 2 | 23 | 29 | 23 | 23 | 29 | 15 | 2 |
| な | 2 | 2 | 7 | 23 | 23 | 23 | 9 | 2 | 2 |
| ら | 2 | 2 | 2 | 2 | 14 | 2 | 2 | 2 | 2 |
| む | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| う | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |

- 23 Fuel
- 29 Neutron source-encapsulated fuel
- 2 Moderator
- 14 Detector1
- 15 Detector2

Figure 2. Testing system

# 2.1 Development of Technologies for Sub-criticality Measurement and Criticality Approach Monitoring
## (Reference) Comparison of the performance of neutron detectors used for sub-criticality measurement



[Purpose]

Listing of the candidate neutron detectors that can be used for sub-criticality measurement.

[Results]

The applicability of alternative detectors including corona counter was evaluated.

[Challenges toward the actual application]

- Selection of an appropriate detector based on the gamma dose rate at the site environment
- As some of the required specifications of corona / IPL detectors have not yet been verified, it is necessary to evaluate their performance in sub-criticality measurement using KUCA test.
- The application of SiC type semiconductor detectors for detailed PCV investigation will be studied as well.

| Evaluation items | Detector (Model) | B-10 proportional counter [Highly sensitive type] (E6863-150) | B-10 corona counter | U-235 fission detector (CFUL01) | He-3 proportional counter (E6862) |
|---|---|---|---|---|---|
| Applicability to systems | Neutron flux measurement range [1/cm²/sec] | 0.1 to $10^4$ | to $10^3$ | $10^2$ to $10^8$ | 0.1 to $10^3$ |
| | Neutron detection sensitivity (*1) [ (c/s) / (1/cm²/sec) ] | 1.67 [When there is no gamma irradiation] | (*1) | 1 | 23 [When there is no gamma irradiation] |
| | Neutron sensitivity per sensor size [ (c/s) / (1/s/cm²) /cm³] | 0.013 | (*1) | 0.002 | 0.189 |
| | Identifiable adjacent pulse spacing [ns] | ○ 100 ns or less | (*1) | ○ 100 ns or less | (*1) |
| | Accuracy of pulse arrival time detection / variation in pulse output delay time [ns] | ○ 10 ns or less | (*1) | ○ 10 ns or less | (*1) |
| | Shape of sensor [Φ (mm) x L (mm) ] | 25.4 x 245 | (*1) | 48 x 337 | 25.4 x 245 |
| Response to environmental conditions | Allowable gamma dose rate [Gy/h] | △ (requires shielding) 1.67 cps / nv (< 2.2 Gy / h) 0.5 cps / nv (< 100 Gy / h) | (*1) | ○ (1 x $10^4$ Gy/h) | (*1) |
| | Tolerable integral dose [Gy] / service life | ○ (3 x $10^{10}$Gy) | ○ (5x$10^4$ Gy or more) | ○ (1 x $10^9$Gy) | (*1) |

(*1) Cannot be disclosed as it contains vendor’s confidential commercial information.

# 2.1 Development of Technologies for Sub-criticality Measurement and Criticality Approach Monitoring



## 3) Study on the method for verifying the feasibility of instrumentation systems in actual equipment

[Implementation details]

- The results of the tests conducted before FY2018 were consolidated and the problems to be tested before application to actual equipment, were consolidated.
- The feasibility of SFP test assumed to be the simulated demonstration stage, was evaluated.

| Tests | TRL* | Purpose | Implementation status |
|---|---|---|---|
| NFD test | 3 | Confirming the impact of spent fuel on neutron detector in high gamma ray environment | Confirmed that the decrease in detection sensitivity was about 10% in an environment with gamma ray dose rate of 2.2 Gy / h. |
| Neutron source test | 3 | Confirming that the correlation of neutron sources can be measured | Confirmed that the Y value of initially correlated neutron source (Cf) can be measured properly. |
| KUCA test (1st round, 2nd round) | 3 | Confirming that the sub-criticality can be measured in small-scale systems using uranium fuel | Confirmed that the sub-criticality of small-scale reactors of keff = 0.7 - 0.95, H / U = 50 – 300, can be measured properly. |
| KUCA test (3rd round) | 4 | Confirming that the sub-criticality can be measured in large-scale homogeneous systems using uranium fuel | Confirmed that localized sub-criticality can be measured even in large-scale (homogeneous) systems, when the systems are near the detector. |
| KUCA test (4th round) | 4 | Confirming that the sub-criticality can be measured in large-scale non-homogeneous systems using uranium fuel | Not implemented (confirmation required before implementation) |
| Accessibility verification test | 5 | Confirming that equipment can be installed using remote control in environments similar to the actual equipment | Not implemented (confirmation required before implementation) |
| Simulated demonstration (SFP test) | 5 | Confirming that the sub-criticality can be measured with a system similar to the actual equipment (high gamma + large (non-homogeneous) system) | Not implemented (confirmation required before implementation) |
| Field demonstration (Internal investigation, sampling) | 6 | Clarifying issues at the site | Not implemented (confirmation required before implementation) |

* Level of technological development. TRL-3 indicates applied research, TRL-4 indicates practical research, and TRL-5 indicates simulated demonstration phase.

# 2.1 Development of Technologies for Sub-criticality Measurement and Criticality Approach Monitoring


# 3) Study on the method for verifying the feasibility of instrumentation systems in actual equipment

[Results]

・The test conditions that can be implemented in the Spent Fuel Pool (SFP) of Fukushima Daini (No.2) Nuclear Power Station Unit 4 were evaluated by analysis, and it was found that the neutron flux and gamma dose rate were smaller than the expected on-site environment.

[Challenges toward the actual application]

・Determining whether or not tests need to be implemented due to the limited testing conditions

- Space for placing the detector is limited.
- Even when the 8 combusted fuel assemblies are replaced with un-combusted fuel assemblies, the sub-criticality is deep and the neutron flux and gamma dose rate is low.

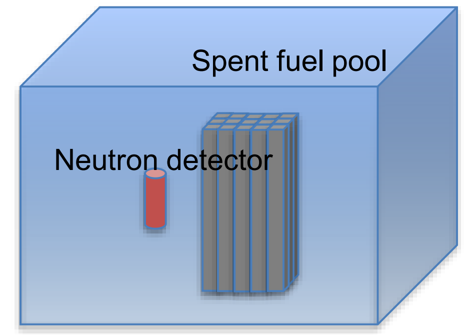



Figure 1. Image of demonstration test for measuring the sub-criticality using SFP

**Neutron multiplication factor keff ~ 0.77**
**Neutron flux ~ $10^2$ (1 / $cm^2$ / sec)**
**Gamma dose rate ~ 10 (Gy / h)**

# 2.2 Development of Re-criticality Detection Technologies

## [Purpose]

- **Development of re-criticality detection system that will promptly detect any critical or near-critical events, should they occur, and accelerate its termination through activation of emergency boron injection.**

## [Overview of the system]

- **Proposal for an advanced system (Figure 1) capable of early detection by measuring Kr that can track the changes in sub-criticality better than Xe that is currently monitored.**

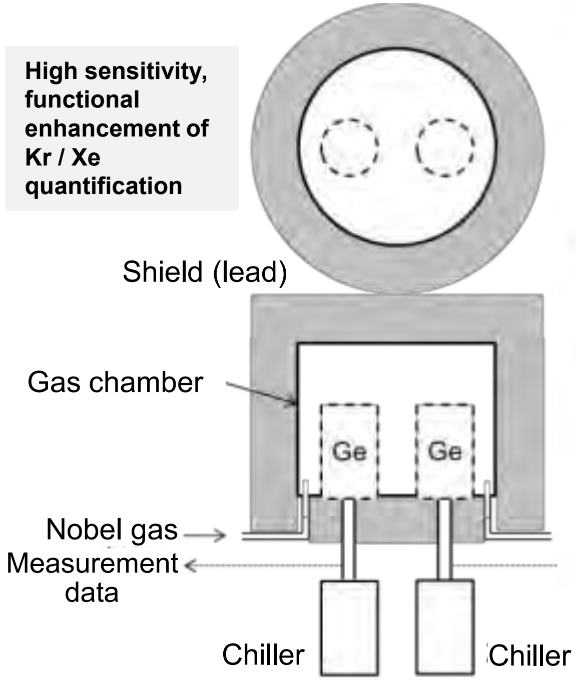



Figure 1. Proposed configuration of upgraded system

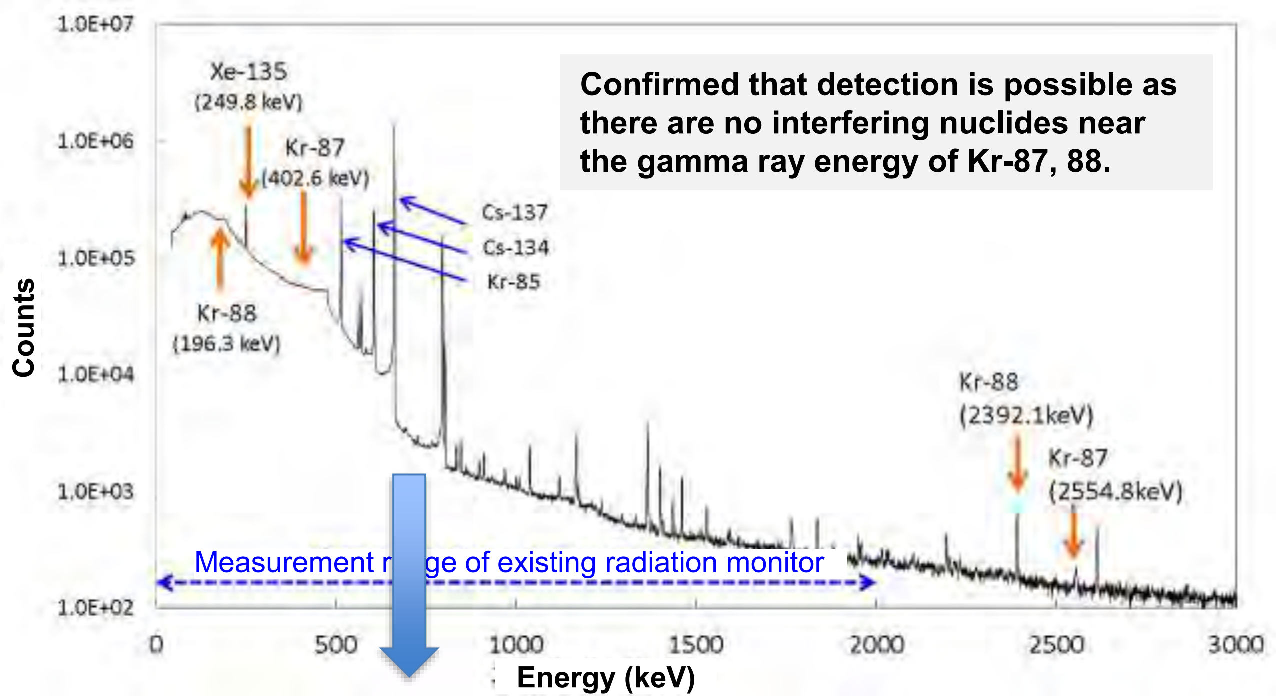



Figure 2. Gamma ray spectrum in Unit 1 (integrated)

# 2.2 Development of Re-criticality Detection Technologies



Details of completed goals (Black) , Details of goals in FY2018 (Blue)

**Table 1. Development results and challenges toward the actual application**

| Final goal | Goals to be achieved toward the actual application | Status of achievements (Results of FY2018) | Challenges toward the actual application |
|---|---|---|---|
| Verifying the feasibility of technology (Confirming the detectability of criticality, estimating the sub-criticality) | ① Confirming the detectability of criticality | ・Superiority of detection using Kr in the case of accumulation of fine powder, was checked. | – |
| | ② Determining the applicability in deciding whether or not the criticality has come to an end | ・The applicability in detecting whether or not criticality has been terminated was studied and challenges were identified. | ・Study on the method of application in deciding about criticality termination |
| | ③ Estimation of sub-criticality | ・The method for estimating sub-criticality was proposed.<br>・The current values were estimated based on the actual measurements of Unit 1: 0. 5 to 0. 7<br>・Sub-criticality can be estimated by increasing sensitivity under the condition of flow rate at the time of full-scale retrieval. | – |
| Implementation of technology (Incorporation into gas systems) | ① Confirming the detectability at current flow rate | ・The superiority of Kr in the current flow rate was confirmed. | – |
| | ② Confirming the detectability at the flow rate expected during retrieval | ・The decrease in delay time was confirmed.<br>・The range within which sub-criticality can be estimated during aerial retrieval, was evaluated. | Confirming the consistency with gas system design progress (rolling) |
| | ③ Establishment of technology for detector calibration | ・Calibration accuracy quantification and experimental verification of calibration method until high energy peak of Kr-88 | – |

# 2.2 Development of Re-criticality Detection Technologies
## 1) Study on the method of operation under negative pressure control



[Implementation details]

The ability to estimate sub-criticality and to detect re-criticality was studied by evaluating the concentration of noble gases from the current state until the time of full-scale retrieval (Figures 1, 2).

[Results]

(1) With a Ge detector like the one presently in Unit 1, it is difficult to determine the Xe concentration under the condition of the flow rate prevalent during full-scale retrieval.
(2) When the sensitivity is increased, both Xe-135 and Kr-88 are expected to exceed the detection limit in one hour.
(3) The same result was seen when installed in Unit 2. An increase in sensitivity is required for monitoring the concentration during full-scale retrieval.

Prerequisite: D/W volume 3600m$^3$, outlet flow 21m$^3$/h (current state), 2100m$^3$/h (full-scale)
Ge detector installed in Unit 1 at present: 10% efficiency, increasing the sensitivity: 120% efficiency x 2, Neutron source multiplication factor: installed in Unit 1

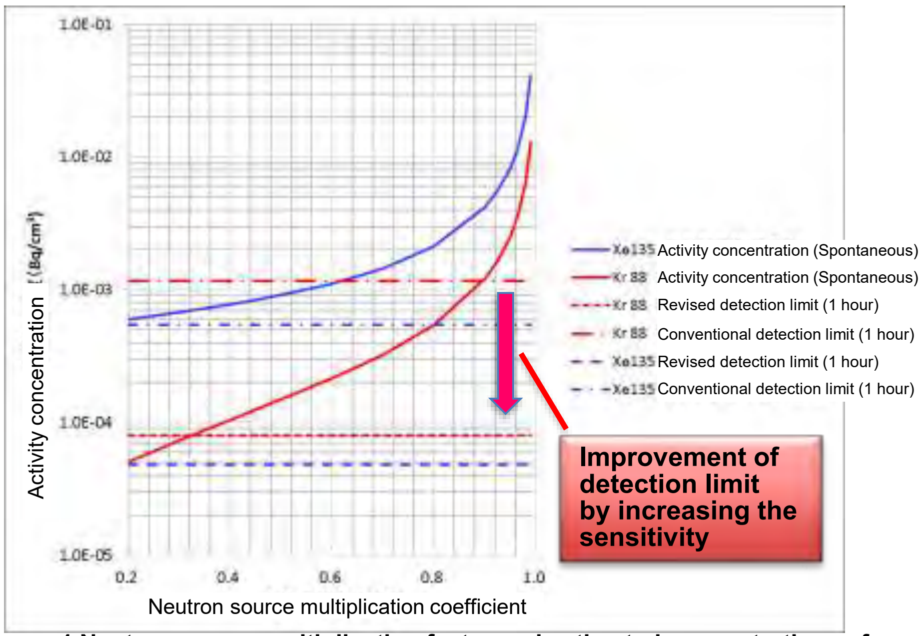



**Figure 1 Neutron source multiplication factor and estimated concentrations of Xe-135 and Kr-88 in Unit 1 (Current flow rate, gas volume 3600 m$^3$)**

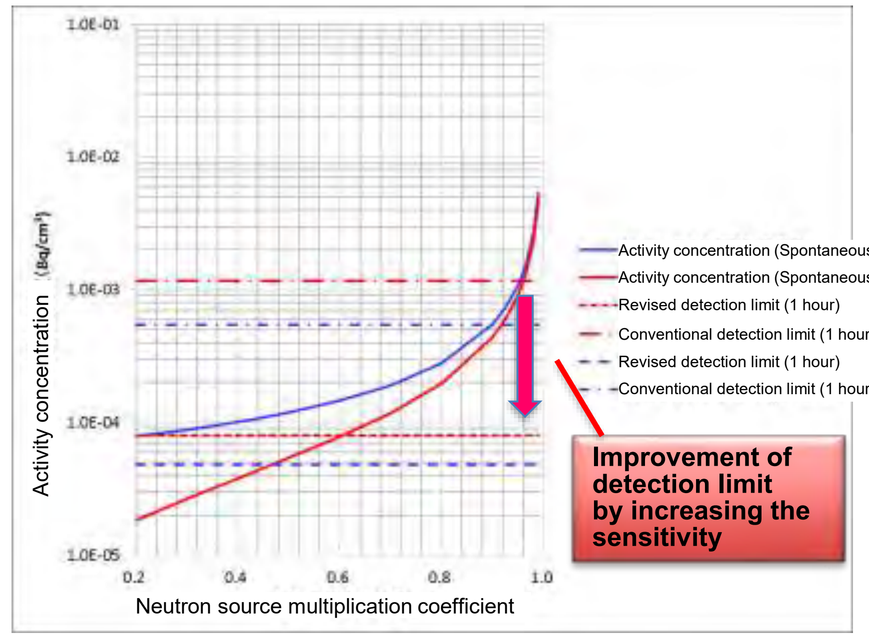



**Figure 2 Neutron source multiplication factor and estimated concentrations of Xe-135 and Kr-88 in Unit 1 (Flow rate 2100 m$^3$/h, gas volume 3600 m$^3$)**

# 2.2 Development of Re-criticality Detection Technologies

## 1) Study on the method of operation under negative pressure control

### Development of detector calibration technology for PCV gas radiation monitor

[Implementation details]

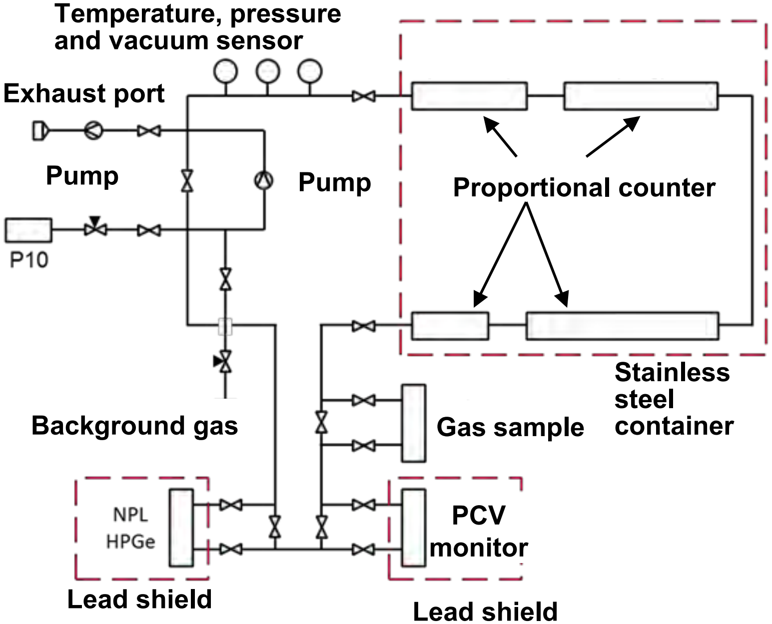
- Activity concentrations for radiation monitors installed in presently in Unit 1 were calibrated at the National Physical Laboratory (NPL).

[Results]

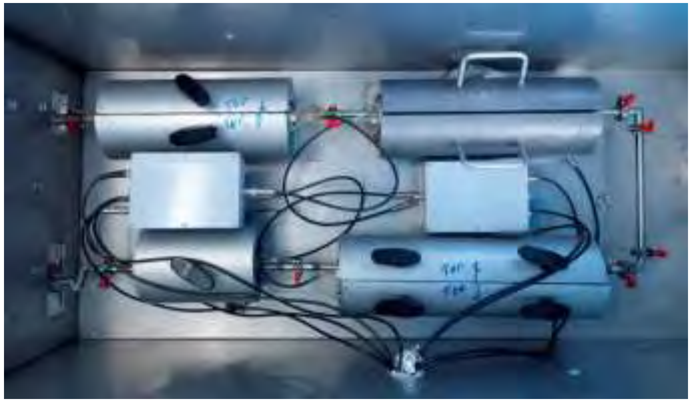
- The calibration procedure for gamma rays up to 2. 5 MeV was experimentally confirmed, and the uncertainty was determined to be about 7 to 8%.

[Future plans]

- These results will be used at the Fukushima Daiichi.




(a) Overall configuration



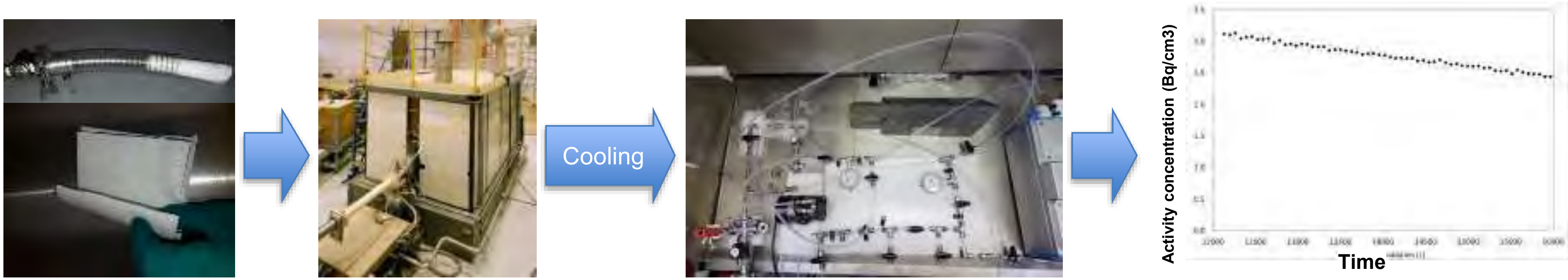
(b) Long gas proportional counter

(c) Gas monitor installed in Unit 1 (During NPL test)

**Figure 1. Calibration circuit for gas activity concentration**

# 2.2 Development of Re-criticality Detection Technologies

## Development of detector calibration technology for PCV gas radiation monitor (continued)




(a) U235 target preparation

(b) Thermal neutron irradiation, FP generation

(c) Loading into measurement system

(d) Quantitative measurement

**Figure 1. Overview of calibration procedure**

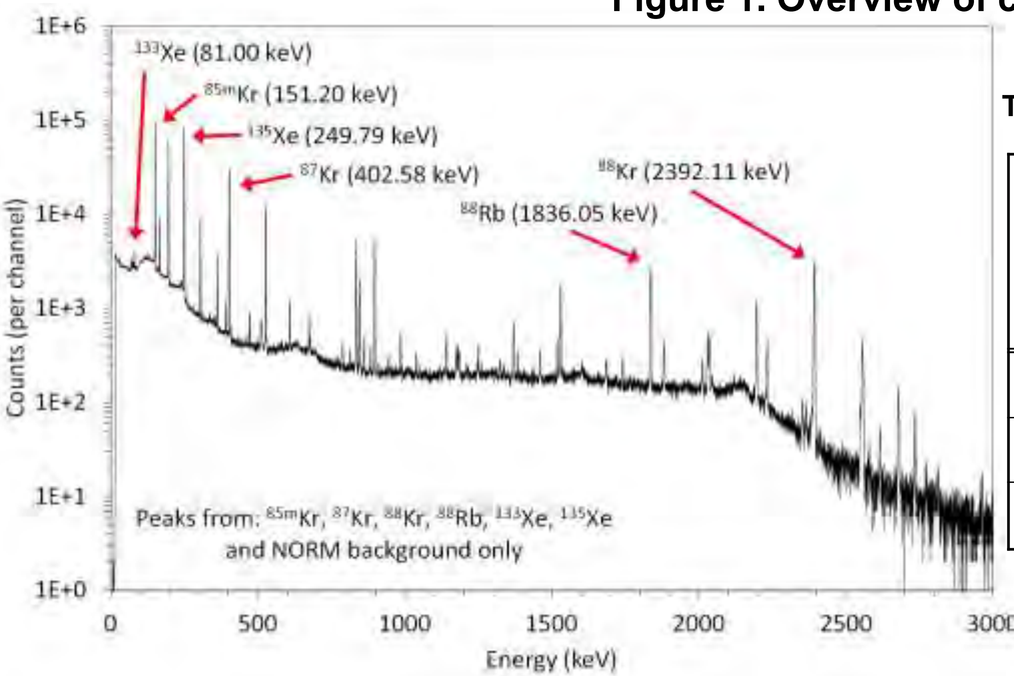



**Figure 2. Gamma ray spectrum of gas to be calibrated (Kr / Xe mixture)**

**Table 1. Activity concentration and uncertainty of target nuclides**

| Nuclides | Value calibrated at NPL | | Uncertainty of the counts to be calibrated (%) | Total uncertainty (%) |
|---|---|---|---|---|
| | Activity concentration (Bq/cm3) | Uncertainty (%) | | |
| Kr-87 | 0. 440 ± 0. 034 | 7. 7 | 0. 6 | 8. 3 |
| Kr-88 | 1. 001 ± 0. 070 | 7. 0 | 0. 9 | 7. 9 |
| Xe-135 | 0. 405 ± 0. 025 | 6. 2 | 0. 3 | 6. 5 |

# 2.2 Development of Re-criticality Detection Technologies

## 2) Study on the technology used for determining the applicability in detecting localized criticality approach events

[Implementation details]

(1) The detectability of re-criticality for fine powder accumulation (micro criticality) (Figure 1) was studied.

Prerequisites: Additive reactivity: 5. 0E-03 $/h (processing amount: 30 kg/day, processing time: 20 h/day, transition rate: 1. 5%)

Burn-up and composition were equivalent to the average of the minimum burn-up of fuel assemblies in Unit 1.

(2) The attenuation characteristics of Kr-88 after criticality termination were evaluated and their applicability in deciding on criticality termination, was studied (Figure 2).

[Results]

(1) The results confirmed that signs of criticality can be detected early by Kr-88.

(2) Applicable. However, the dynamic range is wide, and it is necessary to clarify the applicable range based on the scale of criticality.

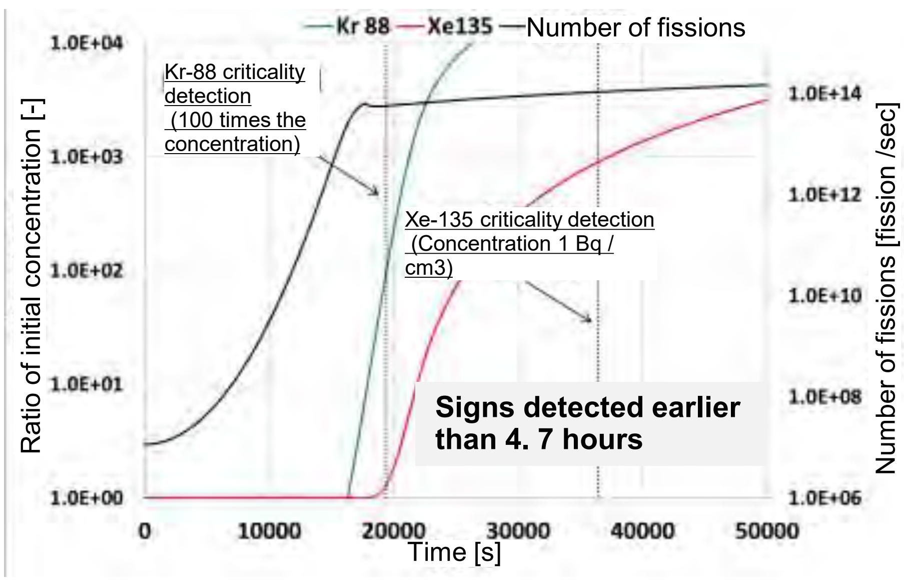



**Figure 1. Results confirming the detectability during accumulation of powder (Current flow rate)**

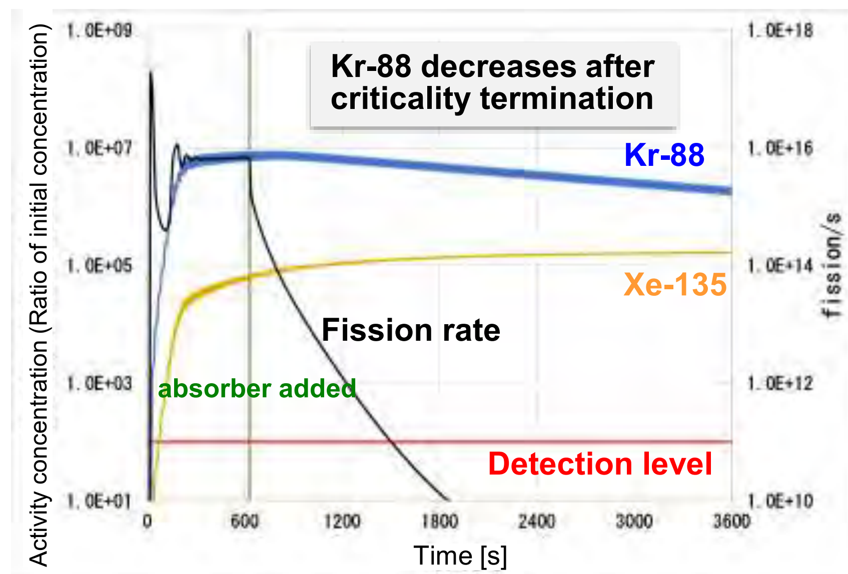



**Figure 2. Change in activity concentration of Kr-88 during criticality termination (Assuming fall of debris and partial aerial retrieval)**

# 2.2 Development of Re-criticality Detection Technologies



## Table 1. Differences in functionality depending on PCV gas radiation monitoring methods

| Items | Scintillation detector (Currently installed in Units 2 and 3) | Semiconductor detector | |
|---|---|---|---|
| | | Similar to the one presently in Unit 1 + Kr detection function | High sensitivity semiconductor |
| Detection limit of Xe135 ($Bq/cm^3$, Measured for 1 hour) | 1. 5 ~ 2. 5 x $10^{-1}$ (Results of Jan 2018) | 4. 0 ~ 4. 7 x $10^{-4}$ (Results of Jan 2018) | ~ 5 x $10^{-5}$ (proposed design) |
| Concentration of Xe135 ($Bq/cm^3$) | N. D in both Unit 2 and 3 | 1. 1 ~ 1. 2×$10^{-3}$ (Results of Jan 2018) | (Concentration at the time of retrieval) |
| Time required for Kr88 detection | Detection not possible | About 30 ~ 70 hours (Depends on concentration and energy) | About 1 hour (Depends on the concentration at the time of retrieval) |
| Concentration of Kr88 ($Bq/cm^3$) | N. D in both Unit 2 and 3 | About 2. 0×$10^{-4}$ (2016 ~ 2017 National project) | (Concentration at the time of retrieval) |
| Successive evaluation of sub-criticality | Not possible | (Current state in Unit 1: 0. 4 ~ 0. 7) | ○ |
| Time required for evaluating sub-criticality | - | About 30 ~ 70 hours or more (Quantitative time when using Kr88) | About 1 hour (Quantitative time when using Kr88) |
| Data interval | Every hour | Every minute (moving average) | Same as left (planned) |
| Criticality approach detection using Kr88 (Setting alarm, addition of absorption materials) | Not possible | (Inferior to Kr quantification) | ○ |
| Challenges | Low sensitivity, Impossible to evaluate sub-criticality | Low sensitivity Requires improvement in calibration accuracy | Requires improvement in calibration accuracy |
| Functions at the time of retrieval | **Only criticality (abnormality) detection** | **1. Evaluating the sub-criticality of the entire system 2. Criticality detection 3. Monitoring after adding the absorption materials (if added) (including criticality termination)** | **1. Evaluating the sub-criticality of the entire system 2. Understanding the successive changes in criticality signs 3. Monitoring after adding the absorption materials (if added) (including criticality termination)** |

# 2.1 Development of Technologies for Sub-criticality Measurement and Criticality Approach Monitoring

## 1) Study on installing neutron detector in retrieval equipment

[Implementation details]

・The neutron flux (1 / cm$^2$ / sec) assumed to be inside the pedestal of Unit 2 was analyzed and evaluated based on the information on the appearance of the sediments observed during internal survey.

**<Evaluation conditions>**

The purpose of this evaluation was to check on the possibility of neutron measurement at the bottom of the pedestal, and to set the conditions that reduce the amount of fuel debris at the bottom of the pedestal.

- Estimate the volume of fuel debris deposited at the bottom of the pedestal.
- Assume a small value as the fuel debris density considering porosity (1. 3 g / cm$^3$) .
- Calculate the amount of fuel debris at the bottom of the pedestal based on the density and volume stated above, and assume the rest to be at the bottom of RPV (not directly linked to the current estimation of fuel debris distribution).
- As Unit 2 is estimated to have a large amount of debris in the bottom of RPV in addition to that at the bottom of the pedestal, neutron contribution from above is expected inside the pedestal. (There is considerable uncertainty depending on the debris composition and water conditions)

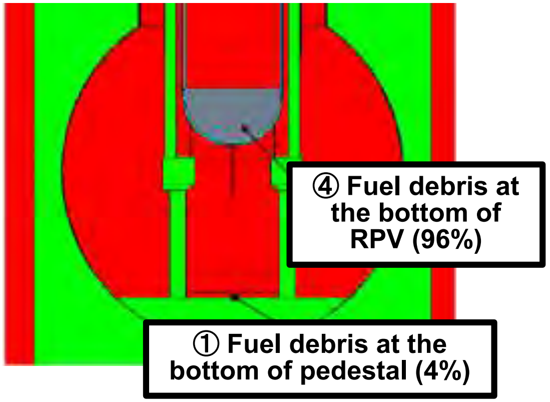



**Figure 1. Neutron flux analysis model**

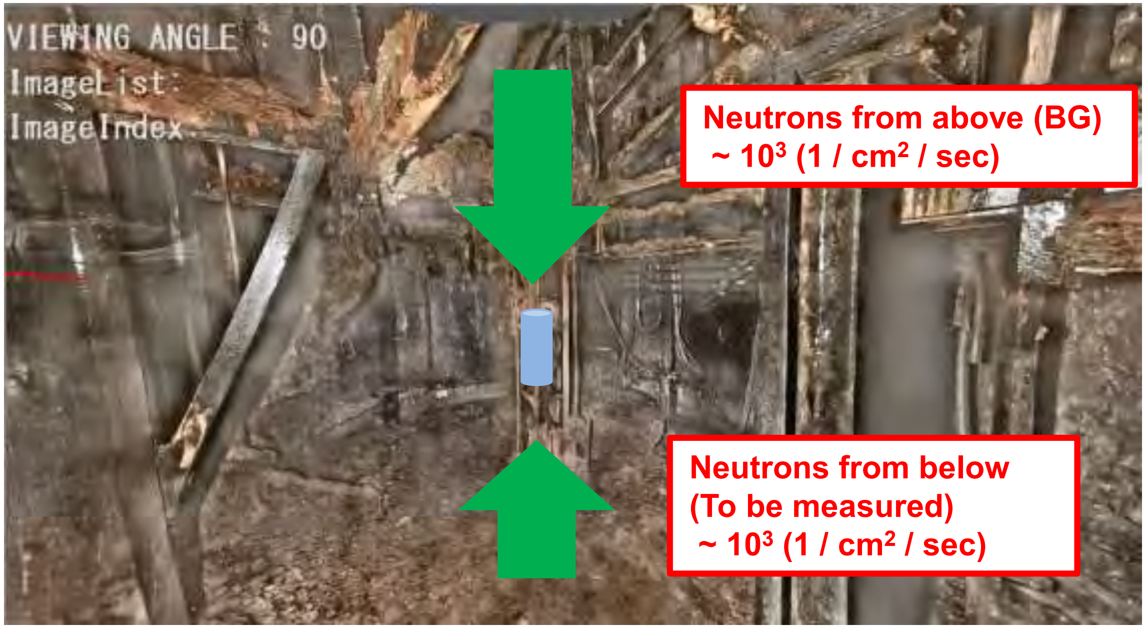



**Figure 2. Image of neutron flux analysis result**

Source: Tokyo Electric Power Company Holdings, HP

# 2.3 Development of Criticality Prevention Technologies Overview (Insoluble neutron absorption materials)

[Purpose]

・Development of neutron absorber for preventing criticality by prior injection. Adopting an applicable method of an insoluble neutron absorber that can locally add negative reactivity instead of a soluble neutron absorber such as boric-acid solution.

[Results and challenges faced until now]

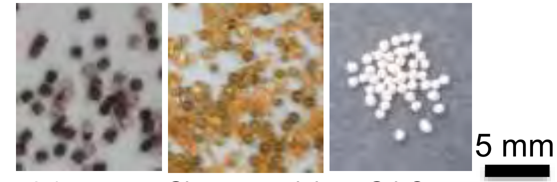
(Challenges for implementation are written in red)

・Selection of candidate materials to be used as insoluble neutron absorber by confirming their basic properties, irradiation properties, and nuclear properties (Table 1, Figure 1)

[Adopting an application method and confirming the workability of debris processing]

・Evaluating the impact at the time of application, such as integrity of canisters (Figure 2)

[Evaluating the amount of waste, confirming the long-term irradiation effects, etc.]




$B_4C$ / sintered stainless material　Glass material containing B / Gd　$Gd_2O_3$ particles

Water glass / $Gd_2O_3$ granulated powder (after hardening)

**Figure1. Appearance of candidate materials**

## Table 1. Selection results of candidate materials

| Classification | Candidate material | Evaluation: Nuclear properties | Evaluation: Workability | Evaluation: Long-term irradiation | Selection result |
|---|---|---|---|---|---|
| Solid | $B_4C$ metal sintered material | ○ | ○ | ○ | Candidate material |
| Solid | Glass material containing B / Gd | ○ | ○ | ○ | Candidate material |
| Solid | $Gd_2O_3$ particles | ○ | ○ | ○ | Candidate material |
| Liquid ↓ Solid | Water glass / $Gd_2O_3$ granulated powder | ○ | ○ | ○ | Candidate material |
| Liquid ↓ Solid | Underwater hardened resin / $Gd_2O_3$ powder material | ○ | △*1 | △ corrosion | Rejected |

*1: Shrinkage / floating was seen when injected into the debris simulation system

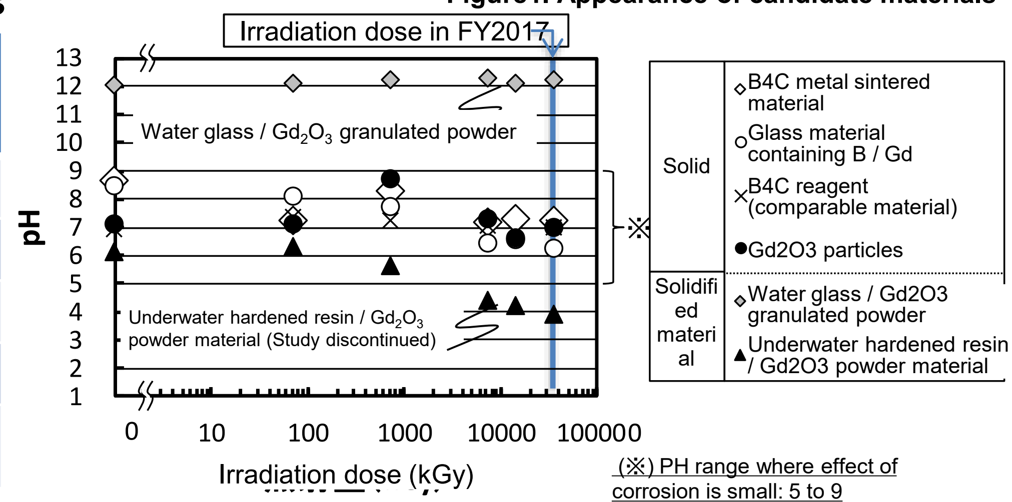



**Figure 2. Long-term irradiation test results (in air, up to FY2017)**

# 2.3 Development of Criticality Prevention Technologies

Details of completed goals (Black) , Results of goals for FY 2018 (Blue)

## Table 1. Development results and challenges toward the actual application

| Final goal | Goals to be achieved toward the actual application | Status of achievements (Results of FY2018) | Challenges toward the actual application |
|---|---|---|---|
| **Verifying the feasibility of technology (Establishment of criticality prevention technology)** | ① Selection of candidate material | Selection of candidate material to be used as insoluble neutron absorber by checking their basic properties, irradiation properties, and nuclear properties (4 types of candidate material were selected). | – |
| | ② Confirming the workability and specifications for sub-criticality maintaining conditions | Trial calculation of the required amount to be injected based on the assumed method of usage<br>Verification of the workability of debris crushed using chisel, verification of the distribution of absorber and evaluation of sub-criticality maintenance (solid absorption material) | Verification of the workability of debris crushed using chisel, verification of the distribution of absorption materials and evaluation of sub-criticality maintenance (solidified absorption materials)<br>Development of specifications for sub-criticality maintaining conditions for each type of debris |
| | ③ Evaluation of secondary effects | From the long-term irradiation test it was seen that the hydrogen generation G value is less than the design value, and the diluted seawater with eluted absorber components has a pH of 6 or more.<br>The number of canisters and the amount of waste increased up to about 10% for solid absorption materials and up to about 40% for solidified absorption materials. | Evaluation of impact on effectiveness of the rust inhibitor under radiation<br>Evaluation of impact of solidified absorption materials on the drying process |
| **Implementation of technology (Incorporation into debris retrieval systems)** | ① Study on the procedures and methods for adding absorption materials | Development of the method of adding absorption material.<br>Development of procedures for adding absorber with respect to debris processed using chisel (assuming MCCI debris under pedestal) | Development of procedures for other locations based on the progress of debris retrieval methods<br>Experimental study on the method for injecting the required amount |
| | ② Designing of absorber injecting equipment | Development of the concept for absorber injecting equipment based on the restrictions in absorber transfer route and restrictions on the weight and dimension of the absorber injecting equipment | Design study<br>Prototyping / elemental tests |
| | ③ Verification in combination with retrieval equipment | Organizing the absorber used in the debris processing methods for each debris location | Testing in combination with debris retrieval equipment |

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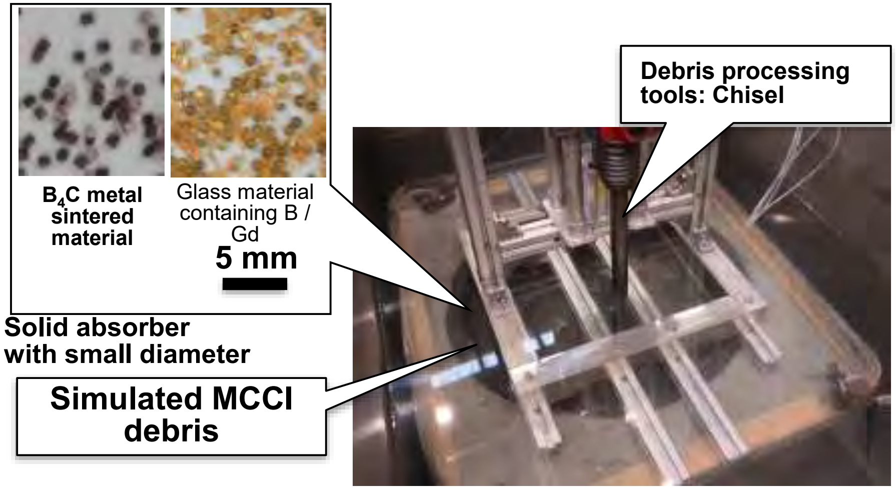
# 2.3 Development of Criticality Prevention Technologies
## 1) Study on the methods for dispersing insoluble neutron absorber on fuel debris and confirmation method for the effect after dispersion

**[Purpose]**

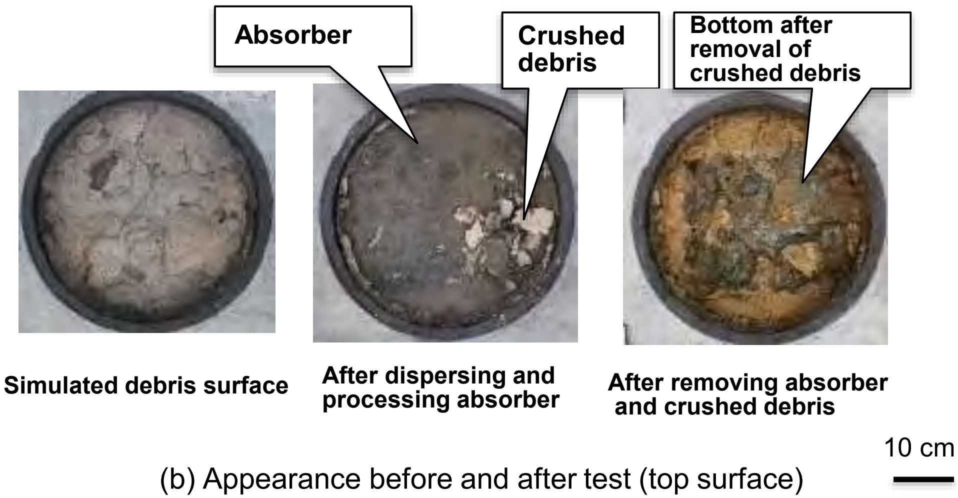
- Confirming the impact of insoluble absorber on debris crushing process and the retention of the absorber in the crushed debris.
- Confirming that additive reactivity due to the change in water-to-volume ratio caused by crushing is canceled by the mixing of absorber.

**[Implementation details]**

- Chisel processing test under water were conducted on simulated debris (simulated MCCI) by dispersing solid absorber of small diameter, under the same test conditions as when absorber was not used.




(a) Test of working with chisel under water (Under-pedestal simulation)




(b) Appearance before and after test (top surface)

**Figure1. Debris crushing test by dispersing insoluble neutron absorber**

# 2.3 Development of Criticality Prevention Technologies

## 1) Study on the methods for dispersing insoluble neutron absorber on fuel debris and confirmation method for the effect after dispersion

### [Test Results 1]

・The results confirmed that there is no impact of the absorber on the processing efficiency and debris dimensions after processing.

Table 1. Processing time using chisel and weight of crushed simulated debris

| Test | Processing time | Crushed weight (kg) |
|---|---|---|
| No absorption material | 11 min. 5 sec. | 6. 8 |
| $B_4C$ metal sintered material | 11 min. 41 sec. | 6. 3 |
| Glass material containing B / Gd | 10 min. 9 sec. | 8. 8 |

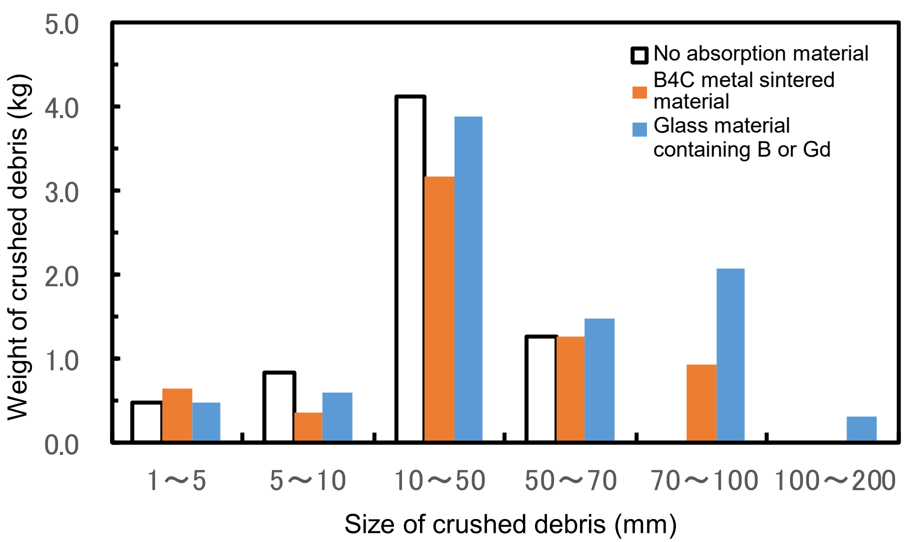



Figure 1. Weight of crushed simulated debris and size distribution

# 2.3 Development of Criticality Prevention Technologies



## 1) Study on the methods for dispersing insoluble neutron absorber on fuel debris and confirmation method for the effect after dispersion

**[Test Result 2]**

- **It was confirmed that the absorber enters the gaps generated during processing, and that the amount of absorber required to cancel the additive reactivity was mixed up with the crushed debris.**

Table 1. Amount of absorber required and amount mixed

| Insoluble neutron absorption material | Amount required* for a crushing depth of 3 cm x 2 times the safety factor (amount added, kg) | Average crushing depth (cm) | Required amount* at average crushing depth (kg) | Amount mixed with crushed debris (kg) |
|---|---|---|---|---|
| $B_4C$ metal sintered material | 9. 0 | 1. 1 | 1. 7 | 2. 9 |
| Glass material containing B / Gd | 3. 6 | 1. 9 | 1. 1 | 2. 7 |

*: Amount of insoluble neutron absorber required to cancel the additive reactivity assuming maximum additive reactivity (state where crushing area is optimally decelerated) in fuel debris containing only fuel (enrichment 5.0 wt%)

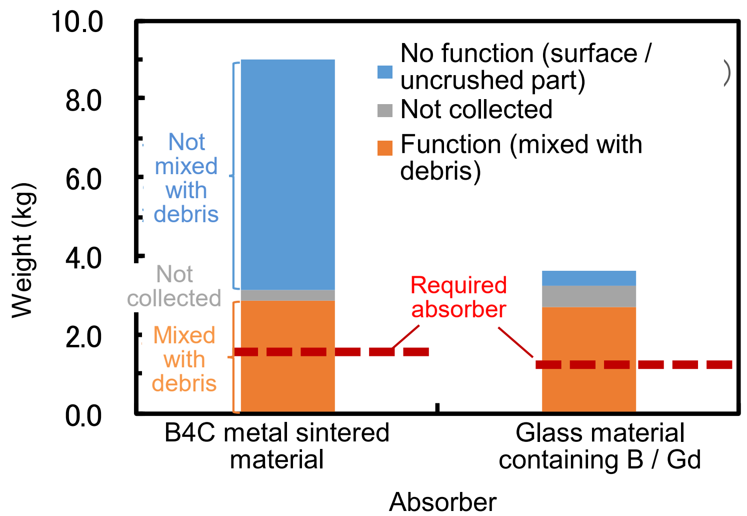



Figure1. Amount of mixed absorber and required absorber

**[Results]**

- **The results confirmed that the absorber can be applicable to the process of crushing fuel debris and the required amount of the absorber can be retained in fuel debris after crushing.**

# 2.3 Development of Criticality Prevention Technologies
## 1) Study on the methods for dispersing insoluble neutron absorber in fuel debris and confirmation method for the effect after dispersion

**[Implementation details]**

- The concept of installing a tank type injecting device on a fuel debris retrieval robot using a tool changer mechanism, assuming full-scale side retrieval and top retrieval methods, was developed.

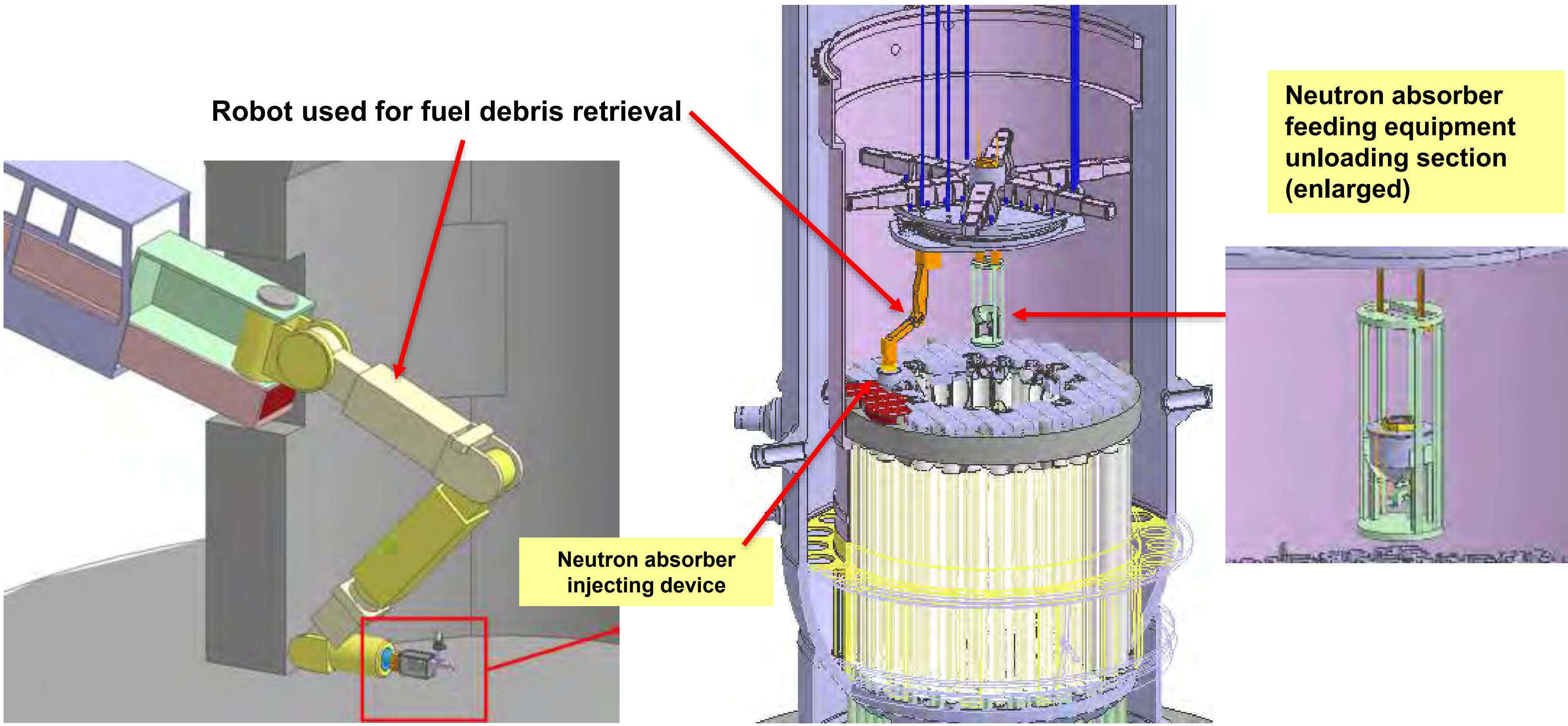



Image showing the implementation of side entry method

Image showing the implementation of top entry method

# 2.3 Development of Criticality Prevention Technologies

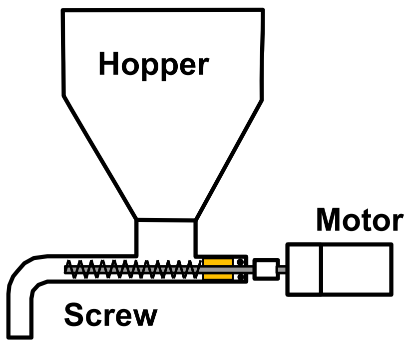


## 1) Study on the methods for dispersing insoluble neutron absorber on fuel debris and confirmation method for the effect after dispersion

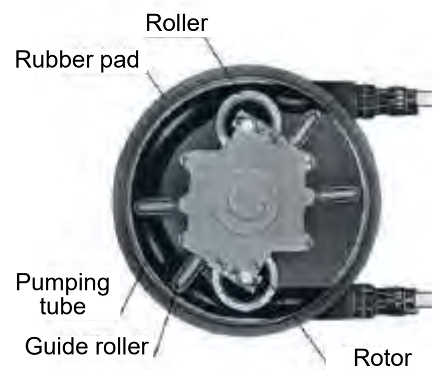
**[Implementation details]**

・**Appropriate feeding mechanism was selected for each type of absorber (solid and solidified).**

Screw feeder method for solid absorber ($B_4C$ metal sintered material, Glass material containing B / Gd, $Gd_2O_3$ particles)




Squeeze pump method for solidified absorber (Viscous substances, water glass)




■ Example of space-saving layout

# 2.3 Development of Criticality Prevention Technologies

## 1) Study on the methods for dispersing insoluble neutron absorber on fuel debris and confirmation method for the effect after dispersion

**[Results]**

- **A proposed concept of injecting equipment to be installed in the debris retrieval robot was developed and the issues in development were identified.**

| | Proposal 1<br>Equipped with standard pump | Proposal 2<br>Equipped with small sized pump | Proposal 3<br>No pump model 1 | Proposal 4<br>No pump model 2 |
|---|---|---|---|---|
| External appearance of device |  |  |  |  |
| Assumed size (mm) | 1030 x 465 x 880 | Φ450 x 960 | Φ360 x 520 | Φ320 x 673 |
| Assumed weight (kg) Excluding absorption material | 82 | 34 | 15 | 29 |
| Capacity of hopper (L) | 25 | 15 | 15 | 15 |
| Remarks | Side entry<br>Squeeze pump | Top entry<br>Squeeze pump<br>valve | Top entry<br>No pump | Top entry<br>No pump<br>Hopper separated |

Main development issues

| Items | Details |
|---|---|
| Conflict with debris retrieval robot | Consistency of tool changer system |
| Remote operation | Operability |
| Environmental conditions | Radiation resistance and waterproofing |
| Transportability of absorption material | Amount and speed of transport |
| Maintenance | Remote disassembly and cleaning of nozzles, valves and tanks |

**[Challenges toward the actual application]**

**Development of specifications, prototyping, and elemental test of absorber injecting equipment**

# 2.3 Development of Criticality Prevention Technologies

## 1) Study on the methods for dispersing insoluble neutron absorber on fuel debris and confirmation method for the effect after dispersion

**[Implementation details]**

- **The means for confirming that the required amount of insoluble neutron absorber has been injected during fuel debris retrieval, were studied.**

**[Results]**

- **Concept of using ultrasonic waves to measure the amount of injected absorber was developed.**
- **Ultrasonic waves were applied to the surface before and after the injection of absorption material, and it was found that the thickness of the absorber could be detected from the difference in time required for the reflected waves to propagate.**

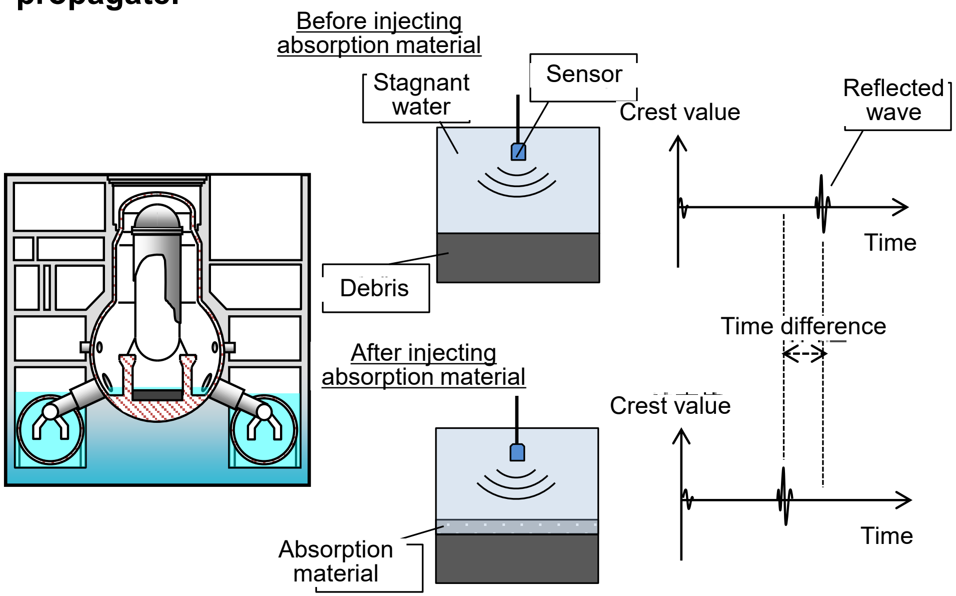



**Figure 1. Conceptual diagram for measuring the thickness of absorber by ultrasonic waves**

Table 1. Conditions required for ultrasonic wave measurement

| Required conditions | Remarks |
|---|---|
| **Sensor is under the water** | The reflected waves do not appear on the received waveform until the sensor lands on the water (in the air). |
| **No large water flow** | In the case of constant flow method, it is necessary to temporarily stop the water flow. |
| **Water temperature is measurable** | Measurement of water temperature is required to correct the speed of sound, if accuracy in thickness measurement is required. |
| **Maintenance of reference points** | To calculate the thickness, it is necessary to maintain the sensor position (reference point) before and after injecting the absorption material. |

**[Challenges toward the actual application]**

- **Development of specifications for measurement systems and coordination with retrieval systems**

# 2.3 Development of Criticality Prevention Technologies
# 2) Study on long-term irradiation effects on canisters

**[Implementation details]**

- **Gamma irradiation tests were conducted to obtain additional data for improving the reliability of the irradiation properties trend related to secondary effects (material corrosion and hydrogen generation) acquired until last year.**
- **Aerial irradiation test (evaluation of material corrosion): The change in the elution of absorber components due to irradiation was evaluated at an irradiation dose of 72 MGy (for 10 months at a dose rate of 10 kGy / h).**
- **Underwater irradiation test (hydrogen generation): Evaluation assuming a tightly closed canister. Data provided up to irradiation dose of 11 Mgy. (Difference in irradiation properties trends of candidate material is clear.)**

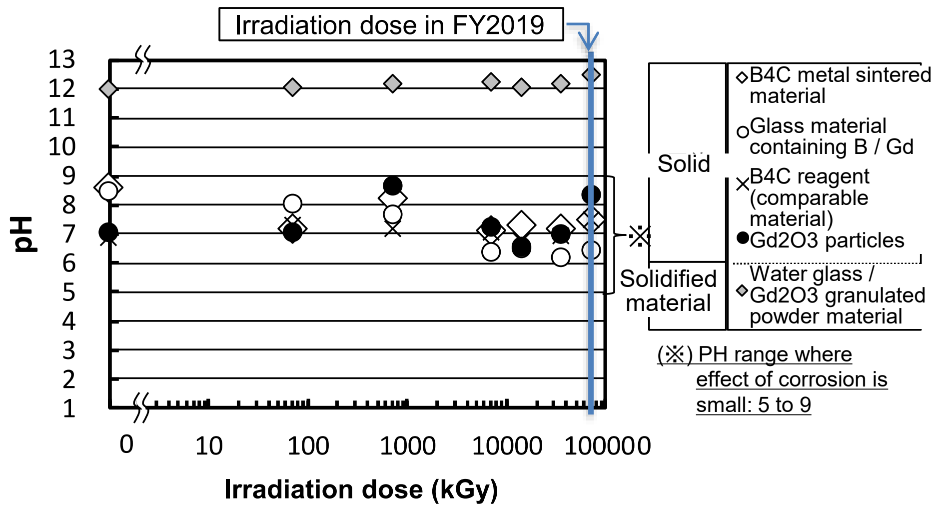



Figure 1. Dependency of eluate pH on irradiation dose (in air)

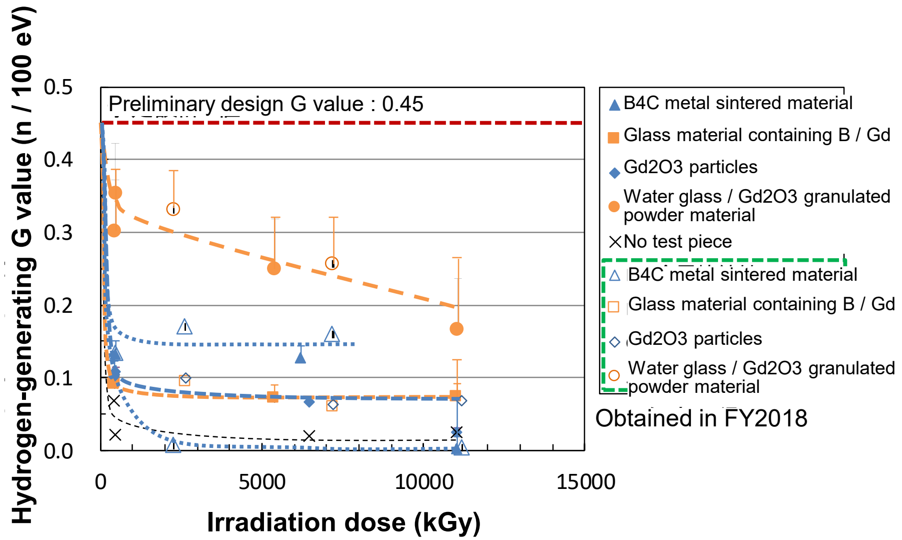



Figure 2. Dependency of hydrogen-generating G value (efficiency with respect to irradiation dose) on irradiation dose (in water)

**[Results]**

- **The impact of corrosion on bottom materials (eluate pH6 or higher) and the amount of hydrogen generated being within the design limits was confirmed, and this data was provided to the Canister Project.**

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# 2.4 Study on Optimization related to Ensuring Safety of Methods and Systems (Related to Criticality Control)

## ① Establishment of criticality evaluation and impact assessment methods

Details of completed goals (Black), Details of goals in FY2018 (Blue)

**Table 1. Development results and challenges toward the actual application**

| Final goal | Goals to be achieved toward the actual application | Status of achievements | Challenges toward the actual application |
|---|---|---|---|
| Evaluation of importance from the viewpoint of criticality scenarios / criticality control | ・Evaluation of importance from the viewpoint of criticality scenarios and criticality control for each location in Units 1 to 3, incorporating the latest findings | ・Criticality risk chart was revised reflecting the latest findings.<br>・Criticality risk chart was quantified by incorporating the results of criticality evaluation / criticality behavior evaluation. | ・Continuing updates incorporating the latest findings |
| | ・Presenting the requirements for internal investigation and sampling for streamlining criticality evaluation | ・The methods for streamlining criticality evaluation and the methods of using the acquired data to increase the scale gradually, were consolidated. | - |
| Understanding realistic risks | ・Realistic criticality risk assessment based on statistical criticality evaluation (statistical criticality evaluation) | ・Refinement reflecting the results of evaluating Unit 1 pedestal part and estimating sub-criticality using PCV gas radiation monitor.<br>・Bottom of RPV in Unit 2 and 3 were evaluated<br>・Unit 2 pedestal was evaluated. (Refinement reflecting internal investigation results) | ・Continuing updates incorporating the latest findings<br>・Confirming the effectiveness of criticality prevention measures using statistical criticality evaluation method |

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# 2.4 Study on Optimization related to Ensuring Safety of Methods and Systems (Related to Criticality Control)

## ① Establishment of criticality evaluation and impact assessment methods

## 1) Study on criticality scenarios and criticality evaluation

**[Implementation status]**

- **The criticality risk of debris accumulated in the Unit 2 pedestal was reviewed based on the images obtained from the PCV internal investigation. It was confirmed that there were no major changes.**

**[Results]**

- **Criticality risk chart was revised reflecting the results of statistical criticality evaluation. (See Slide 13)**

**Table 1. Importance of criticality control in each Unit**

| Location | Criticality Scenarios | Unit 1 | Unit 2 | Unit 3 |
|---|---|---|---|---|
| Reactor Core | ・Residual fuel submergence | Extremely Low (Almost no residual fuel) | Medium (Fuel may be remaining in the reactor core and peripheral area) | Low (The possibility of fuel remaining in the peripheral area cannot be denied) |
| Bottom part of RPV | ・Debris submergence ・Changes in condition during retrieval | Submergence: Low Retrieval: Extremely Low (Small residual amount) | Submergence: Medium Retrieval: Low (Lot of exposed residual amount) | Submergence: Medium Retrieval: Low (Lot of exposed residual amount) |
| CRD housing | ・Adhered debris submergence | Low to Extremely Low (Low risk based on adherence profile and amount) | Low to Extremely Low (Low risk based on adherence profile and amount) | Low to Extremely Low (Low risk based on adherence profile and amount) |
| Bottom of PCV | ・Exposed debris submergence ・Changes in condition during retrieval (including stirring up) | Submergence: Low Retrieval: Low (Large residual amount, small amount exposed) | Submergence: Low Retrieval: Low (Slightly small residual amount and extensive exposure) | Submergence: Low Retrieval: Low (Large residual amount, small amount exposed) |

* The criticality risk mentioned here refers to the importance when studying criticality prevention measures to prepare for future changes in the condition.

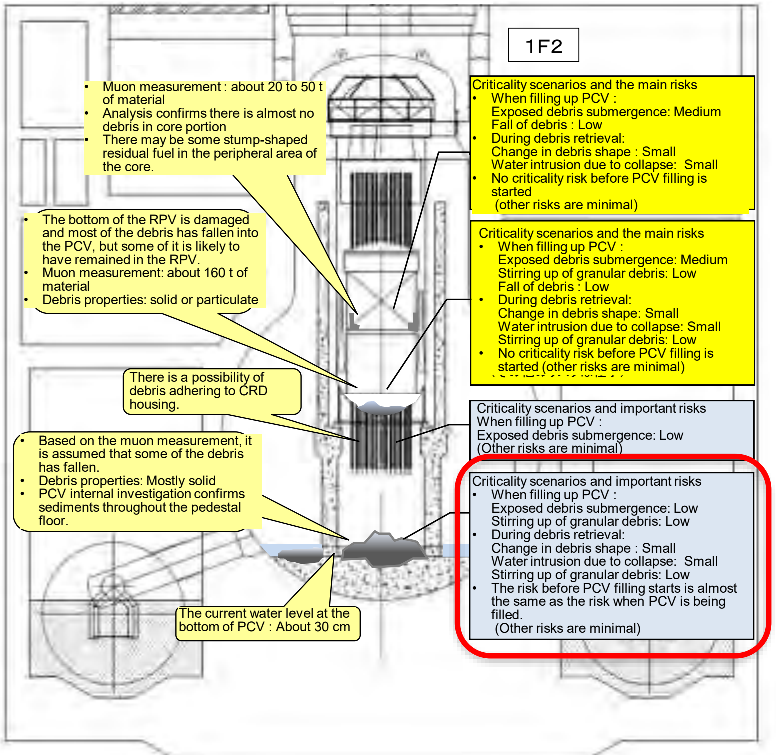



**Figure 1. Importance of criticality control in 1F Unit 2**

# 1) Study on criticality scenarios and criticality evaluation (How to use future survey data)

| Step | Information | Applied to | Usage method |
|---|---|---|---|
| Internal investigation | Information on external appearance<br>Debris distribution, status of interfering objects | Sampling<br>Small-scale retrieval | ・Refining criticality risks<br>・Determining specific details of incidental risks (*1) |
| | Gamma ray dose rate, neutron flux | Sampling to<br>Full-scale retrieval | ・Designing criticality approach detection systems<br>Reviewing assumed dose (easing the specifications) |
| Sampling | Debris composition<br>Content ratio of U235, Gd, SUS | Full-scale retrieval | ・Confirming and reviewing the prerequisites (fuel composition) for criticality evaluation (*2) |
| | Composition distribution (table below)<br>Distinction of fuel / non-fuel<br>Extent of variation in composition | Full-scale retrieval | ・Establishing the criticality approach monitoring methods based on the state (*3)<br>・Confirming and reviewing the prerequisites (uncertainty in composition) for criticality evaluation |
| | Neutron flux during work, change in FP gas concentration | Small-scale retrieval | ・Confirming that no significant criticality approach has occurred, and deciding whether or not to start the next step (figure on next slide) |
| Small-scale retrieval | Same as above | Full-scale retrieval | Same as above |

*1 As incidental events, it is necessary to evaluate debris deformation in the bottom part caused by falling of heavy objects and to determine specific details of the magnitude of the risks based on the possibility of structures falling and their estimated weight.

*2 The criticality risk assessment (including the evaluation of the required amount of neutron absorption materials) incorporates the actual conditions such as Gd content and average composition of the assemblies with maximum in-core reactivity before the accident. Check the appropriateness of the validity of this assumption.

*3 An apparent criticality approach may be observed due to removal of non-fuel deposits, and hence it is desirable to change the monitoring method in the case of non-fuel.

| Sampling | Implementation details | Method of use |
|---|---|---|
| Surface cutting | Pedestal of Unit 2<br>About 30 points | ・Distinction between fuel / non-fuel<br>・Confirm homogeneity |
| Boring | Same, 6 points. | ・Check composition data |

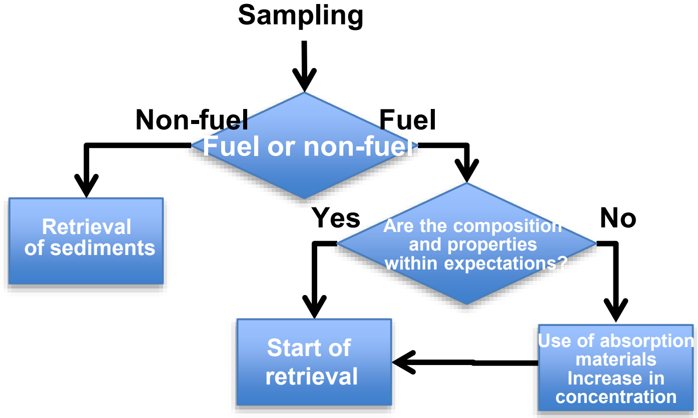


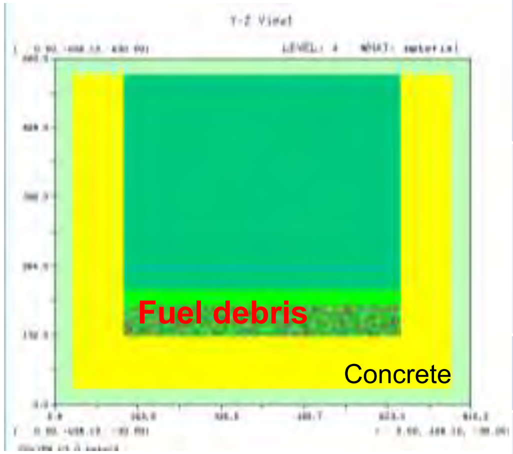

Figure 1. Method of using sampling data

# 2.4 Study on Optimization related to Ensuring Safety of Methods and Systems (Related to Criticality Control)
# ① Establishment of Criticality Evaluation and Impact Assessment Methods
# 2) Advancement of statistical criticality evaluation method



[Implementation details]

- Criticality risk for the debris deposited in Unit 2 pedestal was assessed using statistical methods, assuming that the shape of debris was changed without any processing restrictions.
- The pedestal images (result of Internal Investigation Project), debris distribution estimation map (results of Identifying the Internal Structures in the Reactor Project) and debris characterization list (result of Characterization Project) were investigated, and the analysis conditions required for statistical criticality evaluation were consolidated (table below).




Computational model

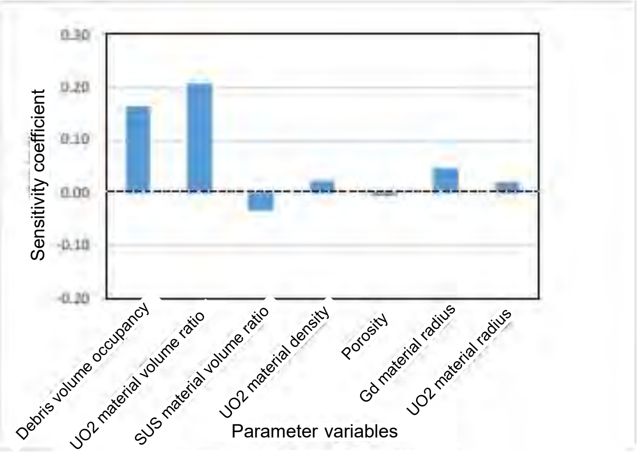
| Items | Values | Basis |
|---|---|---|
| Breakdown of fuel debris (vol%) | $UO_2$: 30 to 70<br>Construction materials: 70 to 30 | Established using the analysis results of the accident analysis code and results of the debris characterization project as reference. |
| Breakdown of construction material (vol%) | Zr: 40 to 60<br>SUS: 60 to 40 | Established using the analysis results of the accident analysis code and results of the debris characterization project as reference. |
| Fuel debris volume occupancy (vol%) | 50 to 90 | Established based on the PCV internal investigation image and assumed future shape changes<br>(If the value is less than 50, it means floating up debris) |
| Size of fuel debris pellets (diameter (cm)) | $UO_2$: 4 to 9<br>Gd: 0.5 to 4 | A model for representing the localized deviation in fuel debris composition<br>Diameter of several cm is a conservative measurement<br>The volume of a pellet with a diameter of 9 cm is equivalent to that of one fuel rod.<br>Gd pellet is assumed to be included in $UO_2$ pellet |
| $UO_2$ density (g/cm$^3$) | 9 to 10.5 | Established using the consultation with the Debris Characterization Project Team as reference. |
| Porosity in fuel debris (air) (%) | 0 to 15 | Established using the consultation with the Debris Characterization Project Team as reference. |

**Analysis conditions for statistical criticality evaluation of Unit 2 pedestal (Assuming uniform probability distribution)**

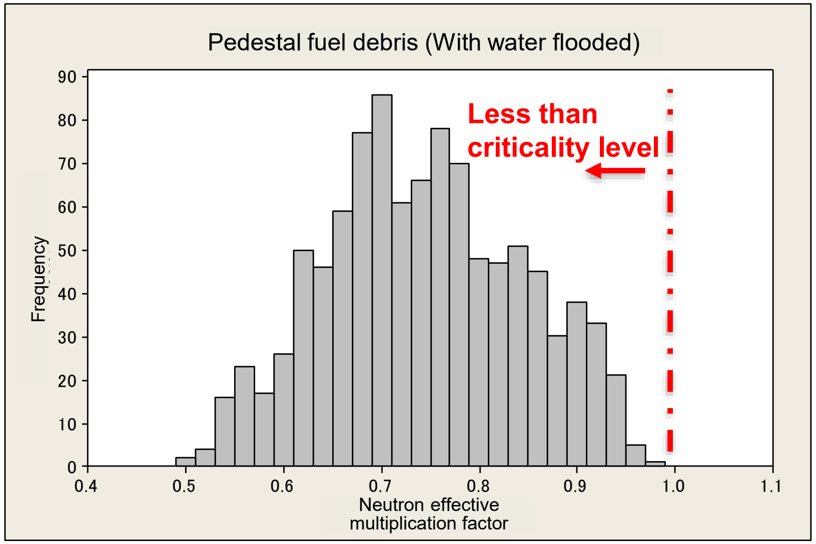
# 2.4 Study on Optimization related to Ensuring Safety of Methods and Systems (Related to Criticality Control)
## ① Establishment of Criticality Evaluation and Impact Assessment Methods
## 2) Advancement of statistical criticality evaluation method

**[Implementation details] (Continued…)**

- Debris is assumed to be deposited in a flat columnar shape with a diameter of 5.4 (m) x height of 0.6 (m) (based on the PCV internal investigation image).
- The uranium enrichment of debris was divided into six batches, each with different burn-ups, and the existence ratio of each batch was set (based on operational history data).
- The model was set such that Gd was locally unevenly distributed only in the first batch of fuel (conservative).
- $B_4C$ is not considered (conservative).
- Frequency distribution of neutron multiplication factor was obtained for the calculation result of about 1000 cases.



Impact of assumed parameters



Frequency distribution of criticality evaluation calculation results

**[Results]**

- There were no cases where the criticality criterion keff = 1.0 was exceeded. (about 0.6% of cases exceeded keff = 0.95)
- The criticality risk of debris deposited in Unit 2 pedestal was quantitatively estimated to be sufficiently small. (Attention must be paid to the reliability of the evaluation as it involves many assumptions)

**[Challenges toward the actual application]**

Improving the reliability of evaluation by reflecting future sampling results in the probability distribution.

# 2.4 Study on Optimization related to Ensuring Safety of Methods and Systems (Related to Criticality Control)

## ② Study on Criticality Control Methods

### i-1) Study on criticality control methods and procedures incorporating the study on fuel debris retrieval methods

**a) Reviewing the concept of defense in depth**

- The level of defense in depth for criticality control was revised in line with the concept of defense in depth studied in Advancement of Methods and Systems (safety design) project. The level of criticality was redefined as Level 3 (accident) (shown on slides 4 and 5).
- The concepts for setting control parameters and reference values for each level and for equipment and facilities used at each level were consolidated. (Table 1 and Reference 3)

**b) Criticality control methods during full-scale retrieval**

- Consistency between criticality control methods during full-scale retrieval (see Slide 5) and daily retrieval schedule were checked. (See Slide 6)

**Retrieval target:** To check the conformance with the retrieval target (300 kg / day), by rationalization of criticality evaluation (rationalization of assumed debris composition) and by limiting the processing size per operation to about 6,900 $cm^3$.

**Daily work schedule:** As criticality approach monitoring measurement, it was confirmed that the work schedule will not be affected even if standard condition measurement (1 hour) during the preparations before the start of the day's operations and criticality approach monitoring and decision to continue work for every debris processing, are assumed.

**Table 1. Reviewing the level of defense in depth**

| Level | State | Control parameters | Control value | Controlling method | Means of response |
|---|---|---|---|---|---|
| 1<br>Normal state | keff < 0.80<br>(Sub-criticality assumed during retrieval) | ・Neutron flux near the place of retrieval<br>・PCV exhaust gas FP concentration<br>・Neutron absorber concentration | keff < 0.75<br>(Neutron flux corresponding to keff, FP gas concentration) | Preventing deviation from normal state<br>・Limiting the processing size<br>・Neutron absorber (optional)<br>・Criticality approach monitoring | ・Suspension of operations<br>・Confirming the concentration of absorption material |
| 2<br>Abnormal state | keff < 1.0<br>(sub-criticality state) | Same as above | 0.85 < keff | Detection of deviation and prevention of its escalation<br>・Criticality approach monitoring | ・Suspension of operations and collection of debris<br>・Increasing the concentration of absorption material |
| 3<br>Accident | 1.0 < keff<br>(occurrence of criticality) | Same as above | 0.95 < keff | Detection and termination of abnormalities<br>・Criticality detection and termination | ・Stand-by liquid control |

## 2.4 Study on Optimization related to Ensuring Safety of Methods and Systems (Related to Criticality Control)



### ② Study on Criticality Control Methods

#### i-2) Assessment of impact on circulation cooling systems when using soluble neutron absorber

[Purpose]

・Impact assessment when using sodium pentaborate water as regular coolant (Consolidating issues in 1F environment)

[Past achievements]

・Evaluation of applied boron concentration: Applied concentration 7,000 ppm
- Boron concentration for criticality prevention: 6,000 ppm
  Average debris composition with maximum reactive assemblies (with Gd):
  Consider optimal deceleration state to minimum boron value state
  Stump-shaped fuel: Consider submergence, fuel pitch change
- Change in concentration per day: 1,000 ppm
  Consider the leakage from PCV to torus room, dilution by mixing with ground water
  Boric acid precipitation due to concrete-derived elements (evaluated FY2018)
- Saturated solubility: 12,000 ppm, when used at a concentration lower than 0℃
- Corrosion effect on structural materials: No corrosion effect if ≥ 4,000 ppm
- Impact on concrete and waterproof material: No effect if ≤ 10,000 ppm
- Uncertainty in criticality evaluation: Confirmed by criticality experiment, but increase in uncertainty could not be confirmed from the concentration used in power plants (about 2,000 ppm).

・Concept of equipment for maintaining boron concentration (See Slide 10)

[Implementation details]

・Evaluating the challenges when using stand-by liquid in 1F environment
- Boric acid precipitation due to concrete-derived elements
- Impact on environment due to leakage of cooling water, etc.

# 2.4 Study on Optimization related to Ensuring Safety of Methods and Systems (Related to Criticality Control)

## ② Study on Criticality Control Methods

### i-2) Assessment of impact on circulation cooling systems when using soluble neutron absorption material

Details of completed goals (Black), Details of goals in FY2018 (Blue)

**Table 1. Development results and challenges toward the actual application**

| Final goal | Goals to be achieved toward the actual application | Status of achievements | Challenges toward the actual application |
|---|---|---|---|
| Study on the application method of stand-by liquid | ・Study on the application method for criticality prevention<br>・Determining the boron concentration for criticality prevention | ・Study on prevention methods using stand-by liquid for each criticality scenario (Completed)<br>・Determining the boron concentration for criticality prevention (Completed)<br>Reviewed based on site conditions<br>Review in consideration of the situations expected at the site | - |
| Impact assessment at the time of application | ・Confirming the various challenges posed due to the application of stand-by liquid | ・Assessment of impact such as corrosion of structural materials, etc.<br>Assessment of impacts such as effects at the time of leakage, constant flow conditions, etc. needs to be studied.<br>Assessment of impact during external leakage, impact when used in contact with concrete and when used in constant flow conditions | - |
| Waste impact | ・Confirming if the waste impact is in the acceptable range | ・Installation of radionuclide removal equipment that is not affected by boric acid in the small circulation loop (demineralizer, etc.), installation of leaked boric acid recovery equipment (study on equipment) | ・Confirming the feasibility as a part of water systems<br>Evaluating the amount of waste during operational state, studying the waste after completion of retrieval (boric acid recovery method and quantity, handling of structural materials with boric acid adherence, etc.) |
| Establishment of stand-by liquid equipment specifications | ・Confirming the feasibility and specifications for concentration maintenance equipment considering leakage of cooling water from PCV | ・Study on the conceptual specifications of equipment for maintaining concentration by means of stand-by liquid enrichment | ・Confirming the feasibility as a part of water system |
| Establishment of on-site operating methods | ・Establishment of operational methods for maintaining concentration | ・Evaluation of concentration margin for operation<br>Study of on-site operating methods such as concentration monitoring methods | ・Study on operating methods such as concentration monitoring method and method of responding to abnormality, as a study on operating methods of water systems |

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## 2.4 Study on Optimization related to Ensuring Safety of Methods and Systems (Related to Criticality Control)

## ② Study on Criticality Control Methods

### i-2) Assessment of impact on circulation cooling systems when using soluble neutron absorption material

Precipitation effects when concrete and sodium pentaborate water come into contact

[Purpose]

Evaluating the effect of decrease in boron concentration due to the eluted concrete components (Ca, Mg, etc.), when sodium pentaborate is used with the aim of criticality prevention during fuel debris retrieval.

[Evaluation conditions]

- ✓ Sodium pentaborate concentration: 4000ppm, 7000ppm
- ✓ Ca concentration: 0 to 1330 mg/L (ppm)*
- ✓ Water temperature: 0 to 5℃, 65℃
- ✓ Seawater concentration: 1/10,000 times

[Evaluation Results]

- **The results confirmed that boron precipitation by concrete-derived elements decreases the boron concentration in the entire system to about 3 ppm / day; and that changes causing operational problems will not occur. (Table 1, see Slide 7)**

Table 1. Evaluation Results

| Case | Ca Concentration (ppm) | Amount of decrease in boric acid concentration (per day) | | Required dosage of sodium pentaborate decahydrate (per day) | Remarks |
|---|---|---|---|---|---|
| | | Localized Near the location where debris is crushed | Overall When homogenized with the amount of water in the entire system | | |
| 1 | 1330 | 1050ppm | 21ppm | 115kg | When 24 kg / day of Ca (conservatively) is assumed to elute in 1 hour worth of circulating water (18 m3) |
| 2 | 133 | 105ppm | 21ppm | 115kg | When 24 kg / day of Ca is assumed to elute in 1 day worth of circulation water (18 m3 x 10 hrs). 24 kg / 10 hrs / 18 m3 = 133 mg / L as Ca |
| 3 | 665 | About 525ppm | 11ppm | 60kg | Rationalization of case 1 conditions<br>Decrease the elution speed by 1/2 |
| 4 | 333 | About 263ppm | 6ppm | 33kg | Rationalization of case 3 conditions<br>Large particles are not eluted and the eluted amount is assumed to be about 1/2 |
| 5 | 176 | About 139ppm | 3ppm | 17kg | Rationalization of case 4 conditions<br>When coarse aggregates in concrete are considered (about 53%) |

**[Results of studying other concerns]**

**Impact at the time of stand-by liquid leakage was assessed, and it was confirmed that effect of boron leakage was reduced when dilution due to groundwater was considered. (See Slide 8)**

- **It was confirmed that the possibility of boric acid getting precipitated, becoming airborne and scattering is very low. (See Slide 9)**
- **The factors leading to fluctuation of boron concentration were consolidated and were incorporated in the boron concentration settings applied to the water system. (See Slide 10)**

# 2.4 Study on Optimization related to Ensuring Safety of Methods and Systems (Related to Criticality Control)

## ② Study on Criticality Control Methods

### ii) Step-by-step approach to fuel debris retrieval

- Criticality control method for internal investigations are studied in cooperation with related projects.
- Gradual scale-up of retrieval work (mentioned as "Small-scale retrieval" in the table below) is assumed.

| Criticality control | | | Internal Investigation | Removal of fallen objects / sediments | Debris Sampling | | | Fuel debris retrieval | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Gripping and suction | Surface sampling | Core boring | Small-scale retrieval | Full-scale retrieval |
| Change in debris state | | | None<br>No change in state | Small<br>Sediments are displaced in water and reflector effect increases. | None<br>The amount of debris which undergoes change is small. | Extremely small<br>The amount of debris which undergoes change is small. | Small<br>Water penetrates through the holes. | Medium.<br>Excavation of a limited area | Large<br>Debris deformation due to excavation |
| Incidental events associated with operations | | | Debris falling from above, deformation of underwater debris due to those falling objects | | | | | | |
| Prevention of deviation from normal state | Work limitations | Criticality evaluation | - | Selection of appropriate work methods | Selection of appropriate work methods | Processing size / pitch limitation | Processing size / pitch limitation | Retrieval amount limit per operation | Retrieval amount limit per operation |
| | Criticality approach monitoring | Criticality approach detection | - | - | - | - | Neutron flux monitoring (simple) | Neutron flux monitoring (simple) | Subcriticality monitoring (detailed) |
| | Insoluble neutron absorption material | Neutron absorption material | - | - | - | - | - | - | Insoluble absorption material |
| | Soluble neutron absorption material | Neutron absorption material | - | - | - | - | - | - | Sodium pentaborate water (6000ppm) |
| Abnormality measures | PCV gas radiation monitor | Re-criticality detection technology | ● Existing | ● Existing (*1) | ● Existing (*1) | ● Existing (*1) | ● In combination with neutrons | ● In combination with neutrons | ● In combination with neutrons |
| | Emergency stand-by liquid control | Evaluation of behavior during criticality | ● Existing | ● Existing (*2) | ● Existing (*2) | ● Existing (*2) | ● Existing (*2) | ● Existing (*2) | ● Existing (*2) |
| Control methods (reference) | | | 11-1 | 11-5 | 11-2 | | | 11-3 | 5 |

Selection

* 1: Study on the time when it is necessary to introduce upgraded system by means of Kr detection
* 2: Review of the capacity of stand-by liquid control system and study on post-injection measures

# 2.4 Study on Optimization related to Ensuring Safety of Methods and Systems (Related to Criticality Control)



## ② Study on Criticality Control Methods

## ii) Step-by-step approach to fuel debris retrieval

**[Implementation status]**

・ The criticality control methods were studied based on the assumed state at each stage and the criticality risk of the implemented operations. (See Slide 11)

・Internal investigation: Although there is no change in debris state, criticality risk assessment of incidental events is conducted during the investigation itself.
RPV Internal investigation: Impact of falling RPV fragments, PCV detailed investigation: Impact while severing obstacles (beams) was assessed.

・Sampling to Full-scale Retrieval: Control methods were studied based on the scale of debris processing / retrieval.

| | Concept | Sampling and Small-scale retrieval | Full-scale retrieval |
|---|---|---|---|
| Limiting the processing size | Established based on effectiveness of criticality prevention and criticality approach monitoring. Increased based on the results. | ・Limited to small-scale due to lack of records (equivalent to 16 $cm^3$ per side) | ・Increased based on accumulated results (equivalent to 19 $cm^3$ per side) |
| Criticality approach monitoring | Each processing step is monitored, and the propriety of the next processing step is determined.<br>If the initial state (sub-criticality) is not ascertained, the monitoring interval is shortened. | ・Simple method) Relative monitoring based on neutron flux level monitoring<br>- Perform detailed monitoring while gradually scaling up processing. | ・ Detailed method) Direct monitoring by means of sub-criticality measurement<br>- The initial sub-criticality measurement helps to perform retrieval operations without the need to gradually scale-up processing even in areas where composition and properties are unknown. |
| Neutron absorption material | ・Can be applied at any step to terminate the occurrence of criticality (emergency stand-by liquid control).<br>・The decision on application for regular use (criticality prevention means) by prior-injection is based on the necessity of criticality prevention and limitation of facilities at each point in time. | ・Criticality prevention using neutron absorber is not required when debris processing / retrieval scale is small.<br>・When an unexpected criticality approach occurs, operations are suspended and the use of neutron absorption materials is considered. | ・Study on the use of neutron absorption materials (soluble and insoluble) as an option for completing debris retrieval. (See Slide 12)<br>・It is desirable to study the necessity of using absorption materials based on the results up to the previous stage. |

# 4 Conclusion



**・The feasibility of criticality control technology and on-site applicability were checked as part of the conceptual study on the methods and systems used for retrieval of fuel debris and internal structures.**

| Items | Annual results | Challenges toward the actual application |
|---|---|---|
| Establishment of criticality control methods | **1) Study on the control methods and procedures incorporating the study on retrieval methods**<br>The consistency between retrieval target per day, schedule and criticality control requirements was checked.<br>**2) Establishment of criticality control methods during gradual scaling up of retrieval**<br>A control method for full-scale retrieval was developed based on the internal investigation results. | ・Confirming the effectiveness of the control methods developed this time by comparing the latest findings obtained from the internal investigations, etc. with the criticality evaluation prerequisites; and promoting rationalization if possible. (To be continued for the actual application). |
| Implementation of criticality control technology | **1) Sub-criticality measurement and criticality approach monitoring technologies**<br>・The specifications for the monitoring systems and detector unit that can be operated with a robot arm, were developed.<br>・The feasibility of measuring sub-criticality in a large system simulating an actual equipment, was verified.<br>**2) Re-criticality detection technology**<br>・Criticality detectability was checked by formulating an operating method as part of the negative pressure control system.<br>・The calibration accuracy was quantified by establishing a detector calibration technology.<br>**3) Criticality prevention technology**<br>・The concept of dispersing insoluble neutron absorber was developed and the measurement concept for checking the effect after dispersal was drawn up.<br>・It was confirmed that long-term irradiation of insoluble absorber did not affect the integrity of canisters.<br>・ The impact of using soluble neutron absorber(environmental impact at the time of leakage, compatibility with concrete) was evaluated. | ・Detector unit prototyping, checking operability<br>・Confirming the feasibility of measuring sub-criticality using confirmation tests in non-homogeneous complex systems.<br><br>・Continuing to verify effectiveness by reflecting the progress of the study on methods and systems. (To be continued until the application to actual equipment)<br><br>・ Assessment of impact during on-site application, such as compatibility with rust inhibitors<br>・ Incorporation in the establishment of the design and operation methods of liquid systems. |