Current status of R&D for Fuel Debris Retrieval

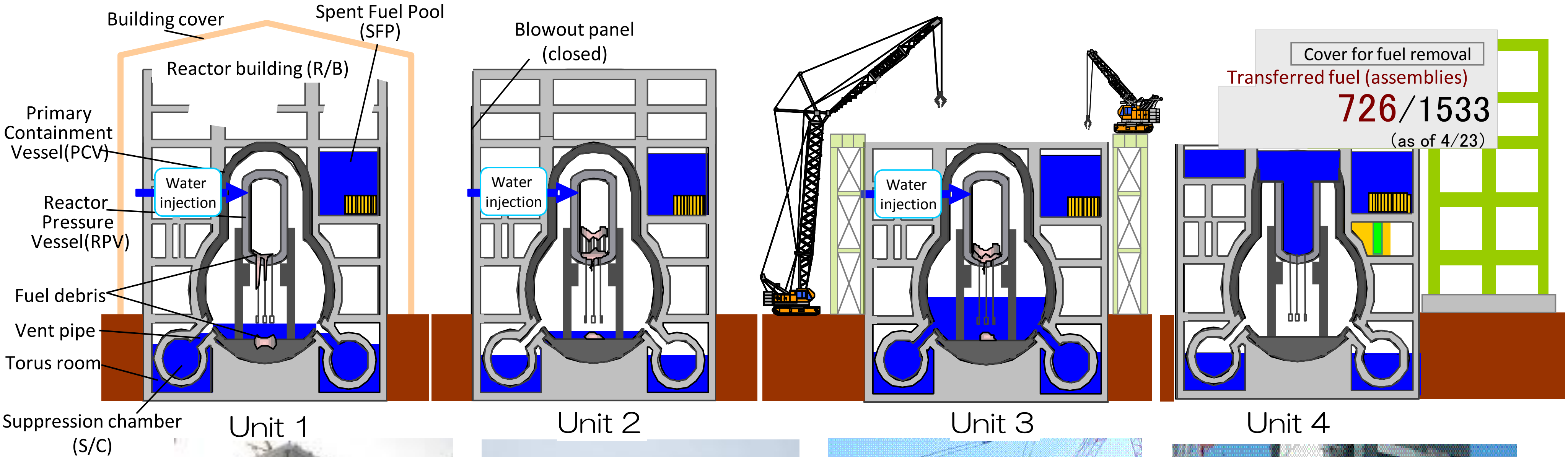
Apr. 25, 2014

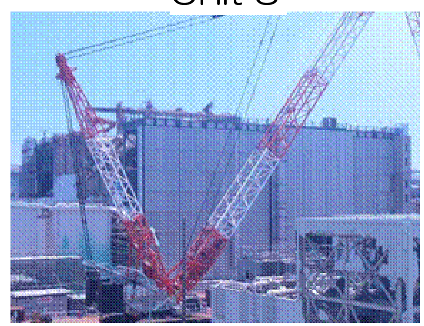
International Research Institute for Nuclear Decommissioning

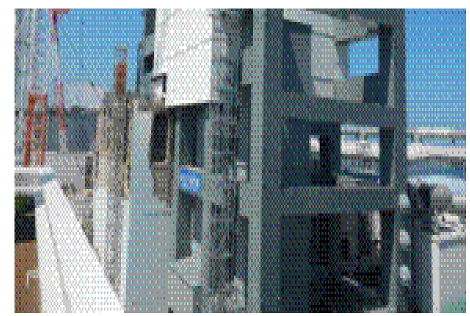
(Plant information included in this document is taken from TEPCO official website.)

Overview of Units 1-4

- The state of progress for decommissioning varies with each unit.
- Removing spent fuels from SFP at unit 4 started from November 18.







Electrical output	460MW	784MW	784MW	784MW
Date of commercial operation	1971/3	1974/7	1976/3	1978/10

Outline of Mid and Long Term Roadmap

- Mid-to-long term roadmap was revised in June 2013.
- Phased approach was confirmed.
- Fuel removal from unit 4 SFP started from November 2013.

Efforts to stabilize plant condition	Phase 1	Phase 2	Phase 3
December 2011 (Step 2 Achieved)	November 2013	1st half of 2020 (fast case)	30 to 40 years in the future
<Cold shutdown achieved> •Achieve cold shutdown •Significantly reduce radiation releases	Period up to the commencement of the removal of the fuel from the spent fuel pool (within 2 years)	Period up to the commencement of the removal of the fuel debris (within 10 years)	Period up to the completion of decommissioning measures (30 to 40 years in the future)

Started first fuel assembly removal from Unit 4 SFP on Nov. 18, 2013

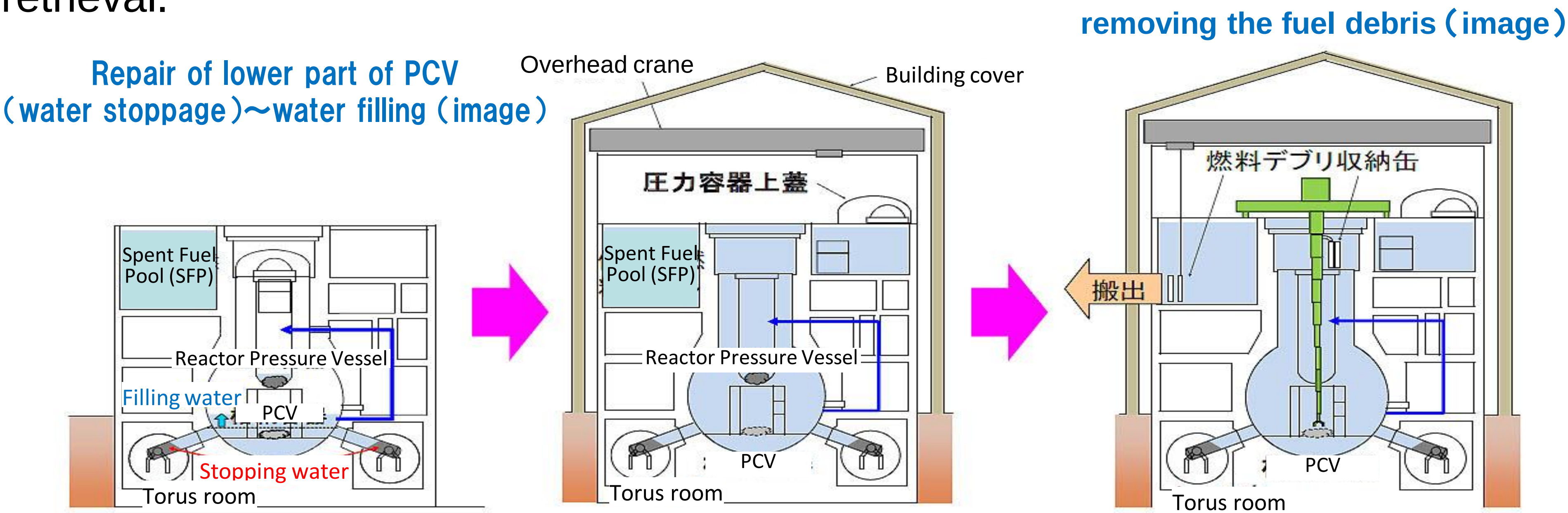
"Mid-to-long term roadmap on Decommissioning of Fukushima Daiichi NPS" was revised on June 27, 2013.

Work image for removing the fuel debris

■The approach of removing the fuel debris submerged in water is the safest approach from the standpoint of minimizing exposure of workers.

■The primary containment vessel (PCV) will be examined and repaired for filling the PCV with water. Furthermore, R&D for the removal and storage of fuel debris will be implemented.

■RFI's were executed to solicit information to overseas countries for contaminated water countermeasures and innovative approach for fuel debris retrieval.



Major Challenges in the Existing Decommissioning Procedures

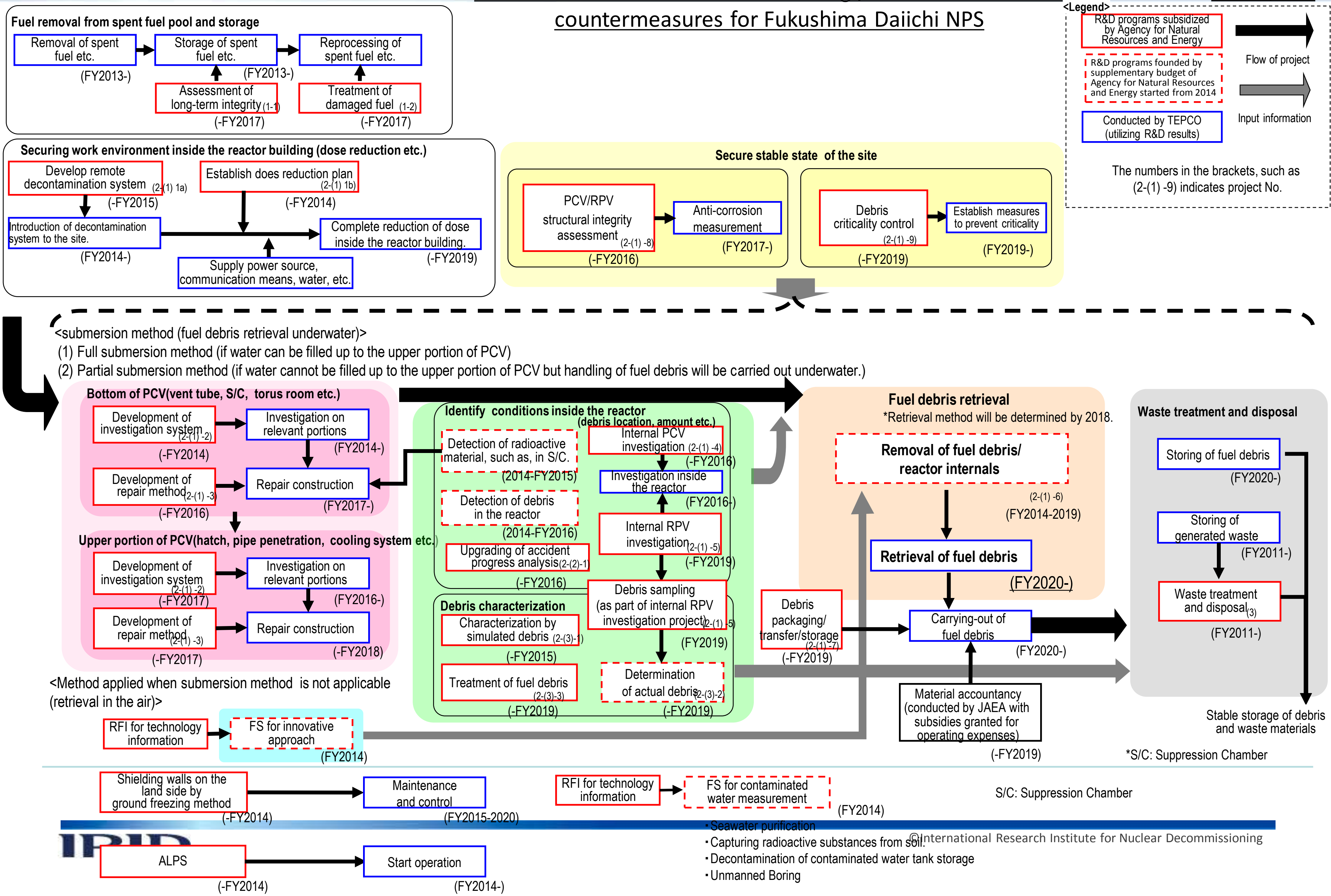
- Final goal is to defuel from the Reactor Building (R/B).
- Defueling procedure would be much more complicated than TMI-2 case due to
- differences like:

	TMI-2	Fukushima Daiichi
R/B Damage	Limited	Damaged by H_2 explosion (Units 1,3,4)
Water Boundary	RV remained intact	Both RPV/PCV have been damaged (Units 1-3)
Fuel Debris Location	Remained in RV	Possibly fallen out from RPV
Bottom of the Vessel	No structural components	Complicated structure with Control Rod Drives

- TMI-2 experience can be utilized more efficiently for post-defueling procedures in decommissioning.

Flowchart of R&D on decommissioning /contaminated water countermeasures for Fukushima Daiichi NPS

Mar. 27, 2014



Progress status of R&D Project in FY 2013

○ Projects related to fuel debris retrieval from PCV/RPV as well as internal PCV/RPV investigation

(2-(1)-2, 3) Development of technology for investigation and repair(water stoppage) for PCV water
(2-(1)-4) Development of internal PCV investigation technology
(2-(1)-5) Development of internal RPV investigation technology
(2-(1)-7) Development of fuel debris packing/transfer/storage technology
(2-(1)-9) Development of criticality control technology for fuel debris
(2-(2)-1) Identify condition in the reactor by upgraded analysis technology for accident progression
(2-(3)-1, 3)Development of characterization using simulated debris and debris disposal technology

Technology development for investigation and repair (water stoppage) in preparation of water filling of the PCV

- Investigation: For bottom section, manufacture device design , manufacturing and plant mock-up test facility and device performance test and actual device applicability evaluation will be completed. For upper section, device design and manufacturing and performance check will be conducted for each investigation portion.
- Repair : for bottom section, in preparation of device design and manufacturing, repair method and detail verification and element test for water stoppage material will be completed. As for (water stoppage) upper section , in preparation of manufacturing of repair device applied for the portion which is highly likely damaged, results of test etc. will be reflected to the detail verification and design for the water stoppage material.

Contents of implemented measures

1. Development of PCV investigation technology

1.1 Development of PCV bottom section investigation equipment

- Manufactured investigation equipment for the leak location from PCV bottom section investigation equipment • reactor building to the adjacent building. Manufacturing of plant mock-up test facility

and device performance check will be completed.

- Actual device applicability evaluation(field validation)plan and field validation will be completed.

1.2 Development of PCV upper section investigation equipment

- As for PCV upper section investigation equipment ,

device design and manufacturing and performance check will be conducted for each investigation portion.
(Leak detection device of investigation equipment of Dry-well(D/W) outer opening section will be of basic small type for small diameter penetration)

- Establish actual device applicability evaluation(field validation)plan. Field validation will be planned in 2015.

2. Development of PCV repair (water stoppage) technology

2.1 Development of PCV bottom section repair device

- In preparation of design and manufacturing of repair device for boundary structure such as by vent piping and suppression chamber, verification of repair method in detail (detailed verification of water stoppage material such as by water stoppage test and optimization of closure auxiliary material etc.) will be completed.

2.2 Development of PCV upper section repair device

- In preparation of manufacturing of repair device applied for the portion which is highly likely damaged (hatch flange, penetration bellows, electric penetration), results from water stoppage test will be reflected to the detailed verification and design.

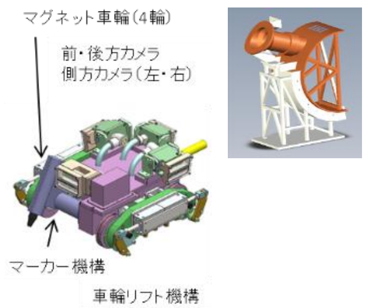


Fig.1 S/C outer bottom section investigation equipment and plant mock-up test facility

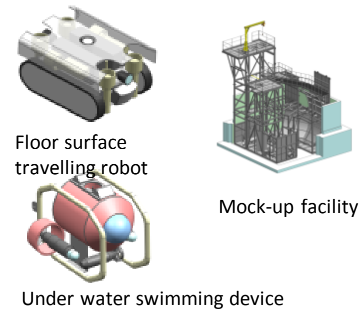


Fig.2 Underwater equipment/ plant mock-up test facility

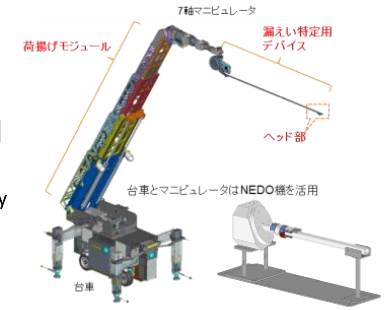


Fig. investigation equipment for D/W outer opening portion and plant mock-up test facility.


Fig.4 Auxiliary material test condition for closure of water stoppage of PCV bottom section


Fig.5 test device for water stoppage of PCV upper section


Fig.6 Water stoppage test status for water stoppage for PCV upper section

Issues and next plan direction

Overall scenario of repair including water filling level needs to be reflected to the design of technology development device by promoting the collaboration and linkage with other projects.

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Development of internal PCV investigation technology

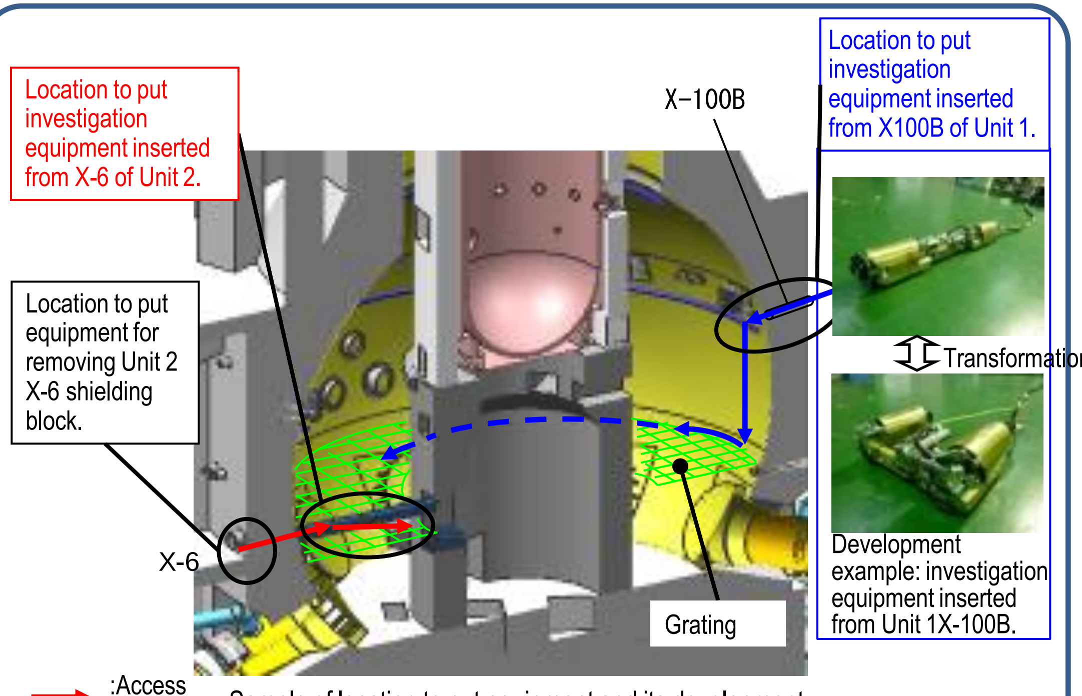
- Investigation equipment for unit 1 was produced and its functioning test completed as for pre-survey of outside of the pedestal (image of PCV, dose, temperatures etc., obtained). Equipment manufacturing for removing shielding block of Unit 2 and its verification test is planned to be completed in the preliminary investigation inside the pedestal.
- Basic verification and element test for additional investigation equipment for the accessing point will be completed to be prepared for full scale investigation in/outside of the pedestal where debris may be existing (distribution state of fuel debris and measurement of shape).

Contents of implemented measures

1. Development of equipment for preliminary investigation of internal PCV:
Sample of equipment development is shown in the figure on the right. Development of equipment below is ongoing for demonstration test to be conducted next year.
(1) Investigation equipment inserted from X-100B (Unit 1)
Completed manufacturing of equipment and function verification test. Improvement items extracted by function investigation will be conducted by FY2014.
(2) Equipment for removing X-6 shielding block(Unit 2)
Manufactured components (manipulator, end effector etc.) of equipment, and equipment assembly is ongoing. Measures on the handling objective with large weight found from the results of on-site investigation is under the verification to be reflected to the development plan.
(3) Investigation equipment inserted from X-6 penetration (Unit 2)
As for the results obtained from the investigation conducted through X-53 in the previous year and issues, they are to be verified for changes in the equipment structure of transfer mechanism, and reflected to the development. Manufacturing of equipment / function verification test is planned to be conducted by FY2014.

2. Development of access method and equipment
(access equipment in/out side the pedestal)
Verified concept of access equipment for inside/outside of the pedestal, and establishment of specification of element making is ongoing. Also, verified is concept for access equipment required for prevention of dispersion of radioactive material when sending equipment into PCV.
Element making/test done by FY 2017.

3. Development of inspection equipment and technology
(debris measurement apparatus)
Established equipment system structure for technology of measuring shape by light cutting method. Also, element test for measurement simulating disturbance environment (spray, rain etc.) inside the PCV is ongoing.



Sample of location to put equipment and its development

Issues and direction of next plan

- Correspond to new issues found in the demonstration test and site investigation results in the previous year (existence of unexpected obstacles and its large weight etc.) and, address the improvement for verification test.
- In the next plan, conduct the demonstration test, and promote equipment development .

Development of internal RPV investigation technology

Established Technology development plan to conduct investigation inside the RPV by verifying the methods of accessing to the investigation location, investigation, and sampling and arranged investigation technology under the high dose environment inside the RPV(provisional value 1,000Gy/h), in order to obtain the location of fuel debris inside the RPV, damaged state of reactor internals, temperature inside the RPV, and dose.
(FY2015/FY2017: Technology to investigate through the system piping, FY2018: Investigation technology for drilling on RPV upper section, FY2019: Technology to investigate after opening of reactor).

Contents of implemented measures

1. Planning of internal RPV investigation

◆ Verification on major investigating item and investigation period
After selecting the investigation items for internal RPV investigation, verified investigation items and investigation period, and established debris plan described in No.2 below (FY 2015/FY2017: Technology to investigate through the system piping, FY 2018: Investigation technology for drilling on RPV upper section, FY 2019:Technology to investigate after opening of reactor.).

◆ Verification on access route
Selected candidate as a route to investigate inside of the RPV from the methods of accessing : from piping, by creating hole on the upper portion of RPV upper section, by opening up the reactor and by evaluating its accessibility. (Fig. 1)

2. Planning of R&D plan

◆ Access technology
Conducted investigation on the existing technology based on the verification results of access route inside the RPV and extracted issues on the development of issues such as technology to penetrate into obstacles.

◆ Investigation technology(radiation resistant camera , dosimeter etc.)
After investigating existing technology, verified applicability and extracted issues regarding measures on radiation resistance etc.

◆ Sampling technology
Investigated existing technology, verified concept of sampling method, summarized those issues and established development plan.

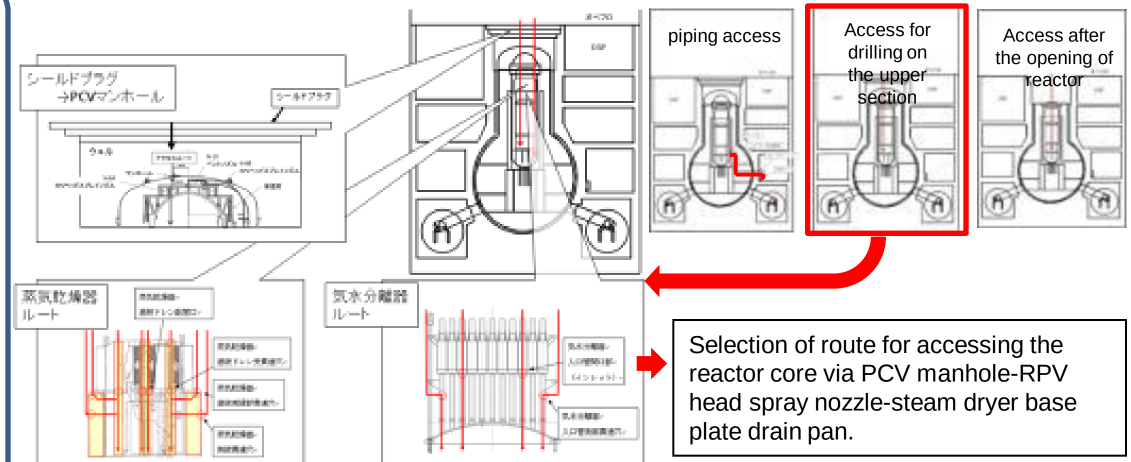


Fig. 1 Verification for the access route inside the RPV (sample of access by drilling on the upper section)

Table 1 Development plan of access technology (sample of access by drilling on the upper section)

No	Development technology element	Issues	2014	2015	2016	2017	2018
1	Boring technology	Creating hole for the steam dryer, and separator					
2	Tube expansion technology	Tube expansion for the hole diameter of steam dryer and separater					
3	Remote control technology	Monitoring the passing on the curve and narrow part , and operating condition					
4	Boundary forming technology	Boundary reforming on the operation floor (sealed plug)					

Issues and direction of next plan

Need to conduct equipment design and element making /test based on the plan for technologies for access, investigation, and sampling investigated this year.

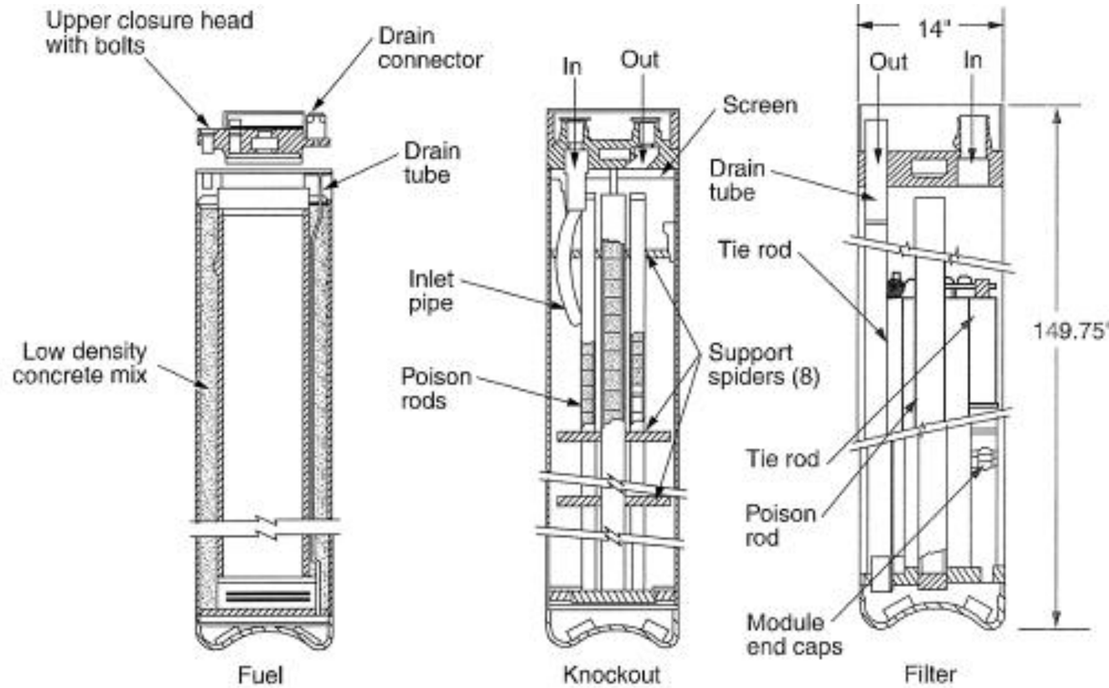
Development of fuel debris packing/transfer/storage technology

Conducted investigation on the overseas technologies such as those applied for the accident occurred in the Unit 2 of Three Mile Island (TMI) Nuclear Power Plant in US. Extracted issues on the development of canister, and established future development plan for the purpose of determining the specification of canister, such as shape , for packing/transfer/storage of fuel debris.

Contents of implemented measures

1. Investigation on the transfer and storage of damaged fuel
   Conducted investigation on overseas information on damaged fuel (including leak fuel) transportation/storage , and collected information to be utilized for design of canister for packing/transferring/storing the fuel debris, including transfer and storage of fuel debris of TMI-2 in US.
2. Verification on the storage system
   Investigated storage system of spent fuel, such as concrete cask etc., which we never experienced in Japan, and collected information to be utilized for the selection of storage system for fuel debris.
3. Extraction of issues and planning of general plan
   (1) Collaborative work with other R&D
   Collaborating with related project, summarized information required for canister design regarding criticality control and basic physical property of debris.
   Also, established plan of the basic process flow up to storing the fuel debris, and extracted issues and required tech development items.
   (2) Selection verification for fuel debris storage method
   Extracted technological issues and problems when serving as fuel debris storing in canister, and made a comparison for those.
   (3) Established general plan
   Established future R&D plan based on the investigation and verification above.

*: From DOE/SNF/REP-084 TMI Fuel Characteristics for Disposal Criticality Analysis(2013)



Sample of canister for fuel debris used in TMI-2 in US. (Reference)*

Issues and direction of next plan

Additional overseas investigation and collection of canister concept based on the investigation results obtained in FY2013 is required. In FY 2014, reflect those and develop safety analysis method required for design of canister.

Development of criticality control technology for fuel debris

In order to develop criticality control method during the fuel debris retrieval by 2019, as a element technology, completed evaluation of criticality scenario in each process up to fuel debris retrieval, manufactured and verified criticality detector as prototype, manufactured and narrowed down the candidate material for insoluble neutron absorber, and summarized soluble absorber issues in FY2013. (re-criticality detector in the reactor is ongoing).
These results will be integrated and criticality control method during PCV water filling and fuel debris retrieval which are major processes will be established in FY 2014.

Contents of implemented measures

1. Criticality evaluation

・Completed preparation of criticality scenario for each process from PCV water filling to fuel debris retrieval, and summarized transitions of state where re-criticality may be happened (Table 1).
Completed criticality evaluation by representative case including interaction of debris with concrete.

・Completed improvement of behavior evaluation model at criticality by adding handling of multiple debris with different properties, thermal-hydraulic model for fuel debris that can handle coolant boiling, and model for evaluation of FP nuclide generation. (to be utilized for planning of criticality control method for next year).

2. Sub-criticality control technology for liquid waste treatment /cooling system

・Manufactured sub-criticality monitor (Fig. 1) experimentally, confirmed detectability of approaches to criticality by critical assembly, and confirmed system feasibility. (The development is planned to be done this year.)

3. Technology of re-criticality detection in the reactor

・Verified and designed neutron detector system specification, and procured its prototype system.

・Verified improvement of FP γ-ray detector system for gas sampling line and procured prototype equipment for feasibility check test to detect re-criticality on early stage.

・Feasibility check tests above will be conducted. (Apr-May, 2017).

4. Criticality prevention technology

・Manufactured candidate material for insoluble neutron absorber experimentally (Fig. 2), obtained basic physical property data (Table 2) , and completed narrowing down the candidates on the first phase (After next year, final candidate will be determined by radiation resistant test and confirmation of nuclear characteristics, and be applied for debris retrieval)

・Completed in summarizing issues when applying soluble neutron absorber, and extraction of required verification items, such as corrosion test. (After verifying issues in the next year, determine application method of absorber).

Table 1 Scenario for criticality status when retrieving fuel debris

フェーズ	場所	初期状態		再臨界シナリオ
		燃料状態	冷却状態	
RPV冠水～燃料デブリ取出し	炉心部 デブリベッド層	炉心平均組成のデブリ(粒状、塊)	非沸騰で冠水状態	(臨界質量増加) ・上部からの非溶融燃料落下 ・上部からの燃料デブリ落下 (減速材/燃料体積比変化) ・ポロシティへの浸水 ・作業に伴うデブリベッド撹拌 (自然災害) ・地震によるデブリ・構造物の落下、移動
		Pu含有率の高いMOXデブリが偏在		
		燃焼度の低い燃料デブリが偏在した状態		
		制御棒由来のボロンが事故時に流出した状態		

Fig. 1 Display for sub-criticality monitor

Table 2 Performance evaluation check items

評価観点	評価項目
中性子吸収能	Gd/B数密度
デブリ冷却	比熱・熱伝導率
水中で流出しない	密度・溶出特性
水質環境への影響	pH
デブリ取出しへの影響	硬さ


Fig.2 Sample of prototype of insoluble neutron absorber (gadolinia/slurry)

Issues and direction of next plan

Integrate technologies developed by this year, and promote establishing the method of development of criticality control collaborating with method verification such as of fuel debris retrieval. Also, start developing in-core sub-criticality monitor for the purpose of detection on the early stage for criticality control reasonably.

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Identifying condition inside the reactor by upgraded technology for accident progression analysis

Completed upgrading of accident progression analysis technology (improvement of core damage progression model and behavior model of debris inside lower plenum etc.) for estimating condition in the reactor of fuel debris location. Utilized the results of upgraded accident progression analysis technology and conducted verification to identify condition in the reactor. In consideration of latest information obtained from site operation, ratio of debris fallen into PCV was found as follows: amount of Unit 1 is maximum , Units 2 and 3 are equal and less than Unit 1.

Contents of implemented measures

1. Confirmation of validity for code improvement and model change

   Re-evaluated and revised the priority rank for the PIRT (Phenomena Identification and Ranking Table) established in FY2012 by sensitivity analysis

2. Improvement and upgrading of analysis code

   Improved analysis code (MAAP, SAMSON) (Fig. 1) based on information obtained from site operation, results of current simulated test, latest findings which is resulted from PIRT and improved accuracy of analysis.

3. Analysis by improved code(MAAP, SAMPSON (Fig.2))

   Conducted analysis of accident progress/condition in the reactor of Unit 1-3 based on the improved latest code and constructed data base, and confirmed impact of the model improvement.

4. Individual event analysis by CFD

   Conducted debris flow analysis as trial using casting simulation code, and confirmed applicability of debris flow behavior evaluation by full-scale system (Fig.3).

5. Mock-up test

   Conducted simulated test etc. (seawater heat transfer test, behavior test for fallen molten fuel) contributing to detailed analysis of progress of severe accident event, and confirmed applicability of current heat transfer evaluation method when injecting seawater in the reactor(Fig.4).

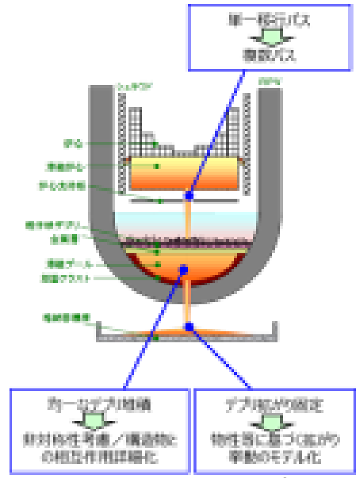


Fig. 1 Improvement of MAAP model

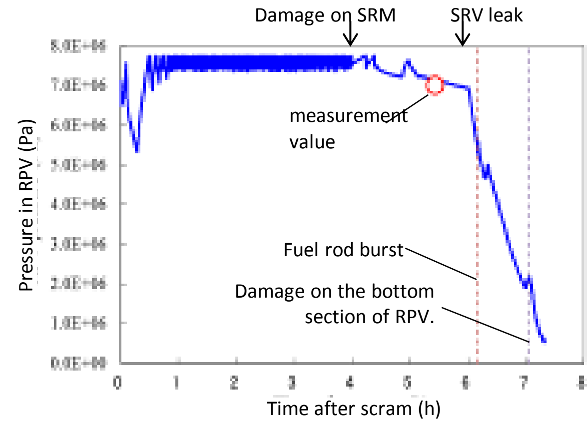


Fig.2 Prediction of pressure change inside the reactor of Unit 1 by SAMPSON.

Simulated debris

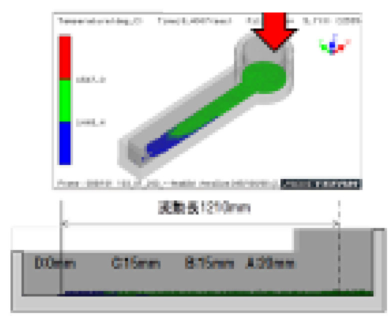


Fig.3 Reproduction of flow cessation test for simulated debris

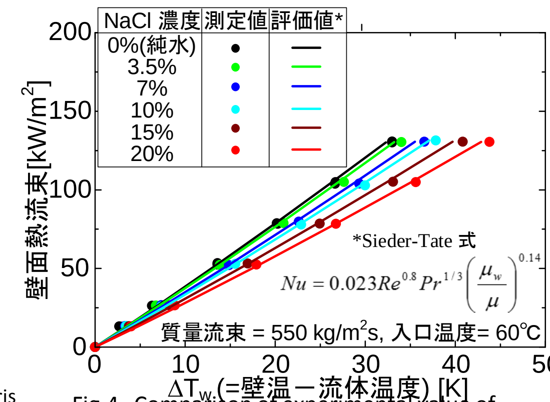


Fig.4 Comparison of experimental value of seawater heat transfer and evaluation value.

Issues and direction of next plan

In collaboration with other projects ,make output for the Decommission project and input for this project effectively by enhancing information sharing.

Study on characterization of debris and development of debris disposal technology using simulated debris

Manufactured simulated debris and obtained data such as hardness in order to estimate the property of actual debris to investigate the fuel debris retrieval technology. Also, in order to verify disposal scenario after retrieving fuel debris, extracted applicability and technology issues on existing fuel treatment technology and compared options to be taken, and clarified those advantage and disadvantage.

Contents of implemented measures

Study on characterization of debris(2-(3)-1)

(1) Verification of physical property required for fuel debris retrieval

- Identified the level of impact to the machinability of physical property such as hardness, for each type of simulated material.
- Assuming the incorporation of metallic components in the reactor, measured mechanical characteristics of $(U,Zr)O_2$ in high Zr area and Fe contained simulated debris, and reflected the measurement value to the estimation of physical property distribution for each chemical system.

(2) Determination of reaction specific to 1F accident

- Confirmed the possibility of generating alloy phase and boride by the reaction with control material. Also, confirmed that trend that oxide (vitreous oxides) and alloy layer were separated by the reaction with concrete (MCCI). The hardest substance was estimated to be boride.
- Confirmed Gd was contained in the some of the fuels, and its impact and area on the thermal properties of simulated debris($(U,Zr)O_2$) of oxide.

(3) Estimation of actual debris characteristics

- Established debris property list (provisional version) from the results above.

Development of debris disposal technology. (2-(3)-3)

(1) Arrangement of technology requirement for fuel debris disposal scenario verification.

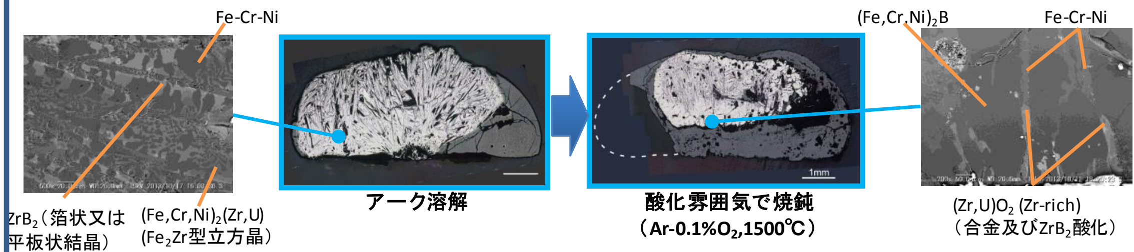
- Compared options for the disposal scenario for the retrieved fuel debris and clarified advantage and disadvantage.
- Evaluated applicability of existing spent fuel transport cask. Found that the water content of fuel debris etc. which has impact on the storage has high priority.

(2) Verification of element technology for debris analysis

- Obtained basic data of melting process, which is a pretreatment technology for analysis of each simulated debris including MCCI product.

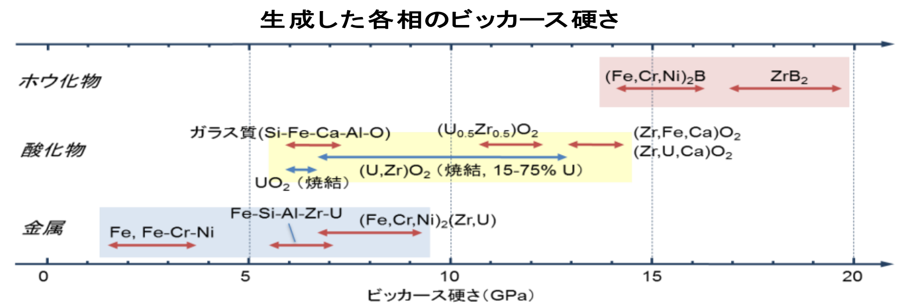
(3) Applicability verification of existing fuel treatment technology.

- Obtained basic date for the applicability of simulated debris to the wet process and dry process.



制御材（B_4C+SUS）との反応（溶融固化物断面観察像の例）

(Obtained knowledge regarding the composition of solidified material generated when control rod and fuel is melted)



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

Direction of next plan

Identify the physical property such as hardness using simulated debris, and evaluate the reactivity with materials in/outside the Pressure Vessel, characteristics evaluation such as of MCCI product material. In 2-(3)-3, verify and evaluate the water content of fuel debris that effects storage technology while continuing the development of analysis element technology.

New R&D project for FY2014

New R&D projects including Fuel debris/reactor internal structure retrieval technology and Detection technology for fuel debris in the reactor are planned focusing on filling water method in FY2014 related to the current project.

(Reference: Decommissioning, and Contaminated Water Response Team on March 27th.)