Fusion Reactor Technology II
(459.761, 3 Credits)

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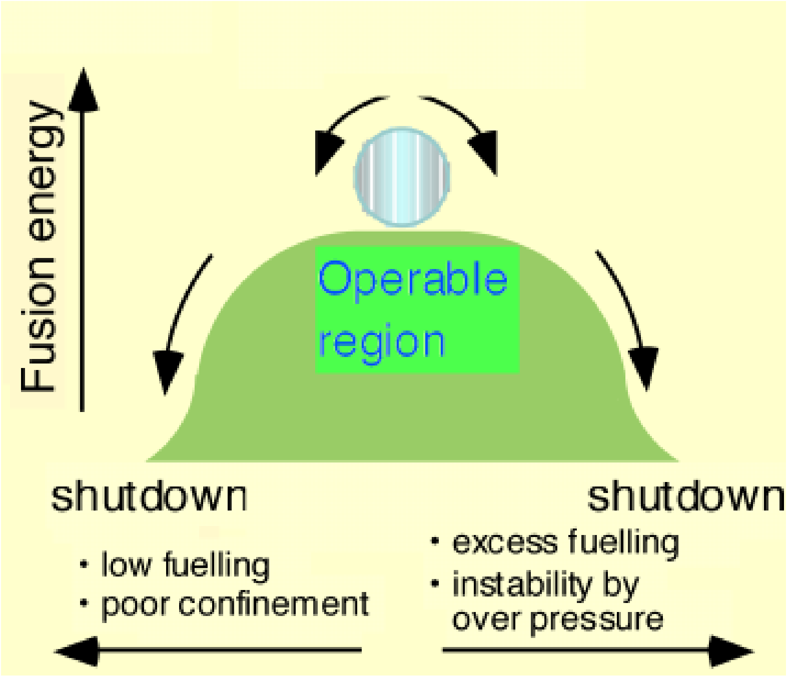
Present status of safety related technologies and future issues

Safety characteristics of fusion reactors

- No nuclear excursion and no nuclear criticality accident
  - Correlation between plasma pressure and magnetic pressure
  - Correlation between plasma density and fusion power
  - Termination of fusion reaction by ingress of impurities, etc.



Safety characteristics of fusion reactors

- Low decay heat density
- Decay heat originating only from nuclides activated by neutrons
- Low decay heat density due to large mass and volume of structures
- Natural convection cooling could be enough even if forced convection cooling is stopped (ITER).

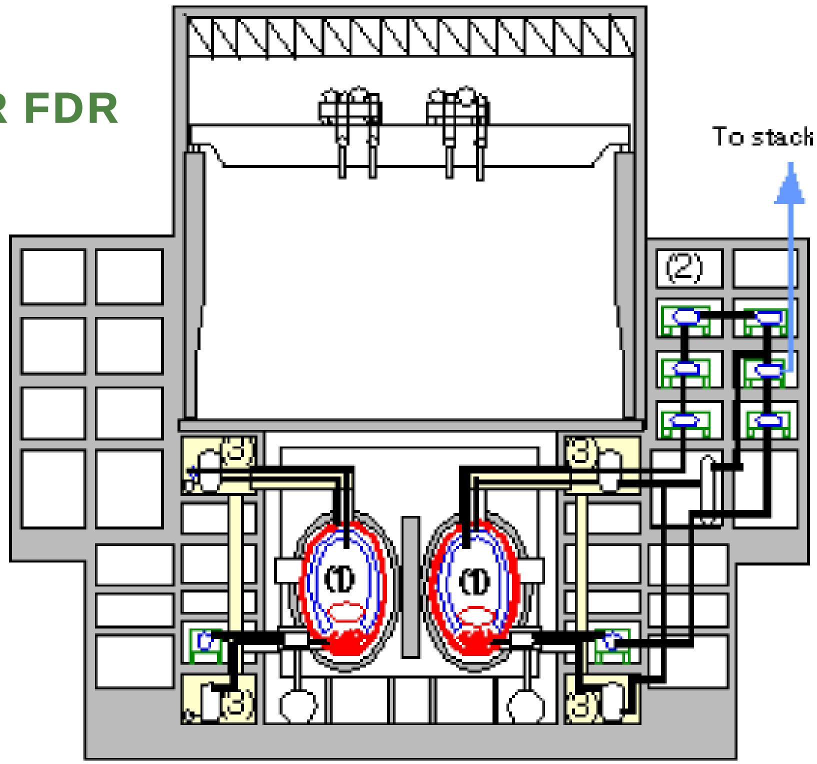
- Dispersed existence of mobile radioactive materials
- Safety measures to cope with postulated accidents where radioactive materials are released from the enclosure are essential.
- Radioactive materials are confined by a series of measures.

- Human error safety concerns
- Abnormal event generally cannot escalate to an accident or an excursion.

Issues for ensuring safety

- Distribution of radioactive materials such as tritium in a tokamak

ITER FDR



: Radioactive materials
: Radioactive dust
: Tritium
: Corrosion products and tritium
: Glove box in tritium plant
: Irradiated air (Ar, etc.)

(2) Inside tritium plant
- Isotope Separation System : 100g-T
- Fuel Storage and Delivery system : 200g-T
- Fueling System : 85g-T
- Others : total 100g-T

(1) Inside vacuum vessel
- Inside plasma : 1g-T
- Adsorbed in in-vessel components : 0.7kg-T
- Radioactive dust: W : 40kg
  Be : 20kg
  C : 100kg
- Cryopumps (16 units) : 160g-T

(3) Inside cooling loops
- Corrosion Products : 1kg / loop

(4) Others
- Long-term storage tritium : 1kg-T
- Hot cell, etc. : 150g-T

Issues for ensuring safety

- Thermal and magnetic energy specific to the tokamak type fusion device

ITER

<table>
<tr><th colspan="2">Category</th><th colspan="3">Energy</th></tr>
<tr><td rowspan="3">Vacuum Vessel</td><td rowspan="3">Plasma</td><td colspan="2">Fusion power</td><td>0.5 GW</td></tr>
<tr><td colspan="2">Thermal energy</td><td>0.4 GJ</td></tr>
<tr><td colspan="2">Magnetic energy</td><td>0.4 GJ</td></tr>
<tr><td rowspan="2">Superconducting magnet</td><td rowspan="2">Coil</td><td rowspan="2">Magnetic energy</td><td>TF coil</td><td>44 GJ</td></tr>
<tr><td>PF coil</td><td>8 GJ</td></tr>
<tr><td rowspan="2">Tritium system</td><td>In VV</td><td colspan="2">Chemical energy</td><td rowspan="2"><0.1 GJ</td></tr>
<tr><td>Fuel cycle system</td><td colspan="2">Chemical energy</td></tr>
</table>

- Combustion reaction prevented by multiple safety measures: physical barrier (enclosure), inert gas or vacuum surrounding the enclosure, limiting of oxygen ingress by isolation valves, specific facility design

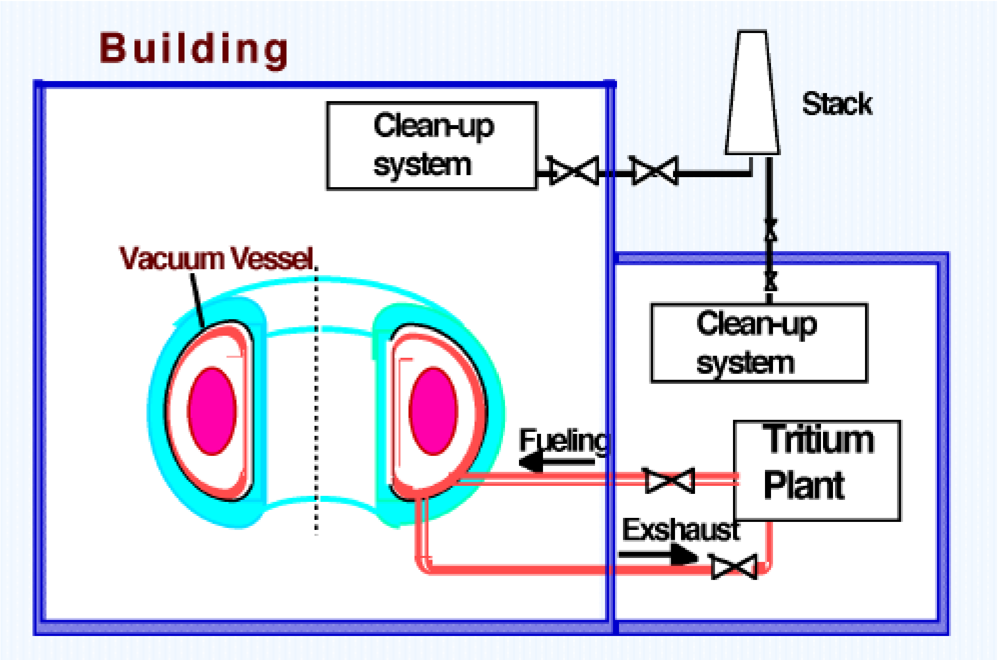
Issues for ensuring safety

- Containment/confinement of the radioactive materials in ITER
- Four kilograms tritium in the ITER facility
- Maximum 1.2 kg of tritium occluded in the vacuum vessel
- Energy sources as listed
- Radioactive waste resulting from neutron irradiation

- Safety goal: to design, construct, and operate the ITER facility, aiming at protecting the public and workers from the radiological risks and demonstrating a high level of safety attractiveness for future fusion power plants.

Issues for ensuring safety

- Under normal operating conditions, the release of radioactive materials to the environment shall be controlled and maintained as low as reasonably achievable, and the worker exposure shall be controlled with appropriate management.
- In case of an accident, excessive release of radioactive materials to the environment shall be prevented by means of the confinement facility with the emergency clean-up system.



Issues for ensuring safety

- Safety analyses of ITER

- In the design activity of ITER, the abnormal events and accidents, 25 events in total (11 types), were categorized into four groups with the probability of every event being greater than 10^{-6}/year.
- The released tritium was sufficiently below 100 g.
- Tritium radiation dose: tritium in the form of HTO was about 10 mSv/g-T. The public exposure dose even in an accident with a maximum release beyond the design basis accident was confirmed to be within the limit (< 50 mSv) recommended by IAEA for not requiring public evacuation.
- Radioactive dust: below the limit of 500 g established as a project guideline
- The project guideline release limits were defined to be less than 1 g/year for tritium and less than 0.5 g/year for radioactive dust.

  The analysis results have shown that the release of tritium and radioactive dust is about 0.3 g/year and 0.4 g/year, respectively.

Present status of the safety research in ITER

- Most analysis codes utilized have been modifications of codes that were originally developed for fission reactors or general purpose analyses.
- Thus, to pursue the regulatory application for construction, further qualification is necessary to validate the appropriateness of the modification of the codes and the reliability of the utilized data for the application to the fusion reactor.

Safety-related issues for future fusion reactors including DEMO reactor

- Improvement of the economic efficiency

- High power density: active removal of decay heat
- High availability: efficient maintenance
- High efficiency: materials and coolants for high temperature use
  → individual issue

- Improvement of environmental and safety characteristics

- Prevention of tritium permeation
- Reduction of tritium inventory
- Material development → low activation, reduction of radioactive waste

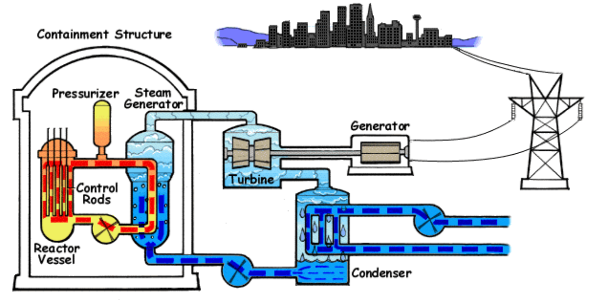
Difference between ITER and DEMO?

Present status of operation and maintenance technologies and future issues

Operation and maintenance conditions of commercial LWRs as a reference

Items	Working results
Start-up test	The output of 100% was confirmed within a year after the completion of individual equipment tests
Capacity factor	> 60-83%
Operator	6-7 persons/unit (10-11 persons/2 units)
Periodic inspection	< 50-70 days/unit/year (worker's exposure ~ 2-3 persons Sv/unit, 1 mSv for one worker)
Unplanned stop/trouble	< 0.2-4.0 times/unit/year (< 0.5 times/unit/year in Japan)

- 4 year construction



http://www.answers.com/topic/light-water-reactor

Projected operation and maintenance conditions in fusion reactors

Items	Large tokamak JT-60	ITER	DEMO (e.g. SSTR)	Prototype/Commercial reactor
Plasma current	< 5 MA	13 – 17 MA	12 MA	12 MA
Major radius	~ 3 m	6.0 – 6.5 m	~ 7 m	~ 7 m
Toroidal magnetic field	4 T (10 T max.)	< 6 T (12 T max.)	9 T (16 T max.)	9 T (16 T max.)
Fusion output power	~ 10 MW equivalent	> 0.5 GW	~ 3 GW	3-5 GW
Neutron wall load	-	> 0.5 MW/m^2	~ 3 MW/m^2	~5 MW/m^2
Pulse length / S-S	15 s	300-500 s	Steady	Steady
Normal / Superconducting	Normal	Super	Super	Super
Blanket	None	Use (test)	Use	Use
Tritium	No use	Use	Use	Use

Projected operation and maintenance conditions in fusion reactors

- Startup tests (commissioning)

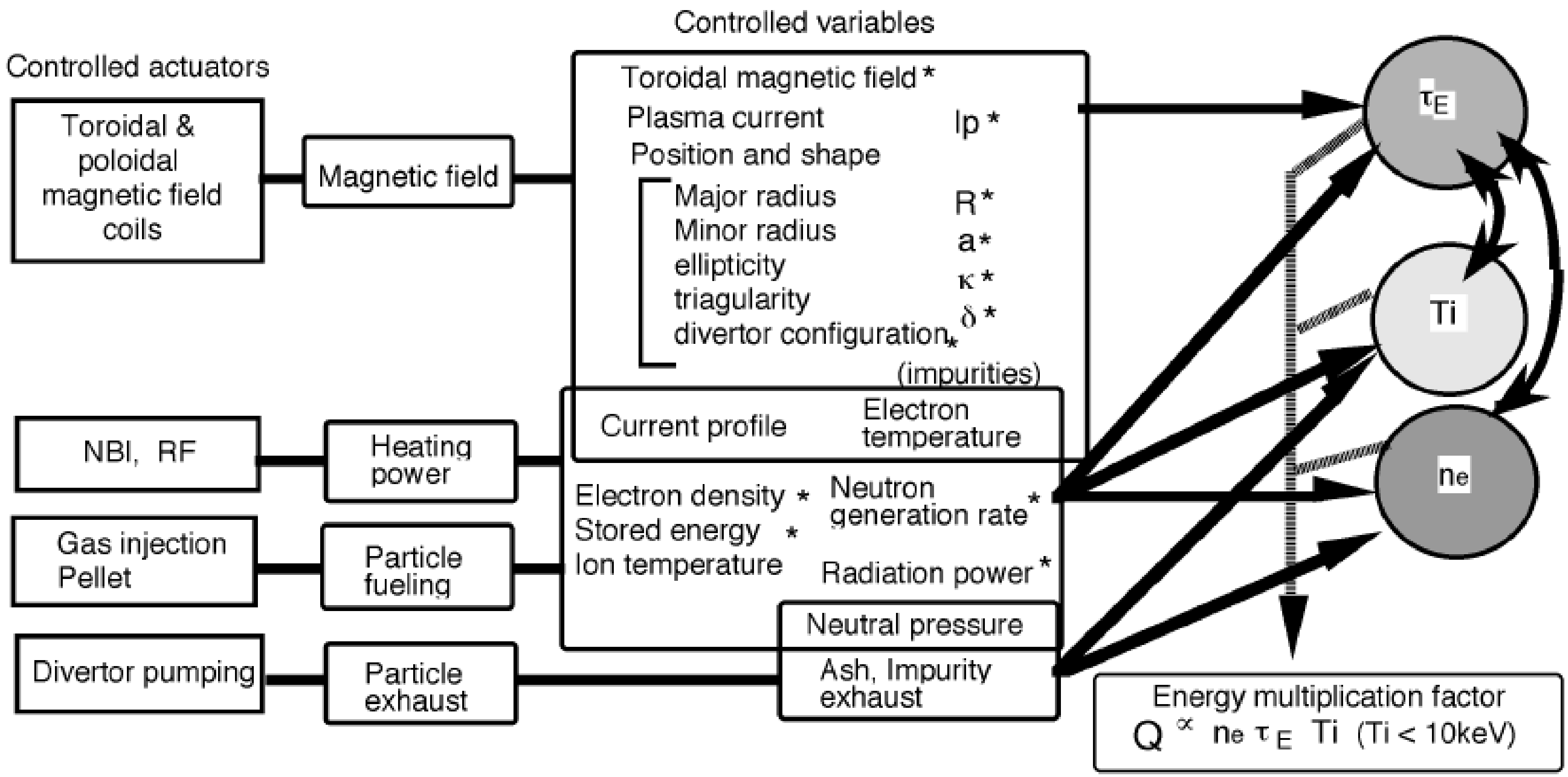
- Commissioning without plasma:
  The number of the test items is about 30.
  The period is about one year.

- Commissioning with plasma:
  After completion of comprehensive tests of all systems as a fusion reactor, the first plasma is produced and commissioning proceeds with plasma.

HW: commissioning in KSTAR

Projected operation and maintenance conditions in fusion reactors

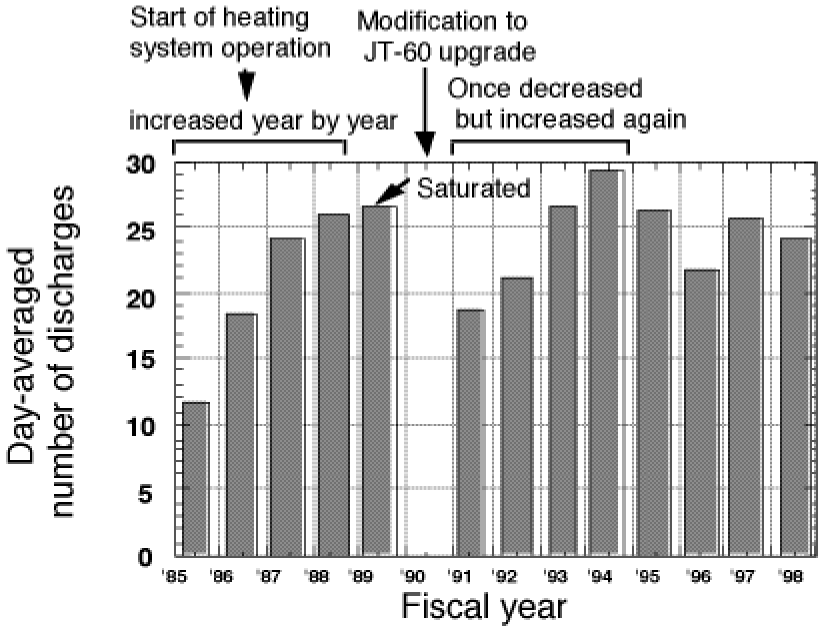
- Kinetics control

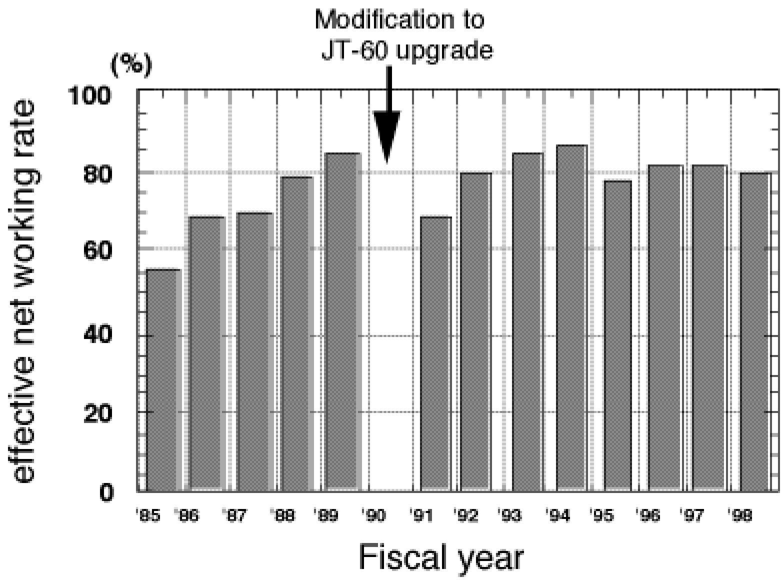


* Feedback control variables in JT-60

Projected operation and maintenance conditions in fusion reactors

- Capacity factor
- The percentage of time when the reactor producing power
- Not including the period in which power generation stopped due to periodic inspections or troubles, etc





- Effective net working rate: defined as the ratio of “effective operating time” to the “sum of the effective operating time and troubleshooting time”

Projected operation and maintenance conditions in fusion reactors

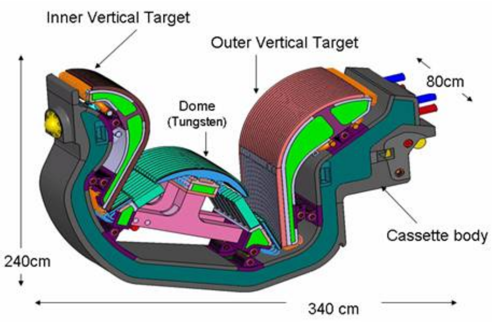
- Operators

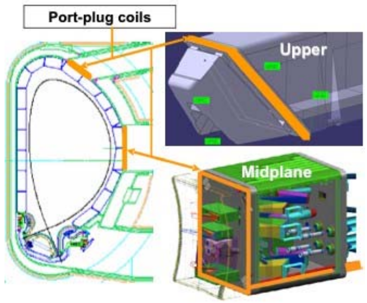
- JT-60: One operating group consists of a JAERI staff of 14 and consigned industry members. Tasks of the consigned members include operation, start-up and shutdown of equipment at the local control room, and inspection.
- Fusion reactor: operating in the S-S mode. Startup/shutdown operations as performed everyday in large tokamaks like JT-60 will not be required.

Projected operation and maintenance conditions in fusion reactors

- Periodic inspection

Items	Frequency	Units	Total period
Divertor cassette	1 time / 1.5 year	60 cassettes	112 days
Shield blanket	-	730 modules	349 days
Test blanket	-	Several assemblies	-





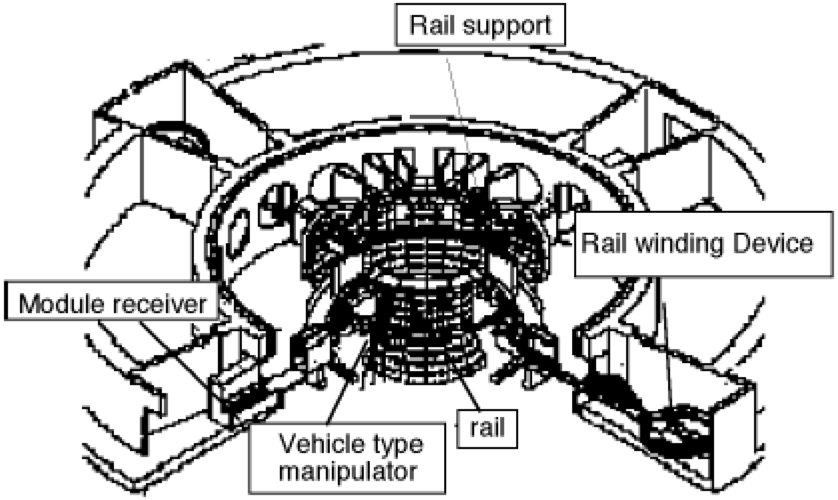
Projected operation and maintenance conditions in fusion reactors

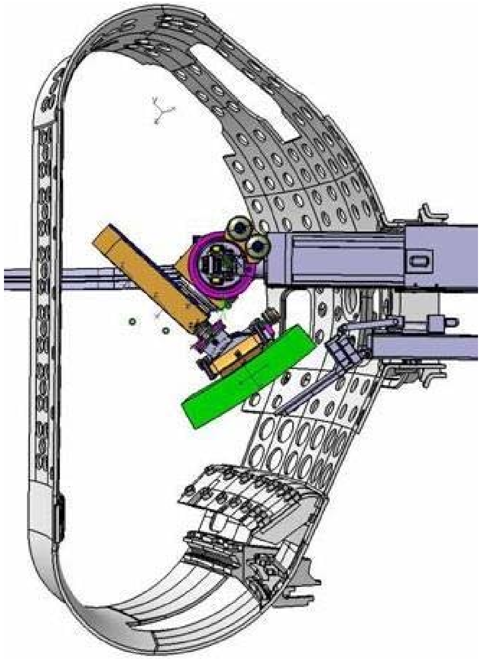
- Blanket exchange work of ITER (FDR)

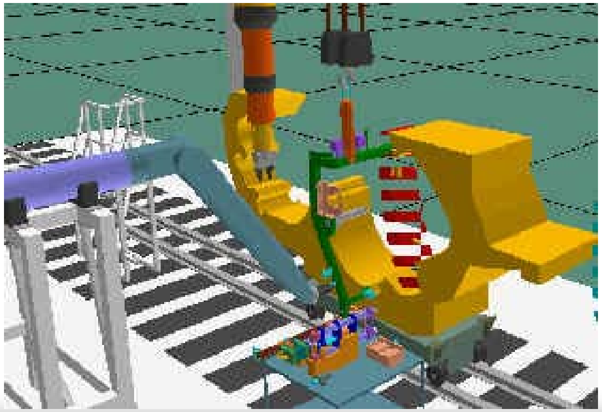
- The preparation time such as for baking, etc., before and after the exchange work is not considered as working time.
- Four vehicle type manipulators are installed (1 unit per quadrant).
- Sixteen units of pipe cutting/welding/inspection tools are installed (4 units per quadrant).
- A blanket weighs 4 tons.
- The number of bolts for fixing a blanket is 14 per four blankets, and 4 bolts are simultaneously mounted/dismounted.
- The working time for 4 days is 16 hours.
- The operating speed of the remote manipulation equipment is assumed to be the actual value obtained by a full-scale vehicle-type maintenance equipment test performed in the engineering R&D of ITER.
- Considering the uncertainty in the working time, 30% is added to the total exchange time.

Projected operation and maintenance conditions in fusion reactors

Modular-unit system,
Vehicle type manipulator for ITER







Projected operation and maintenance conditions in fusion reactors

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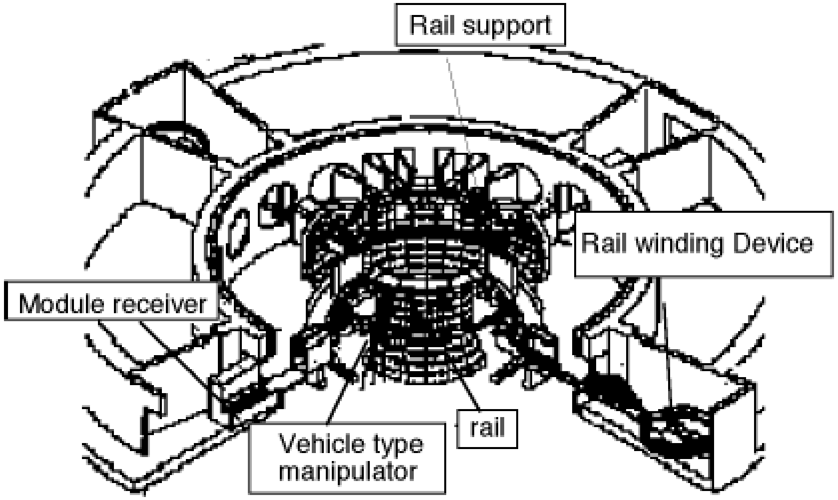
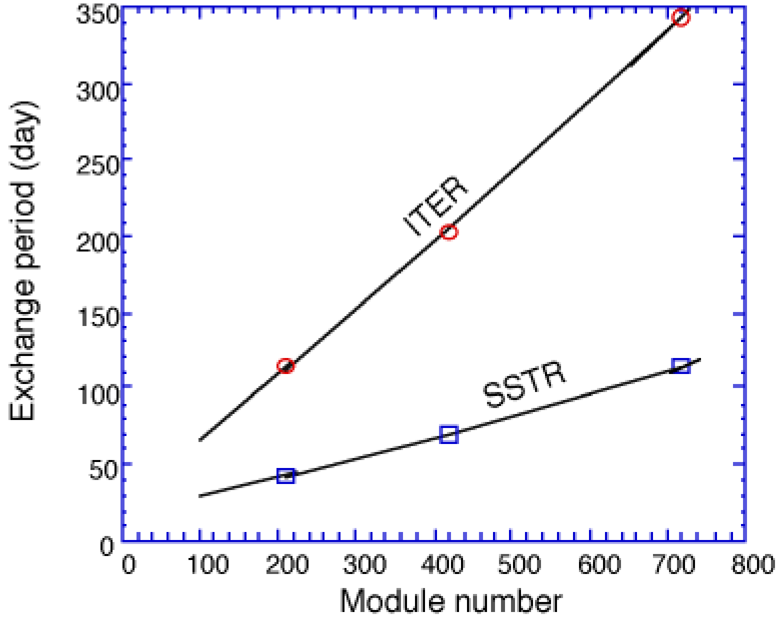
Vehicle type manipulator for ITER





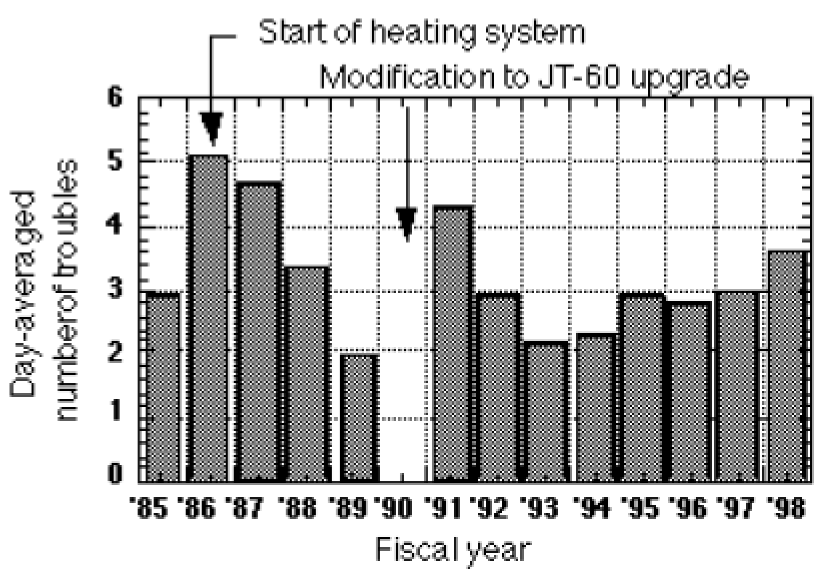
- Blanket exchange work of SSTR

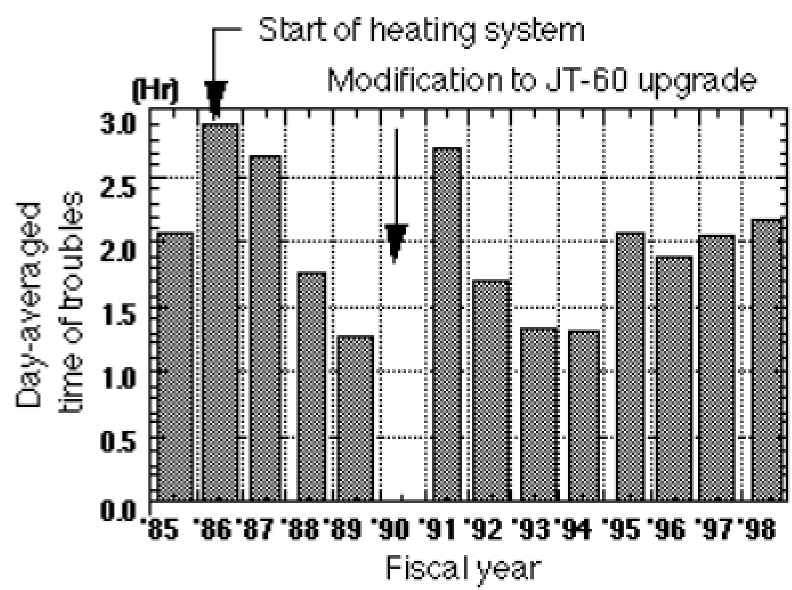
- The number of fixing bolts is four per blanket. Mounting/dismounting of 4 bolts is performed in parallel using the tool installed at the top of the manipulator.
- The available work time per day is 24 hours.
- The operating speed of the remote manipulation equipment is improved by 30%.

Projected operation and maintenance conditions in fusion reactors

- Unplanned shutdown (trouble occurrence rate)

- Trouble (JT-60): failure or malfunction of equipment that interrupts the experiment discharge for one shot, namely, more than 15–20 minutes
- The most frequent time troubles occur is just before and just after a discharge.
- The second most frequent time troubles occur is at plasma disruptions.





Assessment of the feasibility of operation and maintenance of fusion reactor

Items	Present status of fusion devices	Prospect	Performance of LWR
Starting test	< 3.5 years (until initial experiment) (ITER)	2	< one year (100% output)
Operators	< 14 JAERI's staff + consigned staff (JT-60)	1	6 or 7 persons/unit
Periodic inspection	~ 70 days (ITER/SSTR)	2	50-70 days / unit year
Trouble occurrence rate	~ 2.5 events/day (JT-60)	2	< 0.5-4.0 events / unit year
Net working rate	> About 64% (JT-60)	2	> 60-80 %

1: Possibility of realisation is large.
2: Possibility is increased if operation scenario of the S-S operation is established, if disruption avoidance techniques are developed, and if redundant systems are adopted.