Fusion Reactor Technology I
(459.760, 3 Credits)

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Contents

후쿠시마 원전 사고의 교훈 - 안전성

Safety Characteristics of Fusion Reactors

- **Unique and inherent safety features**
  - No nuclear chain reaction excursions
  - Passive termination of the fusion reaction under any disturbance due to operation limits constrains
  - Low decay heat density

- Safety functions for terminating nuclear reactions and cooling the reactor to avoid melting are low priority technical requirements in fusion reactors.

- The structural integrity of the enclosure or confinement of the radioactive materials is the most important requirement for ensuring safety.

No Nuclear Criticality Accident

- **Criticality**

- Neutrons and alpha particles generated by the fusion reaction do not produce the next reaction.

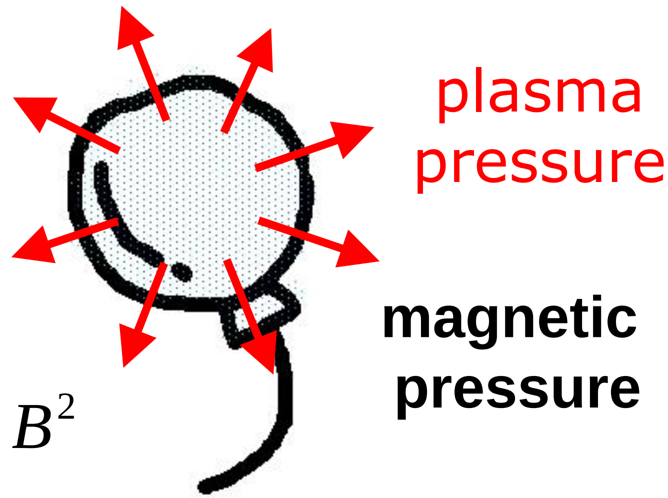
→ no critical mass for the deuterium and tritium fuel

→ no nuclear criticality accident can occur.

No Nuclear Excursion

- **Correlation between plasma density and fusion power**
  - The ratio, the "beta value" of the plasma pressure (the product of plasma temperature and density) to the magnetic pressure is limited to a certain value by plasma instabilities.

$$\beta = 2\mu_0 p / B^2$$



  - A measure of the degree to which the magnetic field is holding a non-uniform plasma in equilibrium
  - The power output for a given magnetic field and plasma assembly is proportional to the square of beta.
  - In a reactor it should exceed 0.1 – economic constraint

No Nuclear Excursion

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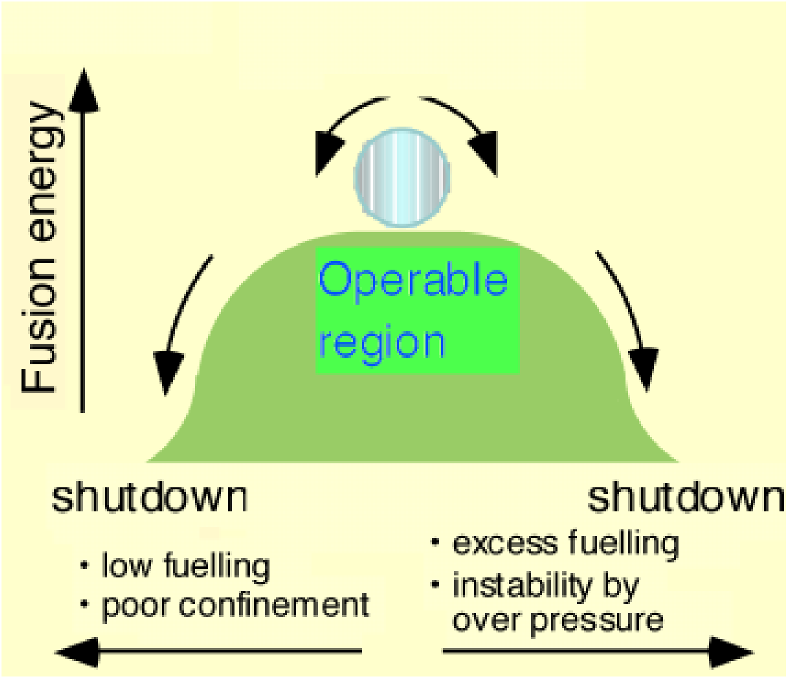

http://blog.daum.net/koreakwh1/3215780

No Nuclear Excursion

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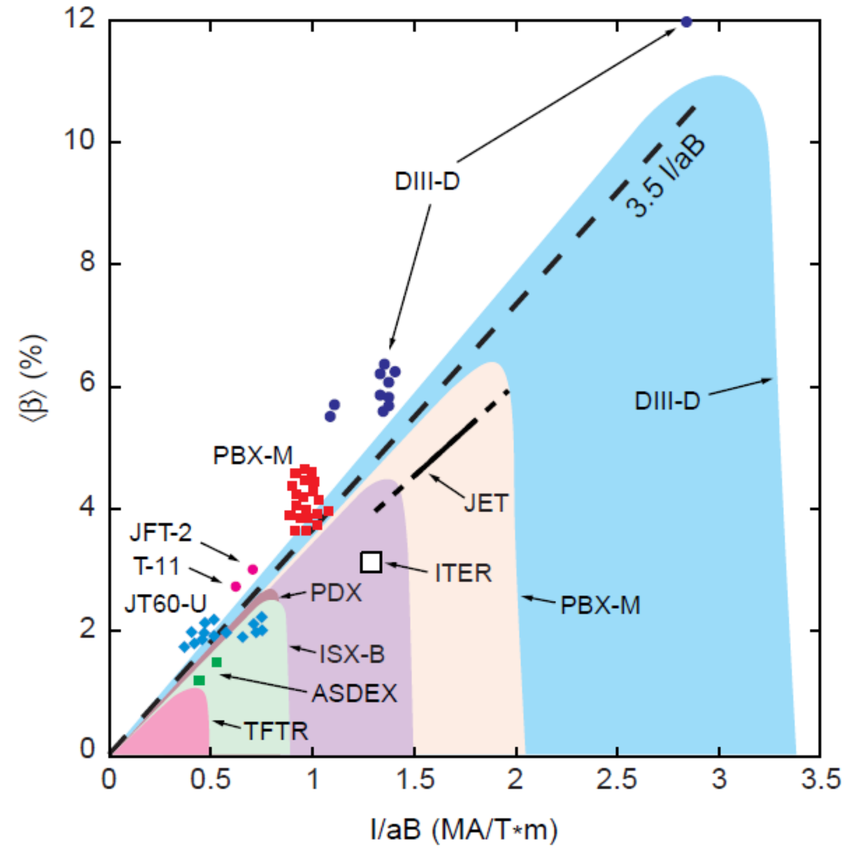


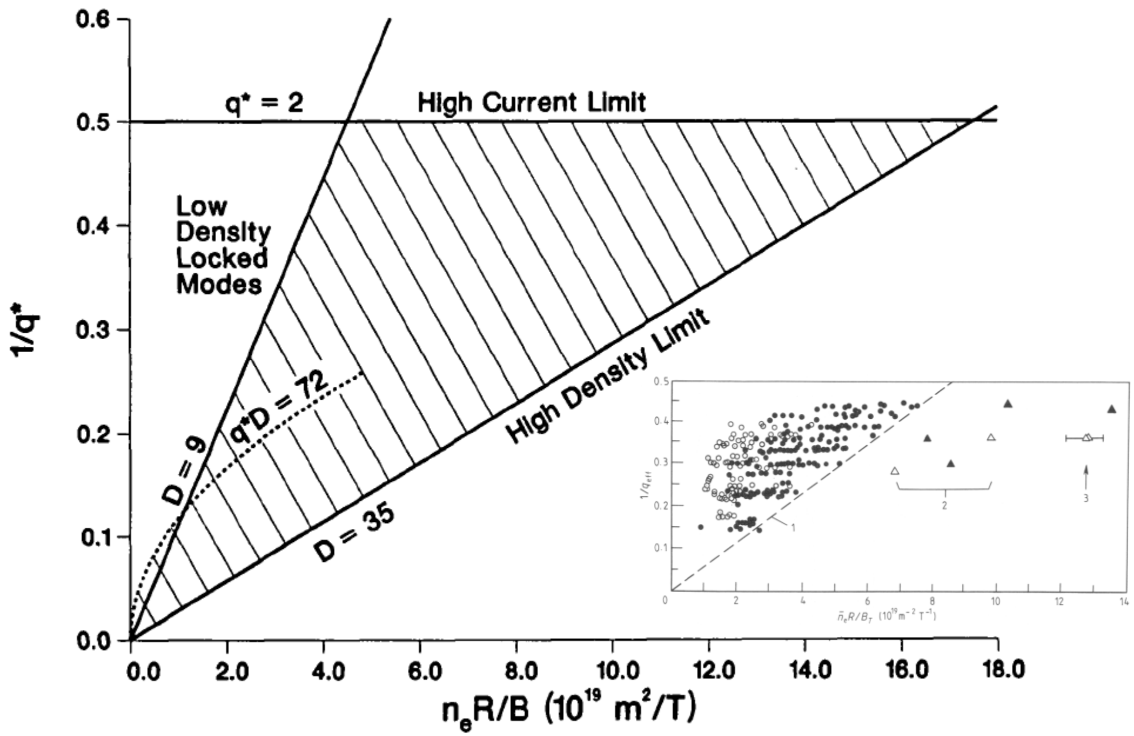
No Nuclear Excursion

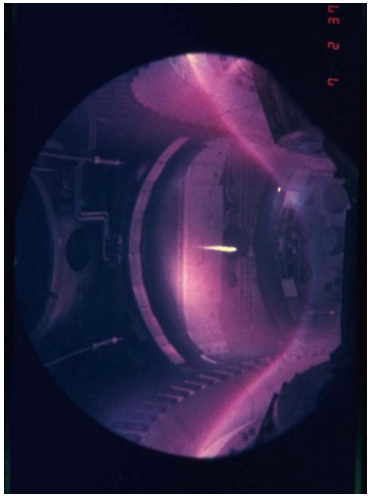
- **Correlation between plasma density and fusion power**

- Density limit: When the fueling rate is excessive, the plasma density increases quickly and reaches the density limit.

→ Degradation of confinement

→ Reduction of the fusion power or termination of the fusion reaction





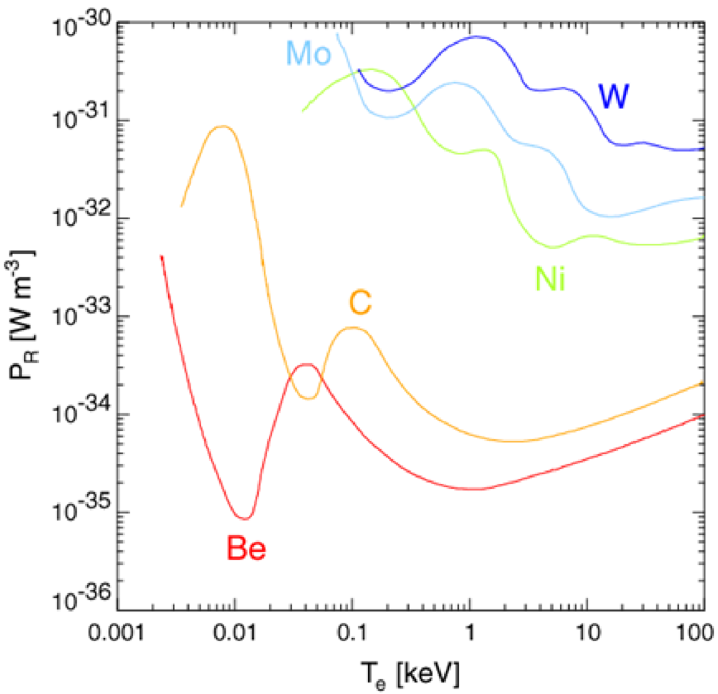
Pellet injection
in ASDEX Upgrade

No Nuclear Excursion

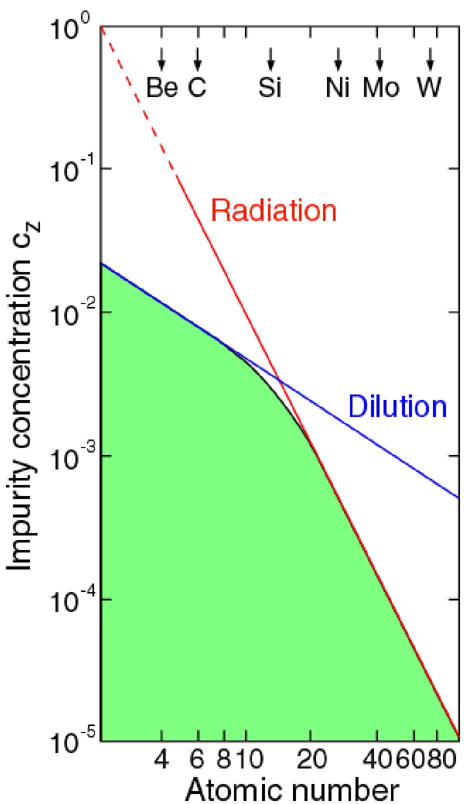
- **Termination of fusion reaction by ingress of impurities, etc.**

\- Radiation: The plasma temperature cannot be maintained with ingress of even a very small amount of impurity.

→ Reduction or termination of the fusion reaction



\- At 10 keV: $(n_Z/n_{DT})_{max}$~0.5% (Fe)
$(n_Z/n_{DT})_{max}$~0.01% (W)



Maximal concentrations for sustained ignited plasma

No Nuclear Excursion

- **Termination of fusion reaction by ingress of impurities, etc.**

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→ Reduction or termination of the fusion reaction

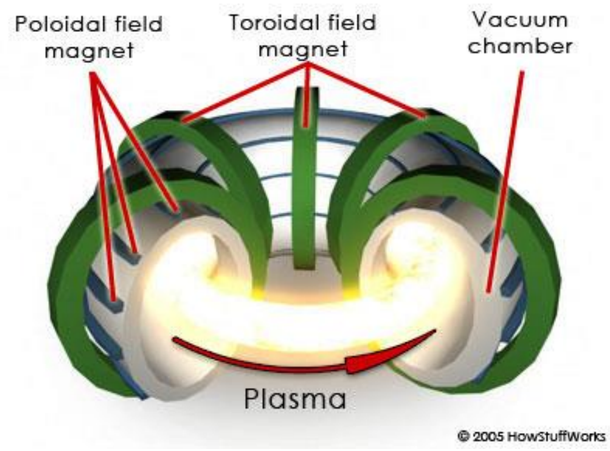
No Nuclear Excursion

- **Termination of fusion reaction by ingress of impurities, etc.**

\- Radiation: The plasma temperature cannot be maintained with ingress of even a very small amount of impurity.

→ Reduction or termination of the fusion reaction

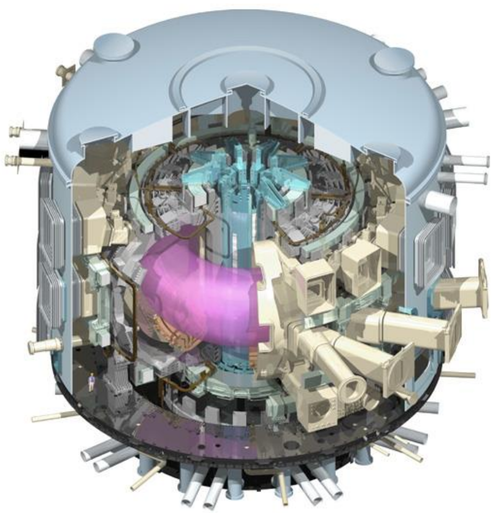
\- Overheating (or air/steam leaked into the plasma) event:
A part of the first-wall material is heated up
→ evaporated owing to the high heat flux onto the first-wall
→ The evaporated material is mixed into the much hotter plasma.
→ Reduction of the plasma temperature
→ Passive termination of the fusion reaction

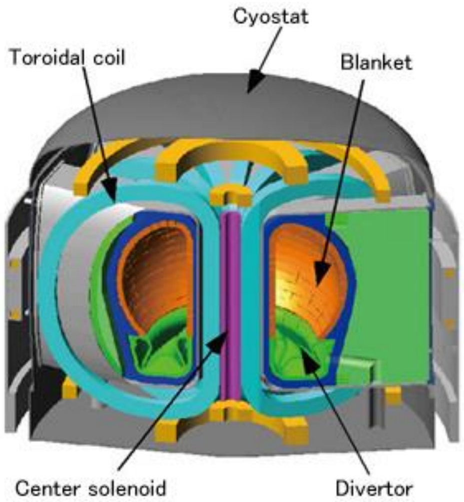


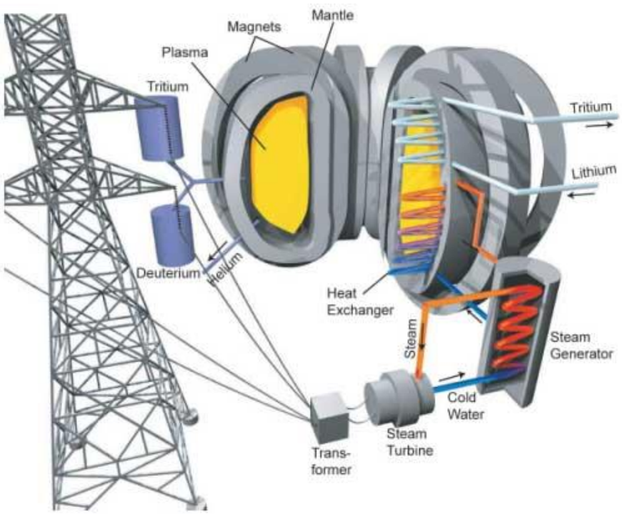
Low Decay Heat Density

- **Decay heat only from nuclides activated by neutrons**

- A major part of the decay heat is generated in the structures surrounding the plasma, such as the blanket and first wall.
- The mass and volume of such structure is comparatively large.
  → low decay heat density
- Heat removal is easily attained and the safety function can be passively maintained under abnormal events.
- ITER: natural convection cooling can achieve decay heat removal even if forced convection cooling is stopped.





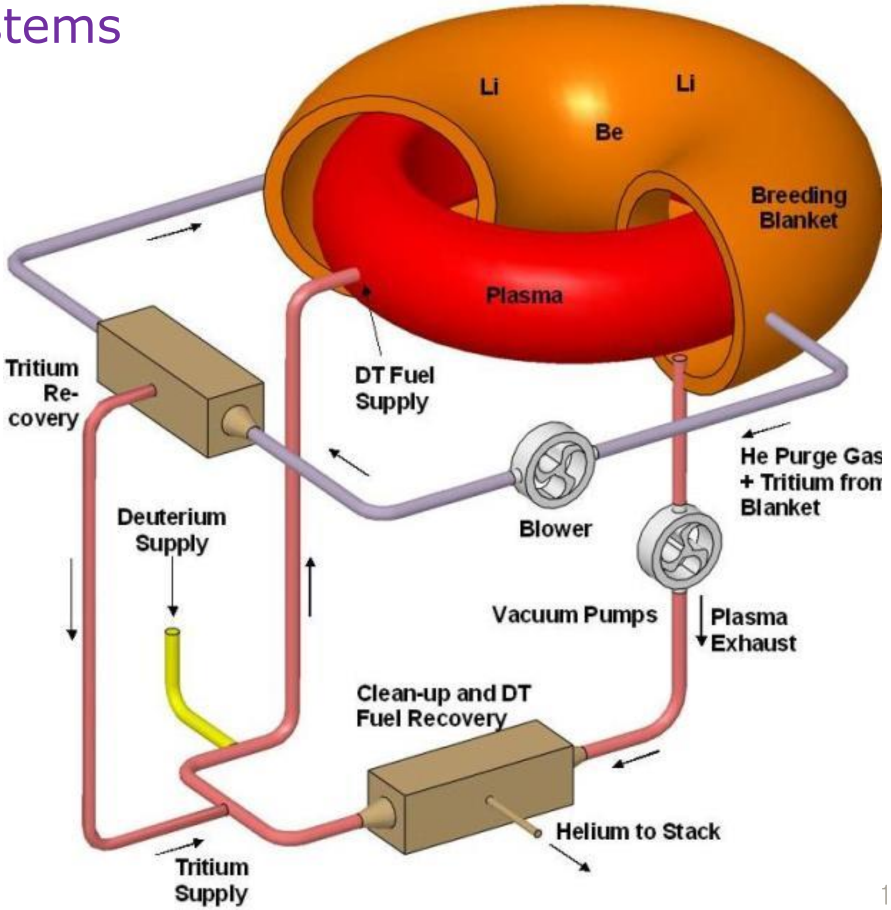


Dispersed Existence of Mobile Radioactive Materials

- **Tritium**
  - Dispersed and contained in the vacuum vessel and fuel processing systems

- **Activated products**
  - Contained in the vacuum vessel and cooling systems

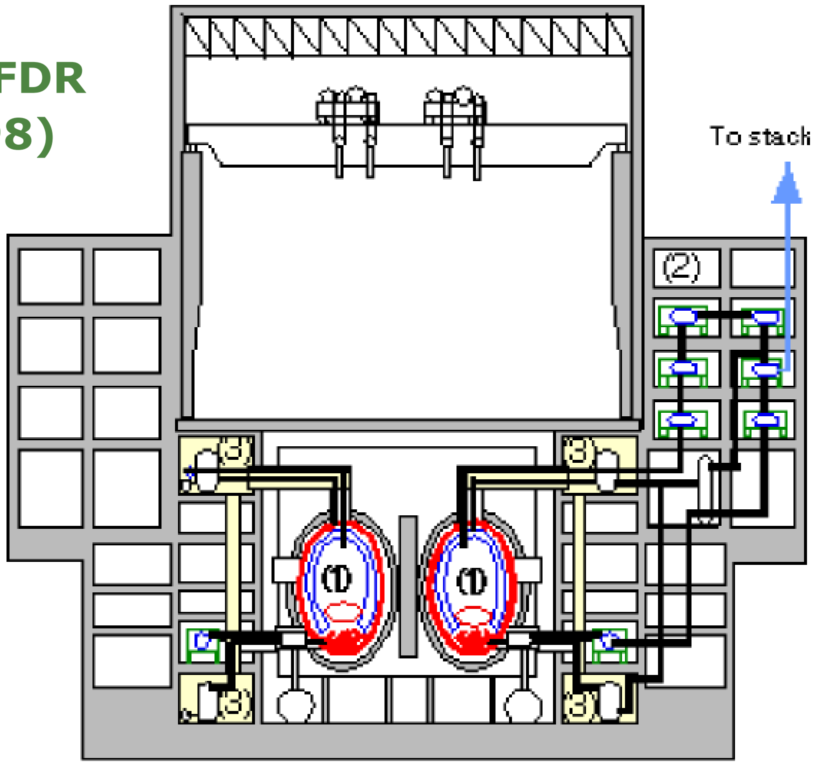
→ Considering those conditions, the safety measures to cope with postulated accidents where radioactive materials are released from the enclosure are essential: Key engineering issue for ensuring the safety in a fusion reactor



Dispersed Existence of Mobile Radioactive Materials

- Distribution of radioactive materials

ITER FDR (1998)



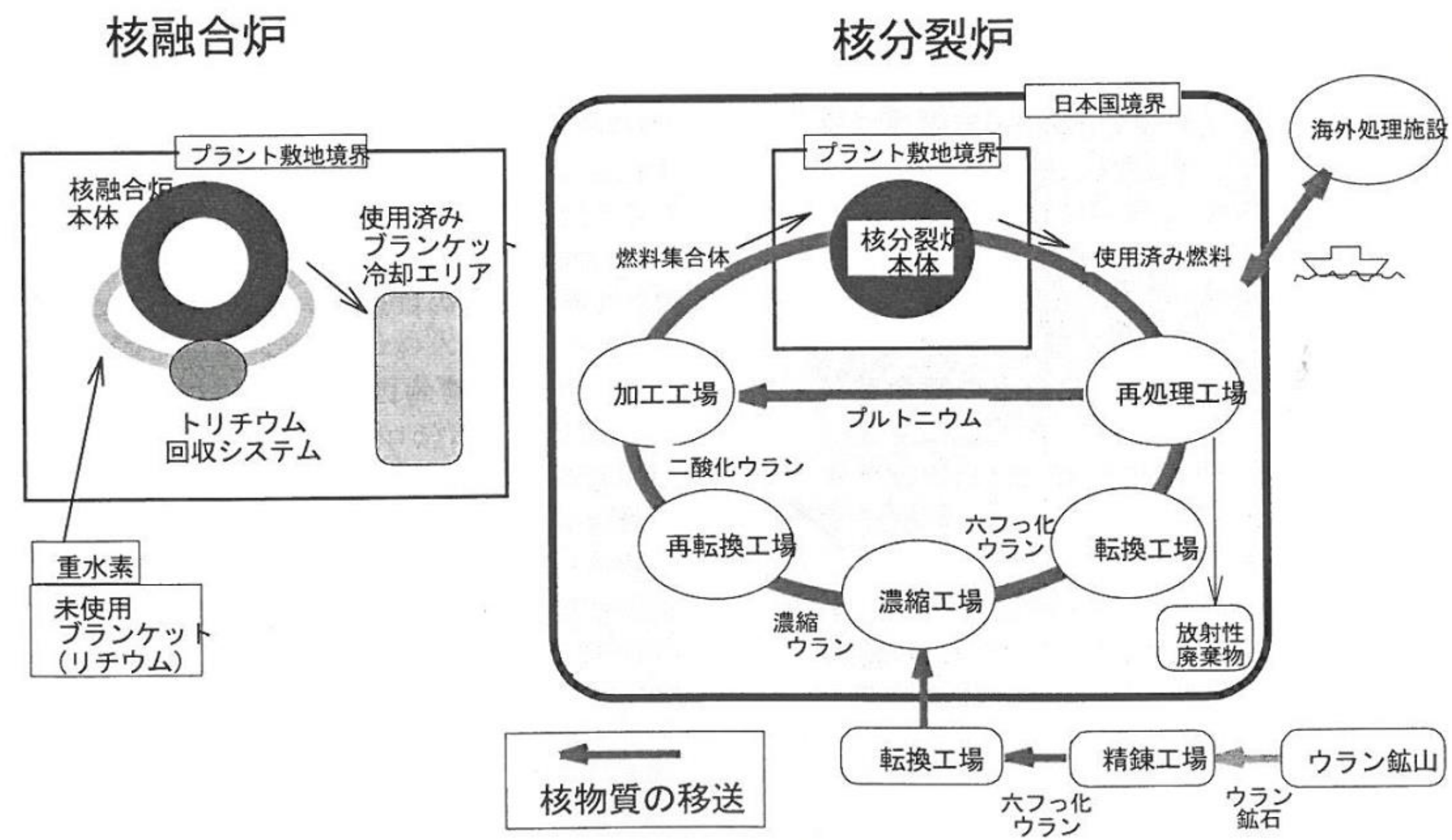
(2) Inside tritium plant
- Isotope Separation System : 100g-T
- Fuel Storage and Delivery system : 200g-T
- Fueling System : 85g-T
- Others : total 100g-T

(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

Fuel Supply and Cycle



Human Error Safety Concerns

- **Fail-safe and foolproof concept (as in fission plants)**
  - To prevent the escalation of abnormal events and accidents, when safety functions are overridden or canceled, so as to avoid an excursion by an uncontrolled reaction

Issues for Ensuring Safety

- **Thermal and magnetic energy specific to the tokamak type fusion device: potential energy to damage the enclosure**

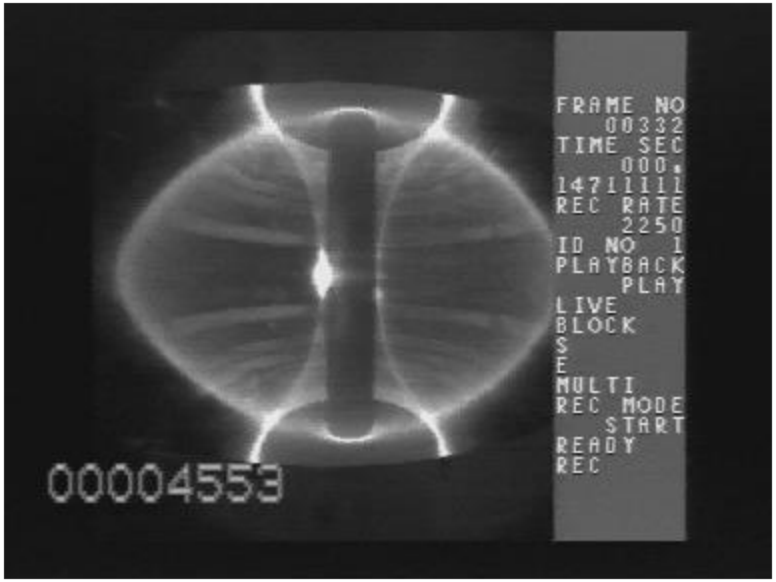
ITER

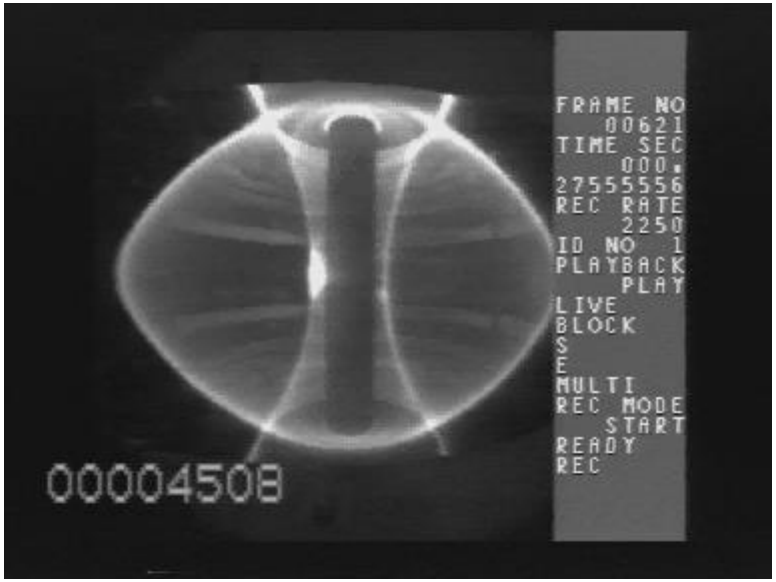
<table>
<tr><th colspan="2">Category</th><th colspan="3">Energy</th></tr>
<tr><td rowspan="3">Vacuum Vessel</td><td rowspan="3">Plasma</td><td colspan="2">Fusion power</td><td>0.5 GW</td></tr>
<tr><td colspan="2">Thermal energy</td><td>0.4 GJ</td></tr>
<tr><td colspan="2">Magnetic energy</td><td>0.4 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 (burning) energy of hydrogen isotope gas</td><td rowspan="2">< 0.1 GJ</td></tr>
<tr><td>Fuel cycle system</td><td colspan="2">Chemical (burning) energy of hydrogen isotope gas</td></tr>
</table>

Issues for Ensuring Safety

- **Energey sources involved in plasma**

- The vacuum vessel and in-vessel components are designed to endure an excessive number of events such as small ELMs (Edge Localised Modes)
- Disruption must be avoided: Issue of plasma physics
- No safety function is required for the components located inside the vacuum vessel, since the vacuum vessel is the enclosure to ensure the containment of tritium.

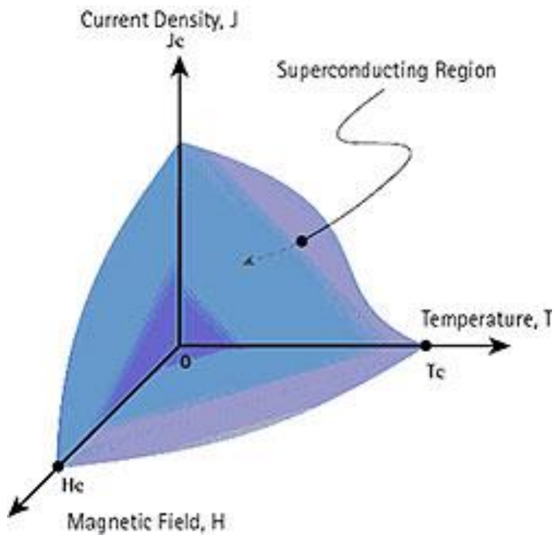


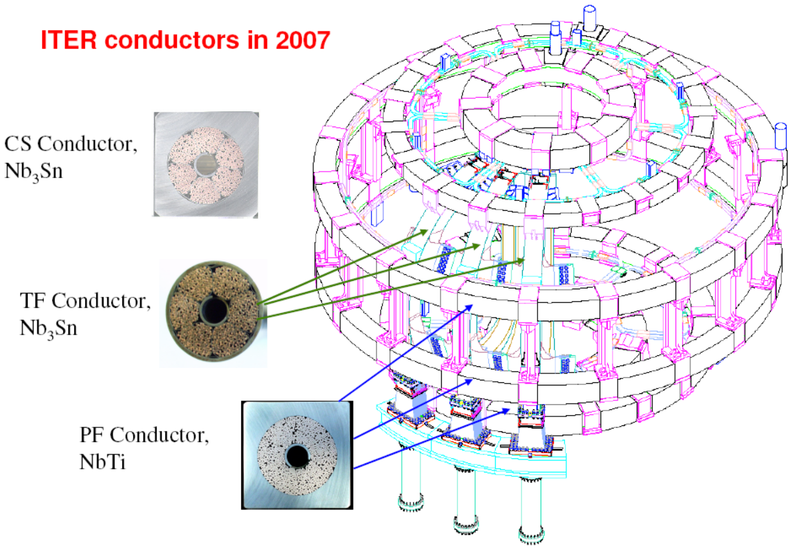


Issues for Ensuring Safety

- **Magnetic energey in the superconducting coils**

- When the superconducting state is failed (quenching), the stored energy is normally released to the external resistance and absorbed as Joule heat.
- Even in the worst scenario, the superconducting coils would not affect the containment function of the vacuum vessel.
  - coils designed to have sufficient strength for the severe load
  - clearance provided between the vacuum vessel and the coils to avoid mechanical contact





Issues for Ensuring Safety

- **Chemical energy of hydrogen isotopes**
  - The hydrogen isotopes can enter into a chemical combustion reaction with oxygen.
  - If all hydrogen isotopes were burned, the generated energy would be less than 0.1 GJ, relatively small.
  - 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

- **Tritium exposure**

\- 삼중수소의 방사선은 피부를 투과하지 않음: 평상 시, 이상 시에 방출된 삼중수소가 환경이나 생태계를 거쳐 생체에 들어가는 양을 평가해 피해유무를 파악해야 함.

\- 수증기 상태의 삼중수소(HTO): 생체 내의 수분과 교환해 피폭 야기
수소 상태의 삼중수소(HT): 대부분 흡수되지 않음.

→ 삼중수소 농도 한도: 수증기 형태 0.005 Bq/cc, 공기 중 수소 형태 78 Bq/cc, 배수 형태 60 Bq/cc

\- 배기통으로부터 방출된 삼중수소는 플럼이라는 기체 덩어리로 이동하면서 확산, 희석됨.

\- 배수로 해수 중에 방출된 삼중수소는 수중에서 동위원소 희석됨.

\- 인체 내 들어간 삼중수소는 수십 일의 반감기로 수분의 대사와 함께 배출됨.

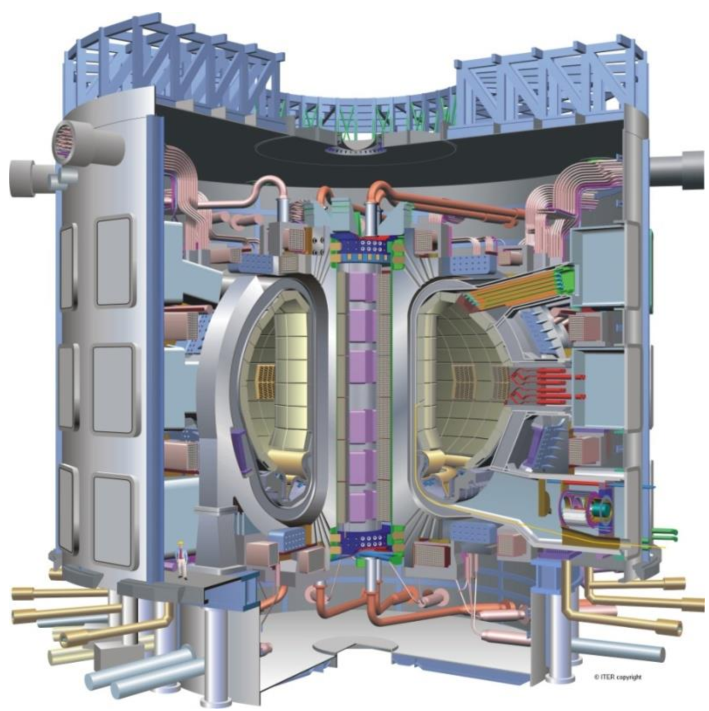
\- 방출된 삼중수소는 환경 중에서 토양 세균 등에 의해 물로 전환되기도 함.

\- 환경 중에서 삼중수소화 된 유기물(OBT)로 전환된 것을 마셨을 경우, 삼중수소 체류시간이 더 길어짐.

Safety Issues in ITER

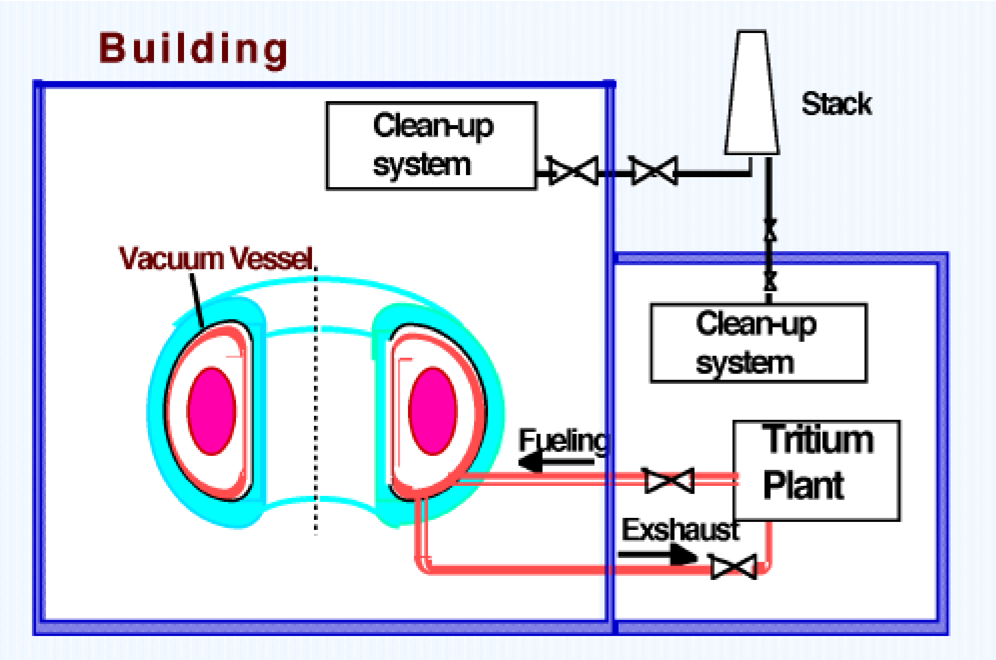
- **Safety goal**

  - 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.



Safety Issues in ITER

- 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.



Safety Analyses in ITER

- **Safety analyses of ITER**

- In the design activity of ITER, the abnormal events and accidents, 25 events in total (11 types), were categorised 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.

Safety Analyses in ITER

- **Present status of the safety research in ITER**

- Most analysis codes utilised 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 utilised data for the application to the fusion reactor.

Safety-related Issues for Future Fusion Reactors Including DEMO Reactor

	KSTAR	ITER	FPP
상위 기능 (목적)	플라즈마 발생	Nuclear facility 플라즈마 발생	열이용 연료 생산
하위 기능 (수단)	전자 기계	전자 기계	Nuclear facility 플라즈마 발생 전자 기계

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