Subsidy Project of Decommissioning and Contaminated Water Management
in the FY 2015 Supplementary Budgets

Development of Technology for Criticality Control of Fuel Debris

Final Report

March 2018

International Research Institute for Nuclear Decommissioning (IRID)

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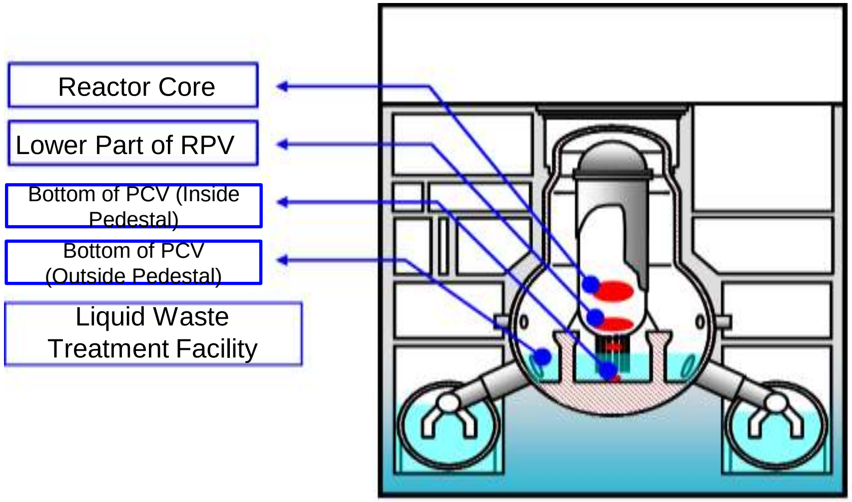
1. Plan Overview

1.1 Research Background and Purposes

[Purpose]
It is estimated that, currently, the fuel debris is not in a critical state. However, the criticality control method will be established to prevent criticality during fuel debris retrieval work in the future, triggered by changes in the shape of fuel debris and/or the amount of water. These technologies will also protect the general public and workers from excessive exposure should criticality occur.

[Goals]
• To determine criticality control methods for each fuel debris retrieval method, develop applicable element technologies, and confirm their feasibility, based on the decision on the fuel debris retrieval policy in the summer of 2017, as scheduled on the roadmap.



The following technologies have been developed to establish criticality control methods during retrieving fuel debris:
1. Criticality Evaluation Technologies:····(1) Evaluate criticality scenarios, (2) Evaluate behaviors during criticality, and (3) Develop criticality control technologies.
2. Criticality Control Technologies:······· (1) Critical approach monitoring technologies.
(Note: The development of a critical approach monitor for small circulation loops was completed in FY 2013.)
(2) Re-criticality detection technologies (for gas sampling system and neutron system).
(3) Criticality prevention technologies (development of insoluble neutron absorber and soluble neutron absorber)

[Project Achievements Application]

Item/FY	2015	2016	2017	2018	2019	2020	2021
Main Roadmap Schedule	Decide on fuel debris retrieval policy ▲				Finalize retrieval methods ∆	Retrieve fuel debris ∆	
[Development of Technology for Criticality Control Methods] Project 1. Establishing Criticality Evaluation Technologies (Evaluation of Criticality & Behaviors During Criticality)	Critical scenario review: Update with latest information Evaluation and criticality control methods for each debris processing technique Criticality evaluation for internal investigation & sampling Technologies review: Feasibility test (verification of principles)						
2. Developing Criticality Control Technologies (1) Critical Approach Monitoring Technologies (2) Development of Re-Criticality Detection Technologies	Advanced system review: Feasibility test Candidate material selection, application method review, and feasibility test Impact assessment on use & facility review: Feasibility test						
(3) Criticality Prevention Technologies Insoluble Neutron Absorber Soluble Neutron Absorber				Reflect the development results in method and facility reviews			
[Upgrading of Approach and Systems for Retrieval of Fuel Debris and Internal Structures] Project							

1.2 Project Goals (Goals and Basic Concepts of Criticality Control)

The objectives of criticality control were set reflecting opinions of external experts (from Evaluation Committee, CRIEPI in FY 2016).

[Criticality Control Objectives]

To prevent excessive exposure (radiation sickness) for the general public and workers by preventing criticality and by detecting and suppressing criticality even if it occurs.

Criteria: General public on the site boundary: 5 mSv, workers: 100 mSv

[Criticality Control Methods Based on Defense in Depth]

	Level 1: Prevention of Abnormality		Level 2: Understanding the State of and Terminating Abnormality		Level 3: Protection of the General Public	Level 4: Addressing Events Beyond Expectation Outside the Facility Perimeter
Criticality Control	Monitoring	Prevention	Defection	Mitigation	• Measures are taken against situations, such as leakage of radioactive materials and fire, as part of overall risk management.	
Specific Methods (Major Ones)	• Monitor critical approach using critical approach monitoring technique • Monitor levels of water and boron concentration, etc.	• Limit the amount of debris that can be retrieved at a time • Apply boric acid solution/insoluble neutron absorber	• Detect criticality based on neutron fluxes/FP gas concentration	• Terminate criticality by injecting boric acid solution/insoluble neutron absorber		
Objectives	• To prevent criticality by monitoring critical approach		• To promptly detect and suppress criticality (Preventing the emission of radioactive materials at a higher level than under normal operating conditions (*))		• To prevent excessive exposure (radiation sickness) for the general public and workers in the event of an accident	

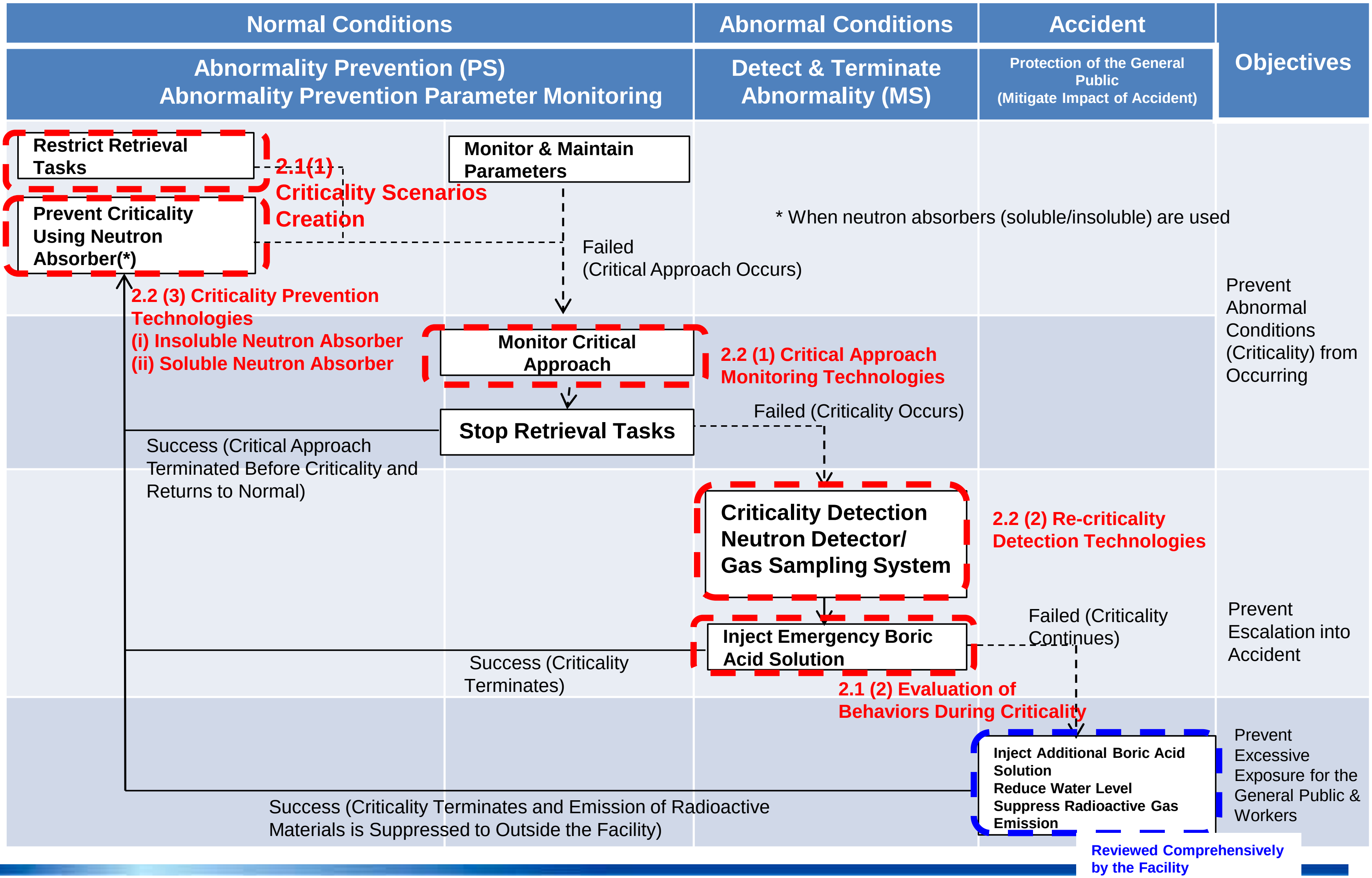
Portion which criticality control focuses on

Portion that should be accomplished by comprehensive efforts

* **Going forward, this level should be reviewed from all aspects of safety control including criticality.**

[Criticality Control Methods Used During Debris Retrieval (Positioning of Element Technologies)]

For more comprehensive information, see 2.1 (3) Drawing up Criticality Control Methods.



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1.3 Implementation Items, Their Correlations, and Relations with Other Research

1. Establishing Criticality Evaluation Technologies

(1) Criticality Scenarios Creation

(i) Revisiting Critical Risks with the Latest Know-Hows

(ii) Statistical Criticality Evaluation

(iii) Criticality Evaluation

(2) Evaluation of Behaviors During Criticality

(i) Evaluation during Debris Retrieval

(3) Drawing up Criticality Control Technologies

2. Developing Criticality Control Technologies

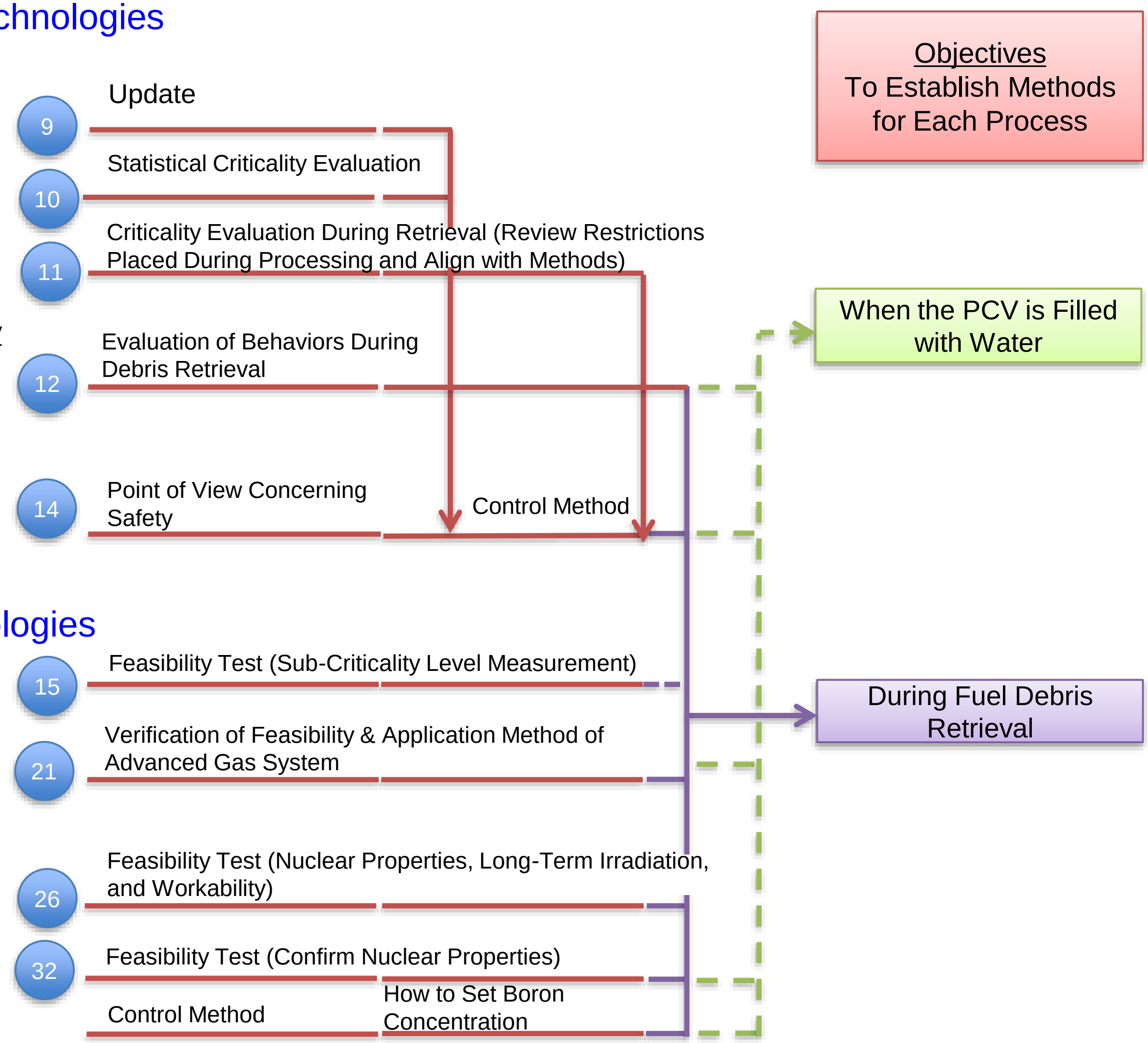
(1) Critical Approach Monitoring Technologies

(2) Developing Re-Criticality Detection Technologies

(3) Criticality Prevention Technologies

(i) Insoluble Neutron Absorber

(ii) Soluble Neutron Absorber



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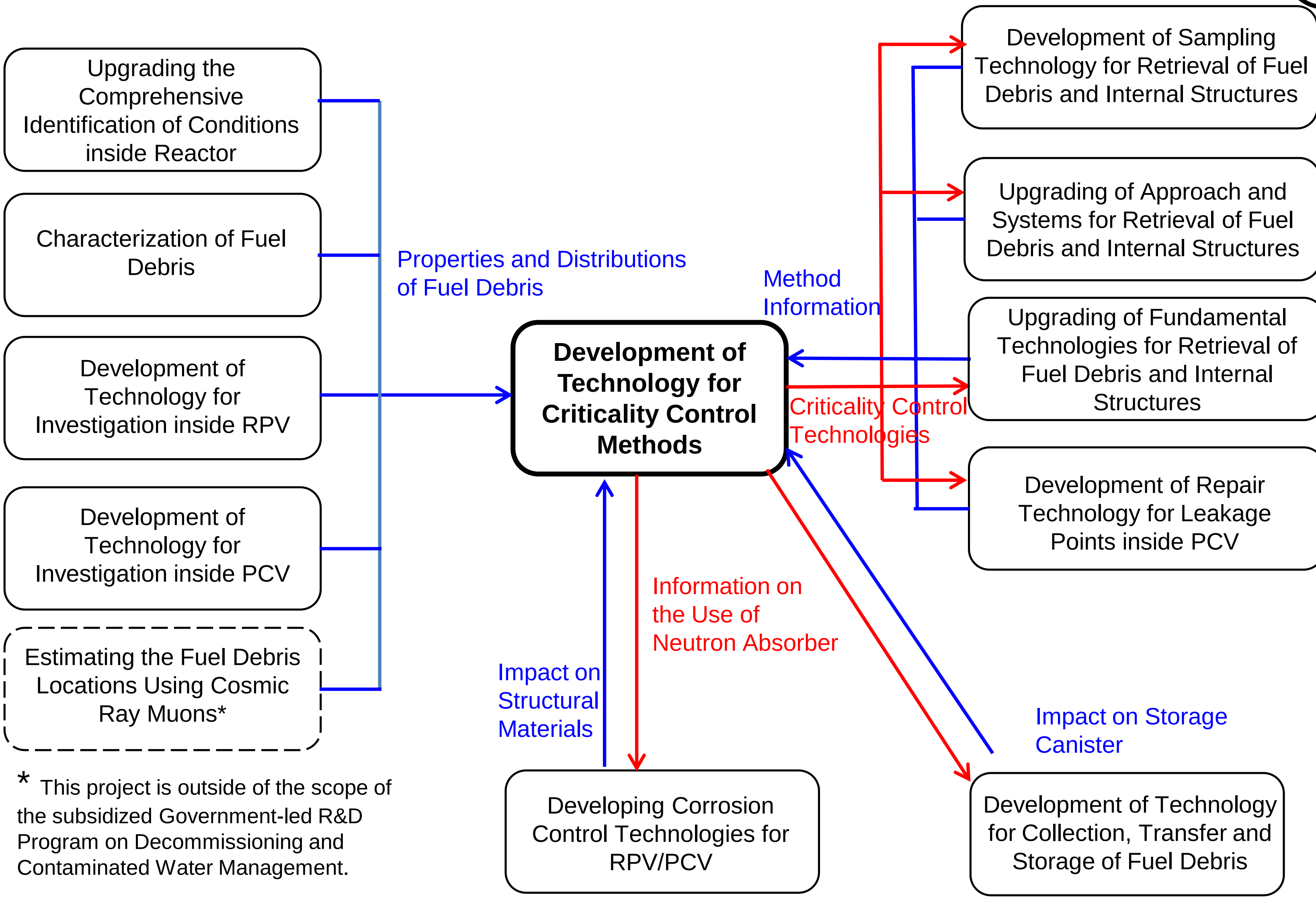
[Correlations with Related Projects]



* This project is outside of the scope of the subsidized Government-led R&D Program on Decommissioning and Contaminated Water Management.

1.4 Project Organization

International Research Institute for Nuclear Decommissioning (Head Office)

- ○ Planning Overall of Project and Supervising Technical Management
- ○ Supervising Technical Management Including Progress of Technical Development

Mitsubishi Heavy Industries, Ltd.

1) Establishing Criticality Evaluation Technologies
   - Drawing up criticality scenarios
   - Evaluation of Behaviors During Criticality
   - Drawing up Criticality Control Methods
2) Developing Criticality Control Technology
   - Criticality monitoring technology
   - Criticality prevention technologies (Soluble neutron absorber)

Toshiba Energy Systems & Solutions Corporation

1) Establishing Criticality Evaluation Technologies
   - Drawing up criticality scenarios
   - Evaluation of Behaviors During Criticality
   - Drawing up Criticality Control Methods
2) Developing Criticality Control Technology
   - Critical approach monitoring technologies
   - Developing re-criticality detection technologies (Neutron system)
   - Criticality prevention technologies (Insoluble neutron absorber)

Hitachi-GE Nuclear Energy, Ltd.

1) Establishing Criticality Evaluation Technologies
   - Drawing up criticality scenarios
   - Evaluation of Behaviors During Criticality
   - Drawing up Criticality Control Methods
2) Developing Criticality Control Technology
   - Critical approach monitoring technologies
   - Developing re-criticality detection technologies (Gas sampling system)
   - Criticality prevention technologies (Insoluble neutron absorber)

2. Implementation Details

2.1 Establishing Criticality Evaluation Technologies (2) Criticality Scenarios Creation
(i) Revising Criticality Risks (Priority in Criticality Control) with Latest Know-Hows

[Purpose]
- To clarify critical scenarios for each process based on multiple methods and present the criticality control priority.
- To provide critical scenarios and risk assessment reflecting the latest information

[Achievements]
- **Latest know-hows were reflected and side access methods were reviewed based on results of Identification of Conditions Inside the Reactor Vessel Project in FY 2016, investigation inside the PCV of Unit 1 (B2), investigation inside the PCV of Unit 2 (A2, A2'), investigation inside the PCV of Unit 3, and muons measurements.**
  No new information was discovered that largely exceeded our original expectations, but the priority of controlling the submergence of the bottom of the PCV in Unit 2 was revised to small (See Table 1).
- **Reviewed the operation and effectiveness of the prevention measures for reducing re-criticality risks**

[Issues for Practical Application]
- To reflect the results of the Identification of Conditions Inside the Reactor Vessel Project, investigation inside the PCV/PRV, and debris sampling etc.

Table 1 - Relative Priority of Criticality Control for Each Unit

Components	Criticality Scenarios	Unit 1	Unit 2	Unit 3
Reactor Core	• Residual fuel submergence	Extremely low (Almost no fuel remaining)	Medium (Fuel may be remaining in the reactor core and peripheral area)	Low (The possibility cannot be denied that fuel remains in the peripheral area)
Lower Part of RPV	• Debris submergence • State changes during retrieval	Submergence: Low Retrieval: Extremely low (Small residual amount)	Submergence: Medium Retrieval: Low (A lot of exposed residual amount)	Submergence: Medium Retrieval: Low (A lot of exposed residual amount)
CRD Housing	• Adhered debris submergence	Between extremely low and low (Small risk based on adherence profile and amount)	Between extremely low and low (Small risk based on adherence profile and amount)	Between extremely low and low (Small risk based on adherence profile and amount)
Bottom of PCV	• Exposed debris submergence • State changes during retrieval (Including stirring up)	Submergence: Low Retrieval: Low (Large amount and small exposure)	Submergence: Changed from medium to low Retrieval: Low (Slightly small amount and extensive exposure)	Submergence: Low Retrieval: Low (Large amount and small exposure)

Note: Relative priority of criticality control during debris retrieval
In the aspect of criticality control, a "high" priority case is where the original fuel profile is retained and the presence of a corresponding amount of fuel debris is expected. The priority of each case is shown using this as the baseline.

2.1 Establishing Criticality Evaluation Technologies (2) Criticality Scenarios Creation (ii) Criticality Evaluation by Introducing Statistical Approach

[Purpose]

- To evaluate criticality based on the estimated distribution instead of selecting areas with more severe evaluation conditions

[Implementation Items]

- Use parameters such as fuel debris properties as random variables and estimate the degree of sub-criticality (neutron multiplication factor).

- Develop the concepts and analysis methods for statistical criticality evaluation
  - Parameters treated as random variables
    - { Debris particle size, porosity, debris volume occupancy, debris composition (mixture ratio of structural materials, etc.), and Gd carrying ratio
  - Case Settings
    - The PCV system of Unit 1 (Achievements of the identification of conditions inside the reactor vessel were reflected.)

[Achievements]

- Considered methods for estimating the current conditions using statistical criticality evaluation
  - According to the neutron multiplication factor based on the radiation concentration ratio of the Unit 1 gas management system, the mixture ratio of metallic component was estimated using the Bayesian estimation.
- Established evaluation methods that take into account fuel debris properties and observed values, and conducted a statistical evaluation consistent with the current estimates of fuel debris properties and the neutron multiplication factor. The results suggested that the system was sufficiently subcritical.

[Issues for Practical Application]

To review the method to improve the reliability by introducing new knowledge.

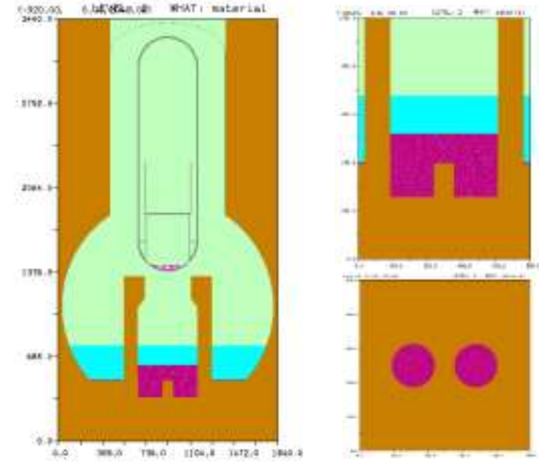


Figure 1 - Analysis System (Left: Entire System, Right: Pedestal Floor)

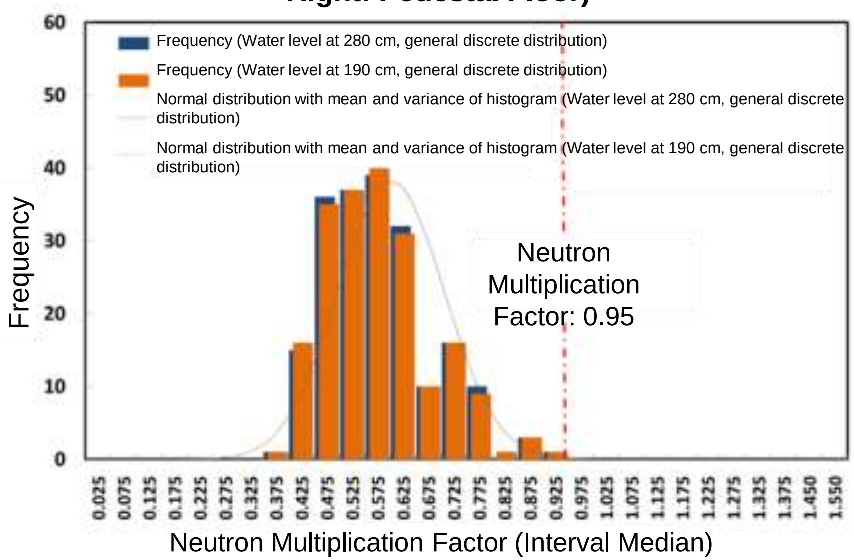


Figure 2 - Comparing Neutron Multiplication Factor Distributions Before and After Water Level Changes

2.1 Establishing Criticality Evaluation Technologies (2) Criticality Scenarios Creation
(iii) Criticality Evaluation Reflecting the Review of Fuel Debris Retrieval Methods

[Purpose] To reflect the criticality evaluation conducted on each debris retrieval method in the safety requirements.

[Achievements] Boring processing: Reviewed the limit on the amount of debris that can be retrieved at a time in order not to add excessive reactivity.

Reviewed the possibility to ease the restriction on the amount of debris that can be retrieved at a time by revising the evaluation conditions.

- Enrichment: 5 wt% (highest of all pellets) → 4 wt% (highest of mass averages)

(A realistic condition was adopted.)

- Additional reactivity: 0.1% Δk/k or less → 0.5% Δk/k or less

(The condition was eased to a level that does not cause the system to go prompt critical.)

Concluded that the limit on the amount of debris that can be retrieved at a time can be reduced from 12 cm cube or smaller to 16 cm cube or smaller

Laser Processing: Surveyed the latest information and found out that the processing speed was slow and the critical mass was not easily reached.

Plasma Processing: Conducted a minimum critical weight evaluation for a case where the debris is being stirred up and determined that the criticality risk was small.

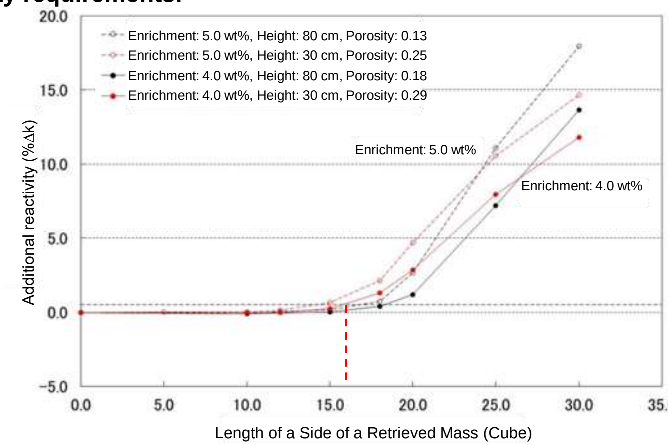


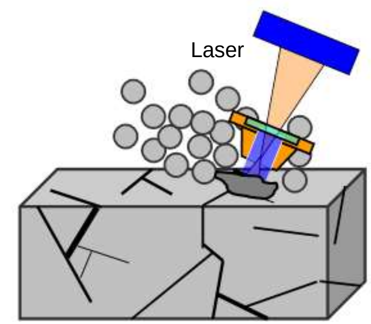
Figure 1 - Correlation Between Retrieved Amount at a Time and Additional Reactivity

Table 1 - Shortest Time to Reach Criticality by Stirred up Fine Debris

Processing Method(*) (Processing Speed)	Minimum Burnup Composition per Mass (Minimum Critical Mass: 46 kg)	Average Core Burnup Composition (Minimum Critical Mass: 109 kg)
Laser Processing (330 g/min)	2 hours 19 minutes	5 hours 30 minutes
Plasma Processing (850 g/min)	54 min	2 hours 8 minutes

(The above table only shows the laser and plasma processing methods, although there are other processing methods including water jet and ultrasonic drilling. This is because these latter methods have a slower processing speed.)

Change of Profile due to Processing and Stirring up of Fine Particle Debris



[Issues for Practical Application] • **Align the requirements for each retrieval method with the requirements of the project for studying the fuel debris retrieval method.**

(*) Based on the results from the “Upgrading of Fundamental Technology for Retrieval of Fuel Debris and Internal Structures” conducted on FY 2013 Supplementary Budget for Government-Led R&D Program on Decommissioning and Contaminated Water Management in FY 2014.

2.1 Establishing Criticality Evaluation Technologies (2) Evaluation of Behaviors During Criticality
(i) Selecting Events to Evaluate

[Subjects of Evaluation]

Impacts of criticality are evaluated to review measures taken for such events assuming conservative conditions.

[Assumptions]

- **As a typical event during debris retrieval, crack generation and occurrence of criticality due to processing fuel debris.**
  It is assumed the fuel debris is solidified in bulk (13 t) on the bottom of the RPV. The fuel debris is submerged. The fuel debris is processed by cutting. Cracks are generated instantaneously across the fuel debris mainly around the position where it has been cut. The volume of the cracks constitutes about 1% of the fuel debris. The water penetrates into the cracks to create an optimal moderation condition causing the entire debris to reach criticality. The critical excess reactivity is about 0.1 %dk. (Figure 1 - Criticality Generation Model)
- **Criticality Detection: Neutron detector near the retrieval position**
  A neutron detector (critical approach monitoring technique) installed within a few dozen cm (preliminary) of the debris instantaneously detects neutrons generated by criticality. The debris reaches criticality when the neutron count rate becomes 1000 times the initial value. (Figure 2 - Criticality Detection Model)
- **Criticality Termination: Injection of emergency boric acid solution**
  Sodium pentaborate solution was started to be injected once criticality is detected. The sodium pentaborate solution reaches the debris in ten minutes, starts to develop a negative reactivity effect, and finally terminates the critical event. (Figure 3 - Criticality Termination Model)
- **Exposure Assessment: Assessment of exposure dose assuming FP gas emission**
  Of the fission products generated before criticality is terminated, FP gas is emitted outside of the building in the exhaust from the PCV gas control system. Internal and external exposure for workers outside of the building and the general public on the site boundary caused by the emitted FP gas cloud. Some of the FP gas is leaked from the cell to the operation floor and cause exposure for operation floor workers. Worker evacuation is completed in one hour after criticality is detected and the exposure event is terminated. (Figure 4 - Exposure Model Caused by Criticality)

Processing devices to cut the debris (candidates)

- Disk cutter • Wire saw • Laser
- Hydraulic cutter • Gas
- Plasma ark • Plasma jet
- Abrasive water jet (AWJ)

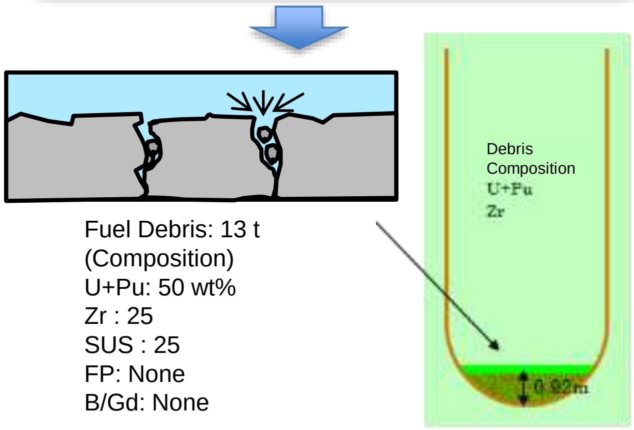


Figure 2.1-1 - Criticality Generation Model

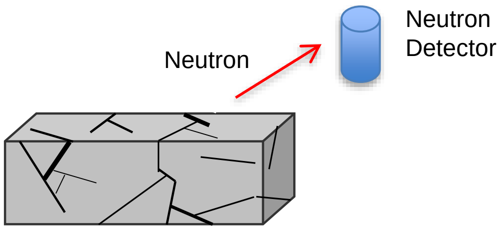


Figure 2.1-2 - Re-Criticality Detection Model

2.1 Establishing Criticality Evaluation Technologies (2) Evaluation of Behaviors During Criticality
(ii) Evaluation of Behaviors During Debris Retrieval

[Analysis Conditions]

- Critical fuel debris: 13 t (including U+Pu/Zr/SUS, without FP/B/Gd)
- Instantaneous reactivity after injection: 0.1 %dk (initial condition is criticality)
- No delay in neutron detection
- Criticality criteria for neutron detector: 1000 times the initial value
- Delay in sodium pentaborate injection: 10 min
- Part of FP gas generated in the PCV goes through the filters and is discharged outside the building in the form of noble gas.

- Exhaust from the PCV gas control system: 3000 m3/h
- Leak rate from the cell to the operation floor: 1%

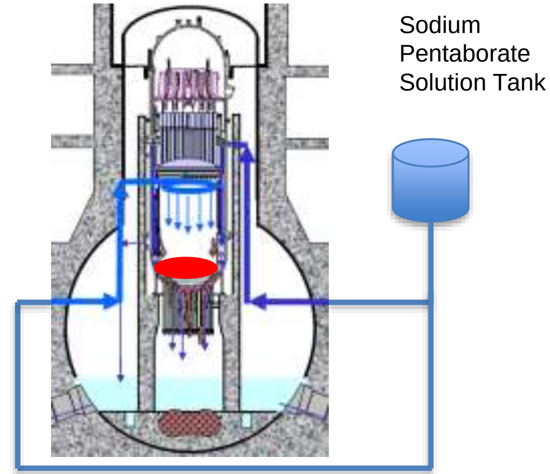


Figure 3 - Criticality Termination Model

[Achievements]

- **Total number of nuclear fissions is up to about 10^{18}.**
- **Public dose on the site boundary is less than the self-management goal (0.1 mSv).**
- **Exposure dose for workers working outside the building is less than the standard for normal operating conditions (20 mSv).**
- Exposure dose for workers on the operation floor is even smaller by two orders of magnitude.

[Issues for Practical Application]

- Present the facility requirements for minimizing the impact of exposure even in the case of criticality.
- Expand the event evaluation to other respective processes including investigation inside the PCV/RPV in addition to debris retrieval.
- Expand data to statistically evaluate the uncertainties of the debris.

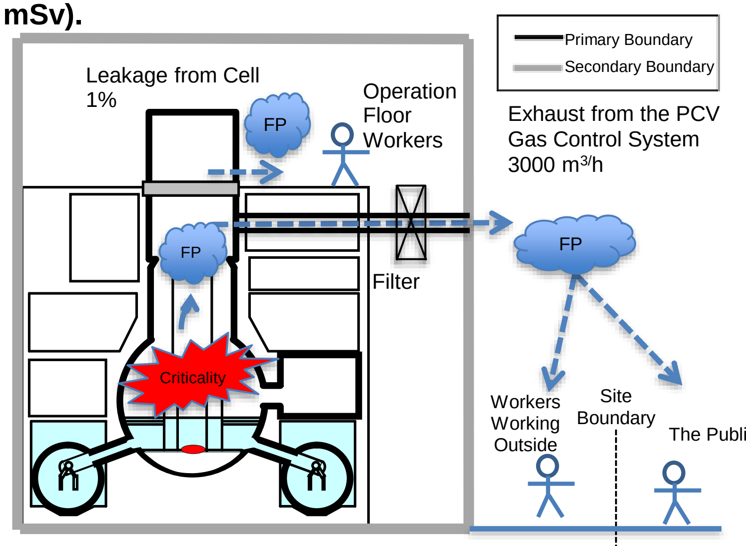


Figure 4 - Exposure Model Caused by Criticality

2.1 Establishing Criticality Evaluation Technologies (3) Drawing up Criticality Control Technologies

[Purpose]

- To develop criticality control methods to meet the target in criticality control in preparation for the decision on the fuel debris retrieval method.
- To confirm their consistency with debris retrieval methods and create procedures for the control methods.

[Achievements]

- **Drew up control methods used during debris retrieval.**
  Presented and aligned requirements for the retrieval facility & method from a standpoint of criticality control.
  - Facility requirements: Installation of a detector for the critical approach monitoring system and the neutron absorber injection facility (soluble and insoluble)
  - Consistency with daily retrieval schedule: Critical approach monitoring method (reduced time)
  - **Control method for each processing method** (See Table 1)
    - Control is unnecessary when the impact of criticality is negligible.
    - Critical approach monitoring is used when the change is gradual and slow.
    - Otherwise, measures such as the use of neutron absorbers are considered.
- **Considered sub-scenarios (for other measures than retrieval position).**
- **Identified abnormal events and reviewed measures.**

[Issues for Practical Application]

- To clarify issues and pros and cons concerning the optional **methods in using neutron absorbers.**

Table 1 - Control Method for Each Debris Processing Method

Type	Processing Method	Criticality Control	Issues
Pick-up	Pick-up	Special control not required	Measures against unexpected events, such as fallen equipment, are considered separately (Applicable to all the methods below).
Suction	Suction		
Surface Machining	Laser gouging	Critical approach monitoring	A measure against the outflow and accumulation of machined powder (Applicable to all the methods below).
Boring	Core boring		
Severing	Disk cutter, AWJ, and hydraulic cutter etc.		A measure against fallen pellets when severing stump fuel.
Crushing	Chisel	Issues	As the change occurs instantaneously, measures such as the used of neutron absorbers are considered.

2.2 Development of Criticality Control Technologies (1) Critical Approach Monitoring Technologies

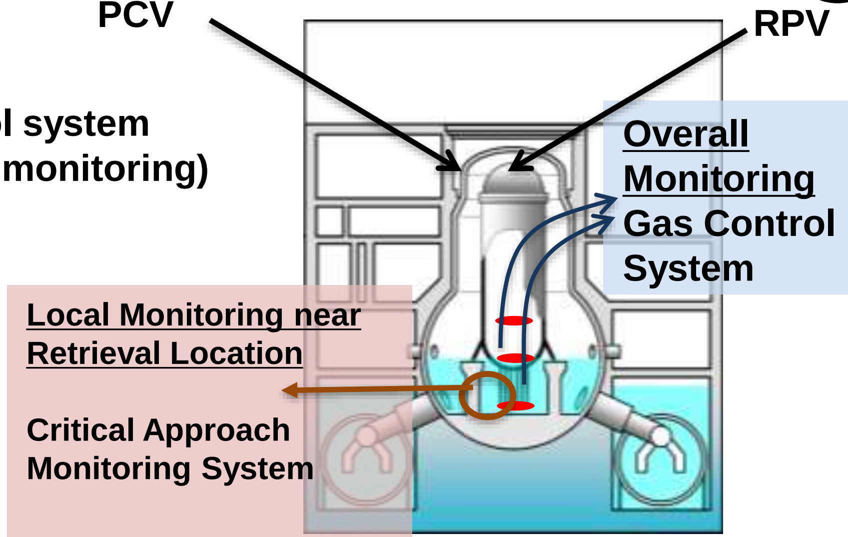
[Purpose]

Current Conditions

Nuclide analysis equipment of the PCV gas control system
➔ Monitoring maintained subcritical state (overall monitoring)

During Fuel Debris Retrieval

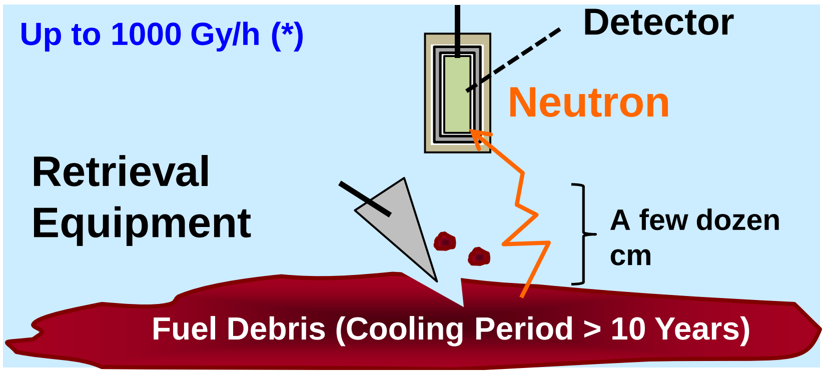
The fuel debris position and the state of moderation in the surrounding area change
➔ Sub-criticality Level may change (critical approach)



Critical approach monitoring is used additionally at the debris retrieval location

Developing Critical Approach Monitoring System

- **Applicable to up to 1000 Gy/h (*)**
- **High sensitivity design that allows for realistic measurement time**
- **Weight saving design capable of moving and holding**



Monitoring Technologies Reviewed

Technologies		Application Method
Reactor Noise Methods	Feynman α Method	Main method
	ASC Method (provided by AMETEK) Y ∞ Correlation Equation Method	Advancement of the Feynman α method
Neutron Source Multiplication Method		Continuous monitoring during retrieval
Virtual Neutron Capture Method		Used as a reference for deep subcritical states, etc.

- The Feynman α method was selected as our main method because it provides a sub-criticality measurement capability through simple instrumentation configurations and signal processing.
- Combinations of respective methods were considered based on their characteristics. (These methods differ in their signal processing but can be combined, as their measurement system is the same.)

* Based on the results of investigation inside the PCV this may be able to be revised down to a lower value

2.2 Development of Criticality Control Technologies (1) Critical Approach Monitoring Technologies
(iii) Sub-criticality Measurement Performance Test (KUCA)

[Purpose]

- To verify the operation of a prototype system.
- To confirm the feasibility of critical approach monitoring technologies.

[Test Method]

- Establish a subcritical system at KUCA, analyze the neutron signals (for about 30 min) using the Feynman α method, estimate the sub-criticality level, and compare the result with the reference value (nucleus calculation result).

[Achievements]

- The sub-criticality level with an error of estimate at about 1% near criticality (neutron multiplication factor keff ≈ 0.95) and about 10% at deep sub-criticality (keff ≈ 0.7) was able to be measured.
  ⇒ This provided an outlook that the method could be realized within the period of time expected on the field.
- Confirmed that the impact on the error of estimate due to the uncertainty of the water-to-fuel ratio (neutron spectrum) was small.

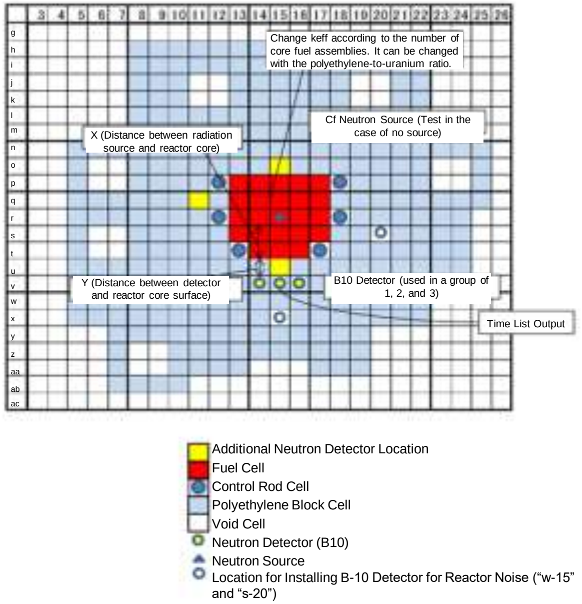


Figure 1 - KUCA Experiment Image

- The error of estimate was affected by the types and layouts of neutron sources.
- The distance between fuel debris and neutron detector at which measurements can be made with the above mentioned accuracy:

  Wet condition : about 20 cm, dry condition: about 35 to 60 cm, partially dry condition: about 25 cm

  ⇒ Used to review specific application methods during debris retrieval.

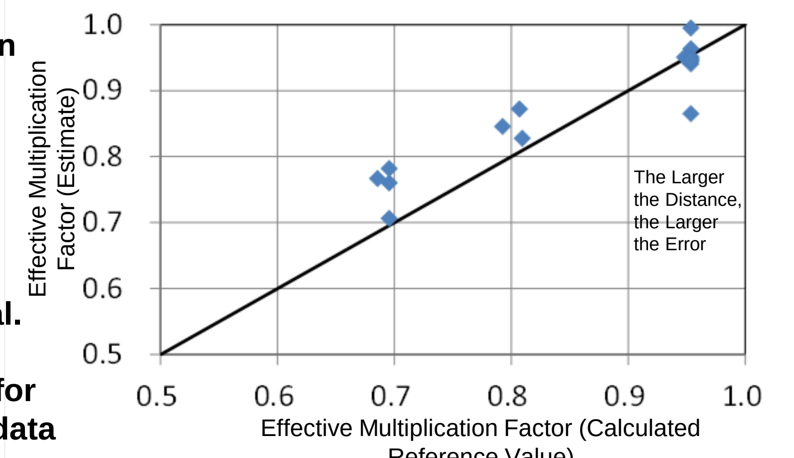


Figure 2 - Comparison of Sub-criticality Measurement Results and Calculated Reference Values

[Issues for Practical Application]

- To review the measurement time required on-site at 1F, requirements for retrieval equipment, and specific application methods, based on the data obtain from this test.

2.2 Development of Criticality Control Technologies (1) Critical Approach Monitoring Technologies
(iv) From maneuverability Test under High Radiation to Detector Specification Review

[Purpose]

- **To confirm the maneuverability of the neutron detector under a high-dose rate gamma ray environment derived from fuel.**

[Test Method]

- **Spent fuel storage facility (Nippon Nuclear Fuel Development Co., Ltd. (NFD))**
- **Change the distance between B-10 proportional counter and spent fuel assembly and measure the neutron count rate (test conducted in FY 2016).**

[Achievements]

- **The test provided an outlook that the target neutron detection sensitivity could be achieved even under a gamma ray environment at certain dose rates derived from fuel by building an appropriate shield.**
  High-sensitivity B-10: 2 cps/nv, Small-sized B-10: 0.2 cps/nv
- **The requirements for a shield (lead) under the 1000 Gy/h (*) environment are as follows:**
  High-sensitivity B-10: 2 cm, Small-sized B-10: 1 cm
- **Reviewed the detector specifications based on the test results.**
  Size & Weight: 350 mm * 310 mm * 130 mm, 150 kg

[Issues for Practical Application]

- **Test results revealed that the size and weight of a neutron detector installed the shield, a high-sensitivity detector, were larger than expected and should be installed closer to debris. Therefore, the criticality control project cooperated with the project of fuel debris retrieval method.**

*** Based on the results of investigation inside the PCV, estimation can be revised down to a lower value.**

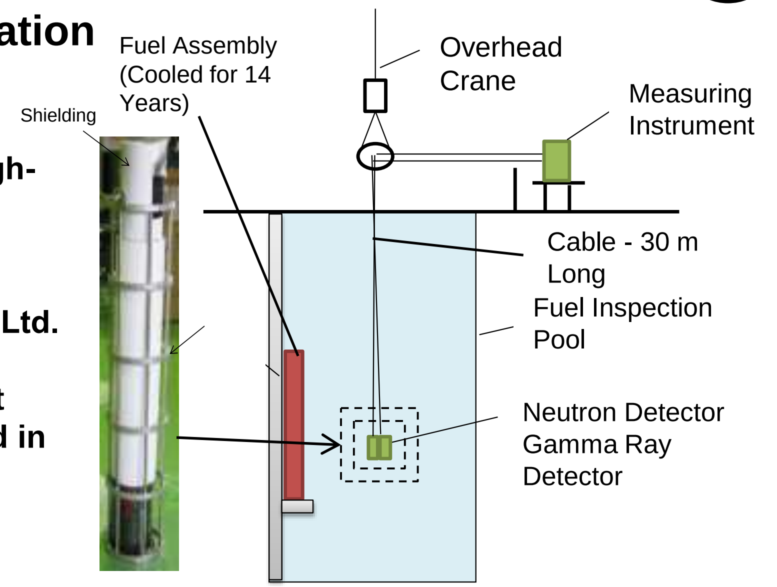


Figure 1 - Testing System Overview

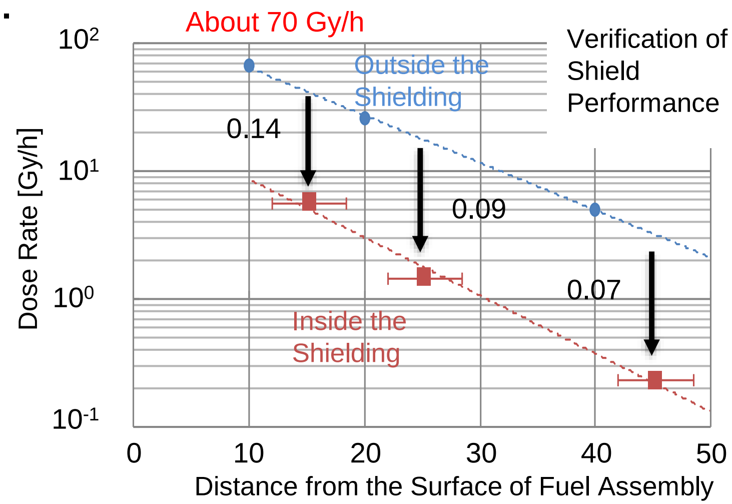


Figure 2 - Dose Rate at Test Position

2.2 Development of Criticality Control Technologies (1) Critical Approach Monitoring Technologies
(v) Application Method during Debris Retrieval

[Purpose]

- **To develop procedures for critical approach monitoring consistent with debris retrieval tasks.**

[Issues]

- **Sub-criticality level measurements based on the reactor noise method (Feynman α method) require 30 min or more of time.**

The frequency of sub-criticality measurements affects the daily retrieval workload.

⇒ Review a technique that enables monitoring in a short period of time by combining the reactor noise and neutron source multiplication methods (Figures 1 and 2)

[Achievements]

- **The review provided an outlook that, by reducing the measurement time for a single debris processing or retrieval task to a few minutes, the impact on the retrieval scheme can be removed.**

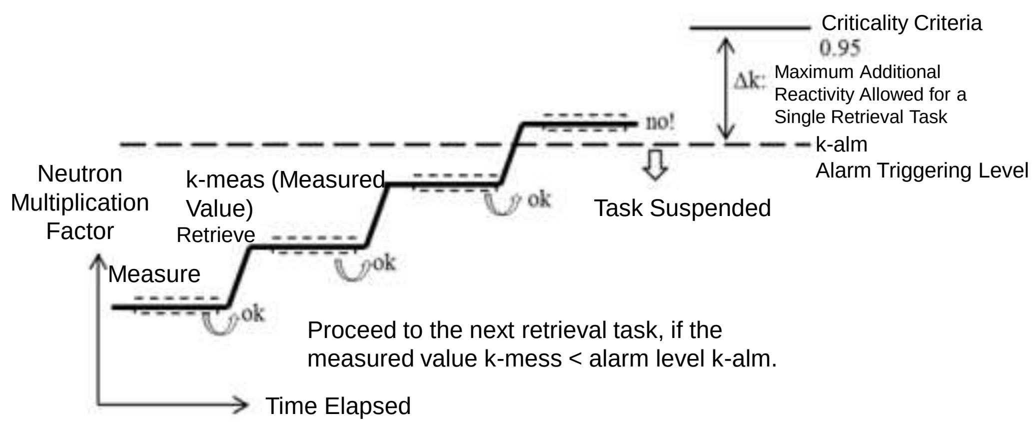


Figure 1 - Image of Criticality Prevention Through Critical Approach Monitoring

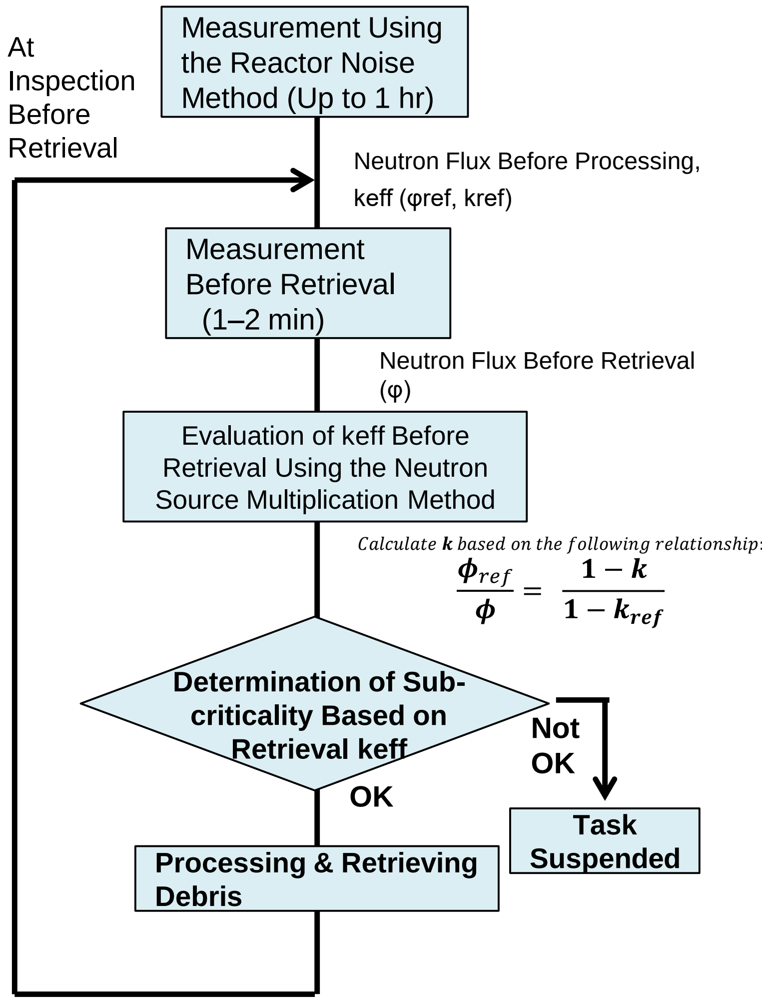


Figure 2 - (Proposed) Critical Approach Monitoring Flow

2.2 Development of Criticality Control Technologies (1) Critical Approach Monitoring Technologies
(vi) Outlook of Feasibility and Issues

[Achievements]

- **Confirmed the neutron measurement performance of the B-10 detector under a gamma ray environment at certain dose rates derived from fuel.**
  - **Shielding of the neutron detector is not required under a gamma ray environment at a dose rate up to 100 Gy/h.**
    Under a gamma ray environment at a dose rate up to 1000 Gy/h (*), lead shielding is required with a thickness of 2 cm (for high-sensitivity B-10) to 1 cm (for small-sized B-10).
- **In a functional test of the prototype system using a high-sensitivity B-10 detector, an offline sub-criticality measurement was able to be completed in a realistic period of time (i.e., within one hour).**
- **For factors that affect the sub-criticality measurement error (sub-criticality level, neutron spectrum, types and layout of the neutron source, layout of the neutron detector, and underwater/atmospheric condition), sensitivity data serves as a basis for design, and measurable conditions were identifies for a range of sub-criticality levels (0.7 < k < 0.95).**
- **It is necessary to position the detector within 20 cm from the debris in the water.**

⇒ Gained a general outlook for the critical approach monitoring technique currently being developed based on the Feynman α method.

[Issues for Practical Application]

- **To review the superimposition of factors affecting the sub-criticality measurement error and consider additional test conditions to confirm their effects.**
- **To put together system specifications and detector layout proposals based on the obtained data, and establish the concepts of equipment by consulting with the debris retrieval system project.**
- **To consider technologies to improve a method (AMETEK method) to reduce the measurement error.**
- **Preferably to conduct a verification test in a complicated and large-scale system simulating the actual debris, as the system that has been tested this time was relatively small and simple.**
- **To review small-sized detectors being considered by other projects as possible candidates.**

*** Based on the results of investigation inside the PCV this may be able to be revised down to a lower value.**

2.2 Development of Criticality Control Technologies (1) Critical Approach Monitoring Technologies
(v) Feasibility Evaluation of Critical Approach Detection System Using Virtual Neutron Capture Method

System Design

[Purpose] **To design equipment applicable to the neutron source multiplication and virtual neutron capture methods.**

[Method] **Review a shielding structure for the 1F environment (1000 Sv/h) based on the operation confirm test under a high-dose rate condition (conducted later year).**

[Achievements] **The detection unit including the shieling is expected to be 5 kg or less per unit.**

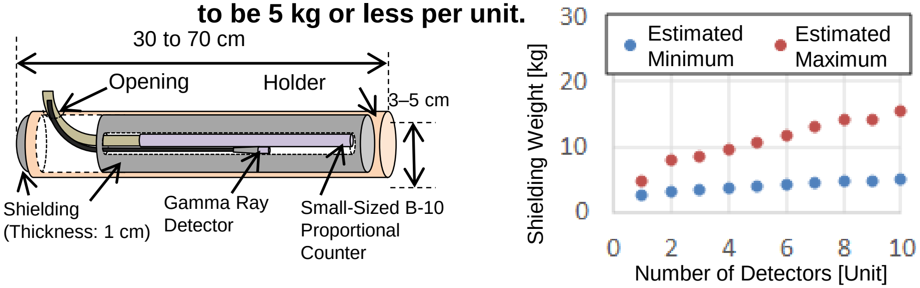


Figure 1 - Shielding Structure and Weight for the Actual Installation

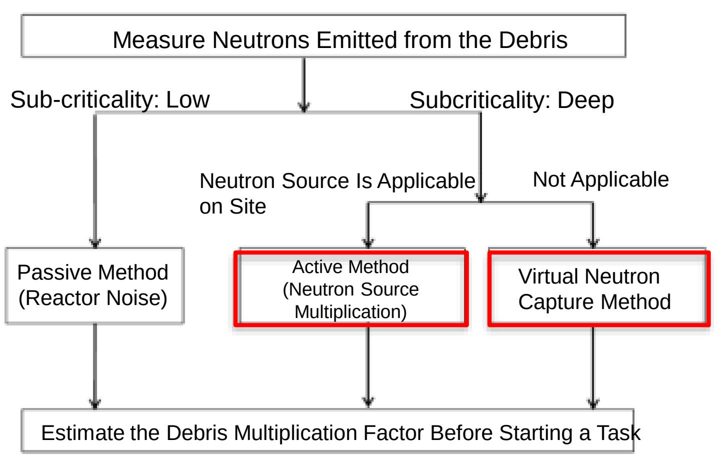


Figure 2 - Flow Chart of Critical Approach Monitoring Technologies

Feasibility Evaluation

[Purpose] **• To verify the operation of a prototype system.**

• To evaluate the feasibility of a system that adopts the critical approach monitoring technique.

[Method] **• Make measurements using a prototype system simulating a reactor core with various levels of sub-criticality.**

• Evaluate the sub-criticality level using the virtual neutron capture and neutron source multiplication methods.

• Evaluate the correlation between measurement time and statistical error.

[Achievements] **• For the virtual neutron capture method, the maximum difference, 4.3 dk%, was observed under a deep sub-criticality condition.**

• The maximum measurement time is 15 seconds to make the statistical error equivalent to 1 %dk or lower.

→ This provided an outlook that measurements can be made within a practical period of time.

[Issues for Practical Application]

• To confirm the degree of dependency of the neutron source multiplication

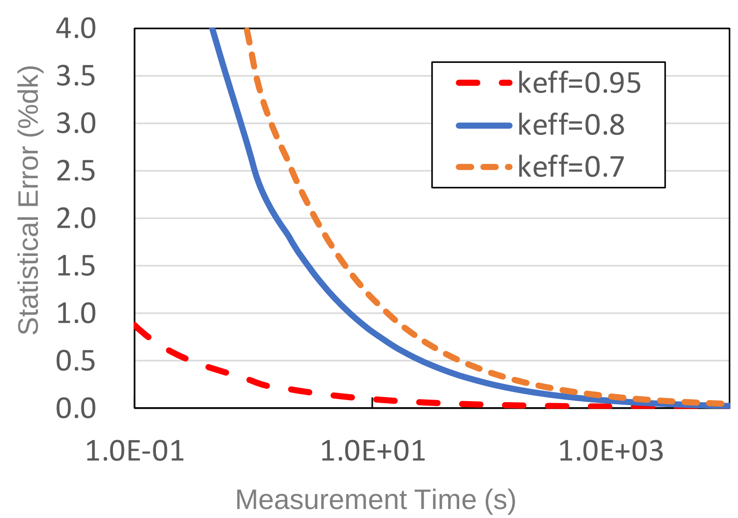


Figure 3 - Correlation between Measurement Time and Statistical Error

2.2 Development of Criticality Control Technologies (2) Developing Re-criticality Detection Technologies (i) Overview & Purpose

[Criticality Control Using a Gas Sampling System (PCV Exhaust Nuclides Analysis Monitoring)]

[Purpose] To detect re-criticality at an early stage in the process from water filling the PCV to fuel debris retrieval.
To apply it to the second layer (abnormality detection and impact mitigation).

[Current Condition] Continuous monitoring by measuring Xe-135 (250 keV) (criteria: 1 Bq/cm3).

[Proposal] The monitoring system is improved for measuring Kr-87 and Kr-88 and monitor criticality using the following in combination with the Xe-135 measurement:
(1) sub-criticality level evaluation for the entire system and (2) early critical approach.

- **Estimate the neutron source multiplication factor by using the yield difference between spontaneous and induced fissions. Currently at 0.5–0.7.**
  (Analysis results of Unit 1 data)

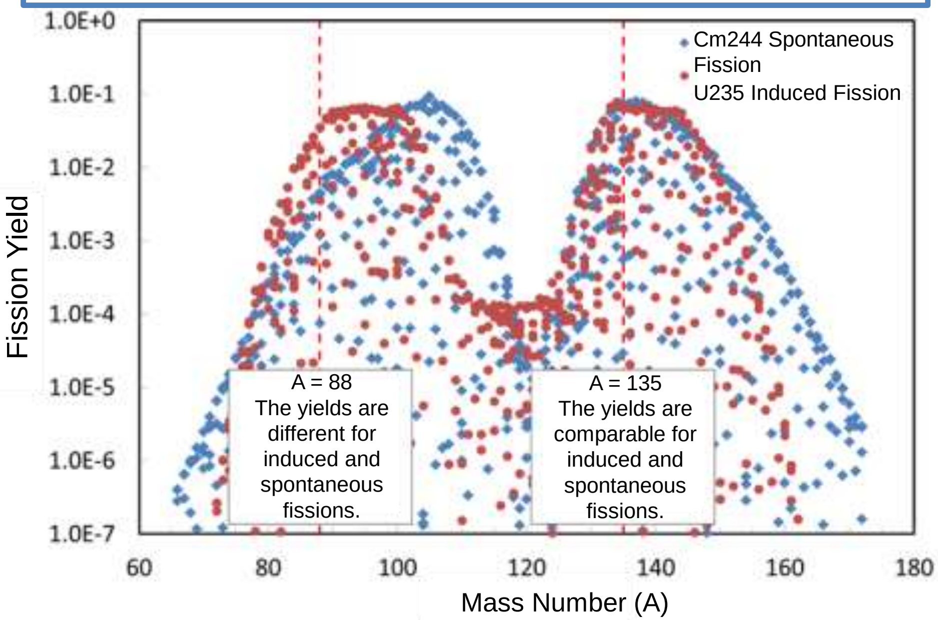


Figure 1 - Yields of Spontaneous and Induced Fissions

- **Detect critical approach quickly by detecting Kr88 that responds faster than Xe135.**

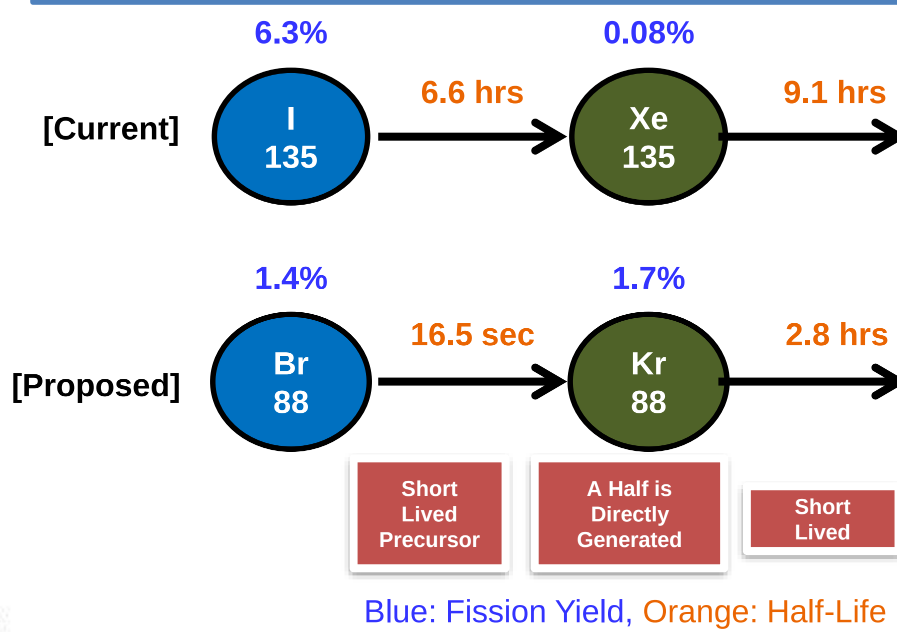


Figure 2 - Behaviors of Monitored Nuclides

2.2 Development of Criticality Control Technologies (2) Re-criticality Detection Technology
(ii) Achievements and Issues

No.	Issues	Actions Taken	Status
1	Select the measurement energy peak for target nuclides	On-site test at Unit 1	Completed
2	Determine system specifications that allow for early detection	Review detector and chamber configurations	Completed
3	Estimate a realistic detection time and set criteria for the actual installation	Gas behavior analysis, detectability when the target is partially in the air	Completed
4	Develop a gas activity concentration calibration technology (initial & maintenance)	Utilize overseas technologies	Under consideration*
5	Create optimal system design consistent with the retrieval method	Configure appropriate flow rate, channel, and detector for the method	In the future

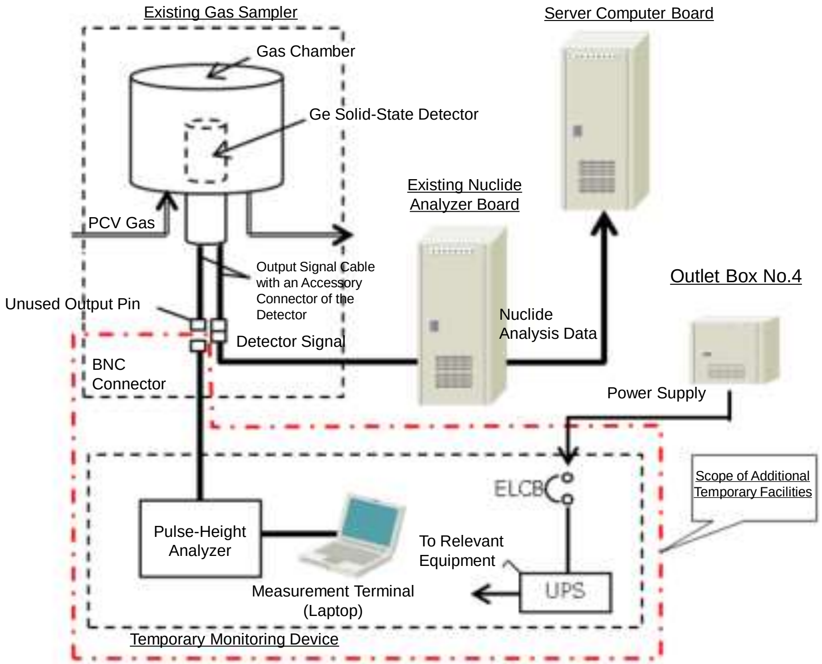
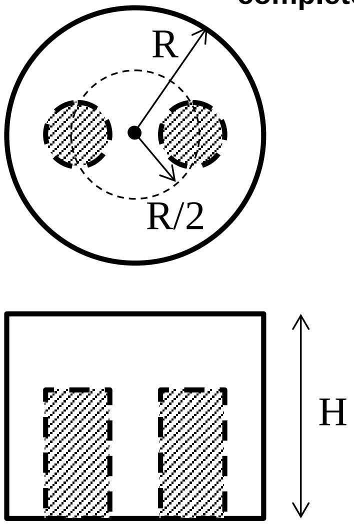


Figure 1 - On-Site Test System for Unit 1 Gas Sampling System

*** A desk study and test planning were completed in FY 2017.**



- 40 L cylindrical chamber
  H: 32.5 cm
  R: 21.0 cm
- The surroundings of the chamber are shielded with lead.
- Two Ge detectors are positioned inside the chamber.

Figure 2 - (Proposed) Chamber Profile of the Enhanced System

2.2 Development of Criticality Control Technologies (2) Re-criticality Detection Technology
(iii) Select the Measurement Energy Peak for Target Nuclides

[Method]

- Conduct a test at the actual installation of Unit 1

Table 1 - Calculated Concentration of Target Nuclides

Nuclides	Energy (keV)	Calculated Concentration (Bq/cm^3)
Xe-135	249.8	$(1.16 \pm 0.01) \times 10^{-3}$
Kr-87	402.6	$(7.72 \pm 0.70) \times 10^{-5}$
	2554.8	$(8.39 \pm 1.54) \times 10^{-5}$
Kr-88	196.3	$(2.06 \pm 0.11) \times 10^{-4}$
	2392.1	$(1.69 \pm 0.06) \times 10^{-4}$

[Achievements]

- For Kr-88, it was determined that measurements on the higher energy side would be more appropriate.
- There were differences in the calculated concentration for different energy levels at which measurements were made.
- There were differences in the activity concentration of systems A and B.
  ⇒ Need to consider a calibration technology

[Issues for Practical Application]

- To establish a calibration technology (leveraging overseas technology).
- To determine the system specifications.

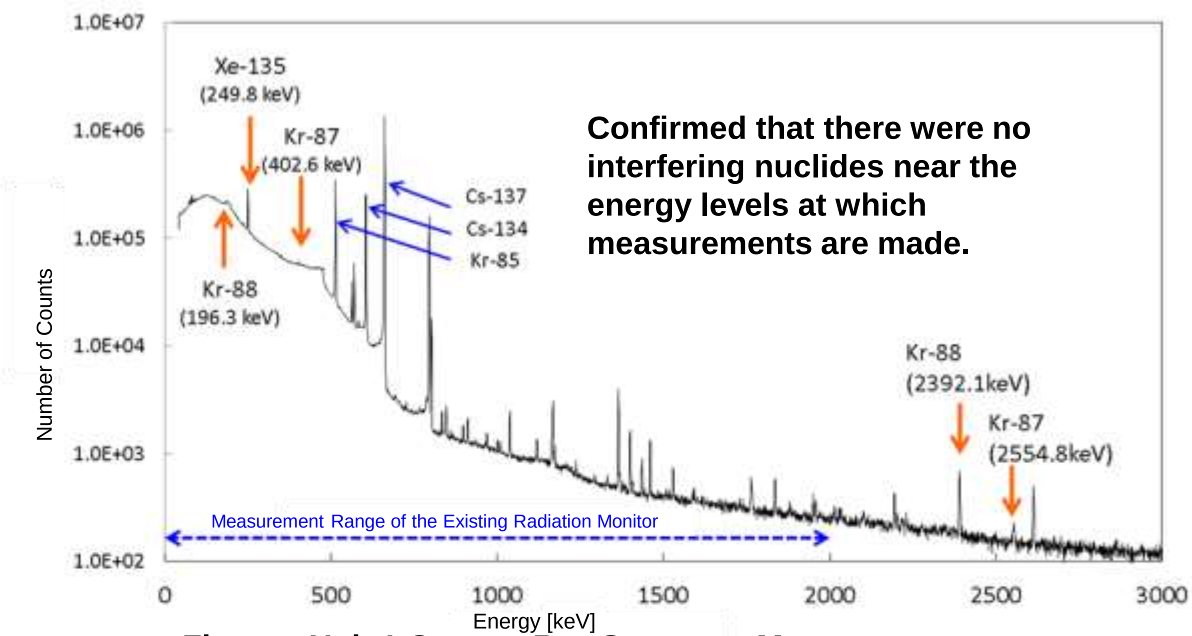


Figure - Unit 1 Gamma Ray Spectrum Measurement Results (Total)

2.2 (2) Developing Re-Criticality Detection Technologies

[Estimate a realistic detection time and set criteria for the actual installation]

[Method]

(1) Estimate the detecting time by analyzing behaviors during criticality by capturing diluted gas behavior.
- Evaluate the concentration rise of Kr-88 at the radiation monitoring position.
- Compare to actual measured radiation concentration.
- Incorporate it as a transfer function model into the analysis of behaviors during criticality.

(2) Review the system's capability to know the sub-criticality level under quasi-steady operating conditions during retrieval in atmospheric conditions.

[Achievements]

(1) It is expected that it is possible to detect in a shorter period of time (about 0.5 hrs) than originally estimated (3 hrs).

(2) It is expected that it is possible to estimate the sub-criticality of the entire system under quasi-steady operating conditions.

⇒ Capabilities to detect critical approach at an early stage and know the sub-criticality level of the entire system during a transition period.

[Issues for Practical Application]

- To review concrete details of the monitoring technology, including other aspects besides the retrieval position.

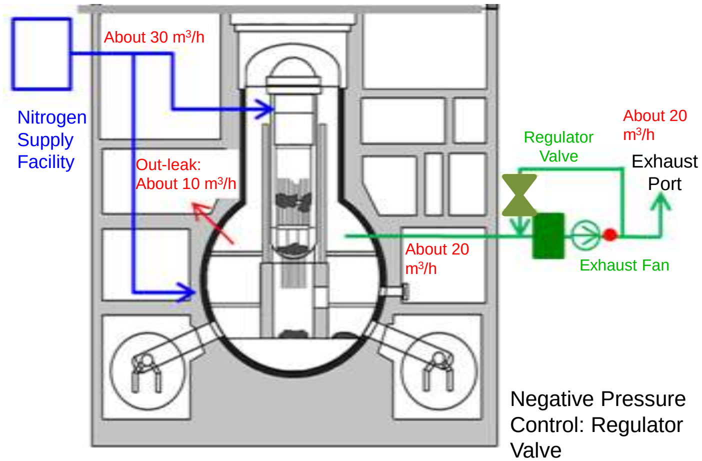


Figure 1 - Current System Configuration

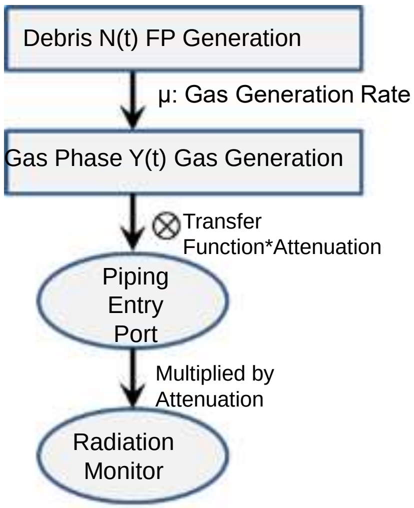


Figure 2 - Capturing Noble Gas Behaviors for Analysis of Behaviors During Criticality

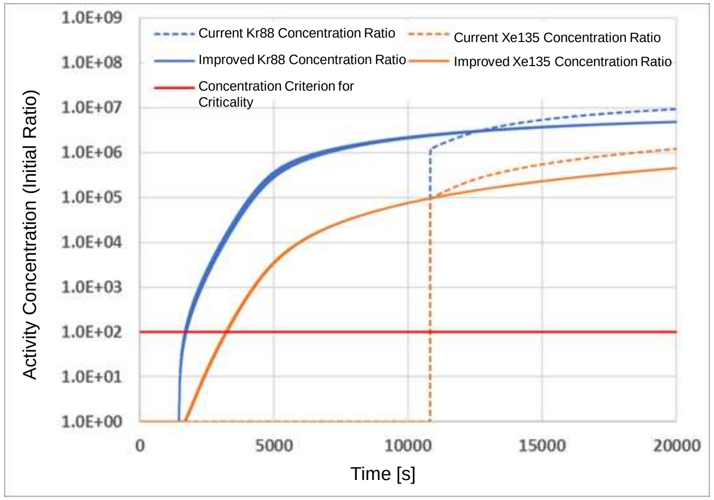


Figure 3 - Change of Activity Concentration During Criticality (Assuming a case where debris adhered to CRD is dropped)

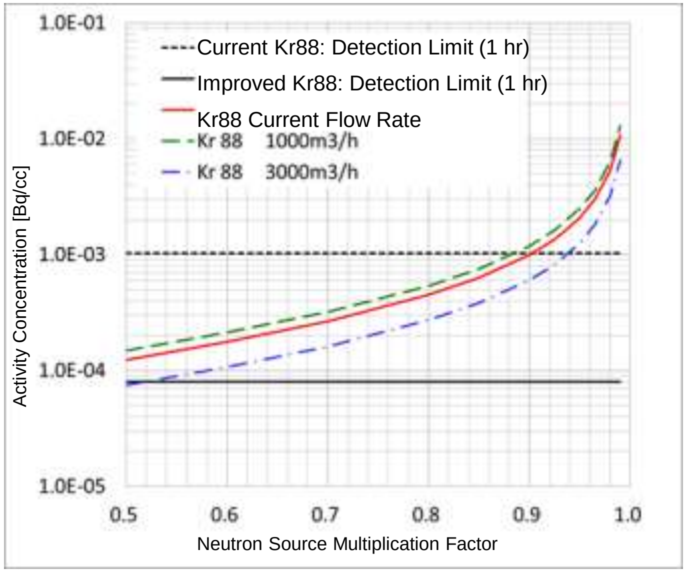


Figure 4 - Applicability to Sub-Criticality Estimate for Retrieval in a Partially Dry Condition

2.2 Development of Criticality Control Technologies (2) Re-criticality Detection Technology
(iv) Calibration Technology of PCV Gas Radiation Monitor


Figure 1 - Research Wing of NPL in U.K.

[Technical Issues for Calibration]

(1) How to generate and purify radioactive noble gas
(2) How to determine the composition of radioactive noble gas
(3) How to handle radioactive noble gas
(4) Design a gas circuit for calibration procedures
(5) Clearly identifying traceability and uncertainties
(6) Conformance to the regulations

[Research Partner for This Year: National Physical Laboratory (NPL) of UK]

- A core research institution highly regarded internationally in metrology and material science.
- Responsible for the development and maintenance of measurement standards in the UK.
- Provides scientific support services to measurements in industry and health care.


Figure 2 - Accelerator Experiment Facility

[Achievements of This Year (Desk Study)]

Methods to generate radioactive noble gas by irradiating enriched uranium owned by NPL inside a thermal neutron pile.

(1) Purification methods for Kr-87 and 88, including the removal of fine particles and volatile substances.
(2) Methods to quantitatively determine the activity concentration of Kr-87 and 88 using γ ray spectrometry based on gas proportional counter.
(3) Review the gas circuit* and calibration procedures.
(4) Evaluation of expected levels of precision.
(5) Confirmationissues related to the regulations.


Figure 3 - Thermal Neutron Pile

[Issues for Practical Application]

To quantify uncertainties by performing trial calibrations.

(* Gas circuit: A circuit that measures the activity of radioactive noble gas by circulating it in the scavenging gas.)

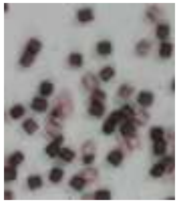
IRI

2.2 Development of Criticality Control Technologies (3) Criticality Prevention Technologies (i) Insoluble Neutron Absorber (i) Overview

[Concepts of Candidate Materials]

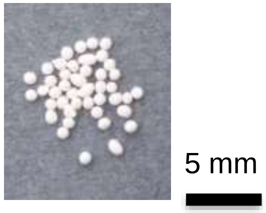
- **Developed as an alternative to the soluble neutron absorber. Used by directly spraying these materials during debris retrieval.**
- **Candidate materials containing highly concentrated B or Gb in three forms to support various types of fuel debris.**

Form	Expected Properties			Candidate Materials
	Invasiveness into Gaps and Cracks of Debris	**Ability to Fit with Changes in Debris Shape Caused by Retrieval**	**Adhesiveness to Tilted Debris Surface**	
Solid	○	○	-	B_4C sintered metal material
				Glass material containing B or Gd
				Gd_2O_3 particle
Liquid → Solid (Solidification material)	○	-	○	Cement/Gd_2O_3 granulated powder material
				Liquid glass/Gd_2O_3 granulated powder material
				Water curable resin/Gd_2O_3 powder material
Viscous Material	○	○	○	B_4C gel material
				Slurry/Gd_2O_3 particle



B_4C sintered metal material

Glass material containing B or Gd



Gd_2O_3 particle

Liquid glass/Gd_2O_3 granulated powder material (After hardened)

Candidate materials were selected as one of the accomplishments in FY 2017, based on the results of confirmation of neutronics, a long-term irradiation test, and a workability test (shaded in yellow).

2.2 Development of Criticality Control Technologies (3) Criticality Prevention Technologies (i) Insoluble Neutron Absorber (iii) Confirmation of Nuclear Properties

Flow of Selecting Candidate Material

Basic Physical Property Confirmation → Radiation Resistance Performance Test → Nuclear Properties Confirmation Test

[Sample Reactivity Worth Measurement in KUCA]

- This is the final phase of selecting candidate materials.
  Five types of materials, selected based on their performance in the radiation resistance performance test, etc., are considered.
- The aim is to confirm their neutronics (neutron absorbing ability) , contribute in verification of analysis technologies, and acquire data required to obtain permissions and authorizations.
- Sample reactivity worth measurement for neutron absorber.

[Achievements]

- Except for Gd_2O_3 particles, the measurement and analysis values matched within a measurement error of 3σ.

  → Confirmed that the neutronics and analysis precision were generally favorable.

  For Gd2O3 particles, the reason for this result is estimated that, as their particle size is large (a few hundred μm), the layout inside the vessel cannot be exactly simulated.

- The tendency was comparable even when the neutron spectrum was changed (to over-moderation at H/U235=322).

Table 1 - Comparison between Reactivity Worth Measurements and Analysis Values

Neutron Absorber	Measured Value ± 1σ (%Δk/k)	C/E
B_4C sintered metal material	0.598 ± 0.052	1.19
Glass material containing B or Gd	0.656 ± 0.048	1.20
Gd_2O_3 particle	0.536 ± 0.036	1.28
Liquid glass	0.463 ± 0.028	1.15
Water curable resin	0.479 ± 0.031	1.05

Optimal Neutron Spectrum Moderation (H/U235=107)

[Issues for Practical Application]

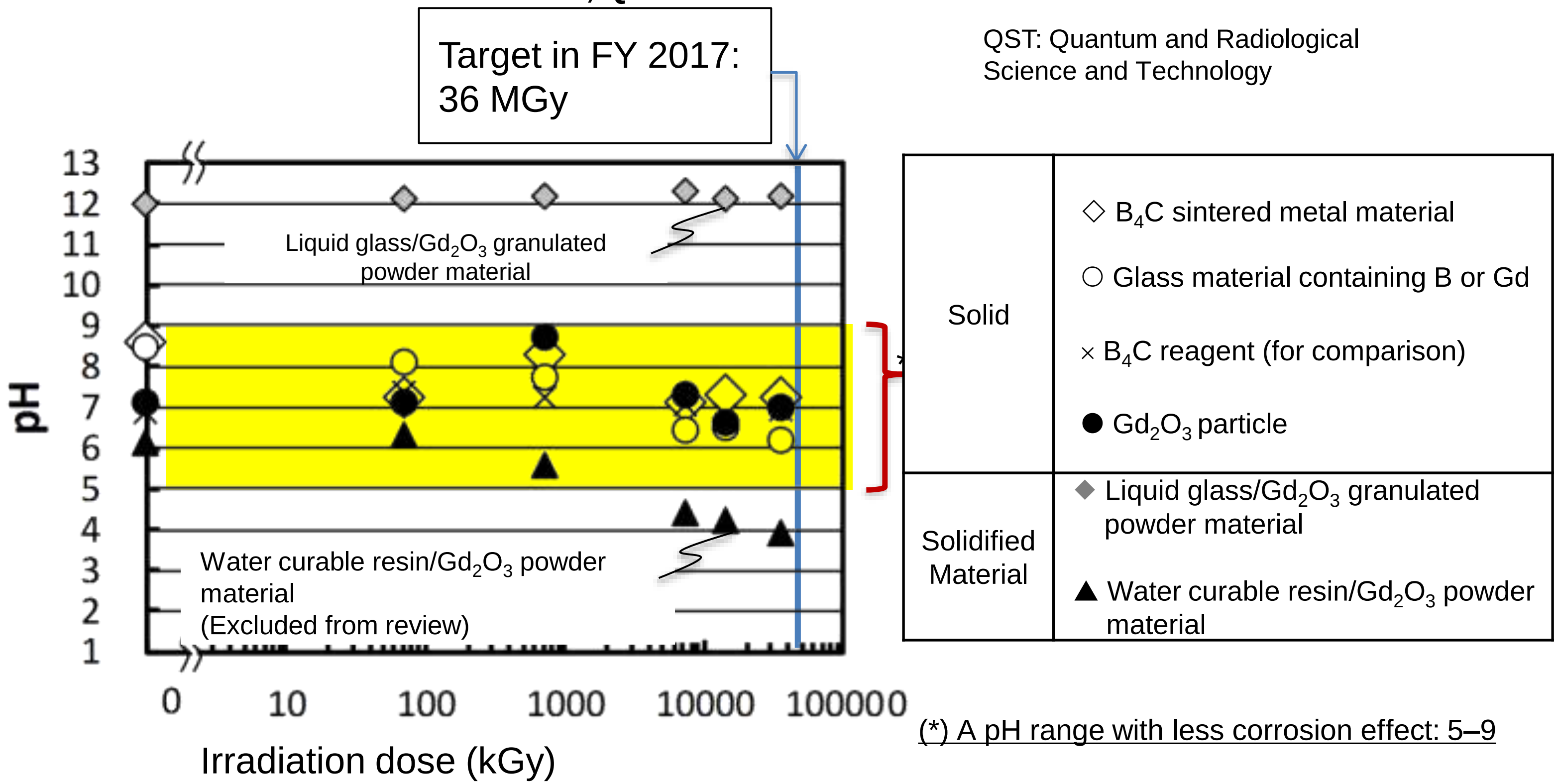
- To study performing measurements by changing the loading amount, location, etc. of the neutron absorber, and enhance the reliability by way of reproduction tests to reduce uncertainties.

2.2 Development of Criticality Control Technologies (3) Criticality Prevention Technologies (i) Insoluble Neutron Absorber (iv) Long-Term Irradiation Test

[Long-Term Irradiation Test]

- **Acquire data to evaluate secondary effects (hydrogen generation and corrosion) of post-retrieval process.**
- **Select candidate materials to be used in a long-term irradiation test and conduct the long-term irradiation test at Takasaki Advanced Radiation Research Institute, QST.**

QST: Quantum and Radiological Science and Technology



(*) A pH range with less corrosion effect: 5–9

Figure 1- Review Results and Plans for Corrosion Risk Arising from Leached Components Caused by Long-Term Irradiation (Example)

(Test solution pH after a leaching test of gamma radiation materials at 80°C)

[Achievements] • **Selected candidate materials assuming they would remain in the reactor and be stored in storage canisters.**

[Issues for Practical Application] • **To improve reliability by adding data.**

2.2 Development of Criticality Control Technologies (3) Criticality Prevention Technologies (i) Insoluble Neutron Absorber (v) Work MethodDuring Debris Retrieval

[Implementation Items]

- **After dropping a neutron absorber onto a specimen (lava) simulating the corrugated surface of the debris, the expanse, coating thickness, and weight of the adhered absorber was measured and the adhesiveness evaluated.**

(Liquid glass based and water curable resin based neutron absorbers)

- **Conducted tests on flat plate, granular lava (about a few cm in size), and plate lava specimens.**
  *** Water curable resin was tested only for flat plate and plate lava specimens.**

[Fundamental Adhesiveness Test]

[Achievements]

- **Evaluated the required input amount for the plate and granular lava specimens simulating the debris.**

[Where to Apply These Achievements]

- **Review of the installation methods of insoluble neutron absorbers.**
- **Reflect them on the final selection of candidate materials, facility requirements, and procedures for debris retrieval.**

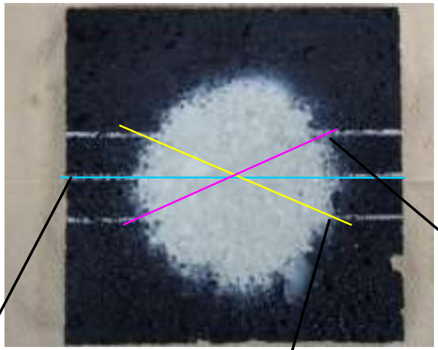
[Issues for Practical Application]

- **Combined test for transportability and workability.**
- **Study on the applicable methods based on the test data.**
- **Study on the impacts on the retrieval process.**

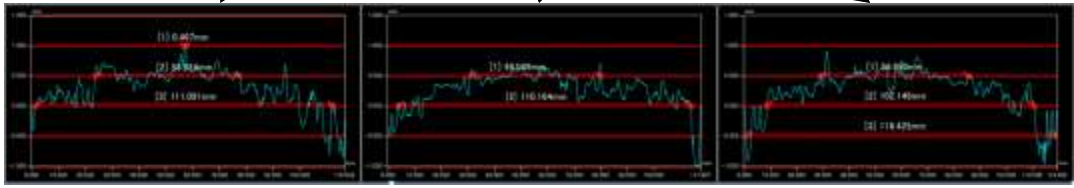
(Processability, visibility, impact on the water treatment system, and equipment configuration)

Plate Lava

Neutron absorber flowing down while expanding in the water



Evaluate the area where the thickness of the adhered neutron absorber meets the prescribed coating thickness (tentatively set to 1 mm)



Measured Sectional Profile of Neutron Absorber Adhered to Plate Lava
(Materials: Liquid glass TX-10, Viscosity: 2000 [mPa･s], Distance between nozzle and substrate: 56 [mm], Underwater environment, and Temperature: 20 [°C])

Neutron Absorber Flowing Down in the Water (Input Amount: 1000 [g])

Granular Lava

Measured Weight of Neutron Absorber Adhered to Granular Lava

Viscosity [mPa•s]	Input Amount [g]	Number of Tests	Weight Increase [g]	Weight Increase (Average) [g]
2000	1000	1	109.2	107.3
		2	105.4	
	100	1	19.5	21.5
		2	23.4	

2.2 Development of Criticality Control Technologies (3) Criticality Prevention Technologies (i) Insoluble Neutron Absorber
(v) Work Methods During Debris Retrieval - Evaluation of Compatibility with Anti-Corrosive Agents

[Implementation Items]

• Conducted tests on flat plate, granular lava, and plate lava specimens and evaluated the impact of an anti-corrosive agent environment on the solidification characteristics and adhesiveness of the insoluble neutron absorber (liquid glass based neutron absorber).

• Evaluated the changes in anti-corrosive agent solution before and after the test.

[Test to Study the Impact of Compatibility with Anti-Corrosive Agents]

[Achievements]

• Evaluated the impact of an anti-corrosive agent environment on the solidification characteristics and adhesiveness of the insoluble neutron absorber.

→ Confirmed the solidification characteristics and adhesiveness to the lava simulating the debris.

→ Reactants were generated for anti-corrosive agent 1 (dependent on the amount of boron).

• Analyzed and evaluated whether there were changes in an anti-corrosive additive component contained in the solution.

→ No significant changes were observed.

[Where to Apply These Achievements]

• Review of the work methods of insoluble neutron absorbers.

• Reflect them on the final selection of candidate materials, facility requirements, and procedures for debris retrieval.

[Issues for Practical Application]

• Combined test for transportability and workability.

• Study on the applicable methods based on the test data.

• Study on the impacts on the retrieval process.

(Processability, visibility, impact on the water treatment system, and equipment configuration)

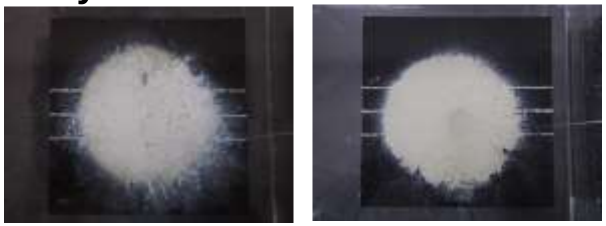
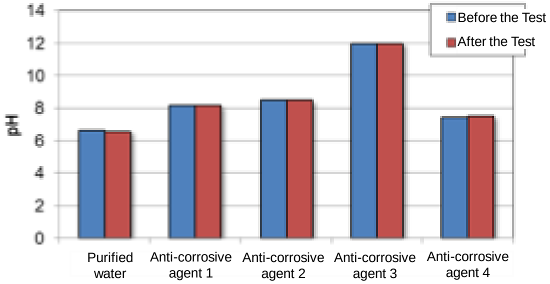


Image of Neutron Absorber Adhered to Plate Lava (Temperature: 20 [°C])
(Left: Sodium pentaborate (anti-corrosive agent 1),
Right: Zinc/sodium molybdate mixed phosphate (anti-corrosive agent 3))

Sampling for Water Quality Analysis



Water Analysis Results for Samples Before and After the Test
(Impact Assessment of Anti - Corrosive Agent)

Measured Weight of Neutron Absorber Adhered to Granular Lava

Measured Weight of Neutron Absorber Adhered to Granular Lava

Viscosity [mPa•s]	Input Amount [g]	Test Atmosphere	Number of Tests	Weight Increase [g]	Weight Increase (Average) [g]
2000	1000	Anti-corrosive agent 1	1	141.2	160.2
			2	179.1	
	1000	Anti-corrosive agent 3	1	100.5	98.8
			2	97.0	
	1000	Underwater	1	109.2	107.3
			2	105.4	

Anti-corrosive agent 1: Sodium pentaborate
Anti-corrosive agent 2: Sodium tungstate + Sodium pentaborate
Anti-corrosive agent 3: Phosphate-based anti-corrosive agent (Zinc/sodium molybdate mixed phosphate: ZSMMP)
Anti-corrosive agent 4: Phosphate-based anti-corrosive agent (Zinc/sodium carbonate mixed phosphate: ZSCMP)

2.2 Development of Criticality Control Technologies (3) Criticality Prevention Technologies (i) Insoluble Neutron Absorber (v) Work Method During Debris Retrieval

[Workability Evaluation]

- Sorted out workability evaluation items for the candidate materials, and confirmed the adhesiveness and transportability of the solidified materials in a laboratory-scale test.
- Confirmed that, for solid materials, no significant problems were found in a basic study of these materials' ability to be manufactured into a specified shape using a mass-producible method to demonstrate their gap permeability.

Form	Candidate Materials	Mixability with Debris	Adhesiveness to Debris				Transportability
		Gap Permeation	Coating of Tilted Surface - Flat Plate	Coating of Horizontal Surface - Flat Plate	Plate Lava	Granular Lava	
Solid	B_4C sintered metal material	○					
	Glass material containing B or Gd	○					
	Gd_2O_3 particle	○					
Liquid → Solid (Solidified Material)	Cement/Gd_2O_3 granulated powder material	⊙	⊙	⊙	*3	*3	*3
	Liquid Glass/Gd2O3 Granulated Powder Material	○	∆	○	○	○	Can be transported 50 m with a squeeze pump by controlling the viscosity.
	Water curable resin/Gd2O3 powder material	○	○	○	The material was contracted and floated up during underwater work (issue of underwater workability).		
Viscous Material	B_4C gel material	*1	*1	*1	*1	*1	*1
	Slurry/Gd_2O_3 particle	⊙	○	*2	*2	*2	*2

*1: B4C gel material was not tested since it did not meet the requirements for leaching characteristics.
*2: Slurry/Gd_2O_3 particles were excluded from the review because they solidified as a result of irradiation.
*3: Cement/Gd_2O_3 granulated powder was excluded from the review because its alkaline components were leached as a result of irradiation.

Permeation depth of 2 mm wide gap
⊙ 100 mm or more
○ 50-100 mm
∆ Less than 50 mm

Coating of Tilted Surface:
⊙ Good adhesiveness
○ Relatively good adhesiveness
∆ Need to improve adhesiveness

[Achievements]

- Confirmed the workability of expected debris shapes. It is expected that the insoluble neutron absorbers can be thrown in in an amount required for criticality prevention. Four types of candidate materials in two forms were selected (shaded in yellow).

[Issues for Practical Application]

- To confirm the insoluble neutron absorbers' ability to fit with the shape of the debris after it has been processes (crushed, for example).
- To confirm the transportability in a full scale test
- To consider alternatives for cases where the location cannot be identified for a target such as accumulated debris powder caused by cutting.

2.2 Development of Criticality Control Technologies (3) Criticality Prevention Technologies (ii) Soluble Neutron Absorber (i) Confirmation of Nuclear Properties

[Purpose]

- **To confirm the neutronics (neutron absorption capability) of highly concentrated sodium pentaborate solution and verify analysis technologies for calculating criticality.**

[Test Details]

- **Sample reactivity worth measurement in KUCA**
  Tested for 6,000 and 12,000 ppm

  Compared with the nuclear calculation code analysis results

[Test Results]

- **Confirmed the neutron absorber's reactivity effect and that the predictability was generally good for nuclear calculation using the criticality calculation code.**

	H/U235 of the System	Boron Concentration ppm	Sample Loading Position	Measured Value (C) %Δk/k	Difference in Measured and Calculated Values %Δk/k
Sample Value	322	6,000	r16 of Mount A	0.017	0.005
Sample Value	107	6,000	q14 of Mount B	0.224	-0.001
Sample Value	107	12,000	q14 of Mount B	0.356	-0.001
Sample Value (Reproduced)	107	6,000	q14 of Mount B	0.226	-0.001

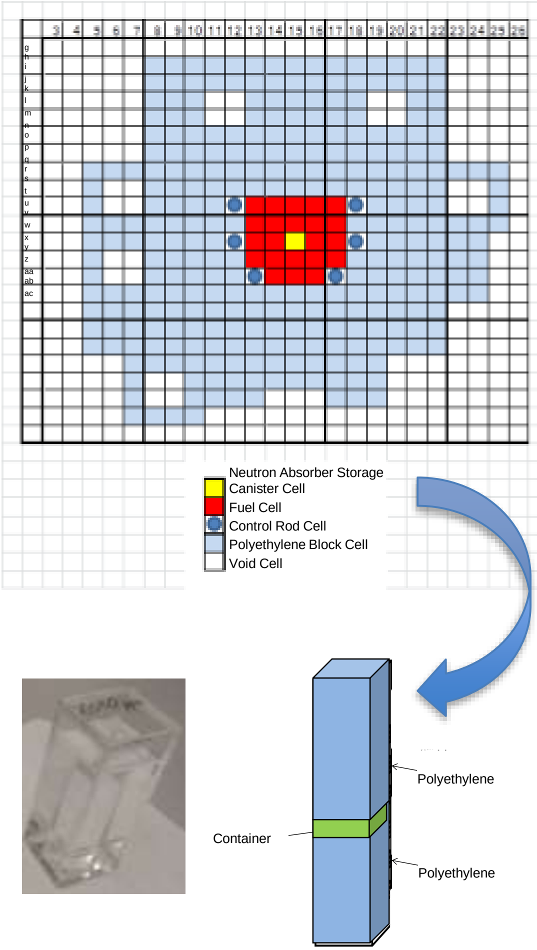


Figure 1 - Test System (Mount A)

[Achievements]

- **Test results proved that highly concentrated sodium pentaborate solution can be handled with the same precision in a conventional manner in evaluating criticality.**

2.2 Development of Criticality Control Technologies (3) Criticality Prevention Technologies (ii) Soluble Neutron Absorber
(ii) Facility Feasibility Confirmation for Maintaining Concentration

[Purpose]

To study the system that collects sodium pentaborate solution leaked from the PCV to the torus room and mixed with groundwater, adjusts its concentration, and then returns it to the circulation loop.

[Achievements]

- **Confirmed the basic feasibility of a proposed facility configuration for maintaining the concentration of sodium pentaborate solution (service conditions: 7,000 ppm) by requesting to the project for upgrading fuel debris retrieval methods (system review).**
  - **Reviewed operation methods (under normal/abnormal conditions).**
- **Confirmed (on a calculation basis) that boron deposition does not decrease even when the sodium pentaborate solution co into contact with the concrete.**

[Issues for Practical Application]

- **The project for the study on fuel debris retrieval methods (system review) will continue to review the feasibility of the system using a boric acid solution.**
- **To select and review measures against operation methods for maintaining the level of concentration and unexpected events in collaboration with the system review project.**

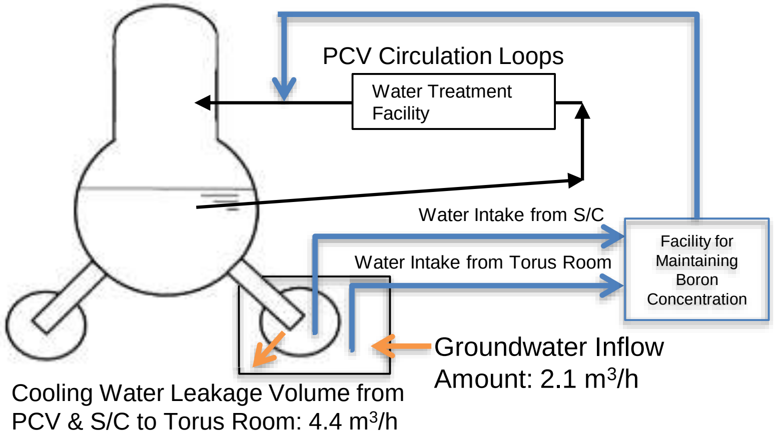


Figure 1 - Overview of the Facility for Maintaining Boron Concentration

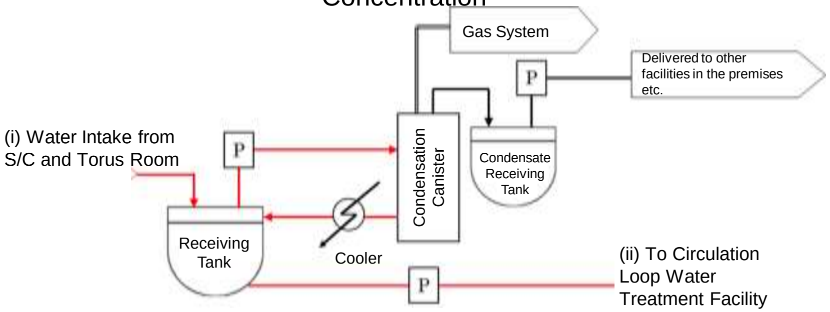


Figure 2 - Boron Condensation System with Condensed Canister

Table 1 - Approximate Dimensions of Each Equipment

Equipment Name	Volume, Throughput	Quantity	Approx. Dimensions per Unit
Receiving Tank	About 40 m^3/unit	2 units	φ4 m × 3 m
Condensation Canister	About 10 m3/h (Evaporation)	2 units	8 mW × 7 mL × 7 mH
Cooler	About 0.25 MW	1 unit	φ1 m × 3 m
Condensate Receiving Tank	About 10 m3/unit	2 units	φ2 m × 3 m

3. Overall Summary

Achievements	Issues to be Solved Before Practical Application
[Establishing Criticality Evaluation Technologies] • Elaborate criticality scenarios and risk evaluation by reflecting latest know-hows. • Establish evaluation methods for behaviors during criticality and exposure, and confirm that the exposure dose is lower than the normal level for representative events. • Set the objective of criticality control and establish the concepts based on the defense in depth	• Continue to update based on the results of investigation inside the PCV. • Evaluation based on the conditions in each process up to the full-scale retrieval. • Determine concrete details of control method (e.g., policy for the application of neutron absorbers, etc.) in light of the progress in retrieval method reviews.
[Developing Criticality Control Technologies] • Monitor critical approach: Establish a critical approach monitoring method based on the reactor noise method and confirm its basic feasibility. • Detect re-criticality: Establish an enhanced criticality detection method using Kr monitoring. • Neutron absorber: Select insoluble absorber candidates and confirm their applicability to the debris system. Establish a soluble absorber facility and its application method.	• Validation assuming the on-site conditions of 1F (i.e. sub-criticality level measurement in complexity systems and on-site measurement system feasibility). Determine concrete details of methods to mount the neutron detector to the retrieval facility. • Determine concrete details of the on-site application method for, for example, Ge detector calibration method, and confirm detectability in light of system conditions up to full-scale retrieval. • Determine concrete details of the on-site facilities & application methods, and their compliance assurance with the debris processing method. • Determine concrete details of the boric acid solution system operation method.

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