Development of Fuel Debris Retrieval Technology at IRID

The 1st International Forum on the Decommissioning of the Fukushima Daiichi Nuclear Power Station

Spa Resort Hawaiians

April 11, 2016

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International Research Institute for Nuclear Decommissioning (IRID)

The results explained here have been obtained under subsidies to development costs for nuclear decommissioning and safety technologies, granted by the Ministry of Economy, Trade and Industry.

Outline of IRID

1. Name

International Research Institute for Nuclear Decommissioning (IRID)

2. Establishment

August 1, 2013: Establishment of IRID was approved by the Minister of Economy

2. Location of Headquarters

5F 3Toyo Kaiji Building, 23-1 Nishi-shinbashi 2-chome, Minato-ku
Tokyo 105-0003, Japan
TEL: +81 3 6435 8601 (representative)
website: http://www.irid.or.jp/en

3. Membership (18)

Research Institutes: Japan Atomic Energy Agency (JAEA), National Institute of Advanced Industrial Science and Technology

Manufacturers, etc.: TOSHIBA Corporation, Hitachi-GE Nuclear Energy, Ltd., Mitsubishi Heavy Industries, Ltd., ATOX Co., Ltd.

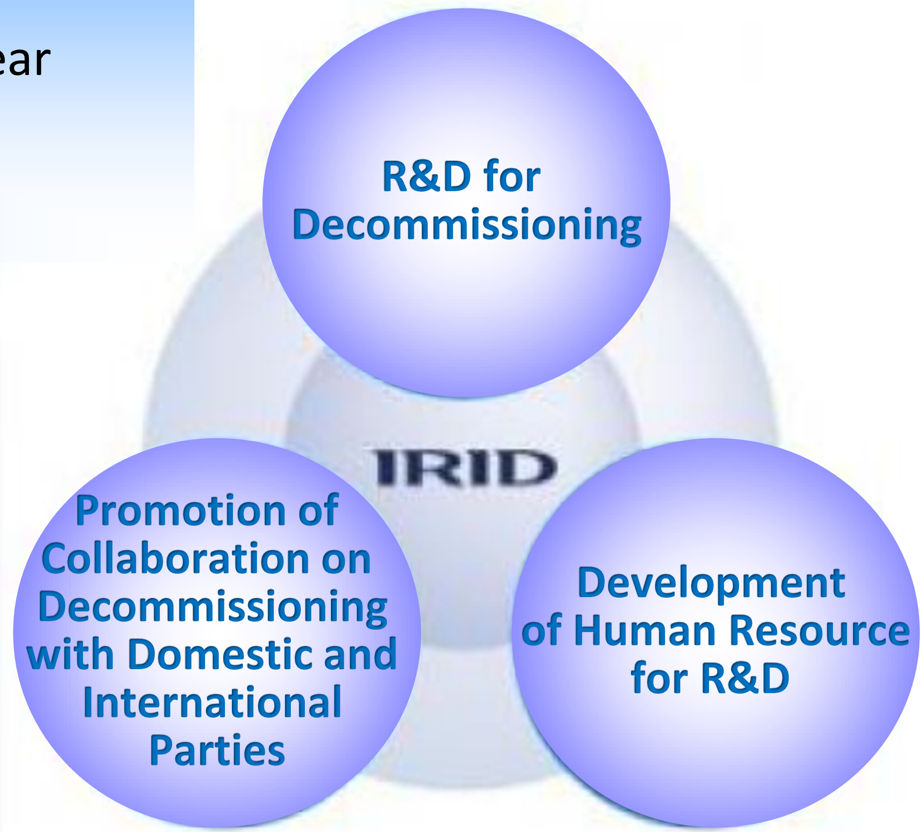
Electric Utilities, etc.: Hokkaido Electric Power Co., Inc., Tohoku Electric Power Co., Inc., Tokyo Electric Power Co., Inc., Chubu Electric Power Co., Inc., Hokuriku Electric Power Company, Kansai Electric Power Co., Inc., The Chugoku Electric Power Co., Inc., Shikoku Electric Power Co., Inc., Kyushu Electric Power Co., Inc., The Japan Atomic Power Company, Electric Power Development Co., Ltd., Japan Nuclear Fuel Limited

Scope of Business

IRID gathers knowledge and ideas from around the world for the purpose of R&D in the area of nuclear decommissioning under the integrated management system.

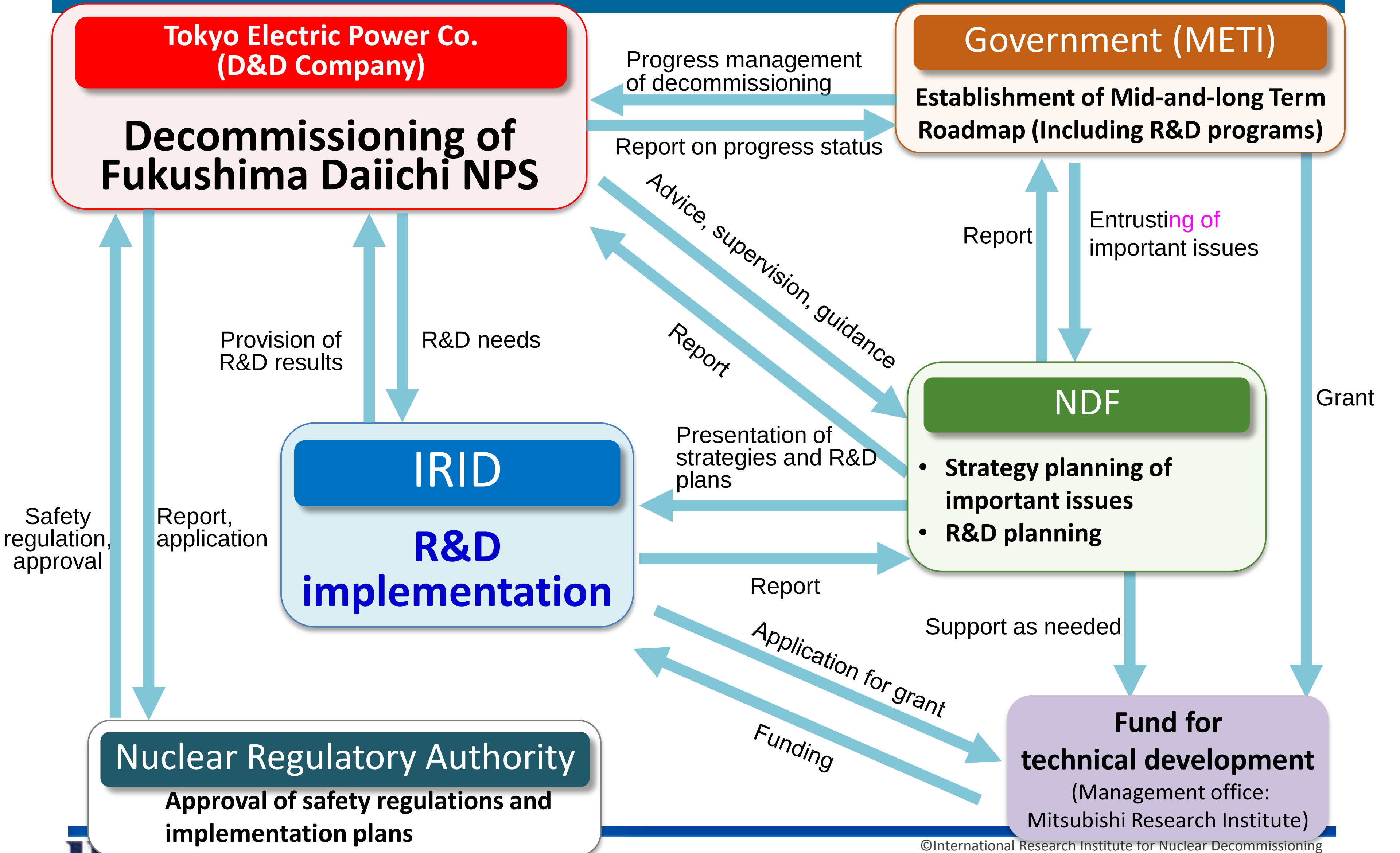
R&D projects:

- Fuel Removal from spent fuel pool
- Preparation for fuel debris retrieval
- Treatment and disposal of radioactive waste



Role of IRID

IRID focuses on a current urgent challenge—R&D for decommissioning of the Fuskushima Daiichi NPS—with a view to strengthening the foundation of nuclear decommissioning technologies.



IRID's R&D Projects

R&D for Fuel Removal from Spent Fuel Pool

- Evaluation of Long-term Structural Integrity of Fuel Assemblies Removed from the Spend Fuel Pool

Decontamination/Dose Reduction

<Securing of work environment>

- Remotely Operated Decontamination Equipment
- Reliability Evaluation of Remotely-operated Decontamination Equipment

Debris Retrieval

<Securing of stable condition>

- PCV/RPV Integrity Evaluation
- Criticality Control in Fuel Debris Retrieval

<Fuel debris retrieval>

- Upgrading of Retrieval Method for Fuel Debris & Reactor Internals
- Fundamental Retrieval Technology for Fuel Debris & Reactor Internals
- Collecting, Transferring and Storing of Fuel Debris

Repair and Water Leakage Stoppage of PCV

- Repair and Water Stoppage Technology of PCV
- Full-Scale Test

Investigation/Analysis in the Reactor

- Investigation Inside PCV
- Investigation Inside RPV
- Identifying Properties of Fuel Debris
- Detection of Fuel Debris
- Accident Progression Analysis

Radioactive Waste Treatment/Disposal

- Solid Waste Treatment and Disposal

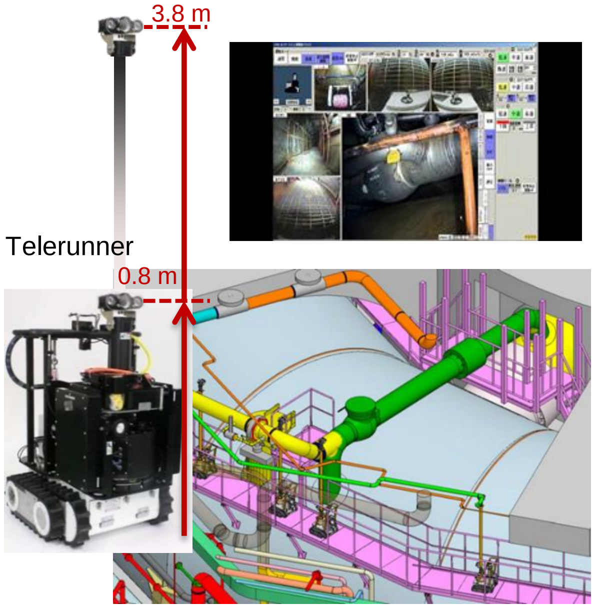
Development of Technology for Remotely Operated Decontamination

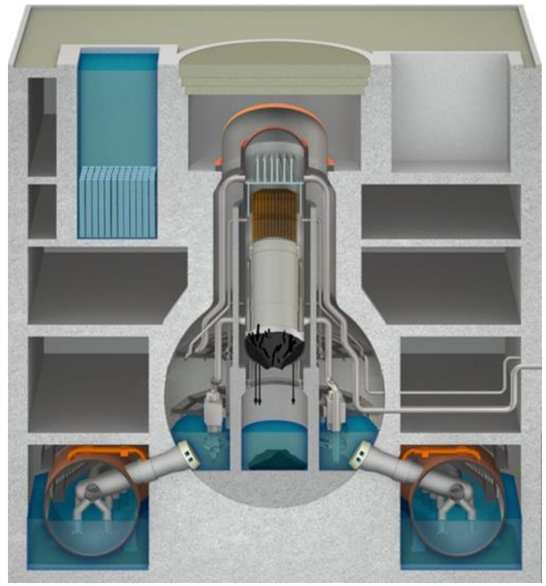
support to reduce the work exposure in the investigations and the decommissioning works

Development of Inspection/Investigation Equipment

Device for Investigation of the S/C upper part

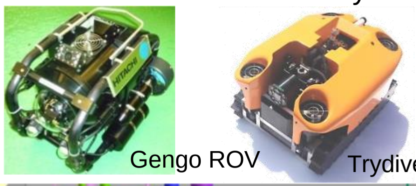
Investigation of leakage from the S/C upper structures

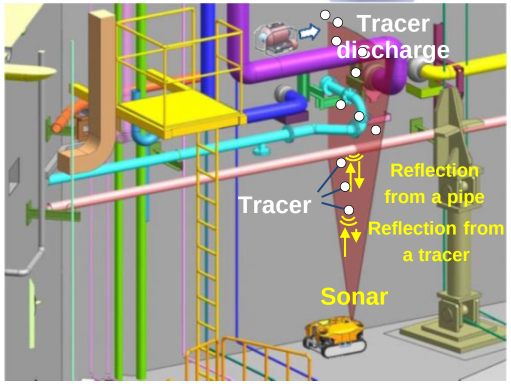




Device capable of underwater swimming and floor travelling

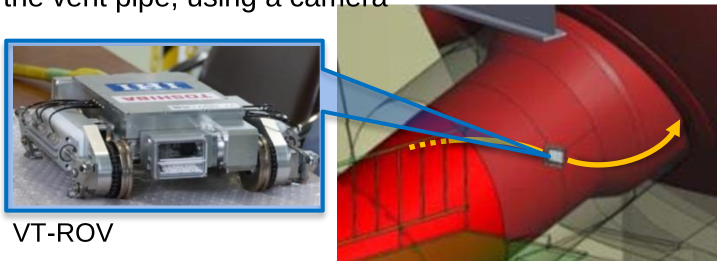
Investigation of areas penetrating walls underwater and in muddy water





Device for Investigation of the joint part between the vent tube and the D/W

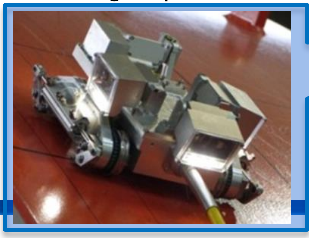
Investigation of water leakage at the bottom part of the vent pipe, using a camera



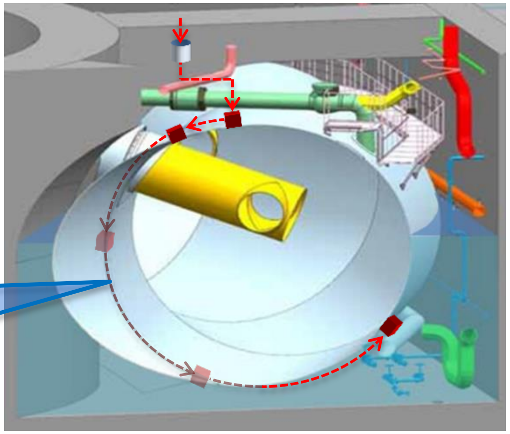
VT-ROV

Device for Investigation of the S/C lower part

Investigation of the existence of a hole with a diameter of 30 mm or more in a submerged part

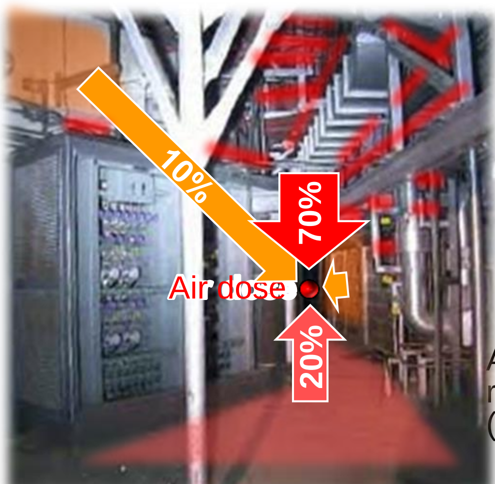


SC-ROV



Development of Technology for Remotely Operated Decontamination

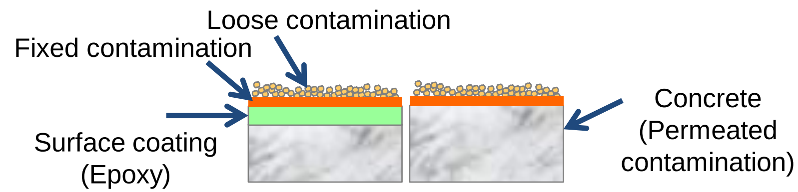
Composition of an air dose



Air doses in the reactor building (example)

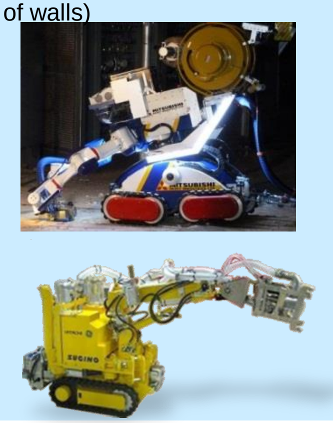
Contamination forms

Loose, fixed and permeated contamination forms are combined.

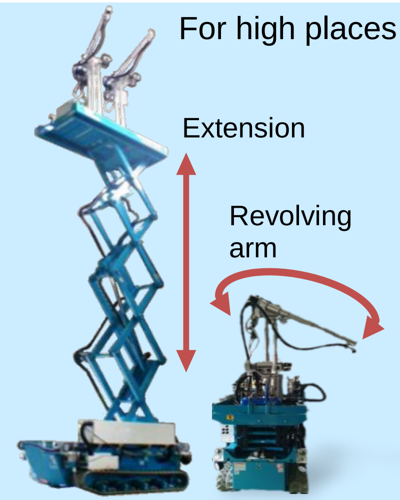


Approaches to decontamination areas

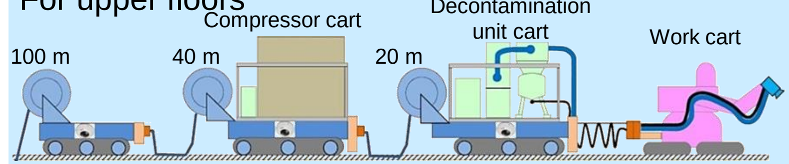
For low places
(the floor, the lower surfaces of walls)



For high places



For upper floors



Decontamination device for contamination forms

High pressure water jet

Dry ice blast

Blast(suction)

Development of remote decontamination technology: Examples of tie-ups with universities

Examples of technical issues

- Operating a robot using only data from a normal robot-mounted camera makes it difficult to understand the robot's surroundings, and operations are not easy.
- Avoiding interferences when using a multi-jointed manipulator in confined spaces is difficult and requires complex operations.

Understanding the vicinity 1 "Tokyo Uni. Yamashita Lab"

- Revised images from multiple robot-mounted cameras, and images looking down at the robot from above (quasi-overhead view) facilitate understanding the condition of the environment
- Development of techniques to allow Changes in camera type, attachment position and direction to be handled flexibly, and easily adjust the amount of image correction

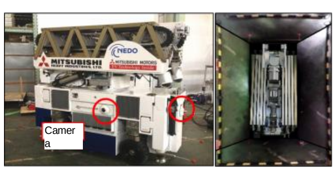
Understanding the vicinity 2 "Tsukuba Uni. Tsubouchi Lab"

- Development of a system that maps 3D measurement data to the robot surroundings, thus facilitating judgements.
- Considering applicability to robots, development of a system that appropriately selects still or moving images of the required definition to enable flexible responses even when signal speed is low.

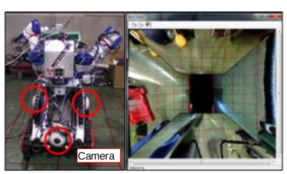
Improved Operability "Kobe Uni. Yokokohji Lab"

- While manipulators with multi degrees of freedom can avoid obstacles and have advantages in confined areas, they are also difficult to operate.
- As operability should be made less complex, the development of an easy to use interface that allows instinctive self-motion* movement commands

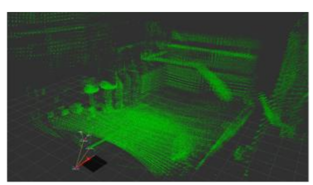
＊: Movements which change the entire shape of the manipulator while the tip of its claw and base are fixed in position



Quasi-overhead images taken from Super Giraffe



Quasi-overhead images taken from MEISTeR



3D mapping screen (currently under development) of data taken with Super Giraffe

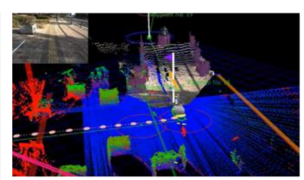
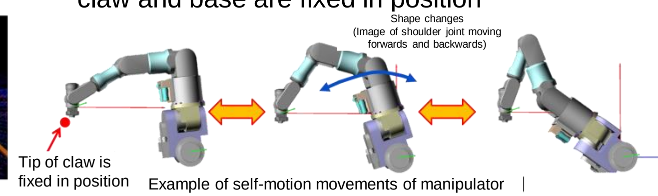


Image showing understanding of surrounding environment using 3D sensor data and camera images



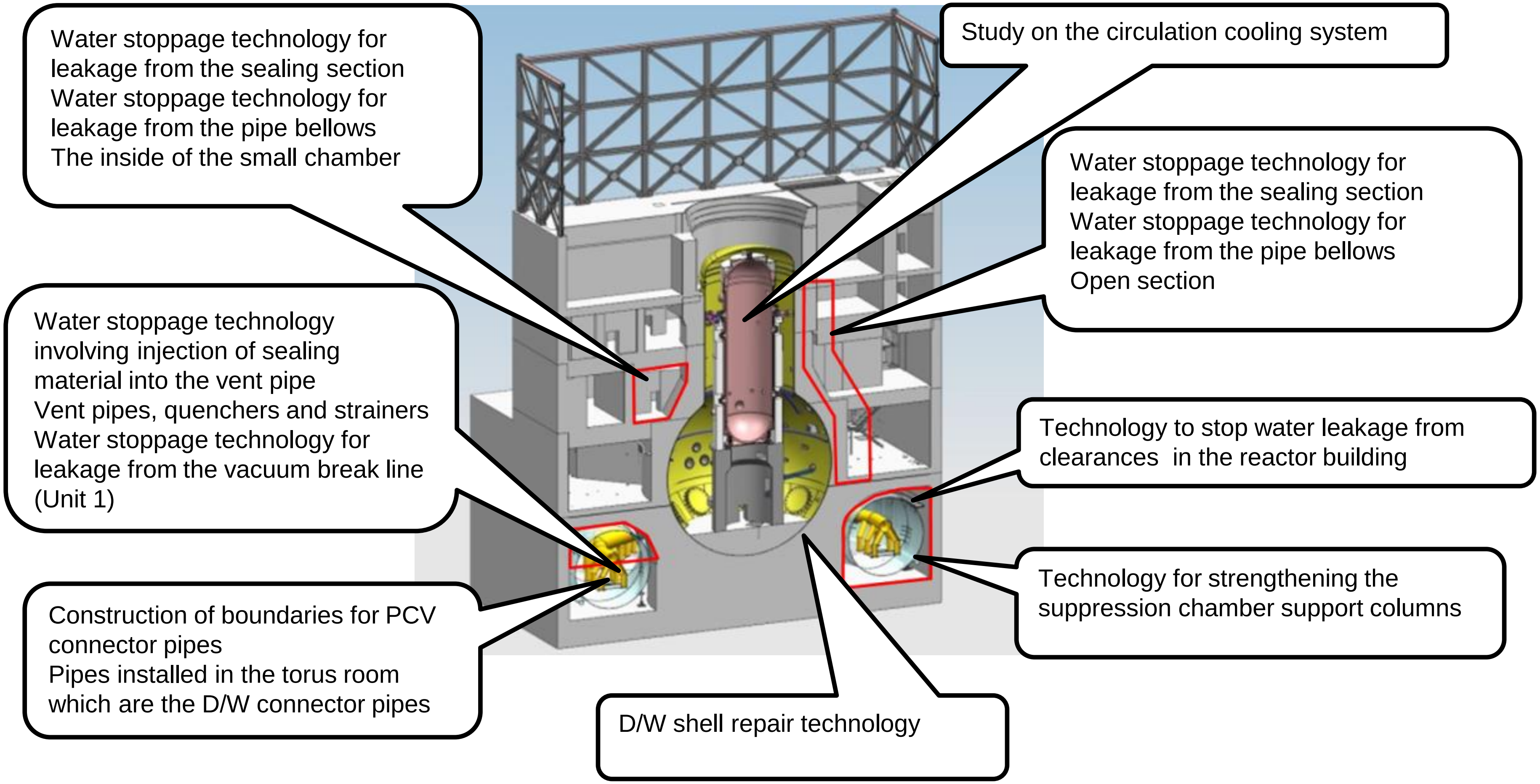
Example of self-motion movements of manipulator with 9 degrees of freedom

Development of Technology to Repair the PCV

Set up of the basic configuration of the debris removal works and reduction of the additional RI release risk

Development of Technology to Repair the PCV

Areas that need to be studied for repair in order to submerge fuel debris in the PCV with water or to form a PCV boundary

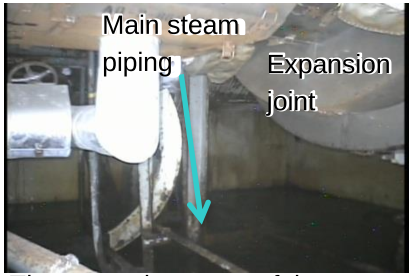


Target areas for Development of Repair and Water Leakage Stoppage Technology

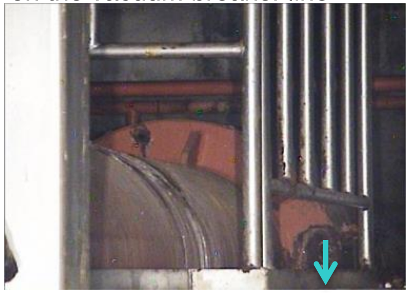
Development of Technology of Repair of the Primary Containment Vessel (PCV)

Check of water leakages

Expansion joint on main steam piping



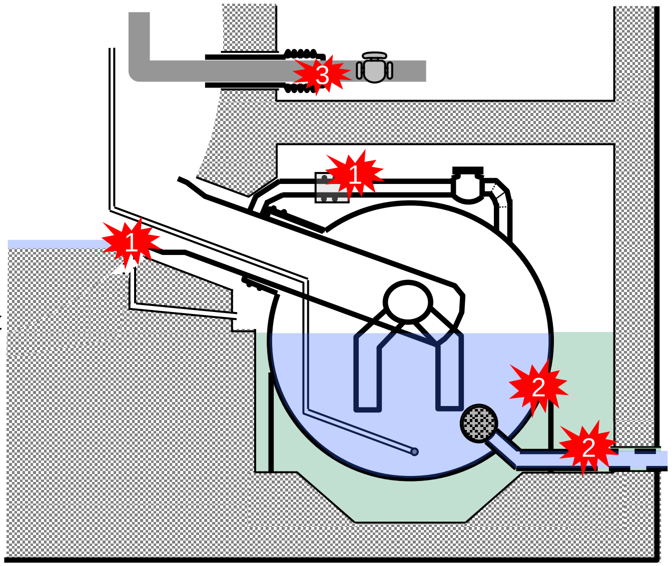
The protective cover of the expansion joint on the vacuum breaker line



Sand cushion drain pipe

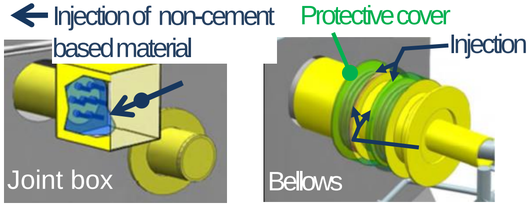
provided by TEPCO

Water leakage points

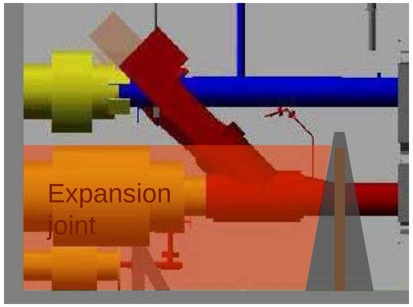


Basic test of a water stoppage method in which the vent pipe is filled up with water stoppage material.

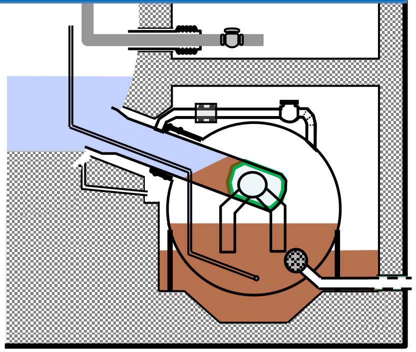
Method to repair openings outside the D/W



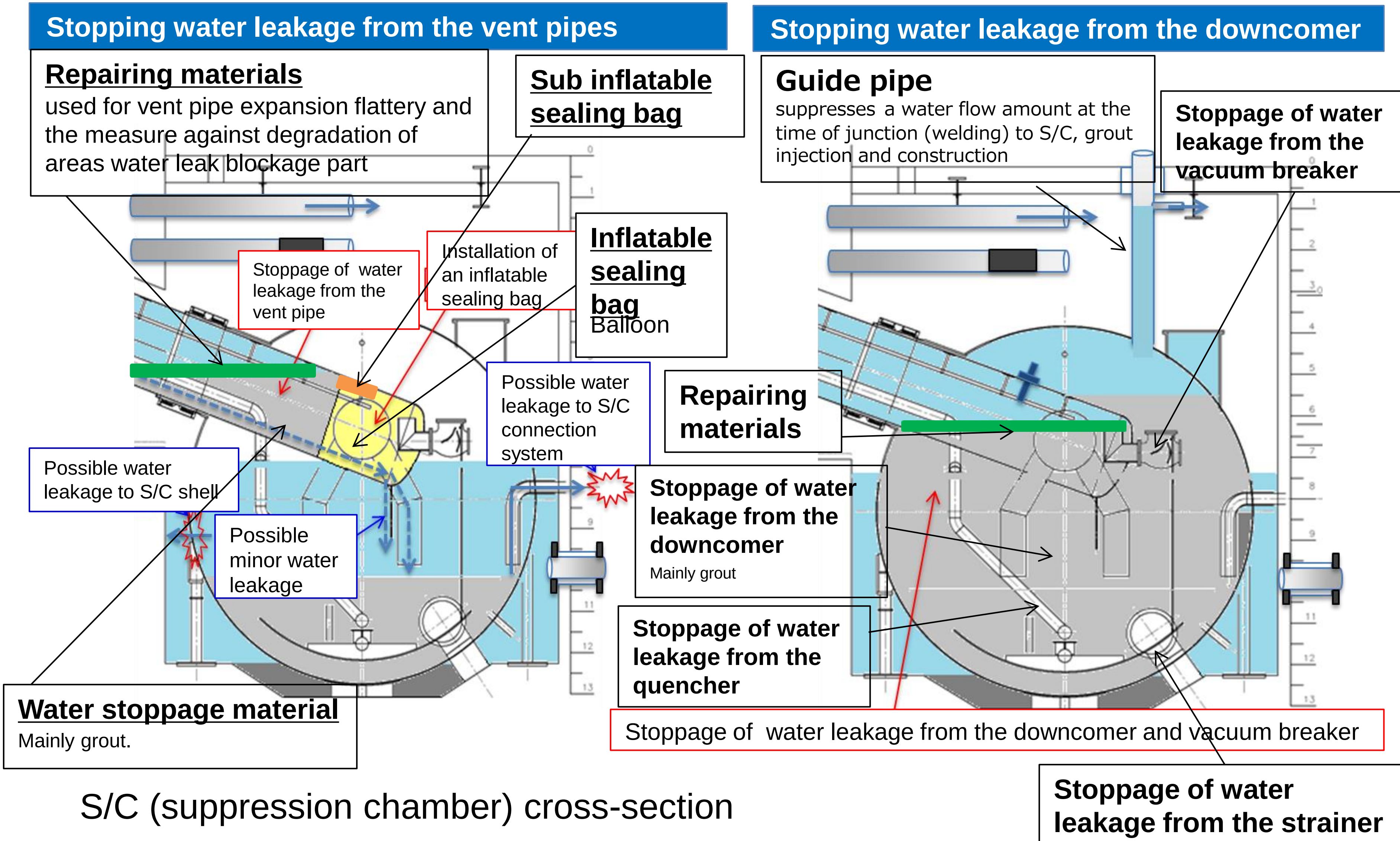
Method to repair narrow spaces outside the D/W



Method to repair PCV lower part



Development of Technology to Repair the PCV



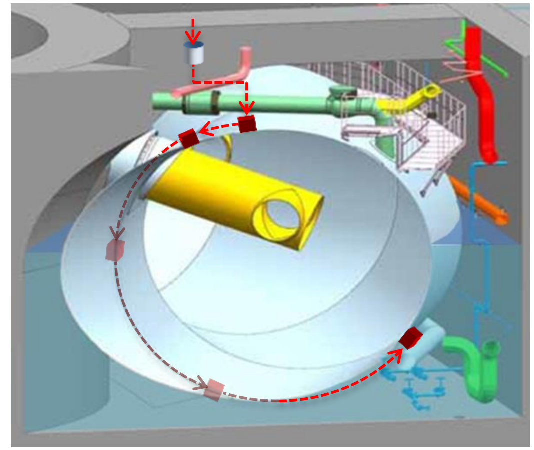
S/C (suppression chamber) cross-section

Mock-up Test

Facilities for the development and validation of remotely-operated devices and equipment

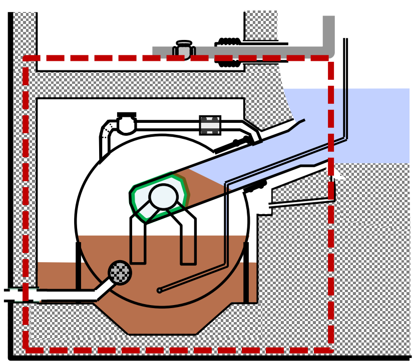
It is necessary to prepare an environment to repeatedly test and verify devices and equipment and avoid checking the applicability of the devices and equipment on site in a trial-and-error manner.

Equipment for Investigation of the S/C lower part

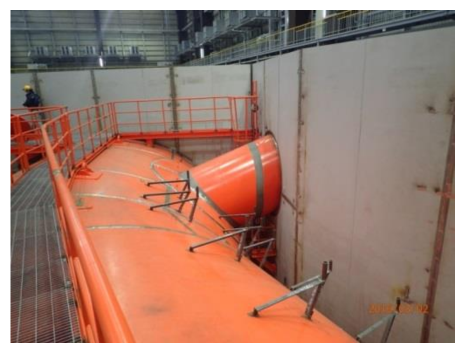


Method to repair the PCV lower part **Full-scale test for repair and water leakage stoppage technology for leakage points inside the PCV**

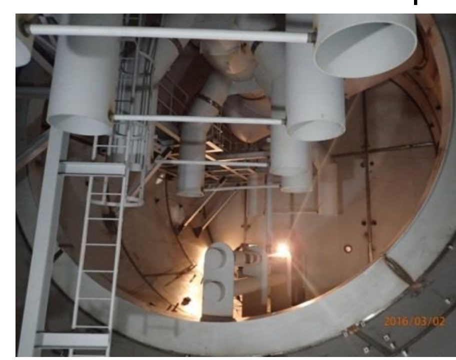
JAEA, Naraha Remote Technology Development Center Test building



1/1(1/8) Sector Suppression Chamber Mock up



Interior of the torus room



Interior of the S/C

Probe for fuel debris

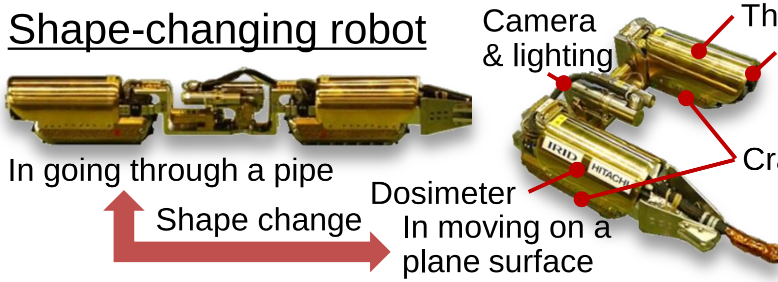
Investigation inside the PCV
Investigation inside the RPV
Muon technique
Identification and Analysis of Conditions inside the Reactor
Severe Accident Progression Analysis Technology

Investigation inside the PCV

Development of robots to investigate inside the PCV

- A linear shape that allows the robot to go through a guide pipe with a diameter of about 100 mm and stable movement in the PCV
- Use of robots under severe environments (high radiation dose, darkness, steamy atmosphere, etc.) , and collection of "image", "temperature" and "dose rate" data

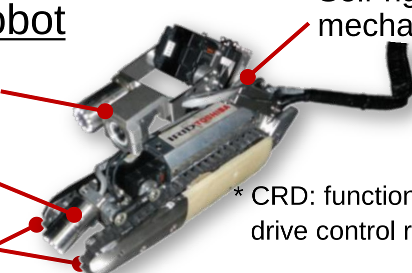
Shape-changing robot



The robot goes into the PCV through a 115 mm-diameter penetration.

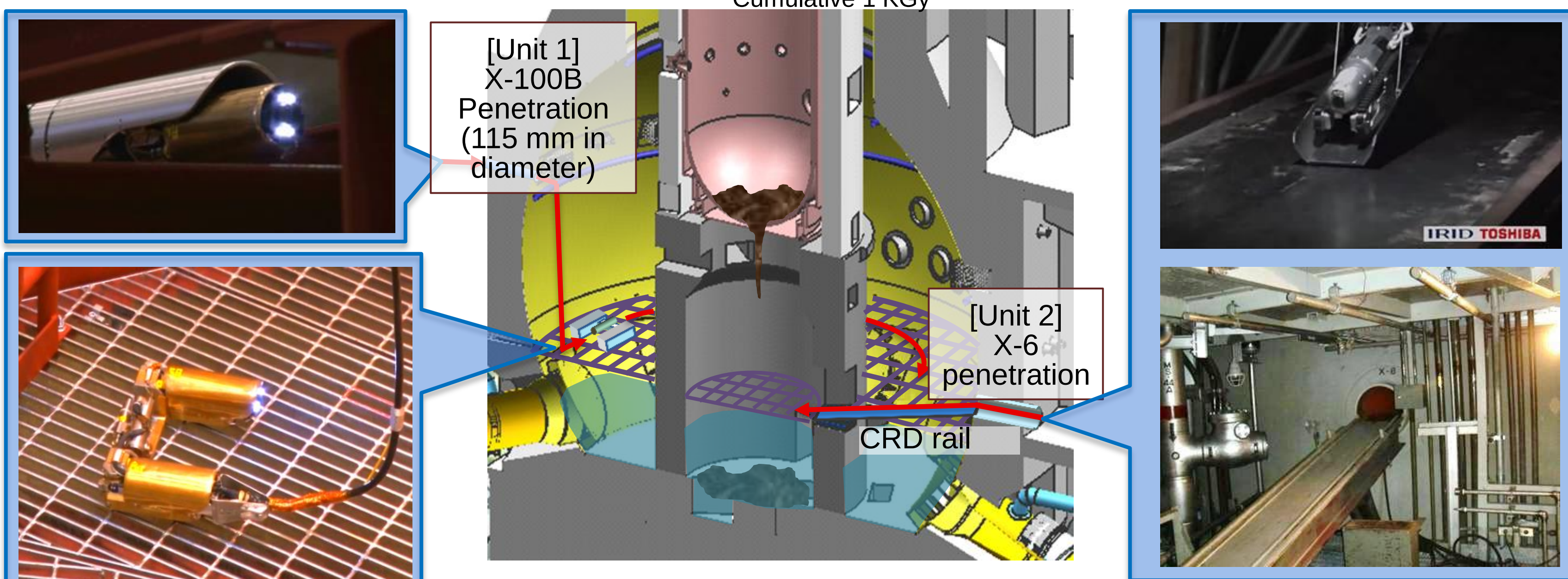
Requirements for radiation resistance
100 Gy/h
Cumulative 1 KGy

Scorpion robot



* CRD: function to drive control rods

The robot goes into the inside of the pedestal from the CRD* rail.



Internal inspection of reactor containment vessel (PCV)

Expectations for internal inspection of PCV

Internal inspection of pedestal

①Location of fuel debris

・Consideration of access, unloading route, cutting method, basic data required for design

②Fuel debris distribution, composition (properties)

・Data required for decision on technical framework to enable risk management and keep reactor safe

・Data required for design that maintains environment and allows provision of cutting so that work proceeds steadily

③Damage and other conditions

・Required data to enable water to be shut-off and allow continuation of removal work that employs water

・Required data to allow debris removal to be completed smoothly, and retain the pressure vessel with certainty

Investigation Steps

Survey of CRD rail condition（A1） Performed Aug 2013 → **Survey of condition of pedestal inner platform / lower CRD / slot opening (A2)** → **Survey of area under platform (A2)** → **Survey for deciding fuel debris removal method (A3)**

Issues in A2: Steps up to survey of inner PCV

・Decrease dose around penetration

・Make a hole in penetration hatch (Φ115mm)

・Secure access route to platform

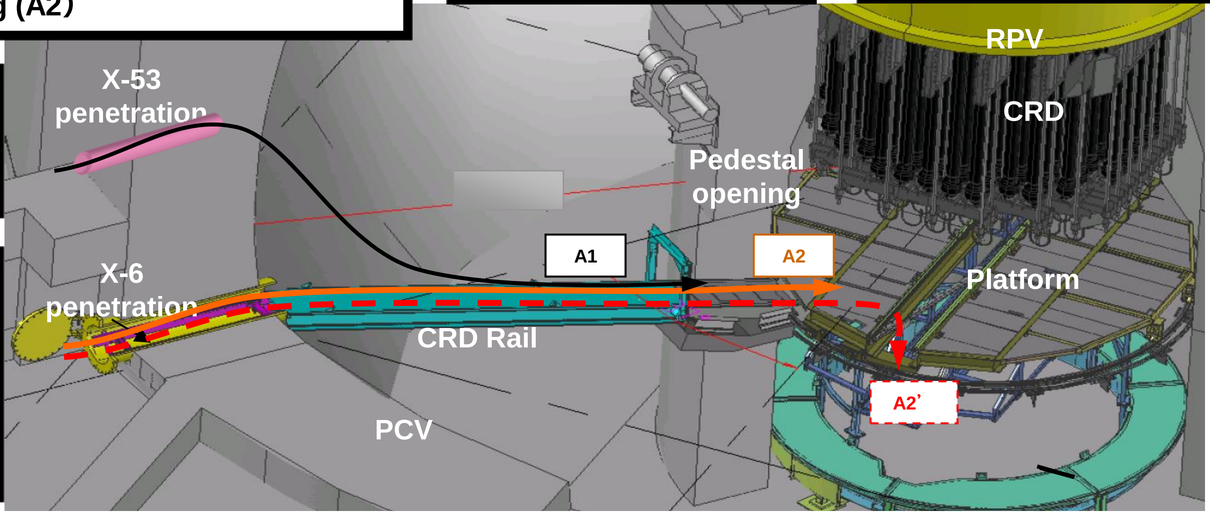
Issues in A3: Steps up to survey of inner PCV

・Opening the hatch

・Avoiding/removing penetration inclusions※

・Avoiding/removing suspended tools on CRD rail※

※Judgement will be made depending on the result of A2 survey



Unit 2: Proposed access route to inside containment vessel and pedestal (below pressure vessel)

Investigation inside the PCV

Future plan

①Development of shielding, isolation and boring device for the X6 penetration of unit #2, Pedestal platform investigation

②Investigation of fuel debris below the pedestal platform of unit #2

③Investigation of PCV lower floor of unit #1 to utilize video camera and dose rate meter from the upper floor

④Investigation of inside the pedestal of unit #3 by underwater ROV

Investigation inside the Reactor Pressure Vessel (RPV)

Purpose of investigation inside the RPV

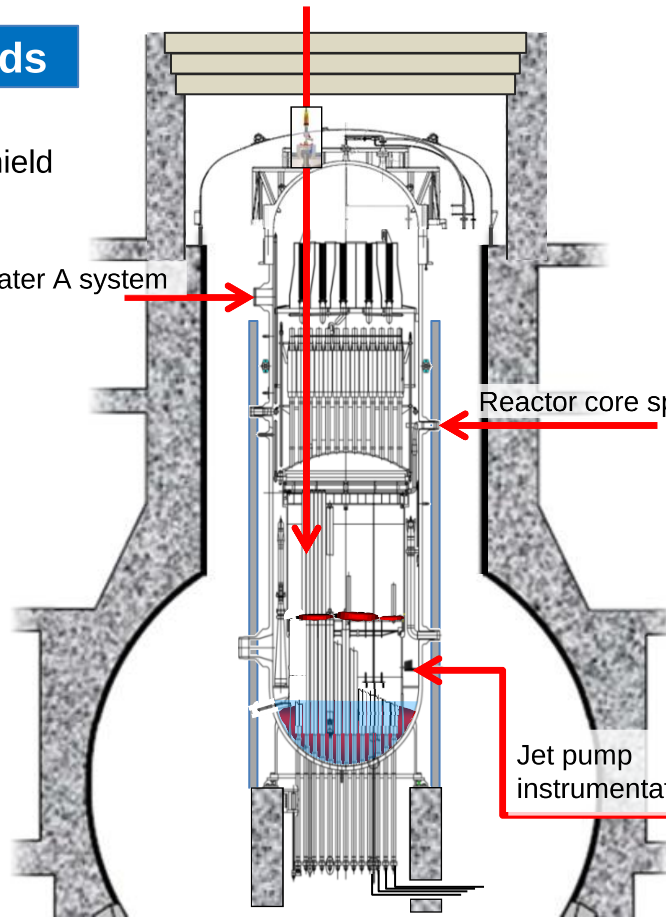
Obtain data on the locations of fuel debris inside the RPV, the damaged condition of reactor internals, temperature and dose inside the RPV, etc.

- Study methods to access, investigate and sample investigation targets

Study of access methods

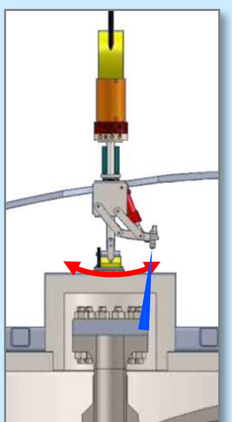
The following is considered

- Doses and the installability of shield
- Accessibility of investigation equipment
- Observability

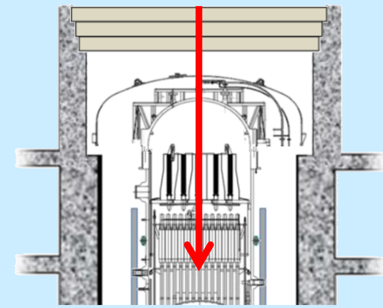


- Access to drill the upper part

Device to drill the RPV head



- Access after the reactor is opened



- Access to system piping

Electromotive travelling device

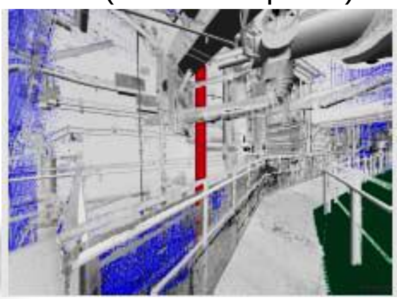
Traveling	Horizontal and vertical Elbow and deformed pipes
Grabbing	Position and posture holding
Bifurcation	Passage of T-shaped bifurcation Directional control

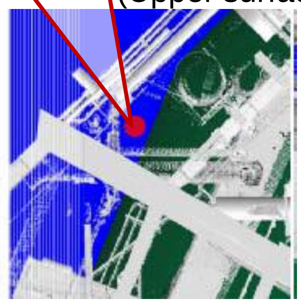
Hydraulic type travelling device

IRID

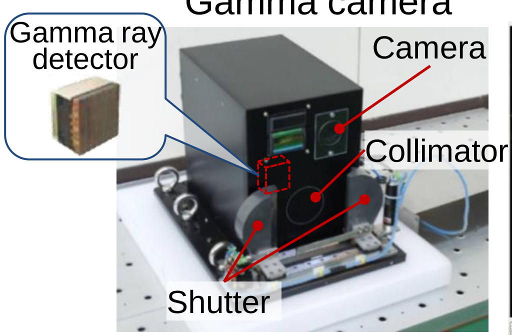
Visualization Technology

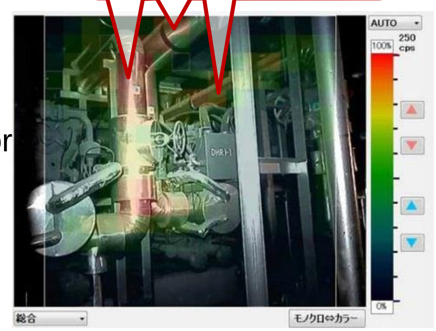
3D imaging of the situation inside the reactor building





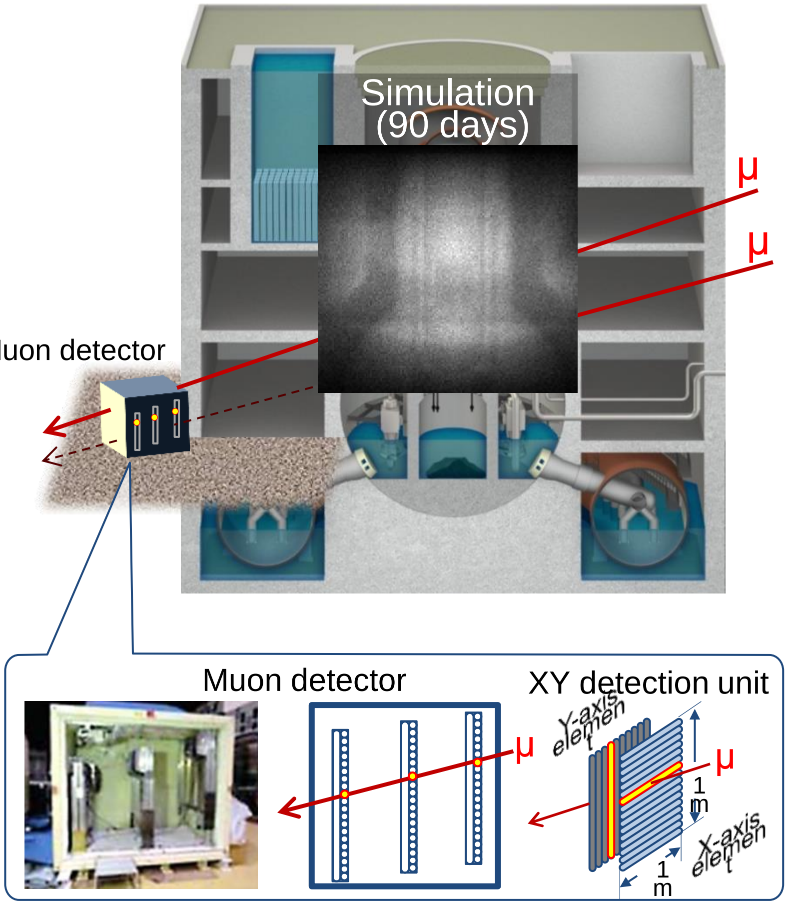
Visualization of air dose





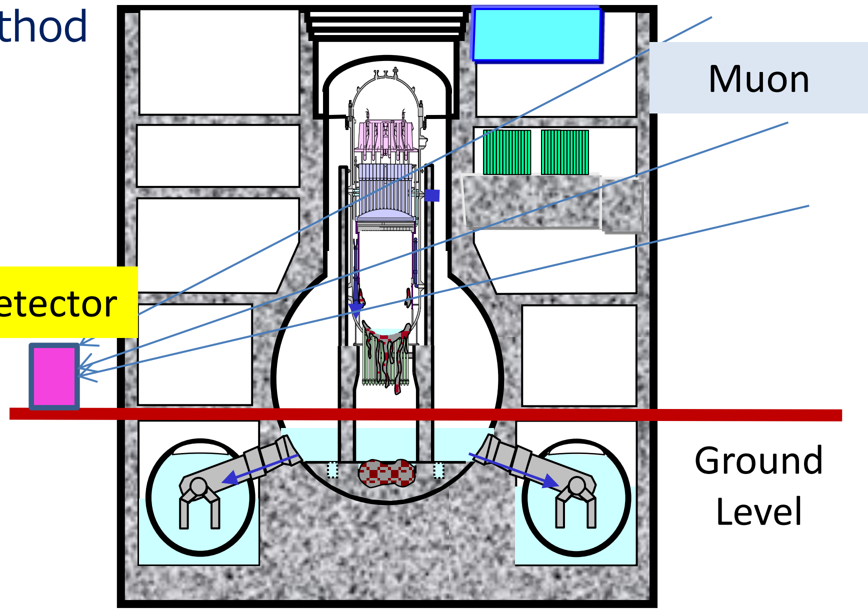
Visualization of fuel debris in the RPV

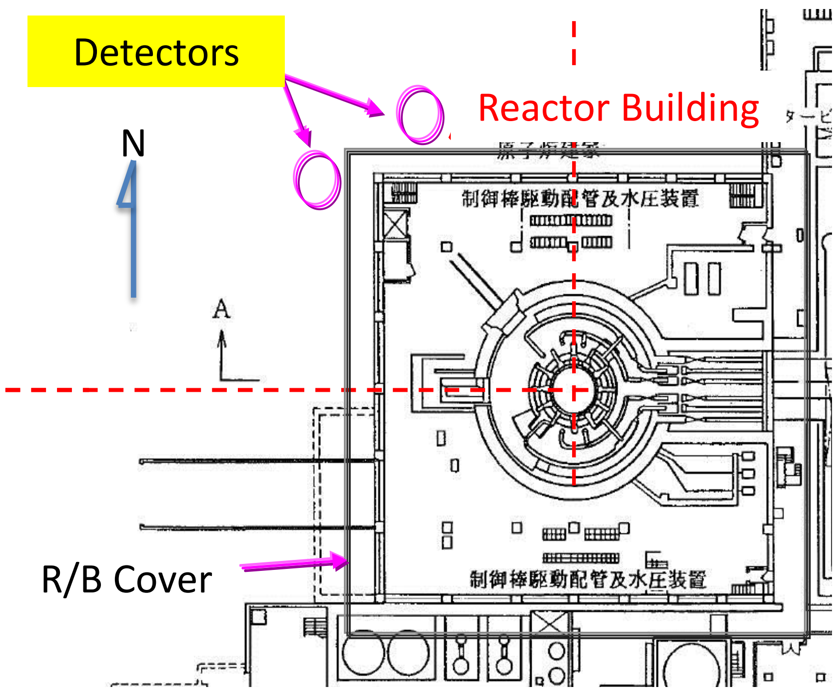
Development of Technology for Detection of Fuel Debris in the Reactor

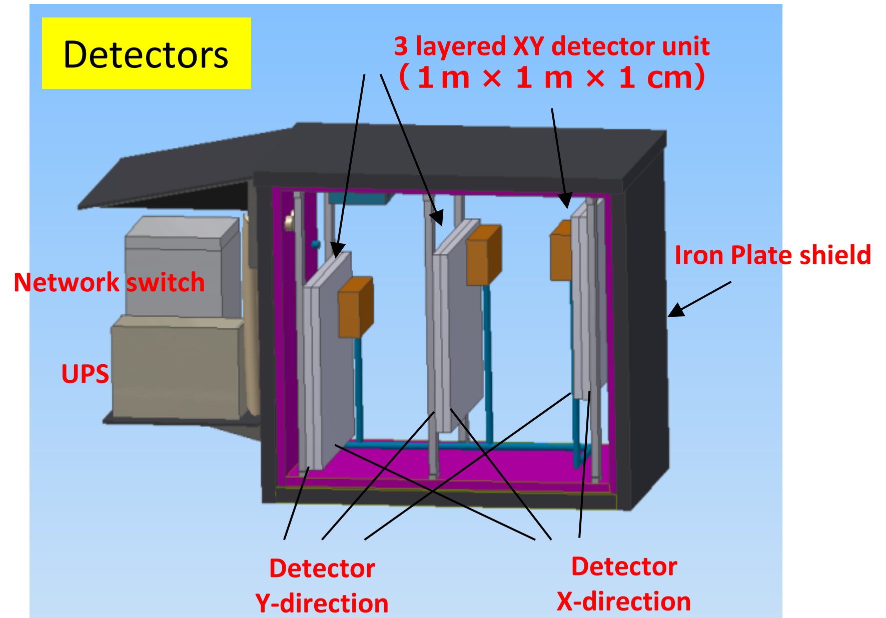


Installation of Detectors Using Transmission Method

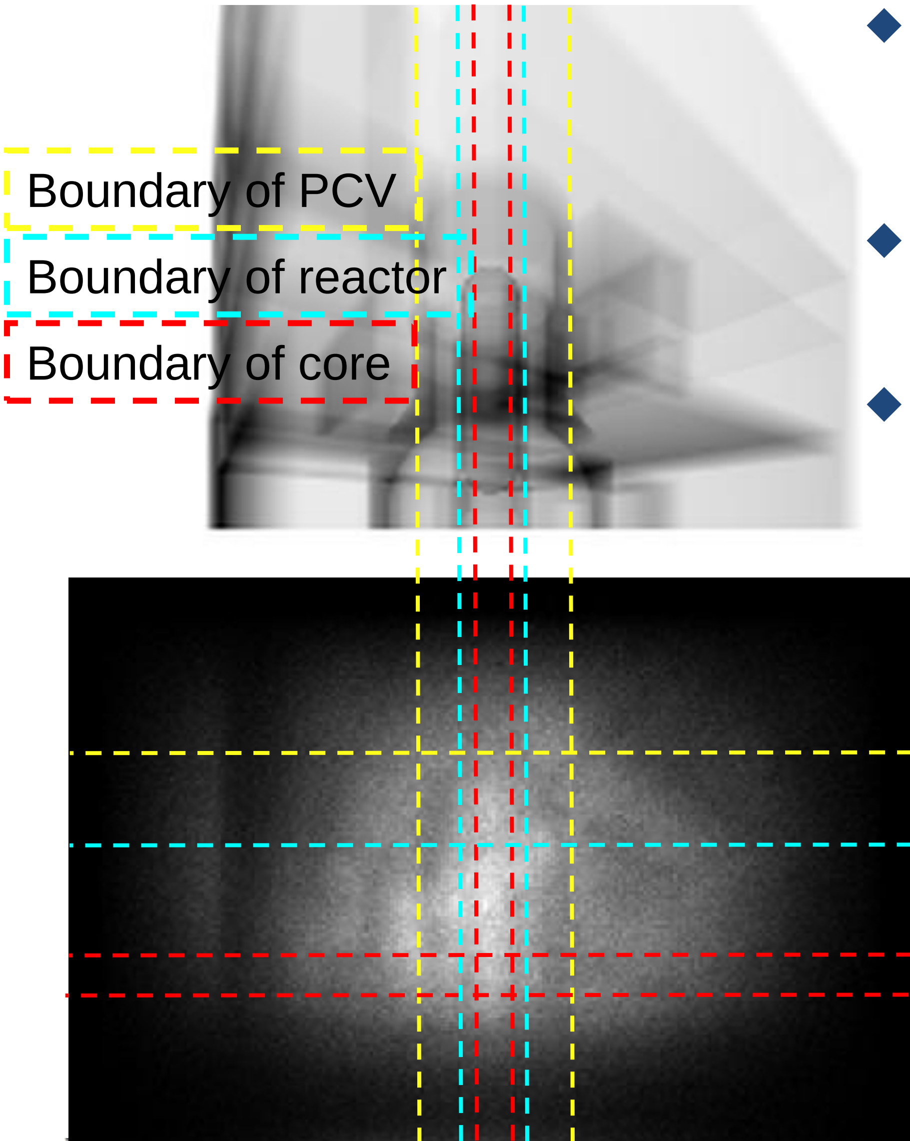
- Detectors were installed at the north and north-west corners of Unit 1 reactor building (late January, 2015)
- Measured from February through May
- Detectors installed in the front of the reactor building were shielded by 10 cm thick iron plates



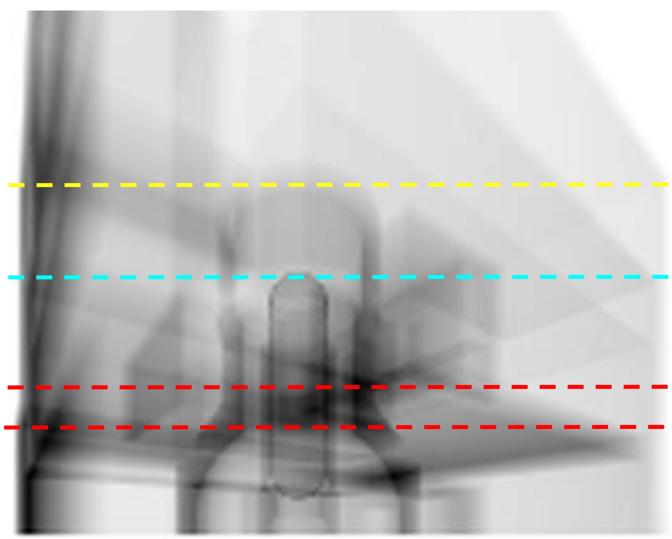




Estimation of Fuel Debris Location Based on Comparison between Design Image and Measurement (Detector 1)



- Measured data, though it does not clearly indicate, shows that equipment, etc. are detected at locations where they are supposed to exist based on the design documents
- The boundaries of the PCV and the RPV in the image acquired from measurement matches those in the image drawn from design data.
- High density material (fuel) is not detected at the area where the reactor core was originally located.



Identification and Analysis of Conditions inside the Reactor

Severe Accident Progression Analysis Code

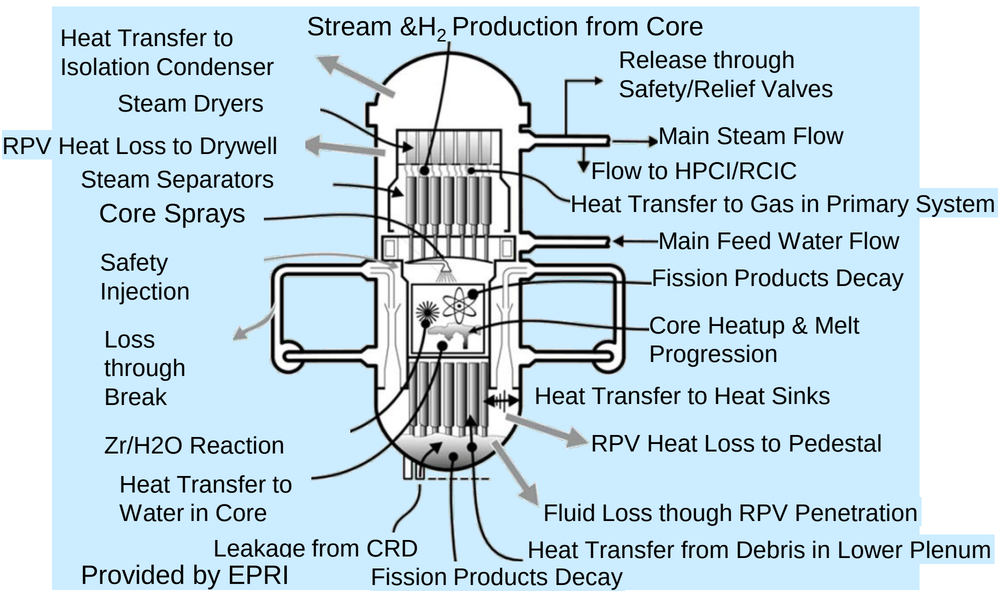
MAAP (Modular Accident Analysis Program)

- "Simplified model" using test result-based correlation formula allows high speed calculation
- Can perform parametric analysis of phenomenon of large uncertainty

SAMPSON (Severe Accident analysis code with Mechanistic, Parallelized Simulations Oriented towards Nuclear fields)

- Uses theoretical models and "mechanistic model" with sophisticated descriptions of physical and chemical phenomena
- Multidimensional analysis of space distribution-related phenomena is possible

MAAP Schematic model of reactor pressure vessel interior



Provided by EPRI

TEPCO: Remote visualization of actual plant status

Understanding reactor internal status using severe accident analysis code

- Improvement of Analysis Codes & Accident analysis using actual data
  ・MAAP ／ SAMPSON
- Individual event assessment through thermal flow analysis
- International Cooperation: OECD/NEA benchmark analysis (BSAF)

JAEA: Mock-up Test (Seawater heat transfer test, etc.)

Relation between analysis item & analysis code

Analysis items:

- **Event description/analysis**
  ・Initial event
  ・Estimate of plant status (temp, press, PCV, RPV, water lev.)
- **PCV leak / RPV damage location & area**
  ・Assessment of PCV leak condition
  ・Assessment of RPV damage condition
- **Location & amount of debris**
  ・Debris temperature
  ・Analysis of core concrete reaction
  ・Re-criticality
- **FP amount in PCV & RPV**
- **Prediction of water feed amount, pressure & temperature**
- **H_2 density (upper limit)**
  ・Prediction of amount of N_2 supplied pressure & temperature
  ・Prediction of N_2 & H_2 densities

Analysis codes:

- Severe accident analysis code MAAP, SAMPSON
- Simple heat transfer flow calculated: Energy balance Thermal conduction, Radiation, Convection
- Transient Analysis Code TRACG, etc.
- Universal heat flow analysis code

"Overview of improvements in assessing conditions inside the reactor through technical progress in accident development analysis" The Institute of Applied Energy 22/10/2012

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Severe accident development analysis technology

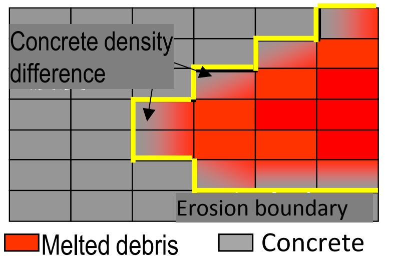
Melted Core - Concrete Interaction (MCCI) Assessment

Example of MCCI assessment performed on the Unit 1 actual sump system with eroded concrete convection flow/spread model added to the DSA module which has a high generality in the SAMPSON codes

Eroded concrete convection flow/spread model

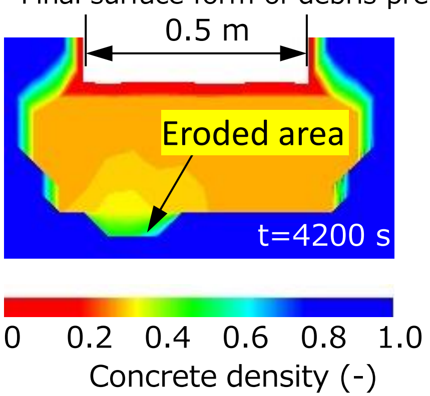
Addition of convection flow/spread of eroded concrete to debris

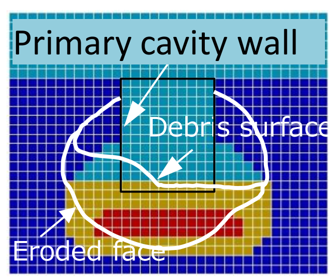
Model: Cross-section of concrete floor



Validation through OECD/MCCI CCI-2Test Results:

Final surface form of debris predicted within an accuracy of 13%



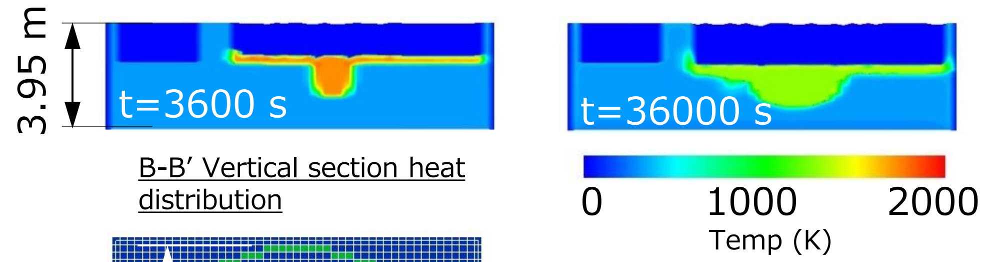


White line: Test observation data

■ Melted debris ■ Solid debris
■ Concrete

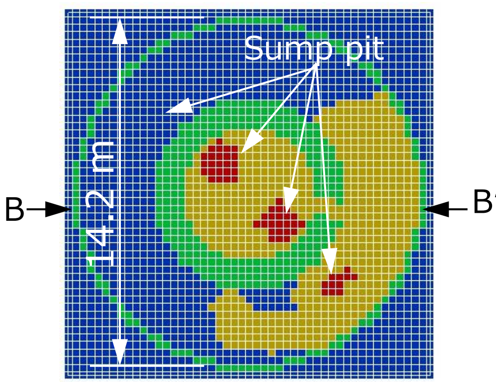
Unit 1 actual sump system measured results

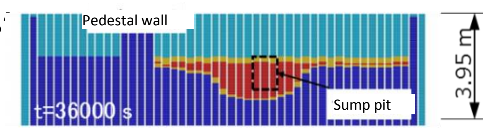
Analysis carried out until 12 hours after RPV damage



B-B′ Vertical section heat distribution

B-B′ Vertical section heat distribution





■ Melted debris ■ Solid debris
■ Concrete

Horizontal section of liquid-solid distribution

(1) Condition where debris spread

B-B′ Vertical section of liquid-solid distribution

(2) Long-term erosion behavior

Severe accident development analysis technology

Summary of overall analysis & assessment results of fuel debris distribution

Fuel debris assessment from severe accident development analysis codes and other survey results

Item	Unit 1	Unit 2	Unit 3
Accident development analysis	Most fuel debris transferred to PCV side	Fuel debris distribution greatly depends on amount of water pumped in by firefighters	Most fuel debris transferred to PCV side
Assessment of heat balance methods	Few heat sources inside RPV	Constant rate in both RPV and PCV	Constant rate in both RPV and PCV
Myuon Measurement	Almost no high density material (fuel) in reactor core	Almost no large pieces of fuel debris in reactor core	Not measured
Internal Inspection of PCV	No large scale damage to PCV wall in confirmed scope	No large scale damage to external area surrounding lower part of RPV	No damage to internal PCV structure in confirmed scope
Overall Assessment	Most fuel debris transferred to PCV side	Constant rate in both RPV and PCV	Most fuel debris transferred to PCV side

Development of Fuel Debris Retrieval

Fuel Debris Characterization
Collection, Transfer and Storage of Fuel Debris
Structural Integrity Evaluation
Assessment of Seismic Resistance
Fuel Debris Retrieval Method

Fuel Debris Characterization

Generation of mock debris

- Estimate of oxidization, metals produced
  ➜Thermodynamic equilibrium calculated
  (fuel distribution, oxygen density, temperature inside reactor)

Oxidation: (U, Zr) O_2
Metals: Zr(O), Fe_2 (Zr, U)

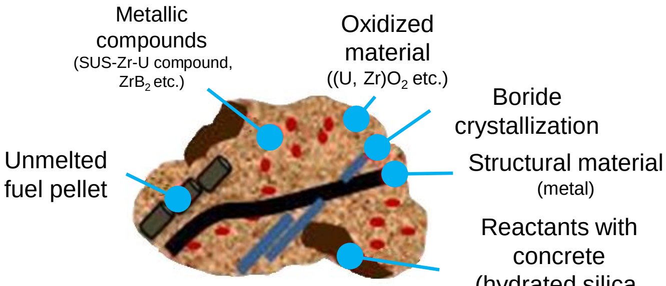


Image of actual debris

Fuel debris from TMI-2

Understanding distinctive reactions at Fukushima Daiichi

- Boron-generated reaction products

  Boride derived from B_4C control material is remarkably hard, and may burden cutting tools

- High temperature reaction with concrete (MCCI *)

  *Molten Core Concrete Interaction

  Product composition varies with concrete composition, melting temperature, time

  Multiple layers of oxidized material between eroded concrete surfaces

- High temperature reaction with seawater sodium

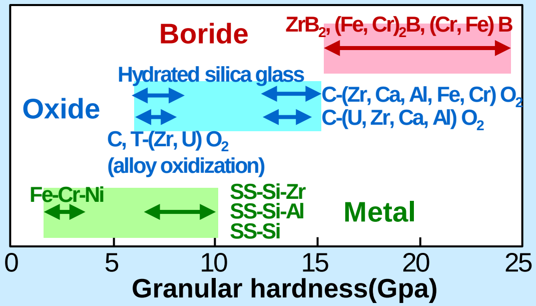
Investigation of physical properties required for extraction & sampling of fuel debris

- Physical Features
  (shape, size, density/porosity, hardness, elasticity, fracture toughness)
- Thermal Features
  (specific heat, thermal conductivity, melting point)

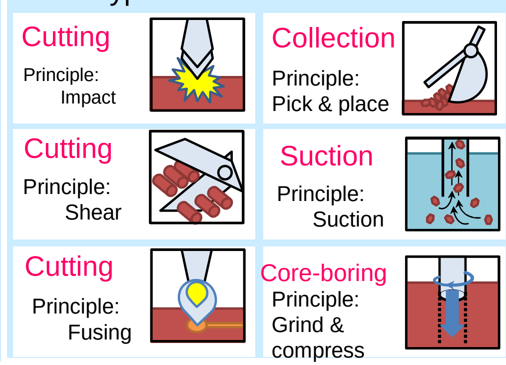
- Comparison with TMI- 2 debris

  Hardness of mock debris is almost identical to TMI-2

Estimate of distribution of hardness for each chemical system of debris
(boride, oxide, metal)

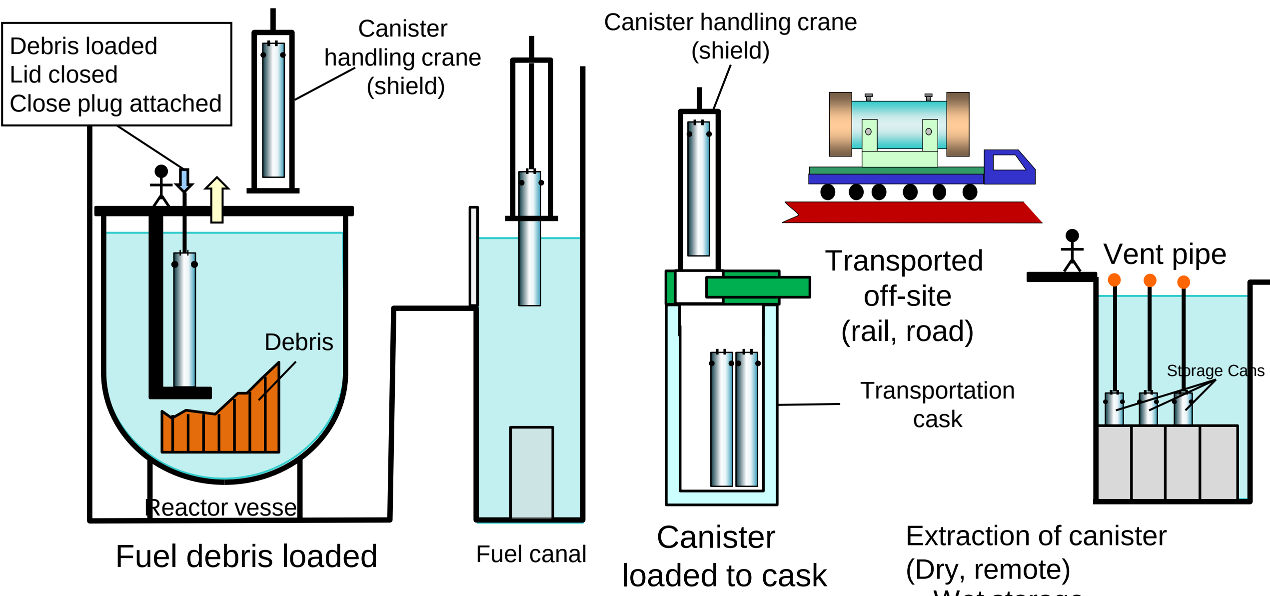


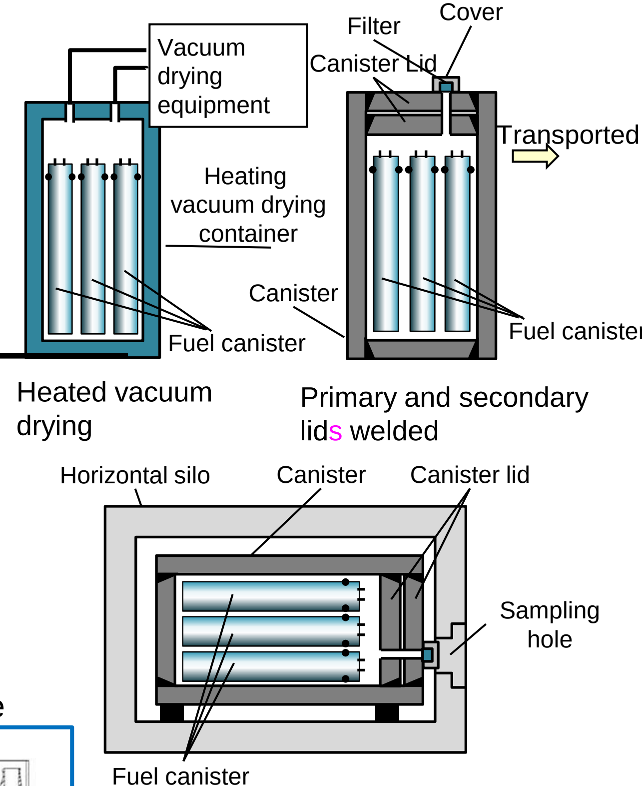
Types of extraction tools



Collection, Transfer and Storage of Fuel Debris

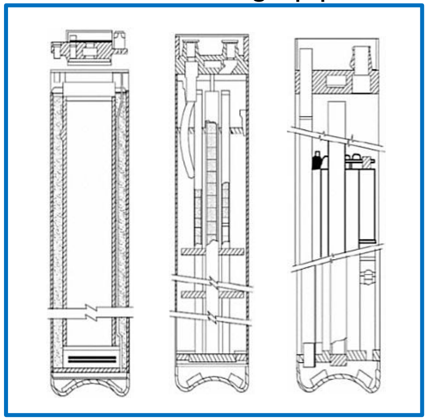
Collection, transfer and Storage of TMI-2 Fuel Debris





Dry storage (horizontal silo)

TMI-2 storage pipe



Fukushima Daiichi Issues

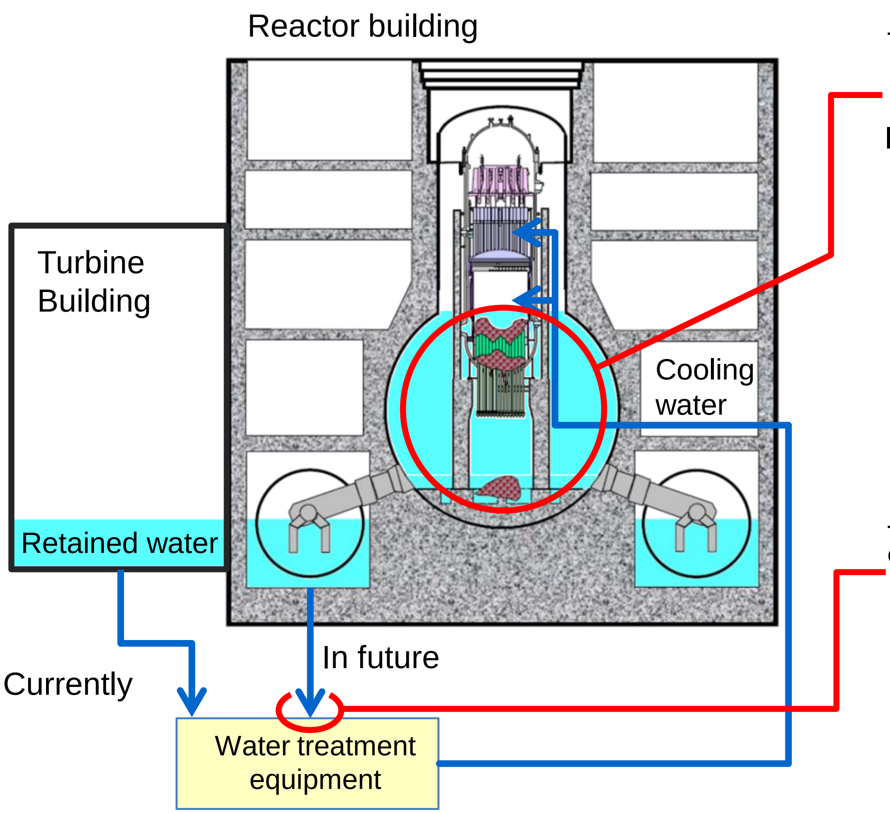
- High degree of burn-up and concentration
  ⇒radiation, large disintegration, high reactivity
- Generation of concrete-related melt product expected
  ⇒Concerns of hydrogen emission via radioactive breakdown of water in concrete
- Seawater injection, melting of instrument cables
  ⇒Effects of sodium in fuel debris, introduction of multiple impurities

Development of Technology for Criticality Control in Fuel Debris Retrieval

Objectives of criticality control technology development

It is believed that currently the fuel debris is not in state of criticality, but alongside future work to retrieve fuel debris, criticality control methods and monitoring will be developed to prevent any re-criticality occurring even with changes to fuel shape and amount of water included.

Technical development point



PCV interior

- Changes to fuel debris shape
- Changes to amount of water included (water level) due to submersion

Small risk of exposure, but important to monitor conditions over a relatively wide area

⇒Development of re-criticality occurrence detection methods

Prevent re-criticality from occurring

⇒Development of neutron-absorbing material to prevent criticality

PCV exterior

- Powder produced when cutting fuel debris has a risk of escaping and collecting in waste water treatment/cooling equipment

Need to preemptively prevent exposure of equipment maintenance workers

⇒Development of sub-criticality monitoring Technologies

Structural Integrity Evaluation

Residual life assessment outline flow

Need a means to maintain reactor structural integrity for a long time until the fuel debris is retrieved from reactor core

- Effect of high temperature during fuel melt
- Effect of corrosion due to inclusion of seawater and foreign particles
- Effect of equipment damage due to hydrogen explosion
- Effect of debris retrieval method
- Effect of further earthquakes

Building behavior analysis(Building damage simulation) → Building-equipment coordination behavior analysis → Organizing loading conditions → Equipment strength assessment → Low margin equipment listed up

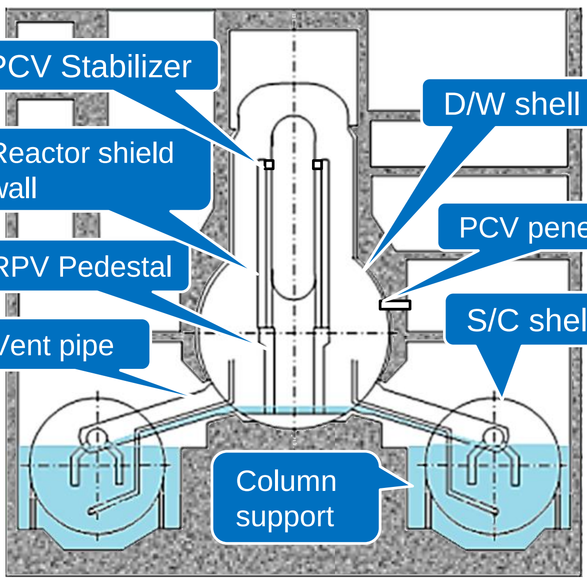
Model Creation

- Water level
- Basic ground motion Ss
- Damage to equipment
- Influence of corrosion

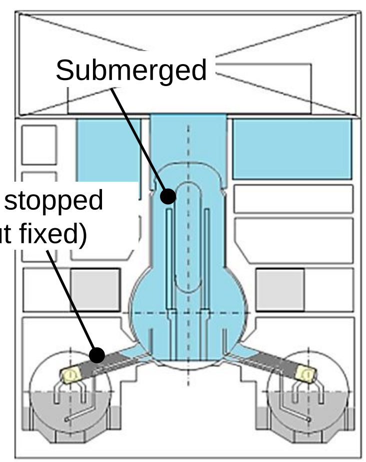
Assessment Conditions

- Allowable values
- Corrosion wall thinning (test data)
- High-temperature strength degradation (test data)

Example of soundness assessment point



Anticipated plant condition



Increased anticipated long-term corrosion wastage

Long-term corrosion test

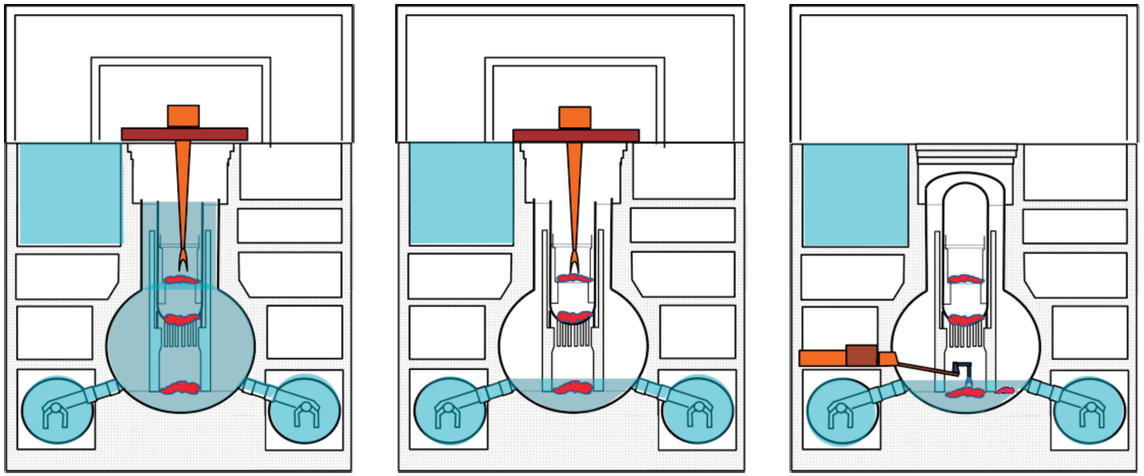
Comparison of corrosion control measures

Methods of Fuel Debris Retrieval

Selection options for method of fuel debris retrieval

Diagram below taken from NDF "Technical Strategic Plan 2015"

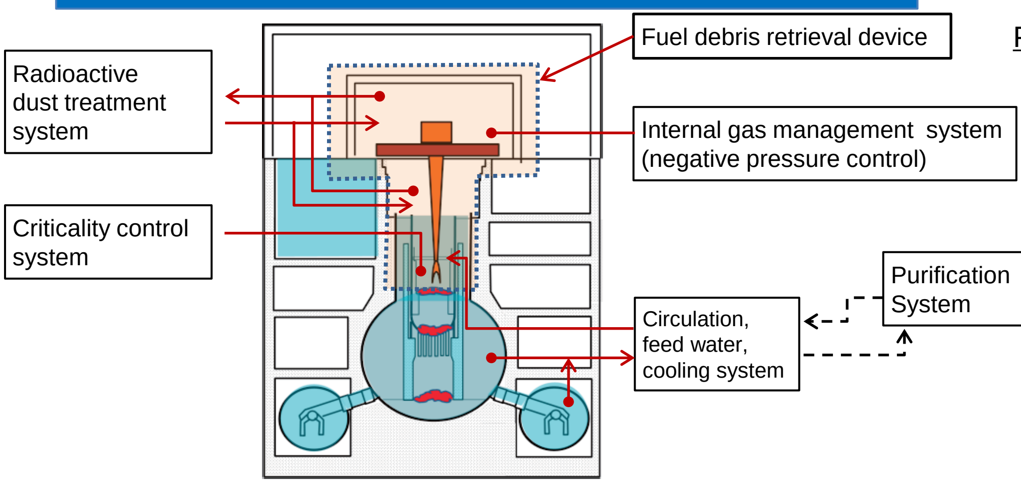
a. Submersion – top entry method b. Partial submersion – top entry method c. Partial submersion – side entry method



<u>Techniques required for method feasibility study</u>

- ✓ Techniques to prevent contamination spread during retrieval of large structure
- ✓ Techniques to prevent contamination spread during retrieval of fuel debris from inside RPV
- ✓ Techniques to access fuel debris
- ✓ Techniques to retrieve fuel debris through remote operations
- ✓ Techniques for cutting, collecting, monitoring, and measuring during fuel debris retrieval

System Concept, Investigation of Method Feasibility



<u>Points to consider regarding fuel debris retrieval equipment</u>

- ✓ Equipment resistance to radiation & maintainability
- ✓ Improved efficiency in fuel debris retrieval method
- ✓ Compatibility with storage cans and other equipment
- ✓ Equipment to collect radioactive dust from around device

Reference:
Guidelines for solicitation of entities to implement with subsidies "Subsidy to Project of Decommissioning and Contaminated Water Management (Project of Upgrading Approach and System for Retrieval of Fuel Debris and Internal Structures)" and "Subsidy to Project of Decommissioning and Contaminated Water Management (Project of Development of Fundamental Technologies for Retrieval of Fuel Debris and Internal Structures)" in the FY2014 Supplementary 23 June 2015

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Summary

1. Development of Fuel Debris Removal Technology
   - ➢ Project of Fuel Debris Retrieval Method Development
   - ➢ Projects to support fuel debris retrieval development
     - ・decontamination, investigations, accident analysis, repair and water leakage stopping, structural integrity evaluation, criticality control
     - ・collection, transfer and storage, waste management

2. Key technologies
   - ➢ Challenges in the extremely high dose environment
     - ・radiation shielding, mitigation of RI release
     - ・remote control technology
     - ・visualization technology
   - ➢ Established reliable technology and flexibility of introduction of new technique

3. To ensure the safety: Nuclear safety is the maximum value
   - ➢ Introduction of debris handling experiences, performance and lessons learned from overseas countries
   - ➢ Design to support the risk management in the site
   - ➢ Establishment of safety design plan and dialogue with the regulator
   - ➢ Verification by examinations and mock up tests
   - ➢ Enough trainings