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Robots Technology for Decommissioning of Fukushima Daiichi Nuclear Power Stations

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Tamio Arai
Vice President
International Research Institute for Nuclear Decommissioning (IRID)
Emeritus Professor, The Univ. of Tokyo

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- **Robots in Fukushima Daiichi**
  - Missions depending on phases
  - Failures & Countermeasures
- **Requirements for Robots**
  - Fundamental requirements for robots
  - Characteristics of robotics for NPP
  - Fuel Debris Detection Technology
- **Developed/-ing devices for decommissioning**
  - Sequence of Fuel-debris retrieval
  - Fuel Debris Retrieval Technology
  - Subsystems of an investigating system
  - Required technology in robot system
- **Design criteria for robots**

Robot technology for decommissioning

- The difficult targets are
  - **to retrieve fuel-debris**
  - **to prevent leakage of radioactive substance**
  - **to prevent re-criticality,**

- under the sever conditions such as
  - **unknown,** undefined environment
  - **high radiation level**
  - **water**, high humidity, existing hydrogen
  - complicated **obstacles**
  - **large**, and **heavy** mechanisms
  - small experiences of operations

- Approach to R&D of robots
  - **to utilize knowledge of robotics**
  - **to introduce the improvements**

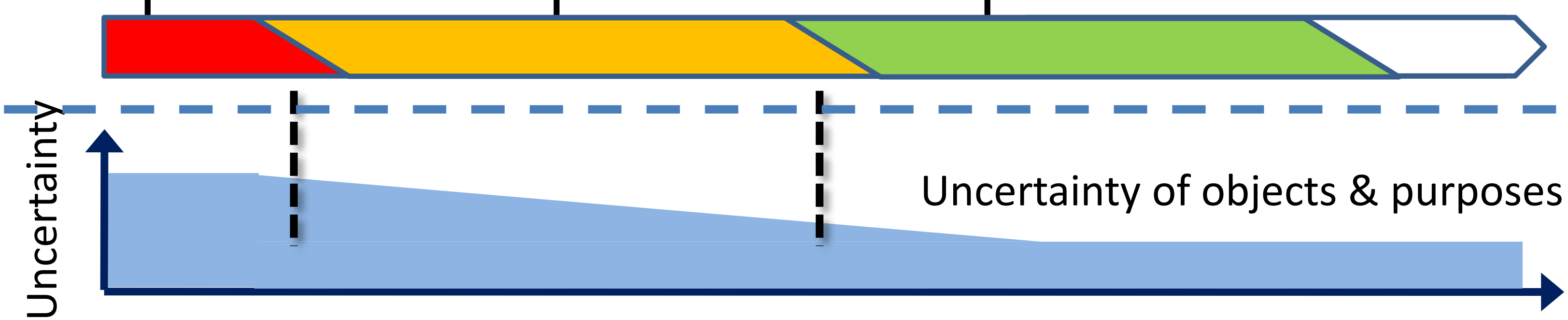
Missions depending on phases

Phase 1: Emergent Situation: Cooling down of reactors

Phase 2: Stabilization: Containment and systems reconstruction for aftershocks

Phase 3: Decommission: Fuel removal

by H. Asama



by Y. Yokokohji

Phase 1: Emergent countermeasure

Existing devices

Phase 2: Investigation and appropriate measure

Combination of established technology

Phase 3: Full-scale development

Development of devices suitable to the site

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Phase 1

by courtesy of Prof. Asama

Procure off-the-shelf robots and equipment (for general purpose)

Putzmeister
Concrete Pump Truck

Remotely Controlled
Construction Machines

QinetiQ Talon

Brokk-90

Honeywell
T-HAWK

iRobot Packbot

iRobot Warrior

QinetiQ Bob Cat

Brokk-330

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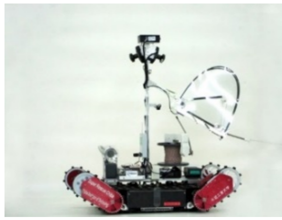
Hajime Asama
Dept. of Precision Engineering
The University of Tokyo

by courtesy of Prof. Asama

Phase 2

Remodel developed system and technology


Quince


Quince 2


Quince 3


Gamma-ray
Measurement Robot

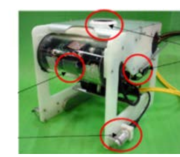

JAEA-3

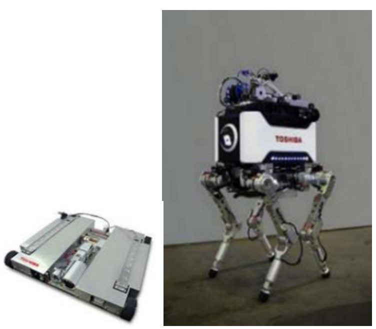

Sakura


Rosemary


FRIGO-MA


Survey Runner


ROV


Quadruped Robot
& Inspection Robot


ASTACO-SORA


MEISTeR


Inspection Robot
Of upper part of S/C


Manipulator
for Robot Set-up

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Phase 3

New development (for specific use)


Robot for Decontamination


Inspection robot for high location


Robot for Measurement of S/C Water Level

PCV Inspection Robot PMORPH


Water Surface Inspection Robot


Inspection Robot for Lower part of S/C


PCV Inspection Robot Scorpion Robot


PCV Inspection Robot Mini Mola Mola

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Failures & Countermeasures

Failures

- **Insufficient specification**/Unknown environment
- Prototypes **without improvement**
- **Operation errors**
- **Wire handling**
- Lighting and vision
- Device failure: communication, **malfunctions by radiation**

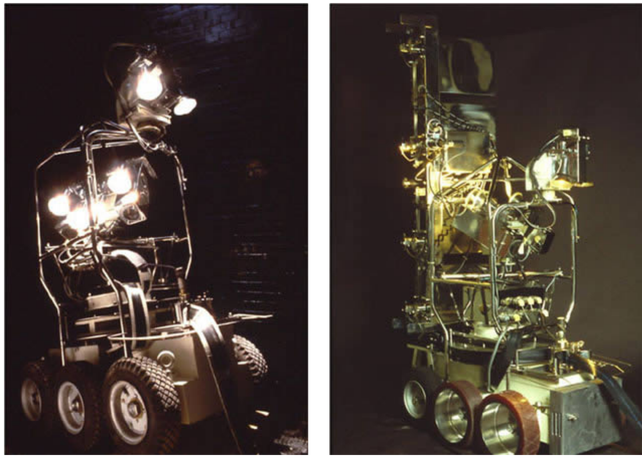
Countermeasures

- System **management**: collaboration among R&D+E&C teams
- **Design**: by frequent design reviews, risk assessment
- Simulations: to estimate effects, time, total quantity
- **Mock-up**: operation training, severe setting of environment
- **Site measurement**: point clouds of real environments

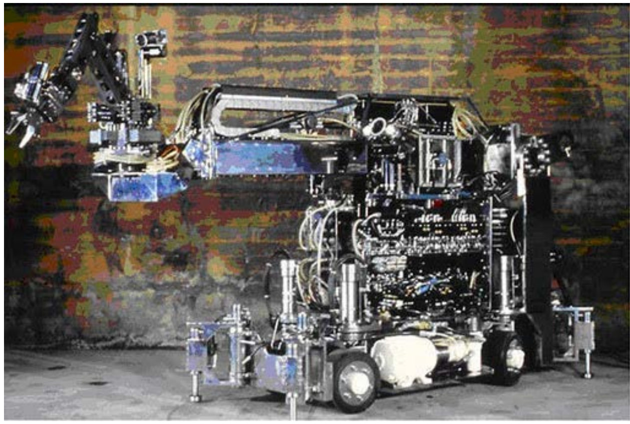
by courtesy of Prof. Yokokohji

Lessons Learned from the TMI Accident

- Successful robots were
  - compact with simple function,
  - easy-to-use and easy-to-maintain,
  - easy-to-modify according to the needs of the site
  - common mobile platform
- High-function, large-sized robot was not eventually used
- Development of new robots should be planned carefully because the situations on the site may change.



Remote Reconnaissance Vehicle (RRV) 1 & 2



Workhorse

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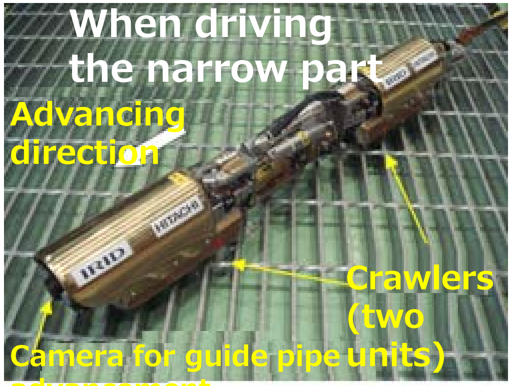
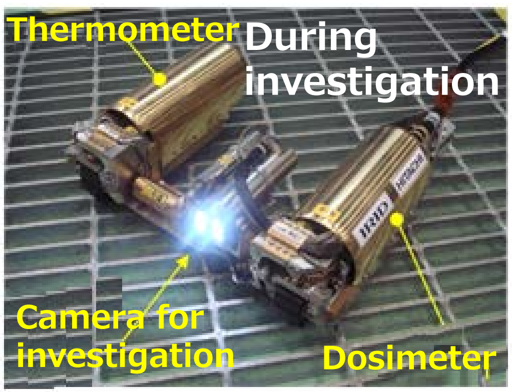
Robots newly developed for Investigation of inside PCV

Two types of shape-changing, remote-controlled, crawler robots for investigation

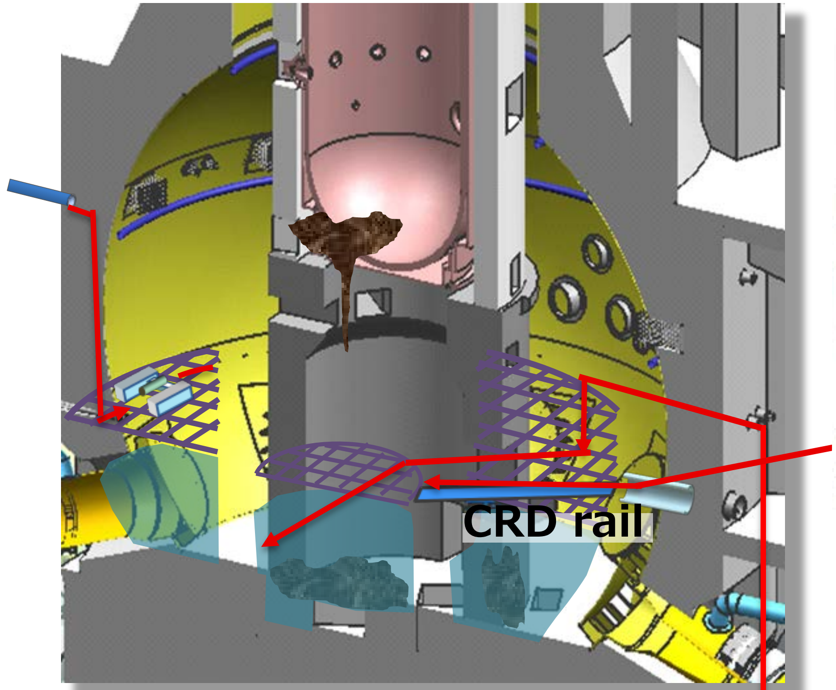
Investigation of outside the pedestal (Unit 1)

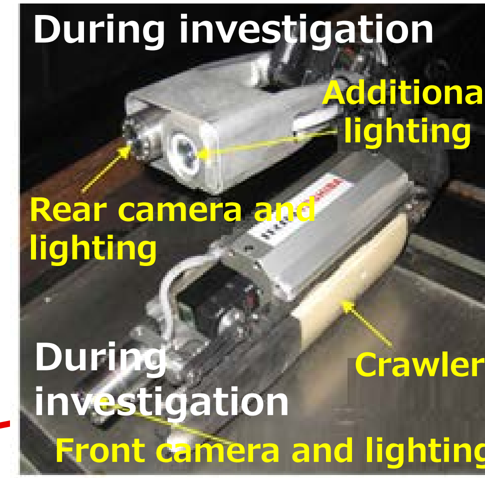


Shape changing

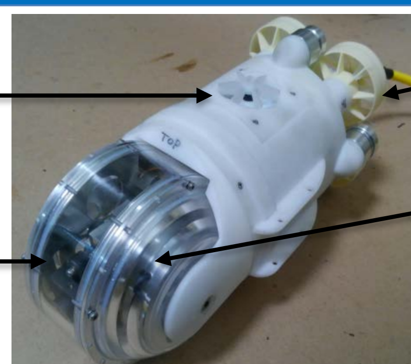


Investigation of inside the pedestal (Unit 2)



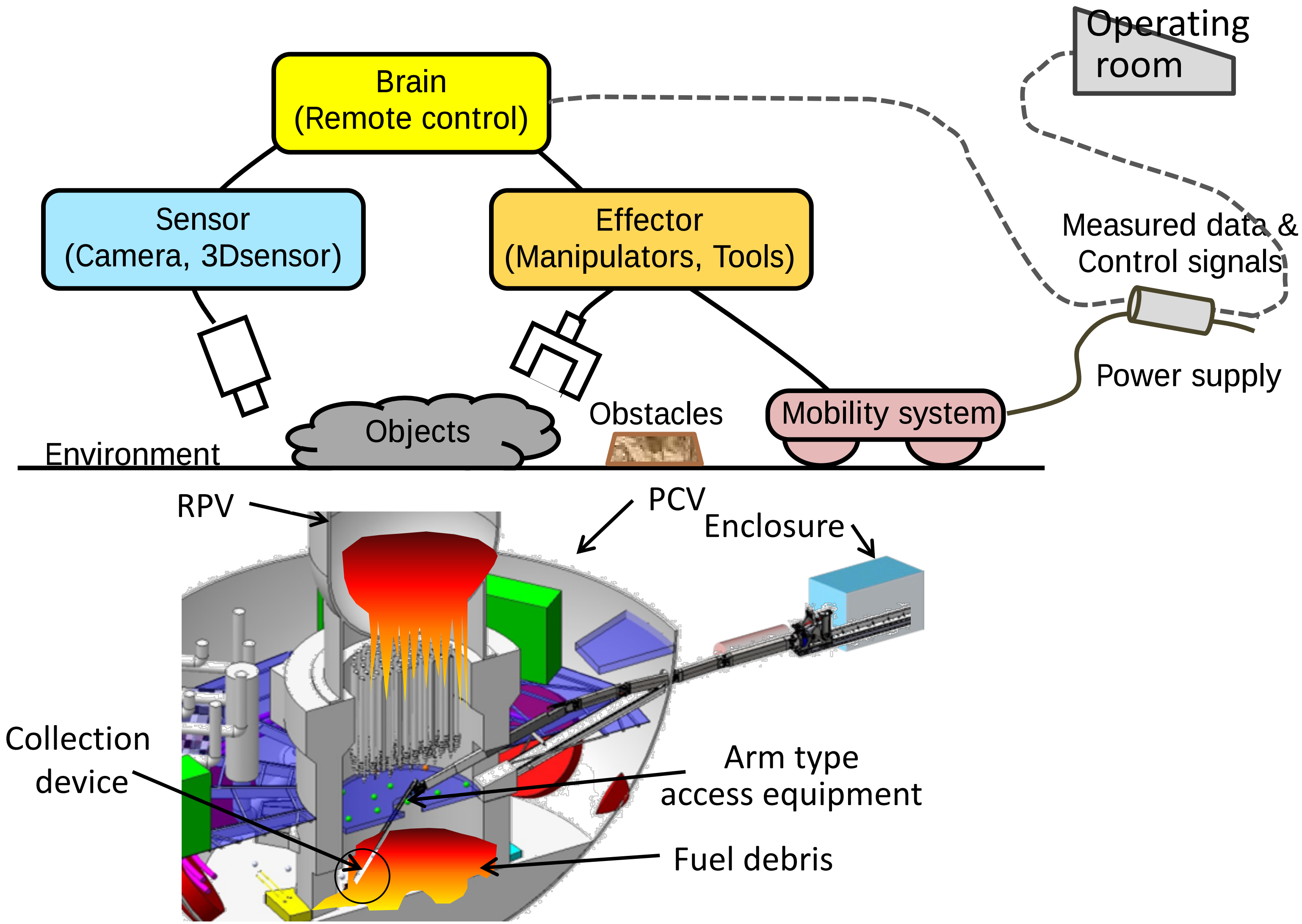


Investigation of inside the pedestal (Unit 3)



○Hanging camera on extension rod

Sub-systems of robot technology



Challenges on Robotics for decommissioning

- High doze rate
  - Weakness of Sensor-Brain-Effector system
    - **Radiation-hardened** electronic devices
    - Sufficient shields onto electronic devices
    - Mechanism without electronic parts
  - Prevention of contaminated parts
    - Washable and fully covered wires, like robots for food industry
- Long/large in size and heavy in weight
  - Low natural frequency of long beams, thus low controllability
  - **Encapsulations** of devices become much larger and heavier
  - Joining devices with heavy cells is required
  - Mock-up needs space and cost
  - Long **turn-around time** of improvement
- Undefined environment and objects
  - No light, high humidity, many obstacles
  - Unknown characteristics of handling objects

Fundamental requirements for robots

- Great amount of debris and obstacles
- Large thus heavy machines

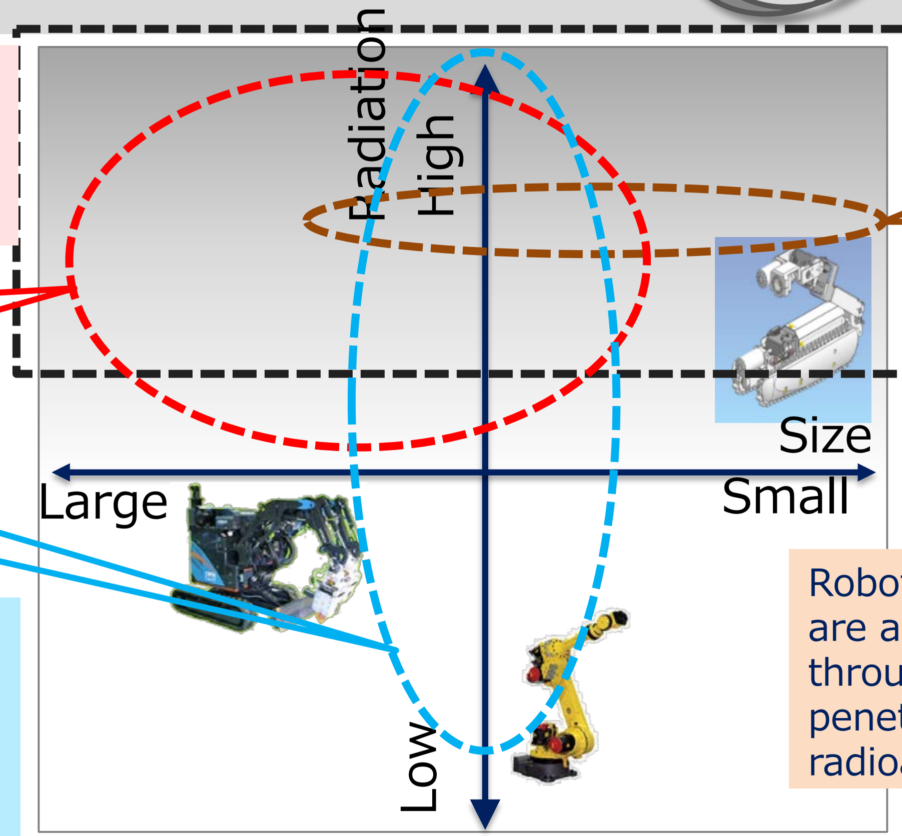
- Radiation resistance
- High Reliability, Maintainability, Easy-to-operate

For retrieval of fuel-debris, large & heavy robots are required to cut and handle debris and obstacles.

Retrieval system for debris & obstacles

Maintenance & Supporting work

Maintenance tasks may change according to the retrieval devices, sensors. The robots need to have longer life-time.



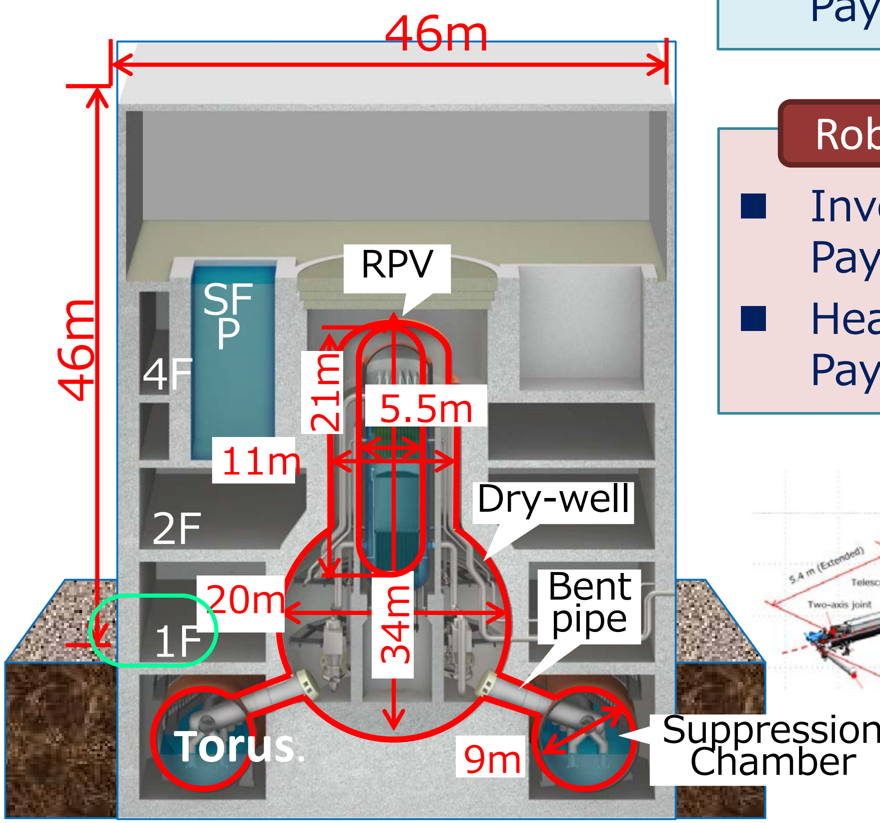
Investigation

Robots for investigation are as small as it can go through small penetration, to prevent radioactive leak.

Characteristics of mechanism

Characteristics of robots:

- Large in size, heavy in weight
- Low natural frequency at TCP

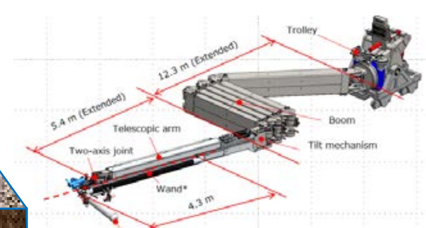


Industrial robots

- Assembly robot: Reach 1.2m, **Ratio≒0.21**
  Payload 10kg, Own weight 48kg
- Large-size robot: Reach 2.9m, **Ratio≒0.20**
  Payload 600kg, Own weight 3,035kg,

Robots for Fukushima *

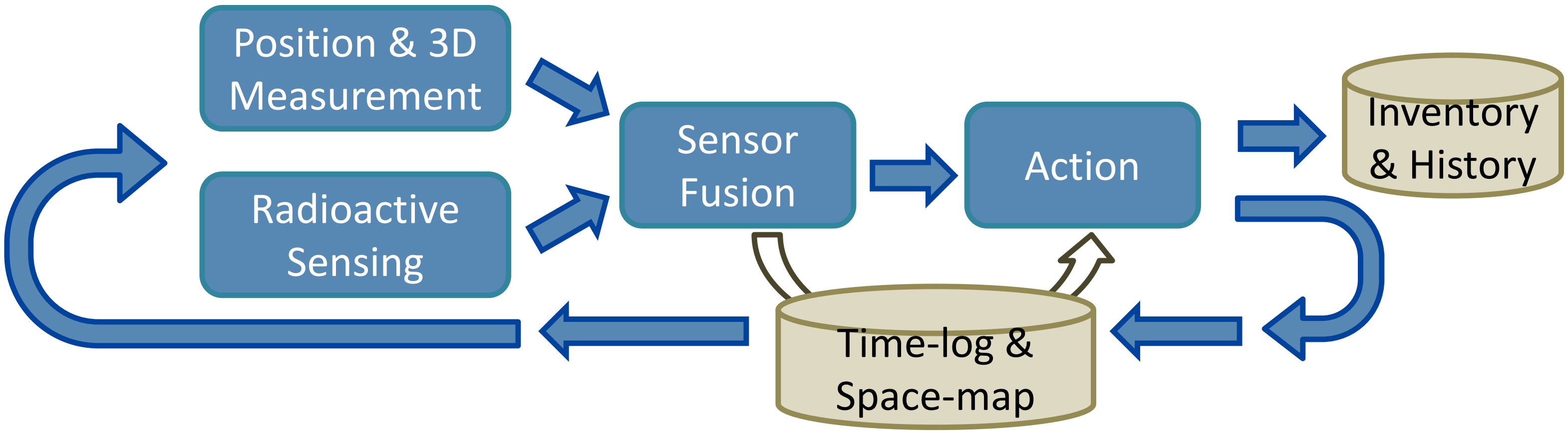
- Investigation arm: Reach 17.7m, <u>Ratio≒0.052</u>
  Payload 54kg, Own weight 1,053kg
- Heavy handling robot: Reach 5m, Ratio≒0.125
  Payload 100kg, Own weight 800kg



*The robot working inside the PCV has the risk of stuck due to failures. In view of such a risk, robots should be designed with a size that can be rescuable.

Purpose of data sensing

Remote-control	High dose radiation
➢ to **estimate** and **calibrate** the pose of sensors ➢ to detect the motions ➢ to introduce **maximum likelihood estimation**	➢ to detect **the leak out** of radioactive substance ➢ to measure **the amount of fuel debris to excavate** ➢ to **record** the process of **fuel-debris retrieval**



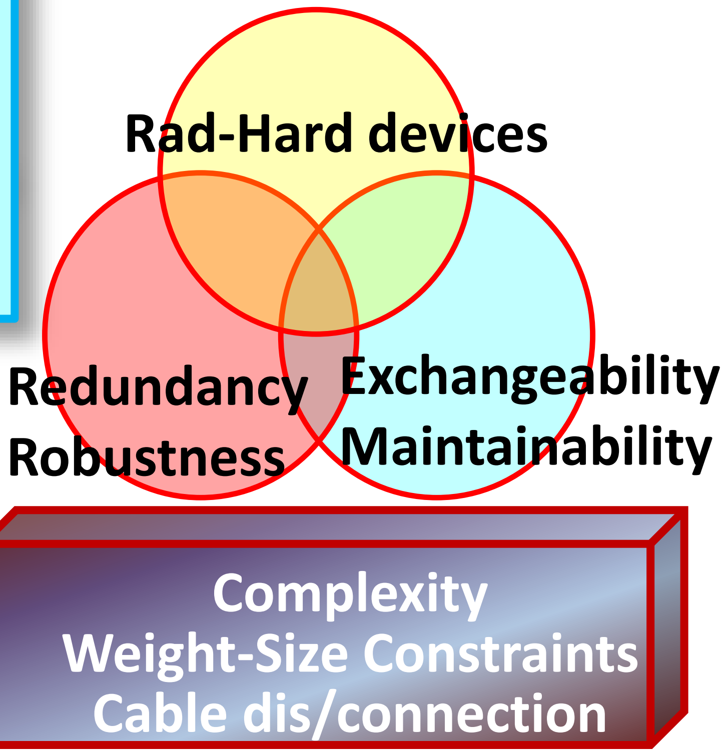
Strategies for Countermeasures against Radiation

by courtesy of Prof. Asama

Shielding
- Shield by lead/steel/tungsten (not realistic)
- Lead glass

Radiation-hardened devices / components
- Radiation-hardened(resistant) Semiconductor
- Camera tube(Hamamatsu Photonics) 2MSv dose
- Radiation-hardened Camera (SONY) 1000Sv dose

Robust design(Fault-tolerance / Maintainability)
- Redundant and functionally degradable
- Modular design and easy replace



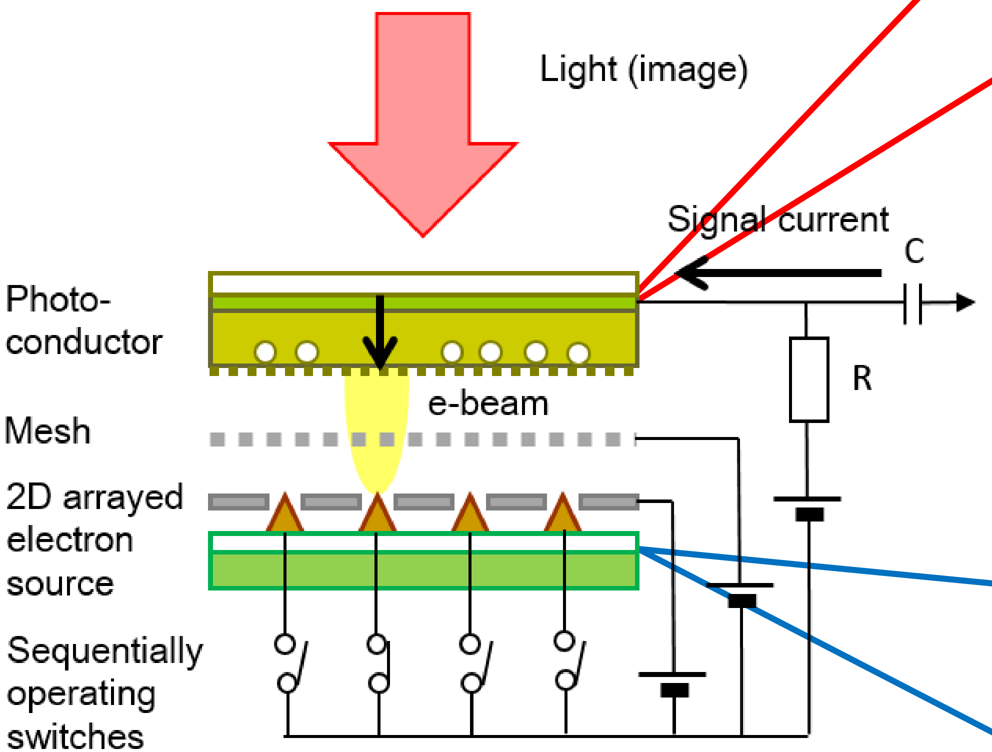
- Mechanical systems
  - Wire-driven/Tendon-driven
  - Hydraulic drive(Water)

by courtesy of Prof. Gotoh

Development of radiation tolerant image sensor

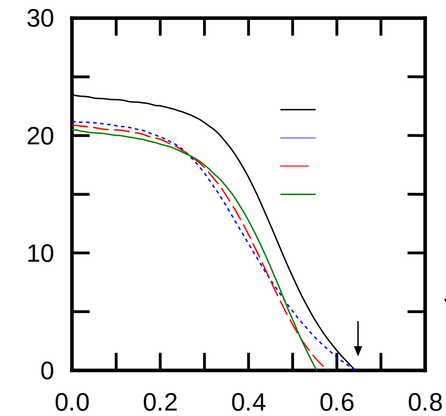
- Vacuum type flat image sensor with 2D matrix electron source

See Y. Gotoh *et al.*, FDR2019-1099



Y. Gotoh *et al.*, FDR2019-1099.

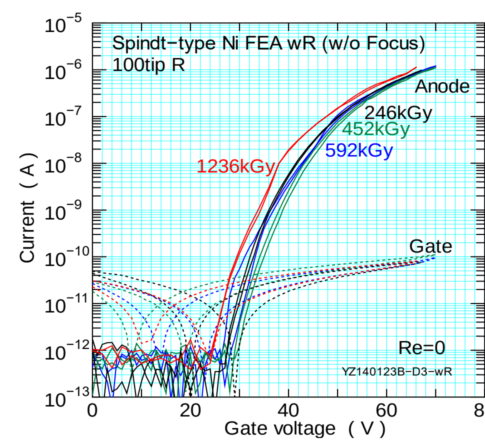
Photoconductor:
little degradation except coloring of glass



Y. Gotoh *et al.*, IVNC2016 p.20.

Changes in photovoltaic properties

Electron source (FEA):
little degradation of insulating layer



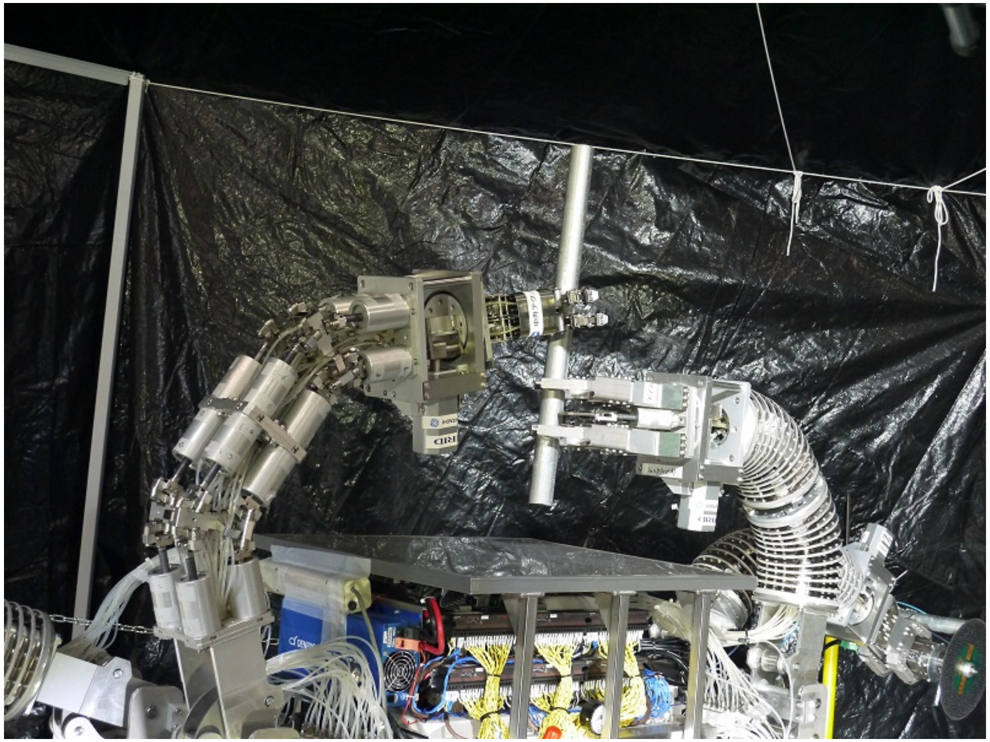
Y. Gotoh *et al.*, IVNC2016 p.20.

Changes in current-voltage characteristics

Radiation-hardened mechanism

■ Flexible Structure Arm (Muscular Robot)

- Control devices are located **outside of the high radiation area**, and connected to the cylinder by a tube.
- Joint: **4 water hydraulic cylinders and springs**
- Elongation of a cylinder causes the joint to bend
- Elasticity prevents unexpected malfunction caused by collision.
- Hitachi GE and Chugai Technos have developed five types of robots using 1 to 4 joints.



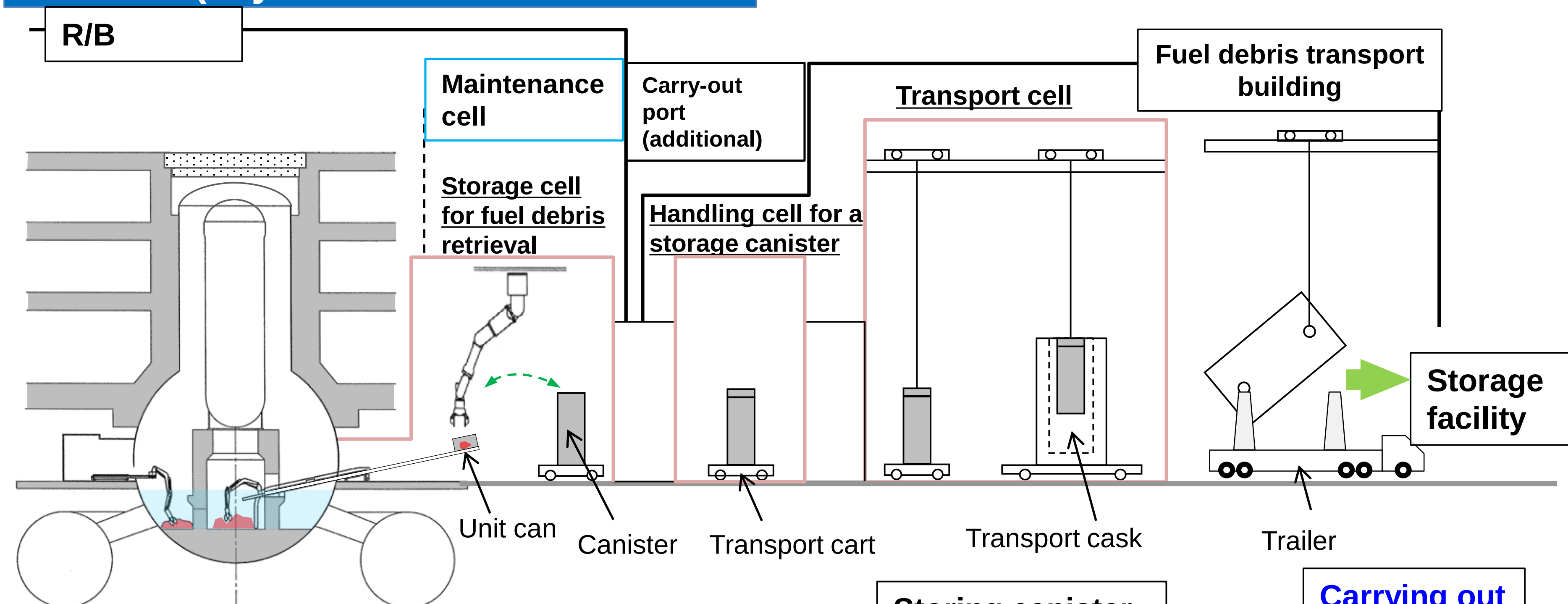
Contents

Sequence of Fuel-debris retrieval
Collection, Transfer and Storage of Fuel Debris

Canister design

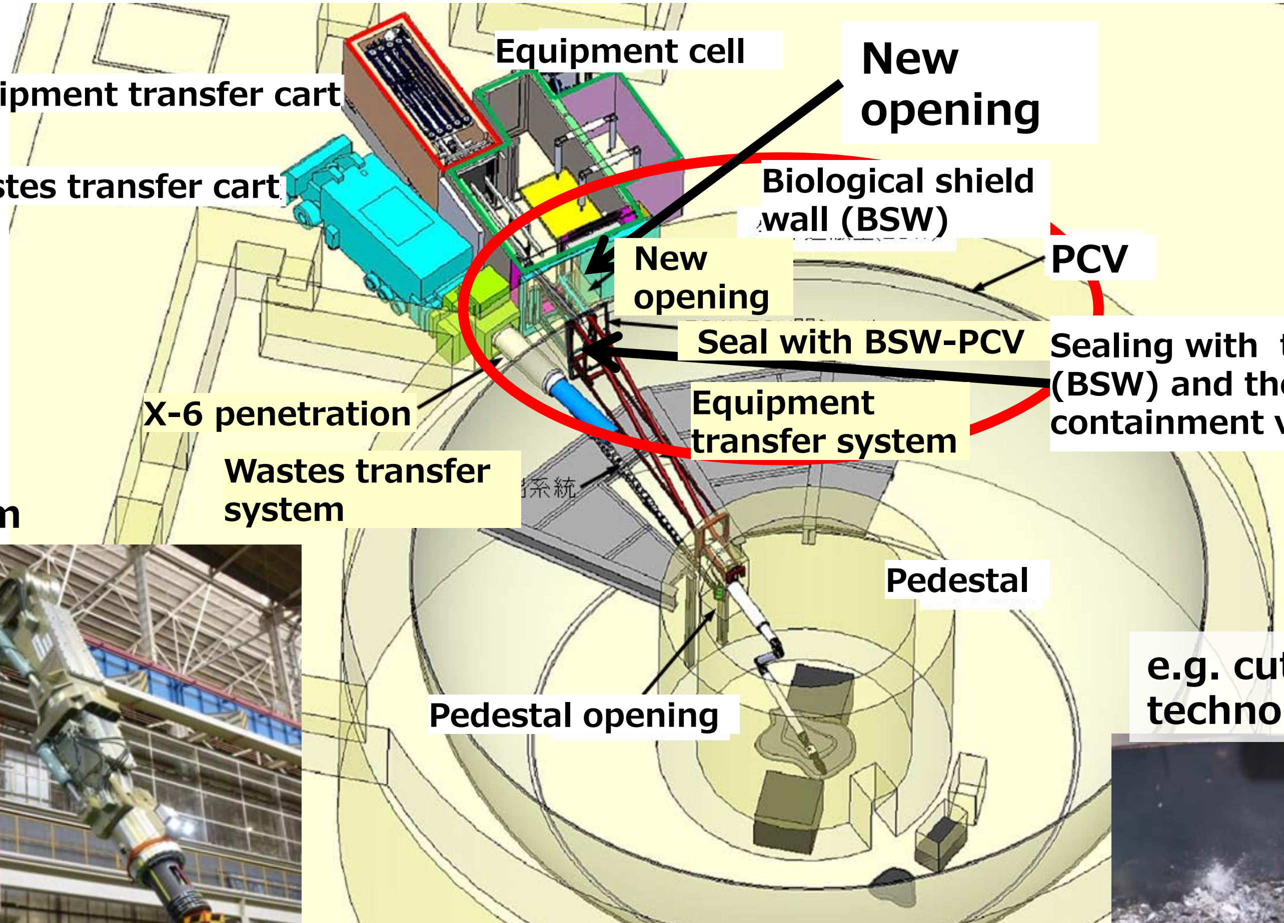
- High fuel exposure and enrichment → high reactivity
- MCCI → hydrogen generation caused by core concrete interaction
- Injecting sea water, melting cable → effects caused by salt and impurities

Transfer (Dry–side access method)



Fuel debris retrieval → **Storing in canister** → **Washing a canister** → **Storing canister in a transport cask** → **Carrying out a transport cask**

Fuel Debris Retrieval Technology
A side access method(image)



e.g. a robot arm

e.g. cutting technology (Chisel)

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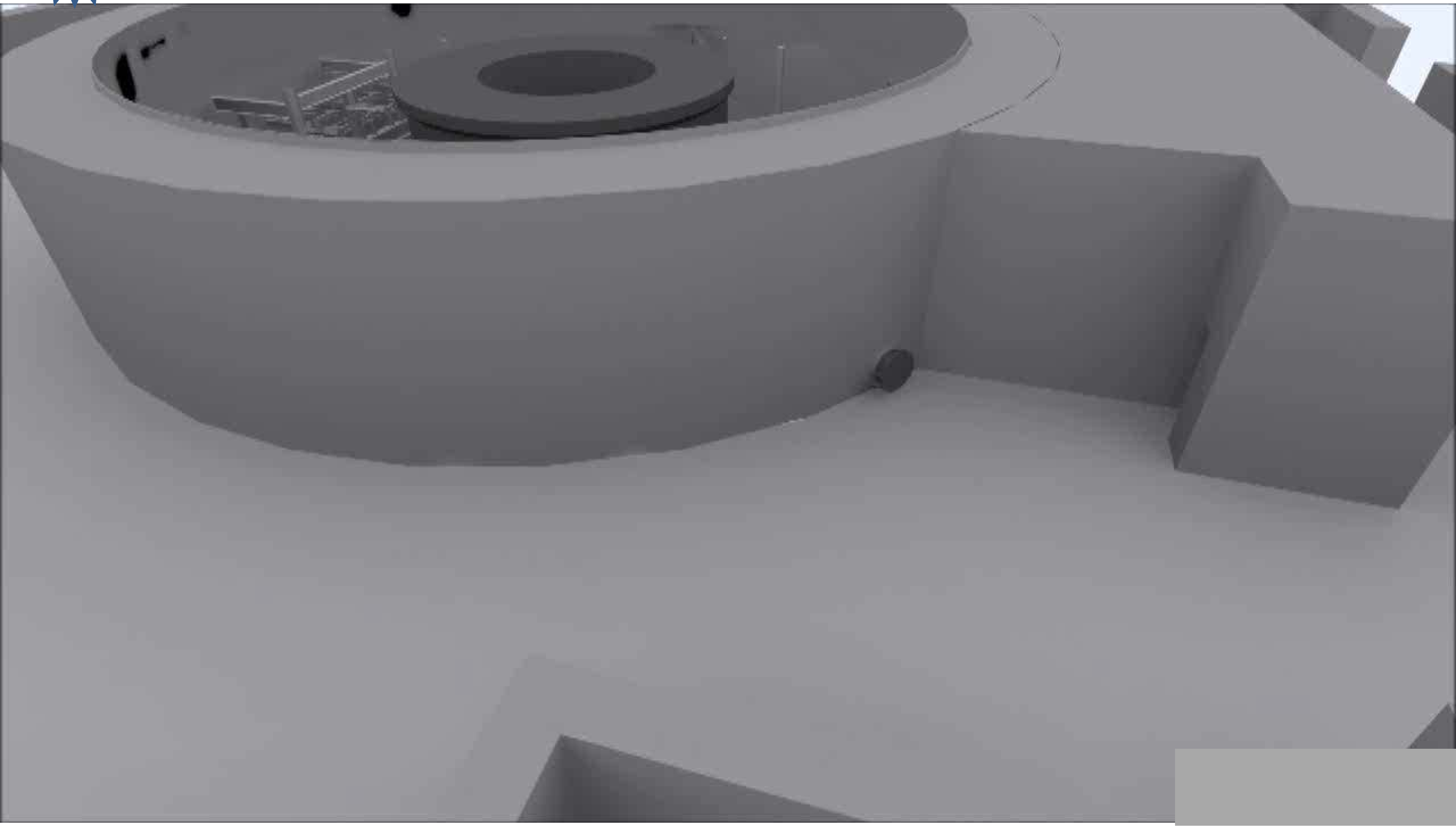
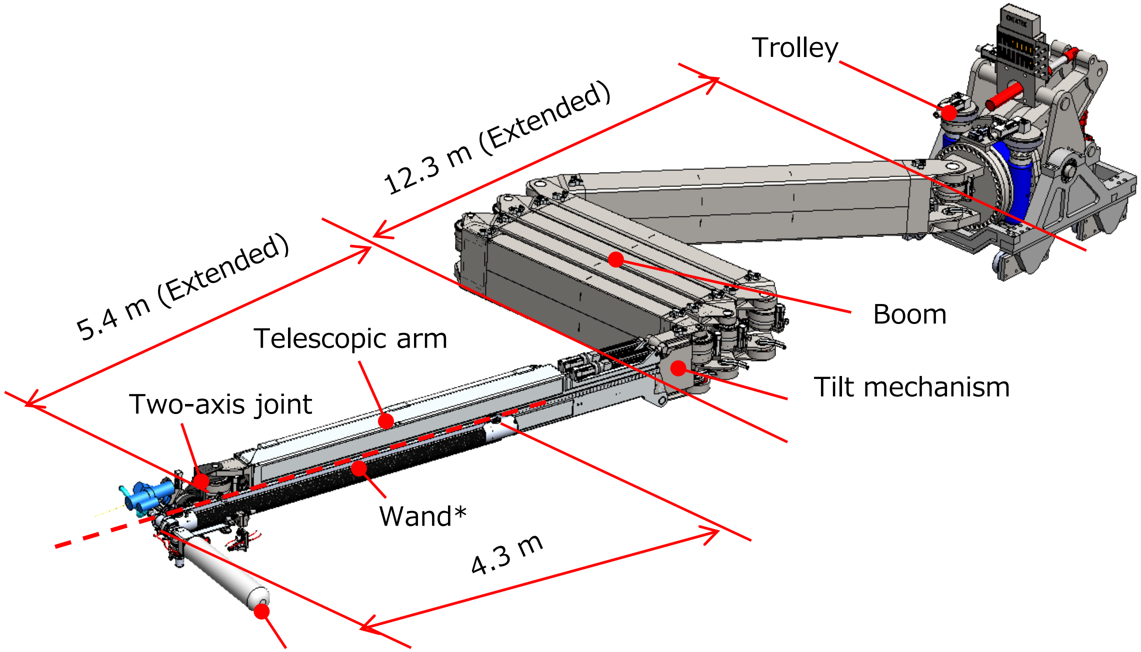
Total:3m40s

Fuel Debris Retrieval Technology: An example



Subsystems of an investigating system
Arm Type Access Device

- An arm type access device has been produced, which can access on a wide range through a penetration (X-6) of PCV.
  - Total length of the arm: Approx. 22m
  - An investigation device up to 10kg can be loaded.



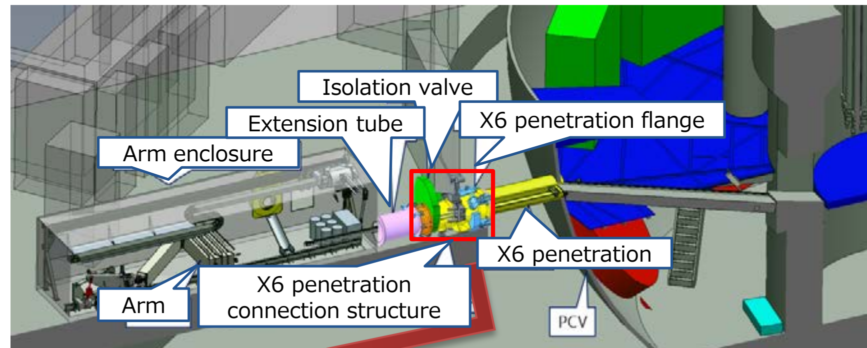
*An alternative tool can be mounted.

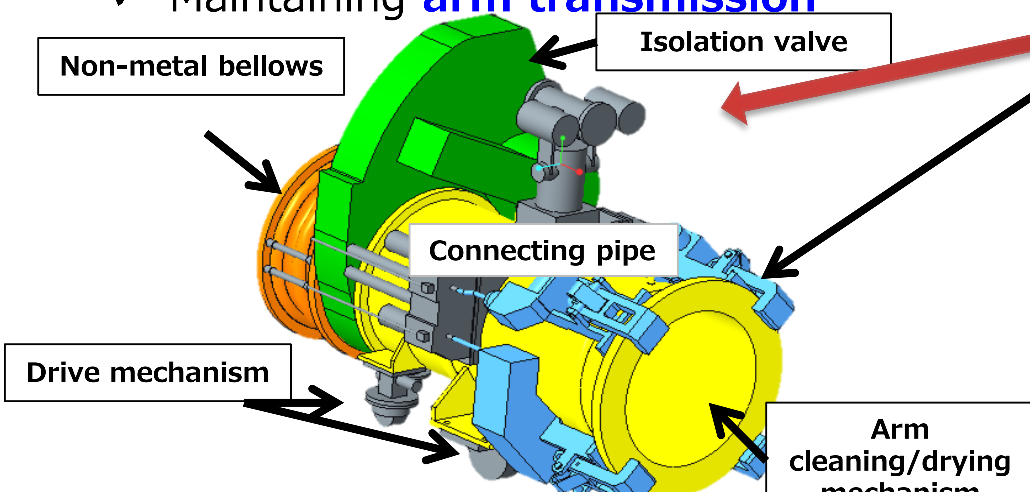
Subsystems of an investigating system
Access Route of Arm Type

■ Connecting structure of primary containment vessel (PCV)

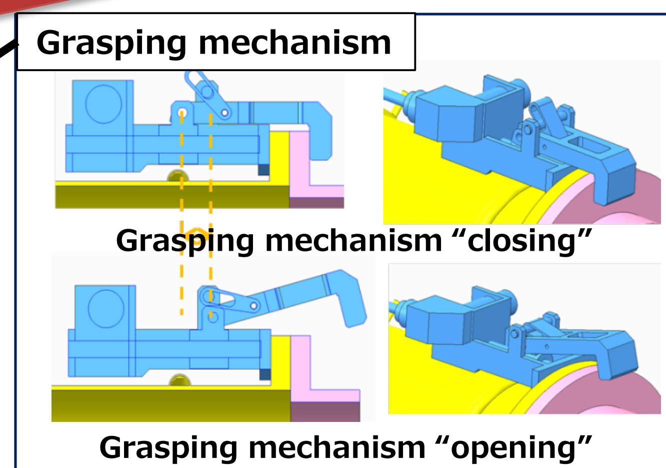
The connecting structure with the following functions has been developed.

- ✓ **Remote-operated** function with approaching/attaching an existing penetration flange
- ✓ **Seismic resistance** of grasping mechanism
- ✓ **Confinement** function
- ✓ Maintaining **arm transmission**



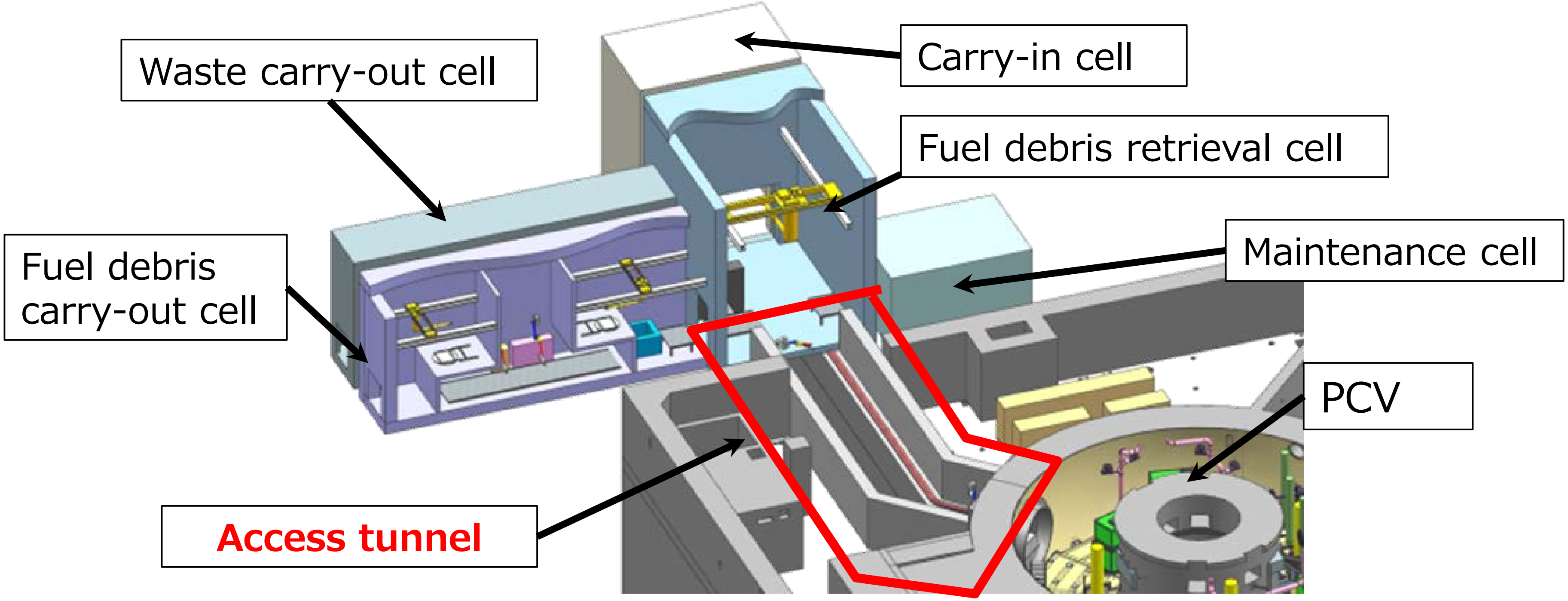


X-6 penetration connecting structure



Subsystems of a retrieval system
Access Tunnel

- The access tunnel is required **to connect a heavy-lift tunnel (approx. 800 ton)** with PCV **through the precise position control system** from outside the reactor building.
- **Delivery technology for curved heavy-lift tunnel in narrow space** has been developed with the technology experienced in bridge constructions.



Fuel Debris Retrieval Technology
Removing Interfering Objects(image)

- Various pumps and other structure must be removed.
- A large amount of rubbles have accumulated in the pedestal.
- Technology for removing the interfering objects has been developed.

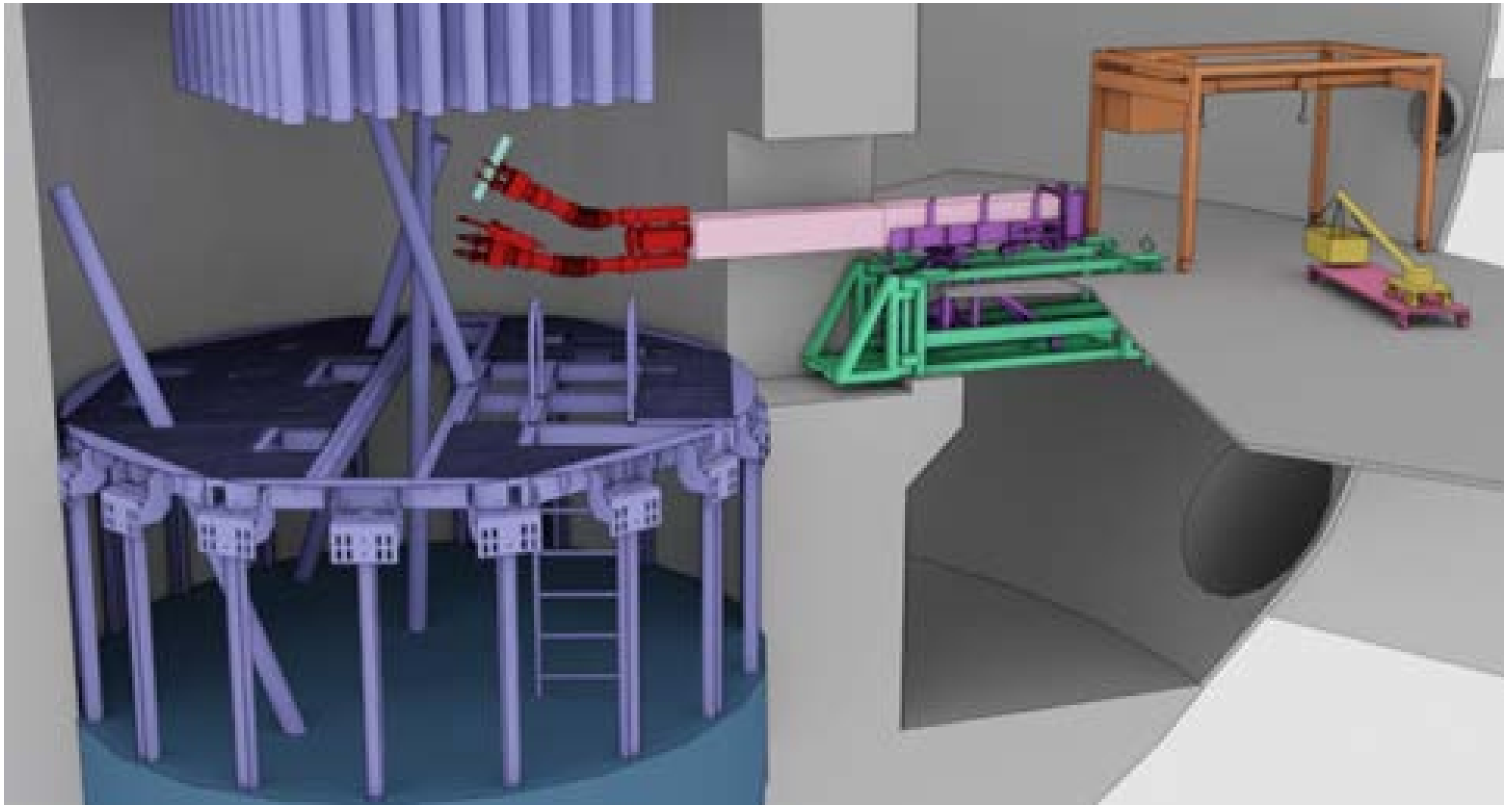
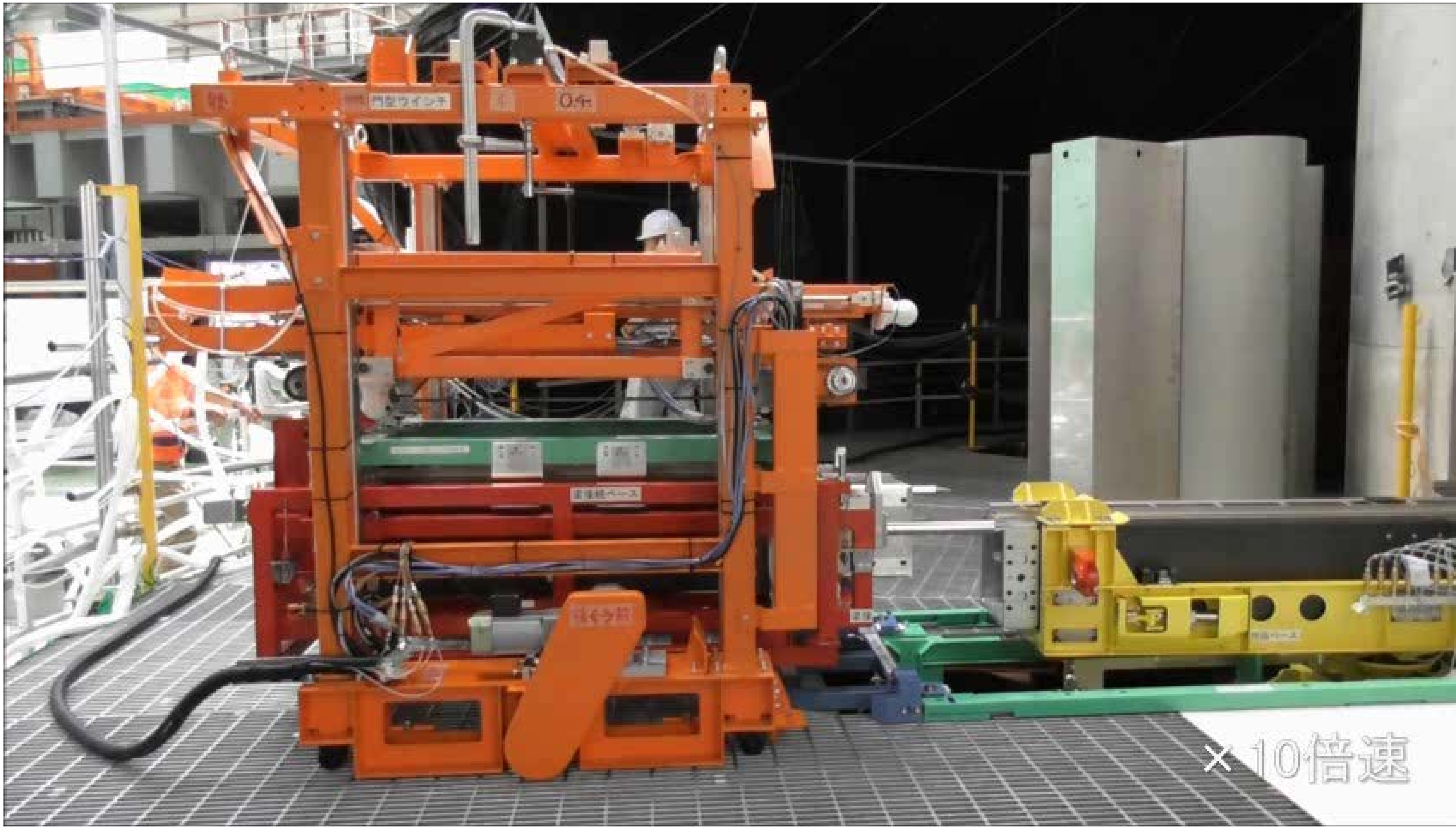


Image of element test of removing interfering materials

Removing Interfering Objects

at 10x speed/ total 1m22s



Required technology in robot system

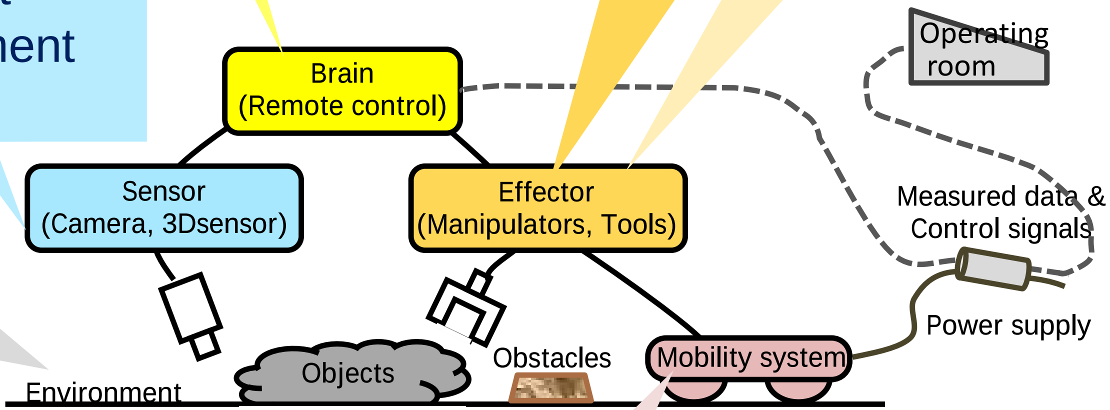
■ **Operation**
- Simulator & VR
- Human interface
- Team training

■ **Assembly/Disassembly**
- Insertion, fitting
- Holding parts

■ **Investigation**
- Shape measurement
- Radiation measurement
- SLAM

■ **Cutting/Coring/Separation**
- breaking fuel debris
- Removing Interfering objects

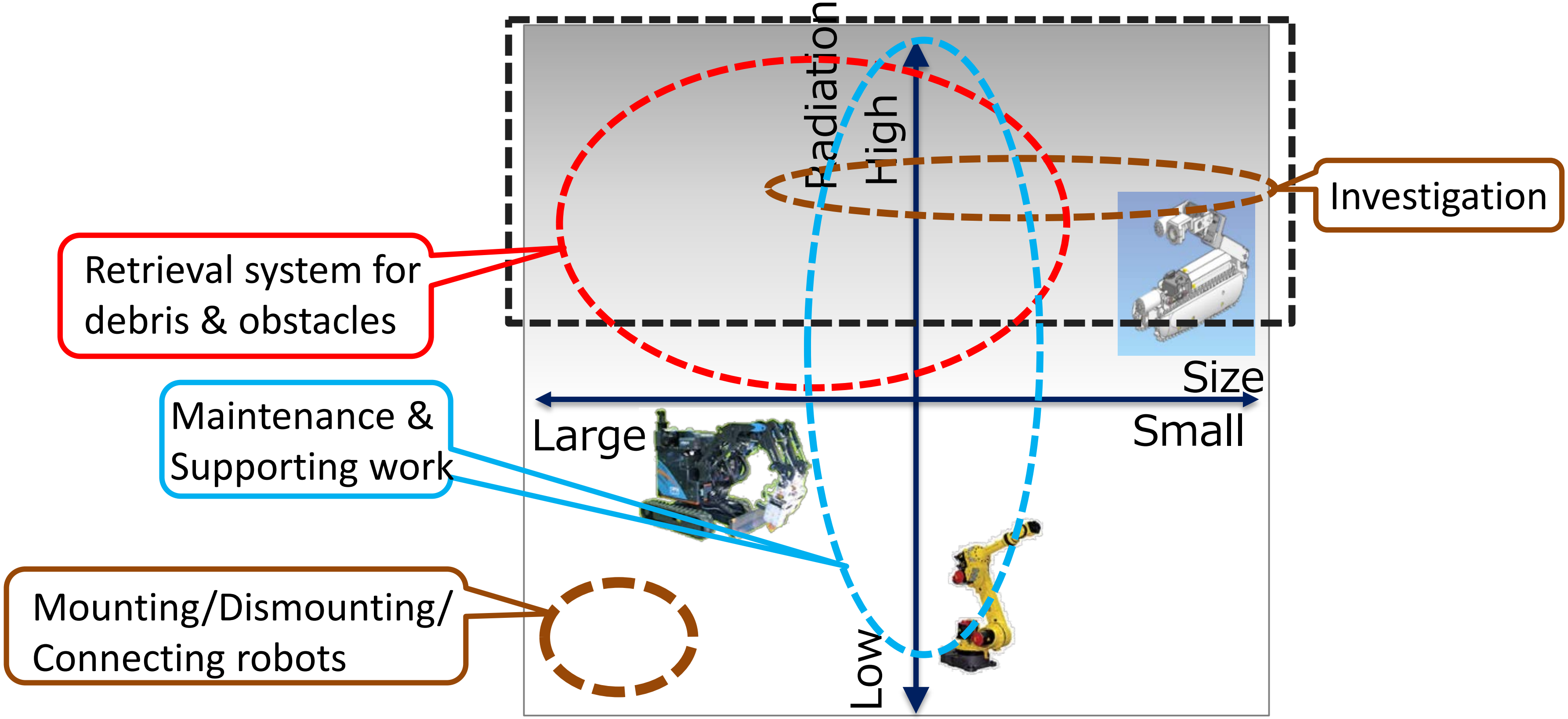
- Wire handling
- Environment design
- Power/Energy supply



■ **Transportation**
- Long transportation of heavy cells in radiative env.
- Precise connection/mantling/dismantling

Four kinds of robots

- Investigation (remote control)
- Retrieval system (remote control + semi-automatic)
- Maintenance robots (remote control + automatic)
- **Mounting robots** (remote control + semi-automatic)

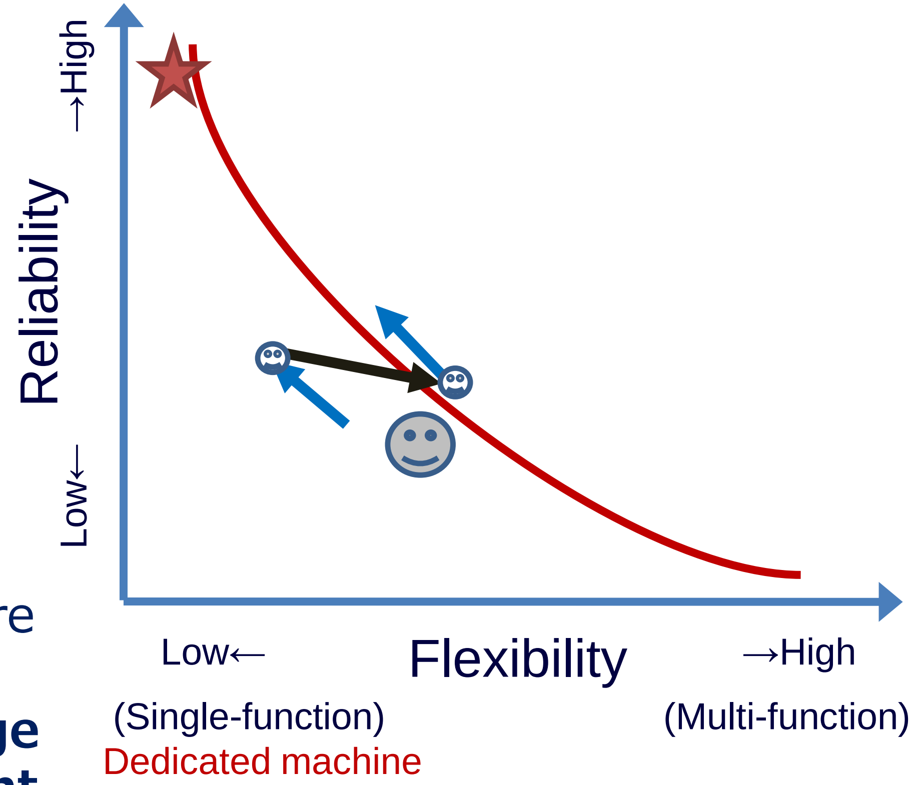


Contents

Design criteria for robots (1)

Machines for nuclear plants are designed as it works in **slow, secured** motion.

When machines are large(ℓ), its weight is in proportional to ℓ^3, and required torque ℓ^4.
Therefore, **largeness in size causes various problems**.



Industrial robots and humanoids are designed as intelligent and **adaptable** as human to **the change of requirements and environment**.
Thus, **higher flexibility** is embedded.

When one ability must be improved, the other often turns worse. By taking zig-zag changes, both ability will be improved.

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Design criteria for robots (2)

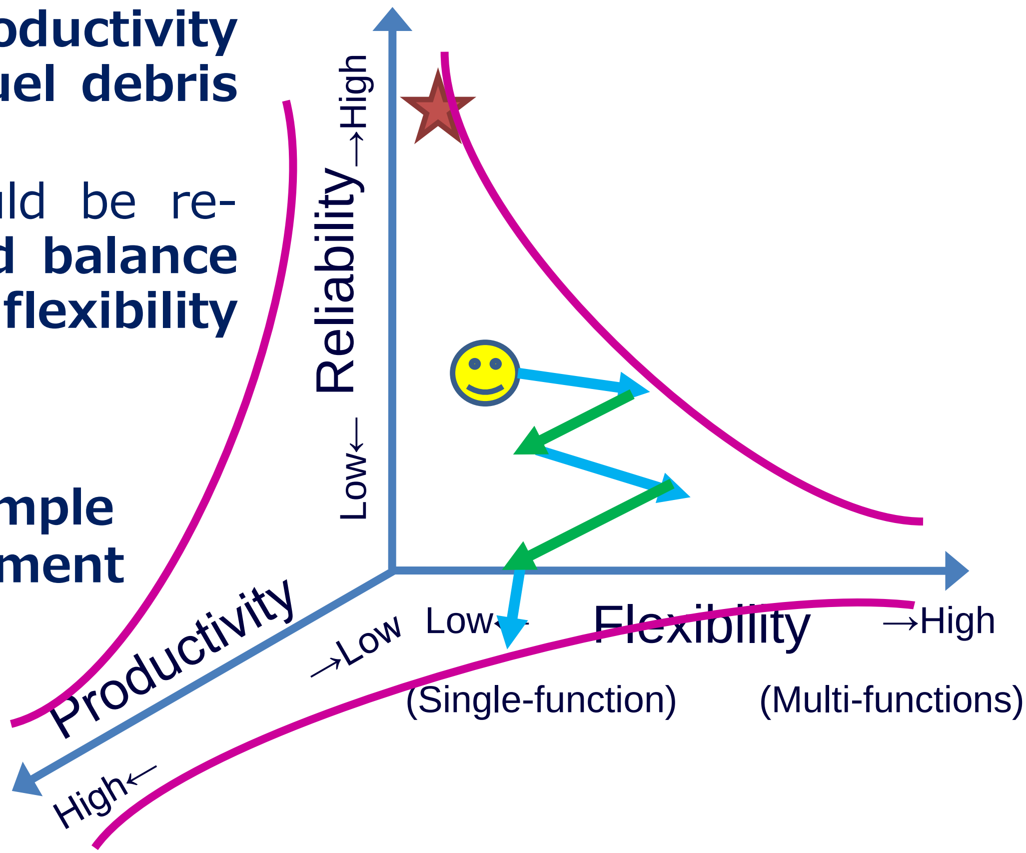
★ Machines in nuclear reprocessing plants can be dedicated to a specialized task.

But decommissioning in Fukushima Daiichi needs to have **higher productivity** because of **huge amount of fuel debris** and other structural materials.

To achieve it, machines should be re-arranged and improved in **good balance of the three axes; reliability, flexibility and productivity.**

☺ An initial machine should be **simple enough**, then **zig-zag improvement** must be introduced.

The effect of size and weight must be taken into account.



Summary

- **Radiation-hardened devices** are key issues for robots for decommission.
- **Size and weight** cause various problems in remote control: long **turn-around time** of improvement and cost.
- **Training of operation teams** is the most important key for remote control.
- Balance of **reliability**, **flexibility** (multi-function), and **productivity** must be well-designed in the development of robots.

IRID

Thank you for your kind attention

Decommissioning of Fukushima Daiichi NPP
is an epoch-making and historical project.

Let us watch, understand and memorize the project.

Tamio Arai
tamio-arai@irid.or.jp