March 8, ASDEX Upgrade Seminar

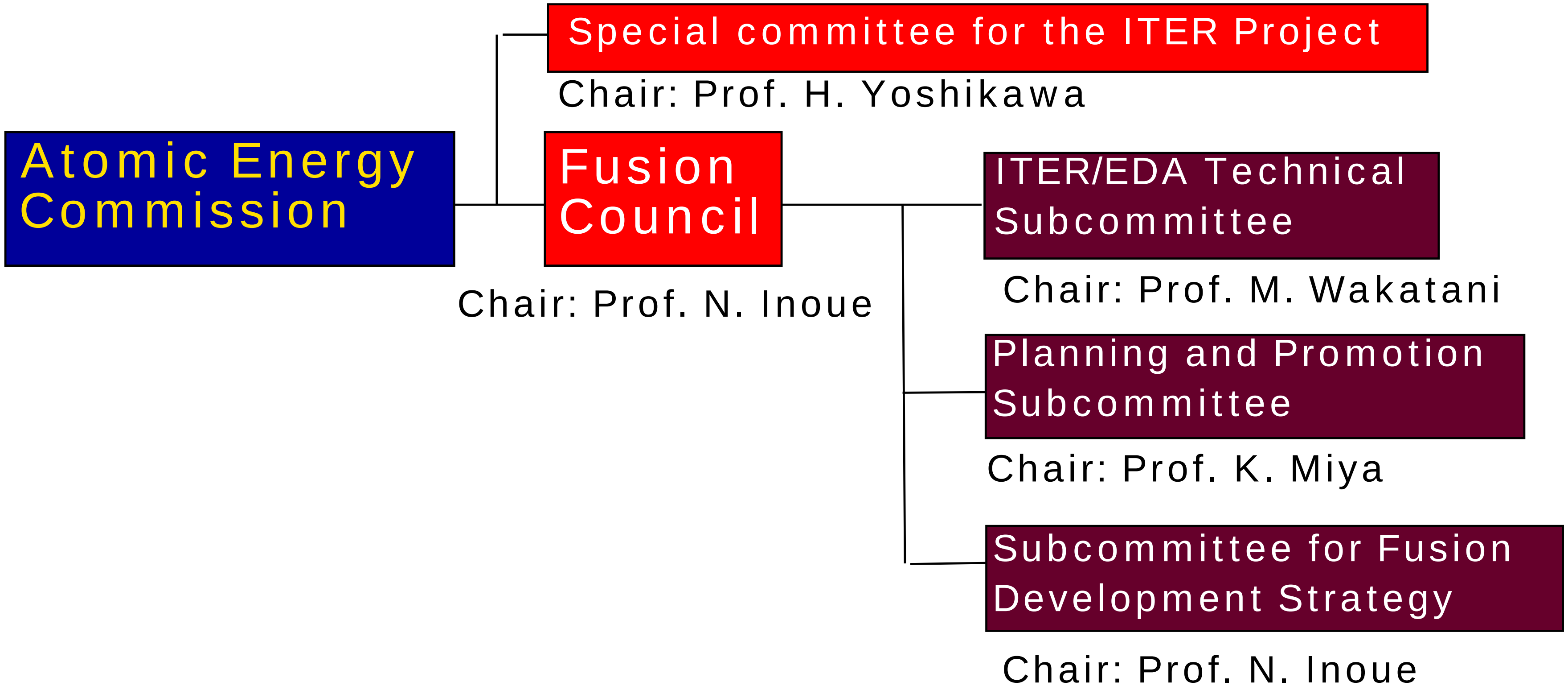
# Report on Technical Feasibility of Fusion Energy to the Special Committee for the ITER Project

M. Kikuchi

Former member of subcommittee for Fusion Development Strategy under Fusion Council

# Structure of Fusion Program Promotion in Japan

(before May 17,2000)



# Charge to Subcommittee for Fusion Development Strategy

(3) Technical feasibility of the fusion energy

(4) Extension of the program and basic supporting research

For topic (3) above, the Special Committee additionally requested an evaluation of the feasibility of fusion energy as a safe and reliable energy source from the aspects of technical potential, management capability, and characteristics of Japanese industrial structure.

Two other subcommittes are formed for answering

(1) Survey of long term demand and supply of energy sources

(2) Feasibility study of alternative energy sources

(5) Distribution of resources for research

(6) International relations.

Members of Subcommittee for Fusion Development Strategy (April 2000)

| | |
|---|---|
| Nobuyuki Inoue (Chairman) | Chairman of Fusion Council<br>Professor, Institute of Advanced Energy, Kyoto University) |
| Katsunori Abe | Professor, Graduate School of Engineering, Tohoku University |
| Kunihiko Okano | Research Fellow, Komae Research Laboratory, Nuclear Energy Systems Department, Central Research Institute of Electric Power Industry, |
| Yuichi Ogawa | Professor, High Temperature Plasma Center, University of Tokyo |
| Mitsuru Kikuchi | General Manager, Tokamak Program Division, Department of Fusion Plasma Research, Japan Atomic Energy Research Institute |
| Shigetada Kobayashi | Chairman of the Committee on Nuclear Fusion Research & Development, Nuclear industry Executive Committee, Japan Electrical Manufacturers' Association (Senior Manager, Advanced Energy Design & Engineering Department, Power Systems & Services Company, Toshiba Corporation) |
| Satoru Tanaka | Professor, Department of Quantum Engineering and Systems Science, Graduate School of Engineering, University of Tokyo |
| Yoshiaki Hirotani | Manager, Department of Project Planning and Promotion, Japan Atomic Industrial Forum, Inc) |
| Masami Fujiwara | Director-General, National Institute of Fusion Science |
| Shinzaburo Matsuda | Director General, Naka Fusion Establishment, Japan Atomic Energy Research Institute |
| Kenzo Miya | Chairman of Planning and Promotion Subcommittee under Fusion Council (Professor, Graduate School of Engineering, University of Tokyo) |

Chapter 1 Future Prospects of the Fusion Energy

1.1 Situations in the 21st century

1.2 Criteria for commercialization

1.3 Comparison with other power sources

1.3.1 Resources (fusion, fission, fossil)

1.3.2 CO2 Emissions and Sustainability of Atmosphere

1.3.3 Safety viewed from Biological Hazard Potential

1.3.4 Radioactive Waste and Environmental Adaptability

1.3.5 Plant Characteristics

1.3.6 Economical Efficiency

1.3.7 Use of Fusion other than Electricity

1.4 Overall Assessment

# Resources required for Fusion Reactor

## (SSTR is adopted as a reference design)

Resource life :

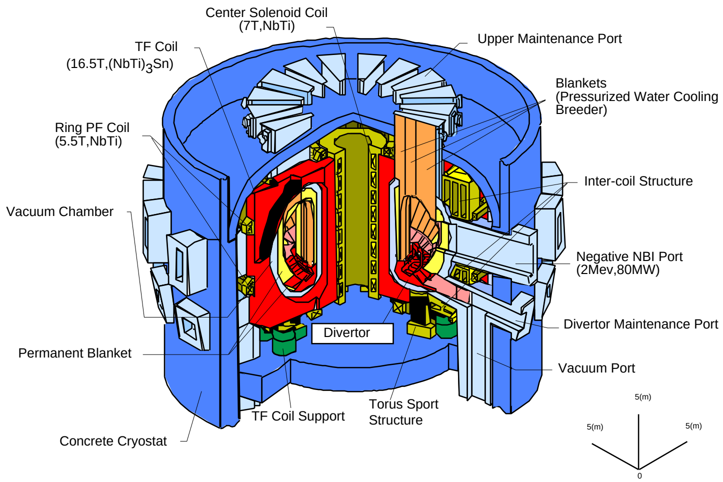
Assuming present-level world electricity is produced by 1500 SSTR

Deuterium : almost limitless ; 144ppm in fresh water

Lithium : 1.5million years ; 233Gtons in sea-water

Beryllium : 70,000 years ; 100Mtons (gross mineral resources)

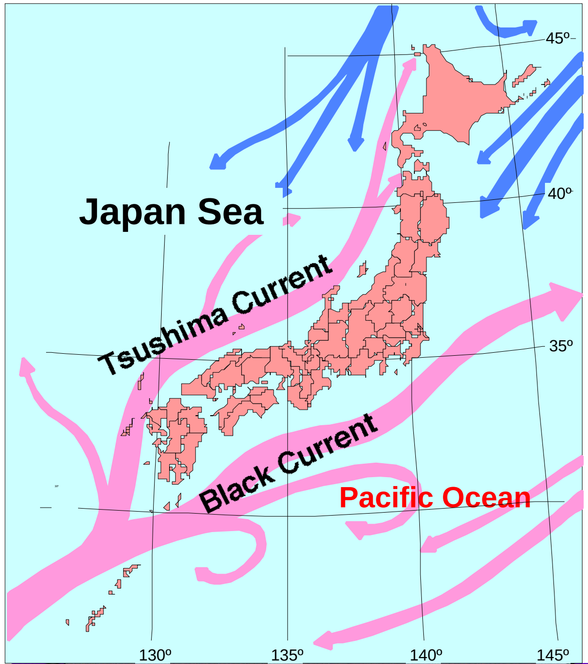
Niobium : 70,000 years ; 700Mtons (gross mineral resources)

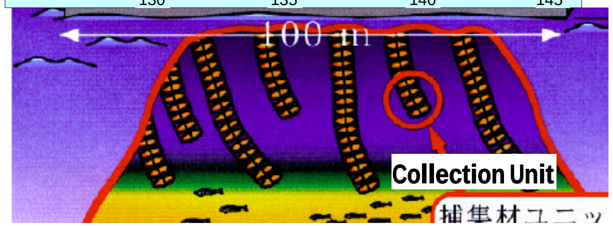



Bird's-eye view of SSTR

| | | Design Value |
|---|---|---|
| Plasma Current | $I_p$ | 12MA |
| Toroidal Field Coil | $B_t$ | 9T |
| Major Radius | R | 7m |
| Aspect Ratio | A | 4.1 |
| Elongation | $\kappa_{95}$ | 1.85 |
| Normalized Beta | $\beta_N$ | 3.5 |
| Fusion Output | $P_F$ | 3GW |
| Current Drive Power | $P_{CD}$ | 60MW |
| Net Electric Output Power | $P_E$ | 1.08GW |
| Fusion Gain | Q | 50 |
| Averaged Neutron Wall Load | $P_{neut.}$ | $3MW/m^2$ |

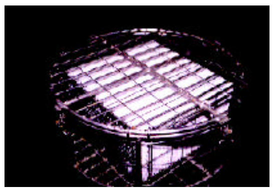
# Uranium Resources

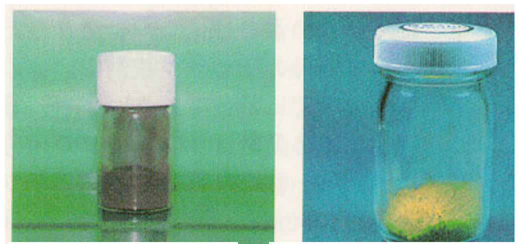


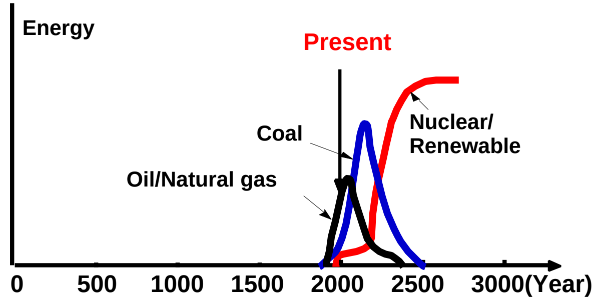

**Uranium is virtually inexhaustible since Uranium extraction from sea-water is technically ready.**

| | |
|---|---|
| **Concentration** | **3.3ppb** |
| **Resource in sea water** | **$46 \times 10^{8}$tons** |
| **Annual consumption** | **$6.14 \times 10^{4}$tons** |
| **Resource life** | **75,000 years** |





# Fossil Resources ( Reserves and Resource Base )



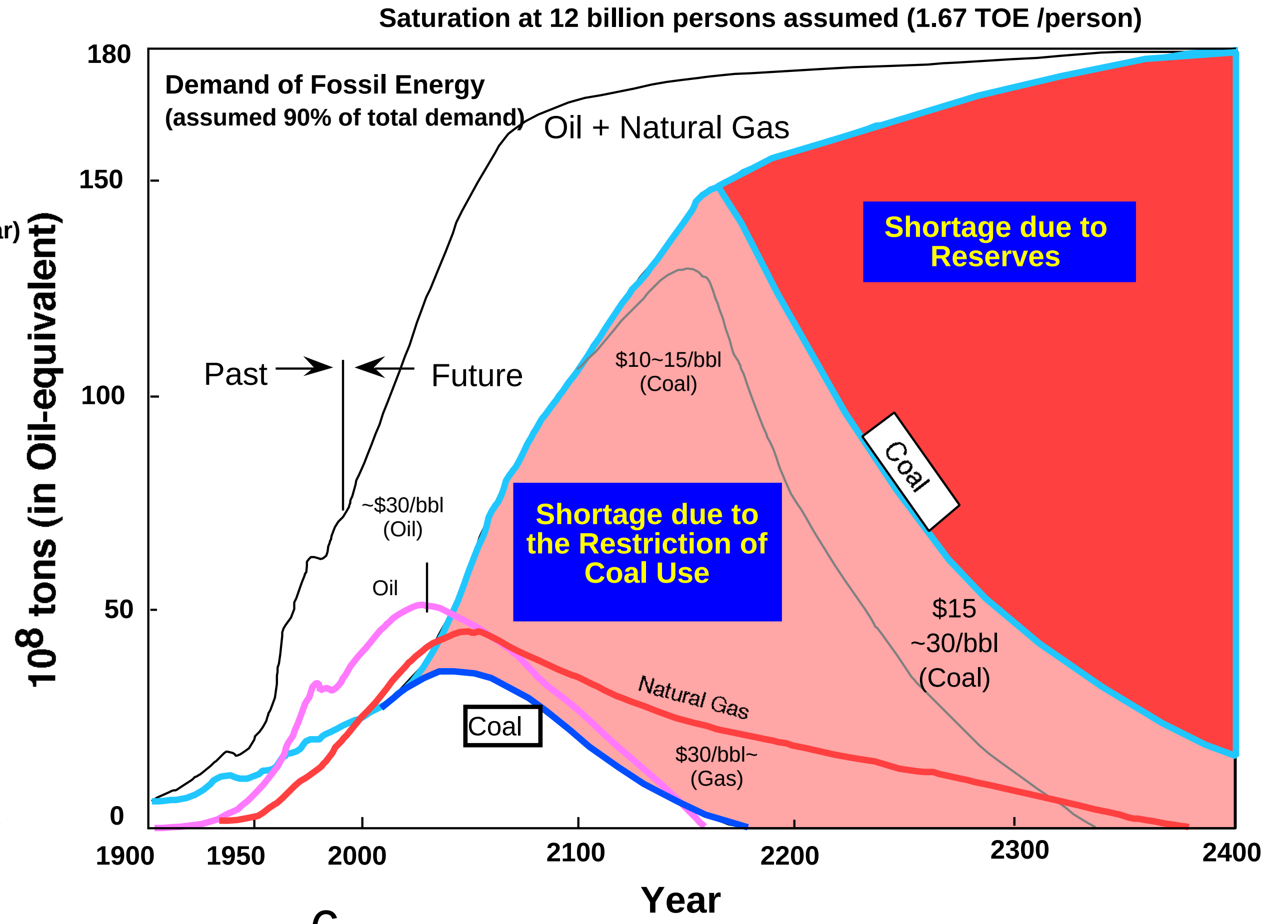

Resource life

For reserve

- Coal ; 231years
- Nat.Gas ; 63years
- Oil ; 44years

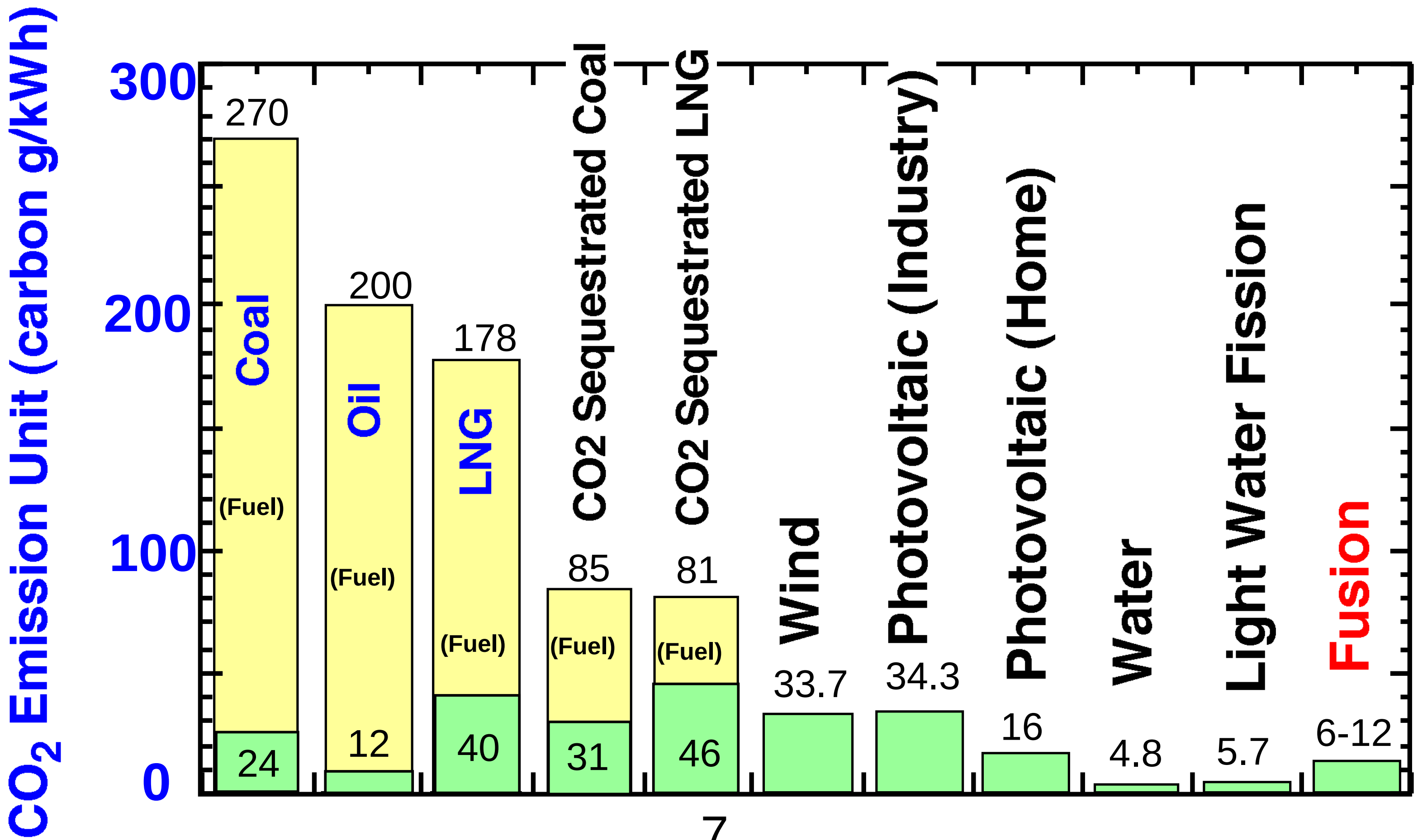
For resource base

- Nat.Gas ; 452years
- Oil ; 242years



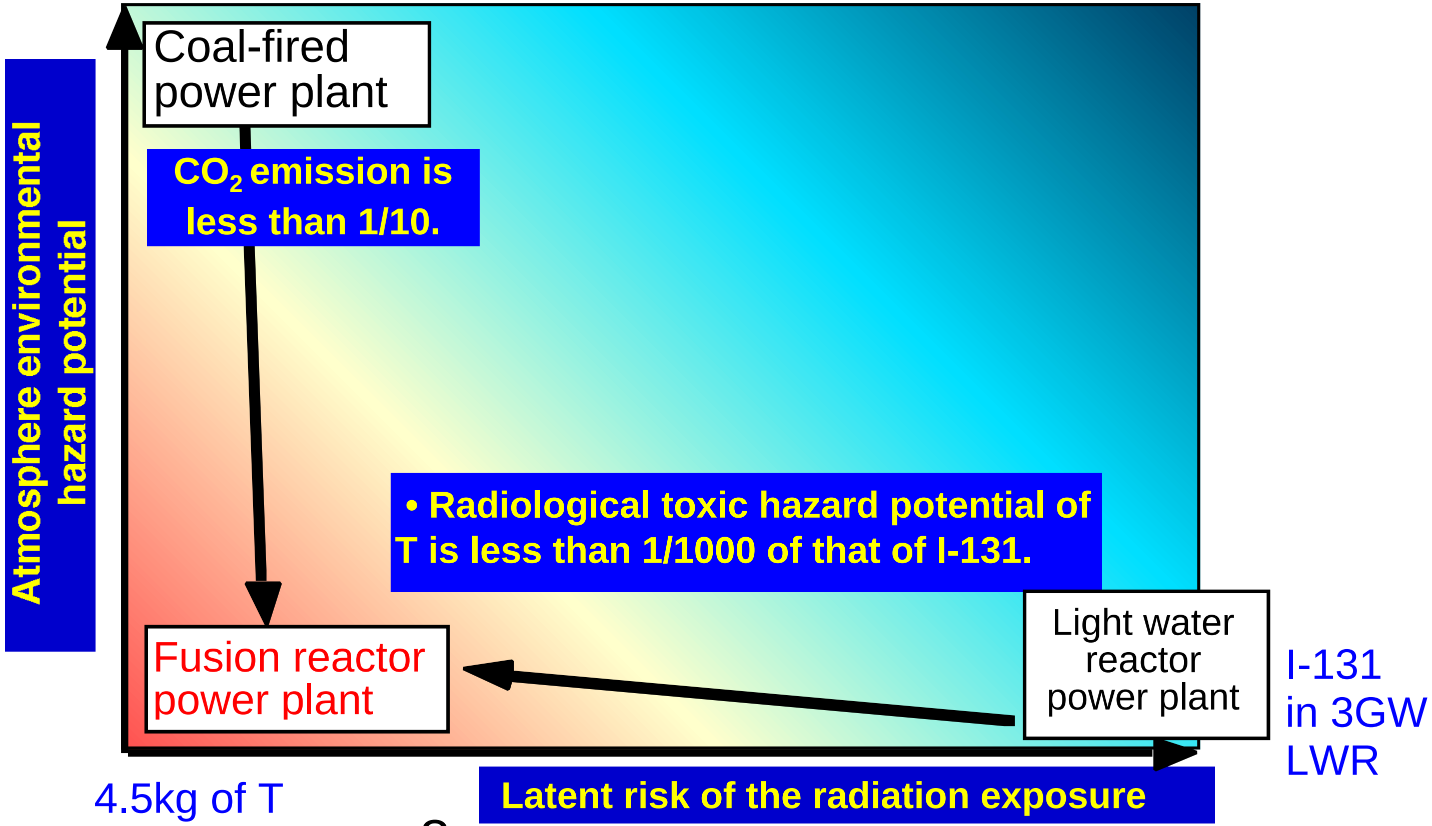
# $CO_2$ Emission Rate

Fusion is environmentally attractive with its low $CO_2$ emission rate.



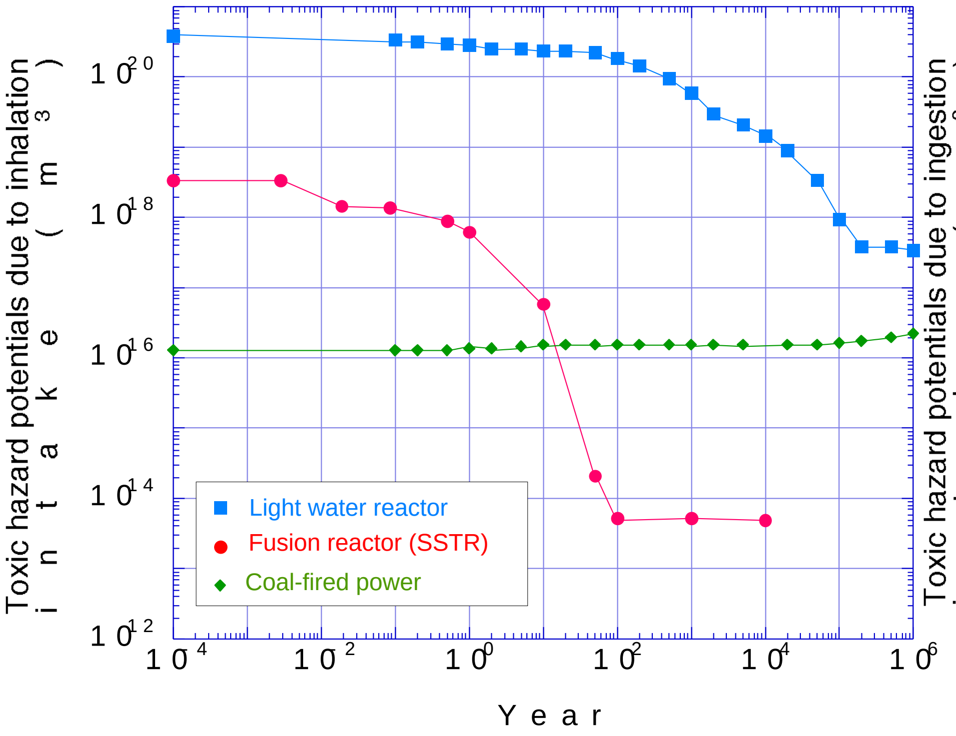
# Radiological Toxic Hazard Potential

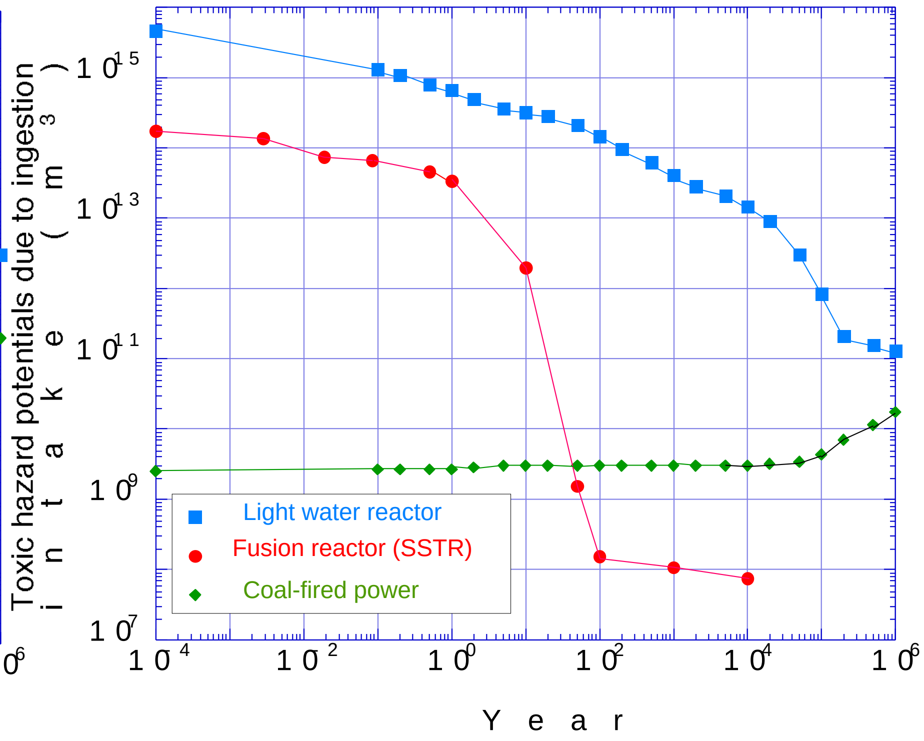
Present large scale energy sources such as fossil plants and LWR have large risks such as Global Warming and Radiological Hazard. Fusion simultaneously reduces both risks.



# Long Term Waste Hazard Potential

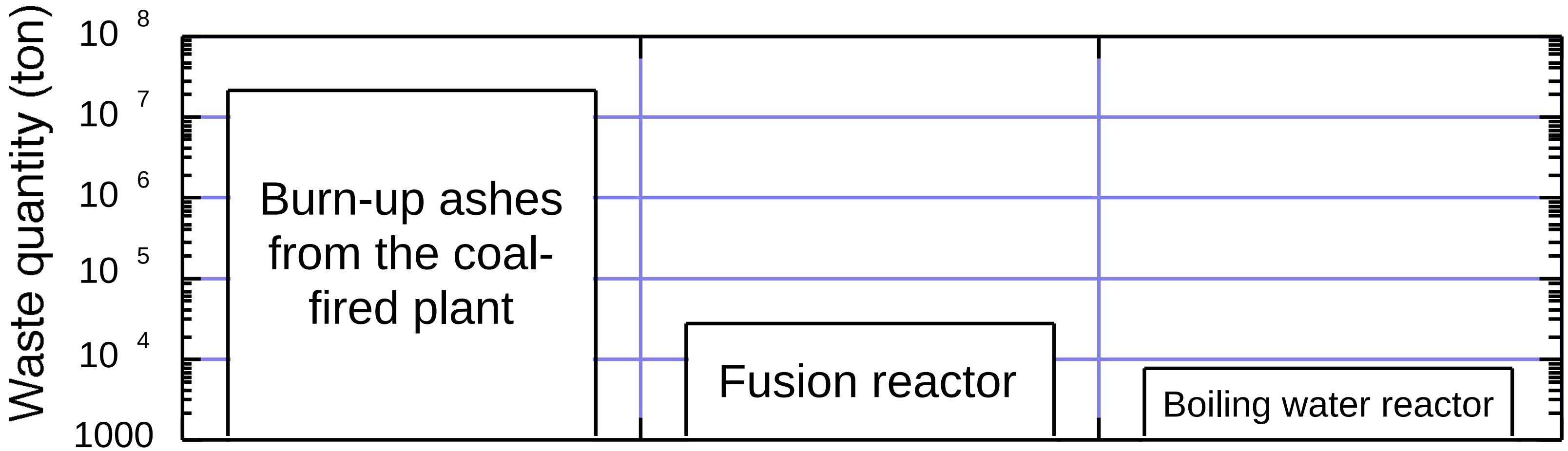
Radiological toxic hazard potential of fusion plant is much smaller than fission and even lower than coal ash (Th-232,U-238)



# Waste Management

Disposal cost is smaller than that for LWR spent fuel management.



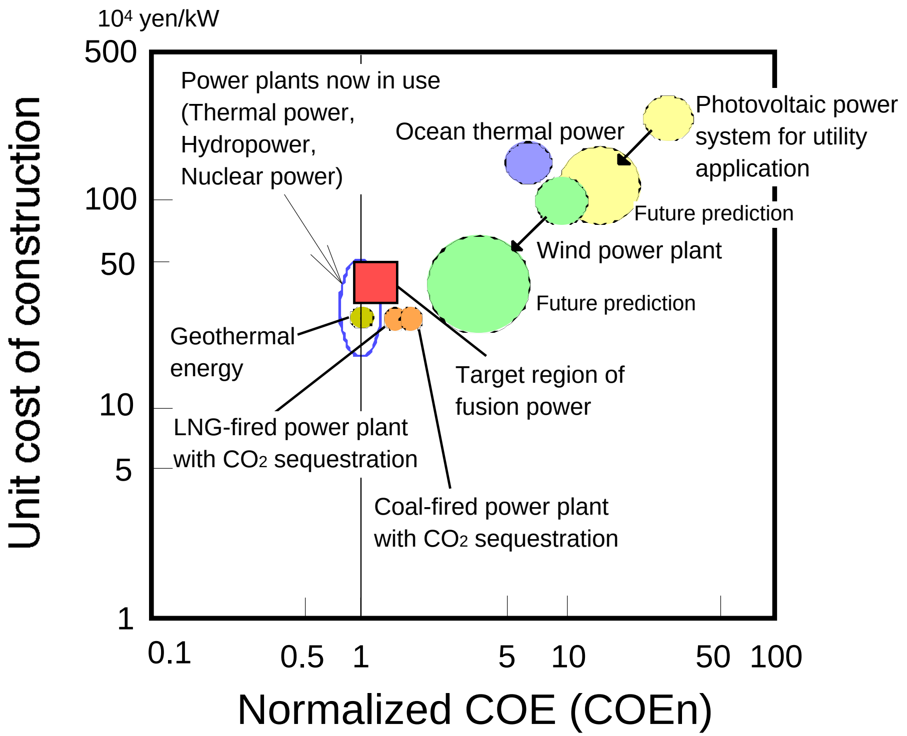

| | High-level radioactive waste | High βγ waste | Low-level radioactive waste | Total |
|---|---|---|---|---|
| Fission reactor with 1GW electricity | 90 billion yen / 180 m3 | 3.84 billion yen / 1600 m3 | 11.7 billion yen / 9750 m3 | 10.554 billion yen |
| Fusion reactor(SSTR, 1.08 GW electricity) | - | 6 billion yen / 2500 m3 | 30.12 billion yen / 25100 m3 | 36.12 billion yen |

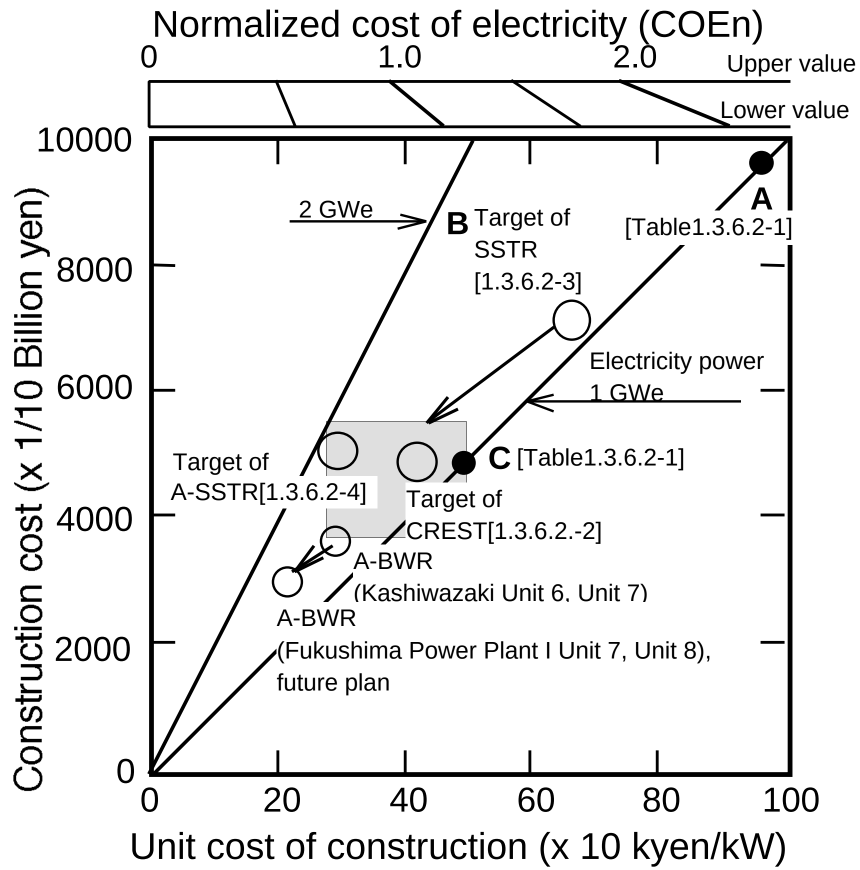
Used disposal unit prices are low-level waste (¥ 1200000/m3), high βγ waste (¥ 2400000/ m3) and high-level radioactive waste (five hundred million yen/ m3)

# Economical Efficiency

1) If fusion power plants are forced to be competitive only for the COE issue, a COEn of 0.5~0.7 must be realized in future.

2) If fusion COEn will be much more than 1.5, fusion will be noncompetitive. Even if fission unavailable for one reason or other, the fossil power plants with $CO_2$ sequestration systems will ne cost than the fusion plants. Furthermore, the cost of $CO_2$ sequestration will be reduced in future.



# Target for Commercial Use

COE : designed value of 10yen/kWh or less 15yen/kWh as upper limit

Stability : less than 1%

Forced outage : 0.5/unit year ( including disruption-induced outage)

Load-following : at least partial load operation in case of emergency

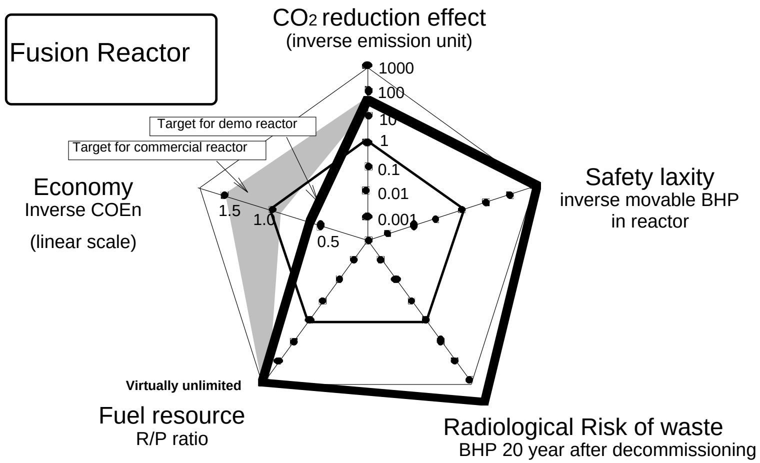
Site requirement : near high demand area if possible

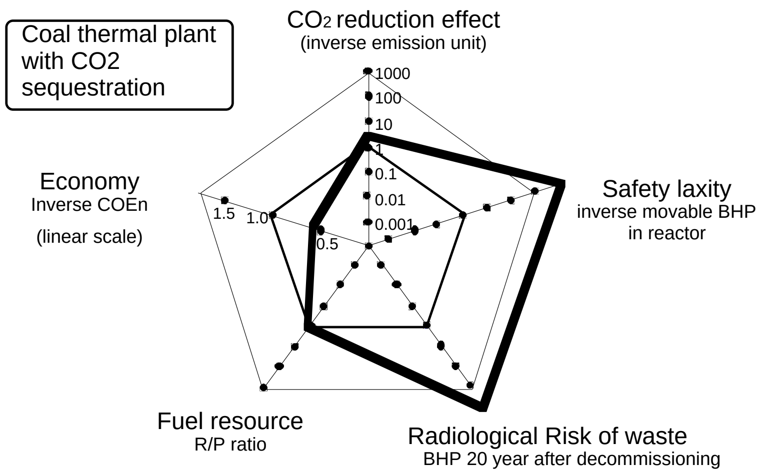
Generation capacity : <2GW/unit

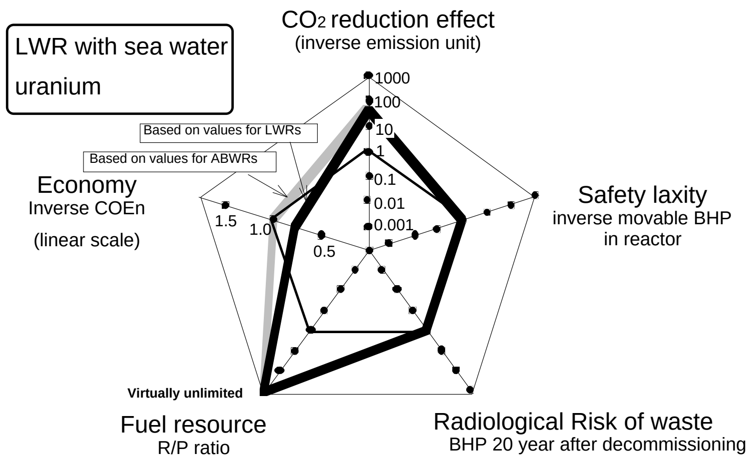
Capacity factor : ideal design value of 85%, initial target 70%

# Overall Assessment

## Fusion can be a balanced energy source

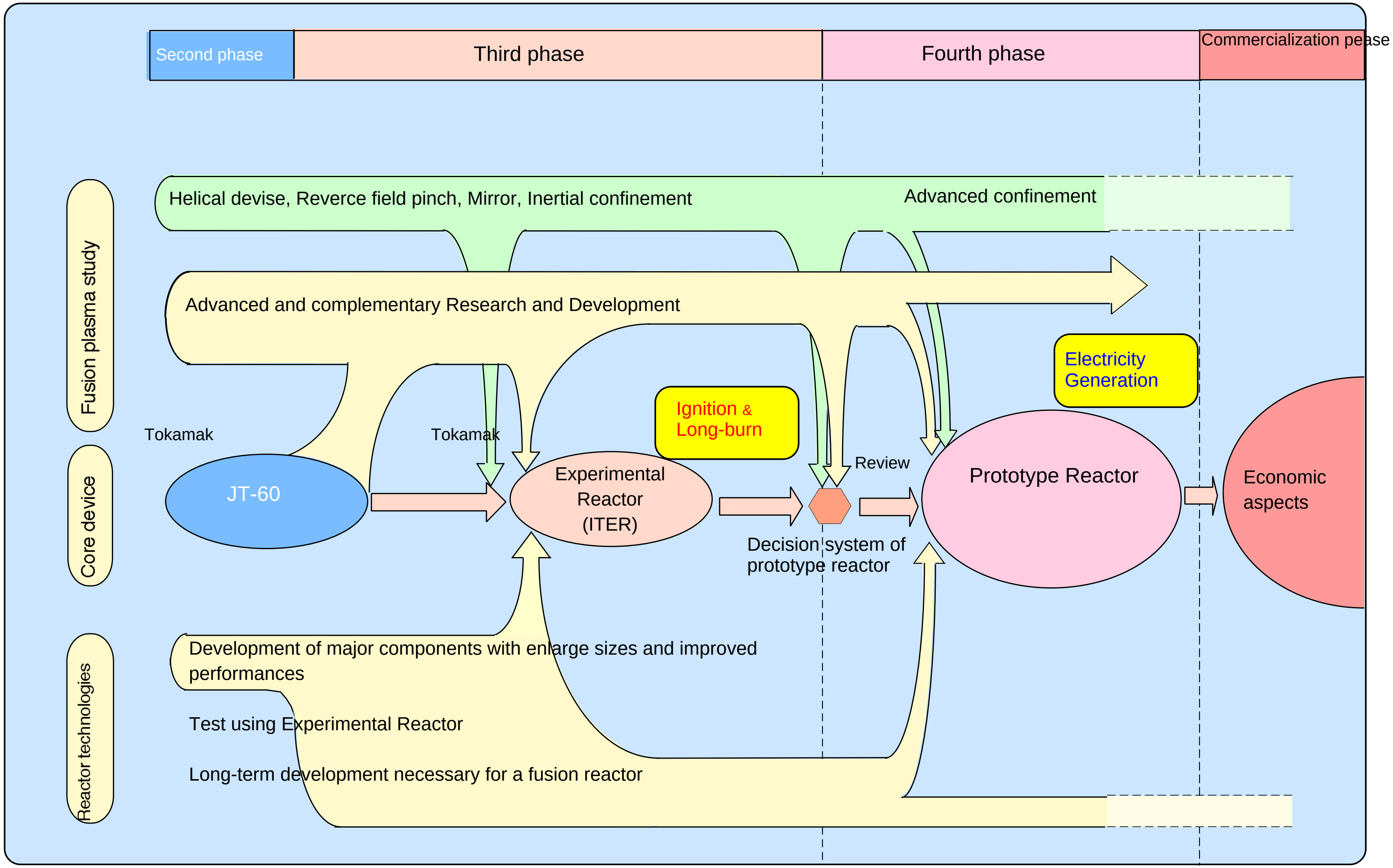


## Chapter 2 Development Strategy based on ITER Project

# Fusion energy development and scenarios toward the fusion power plant



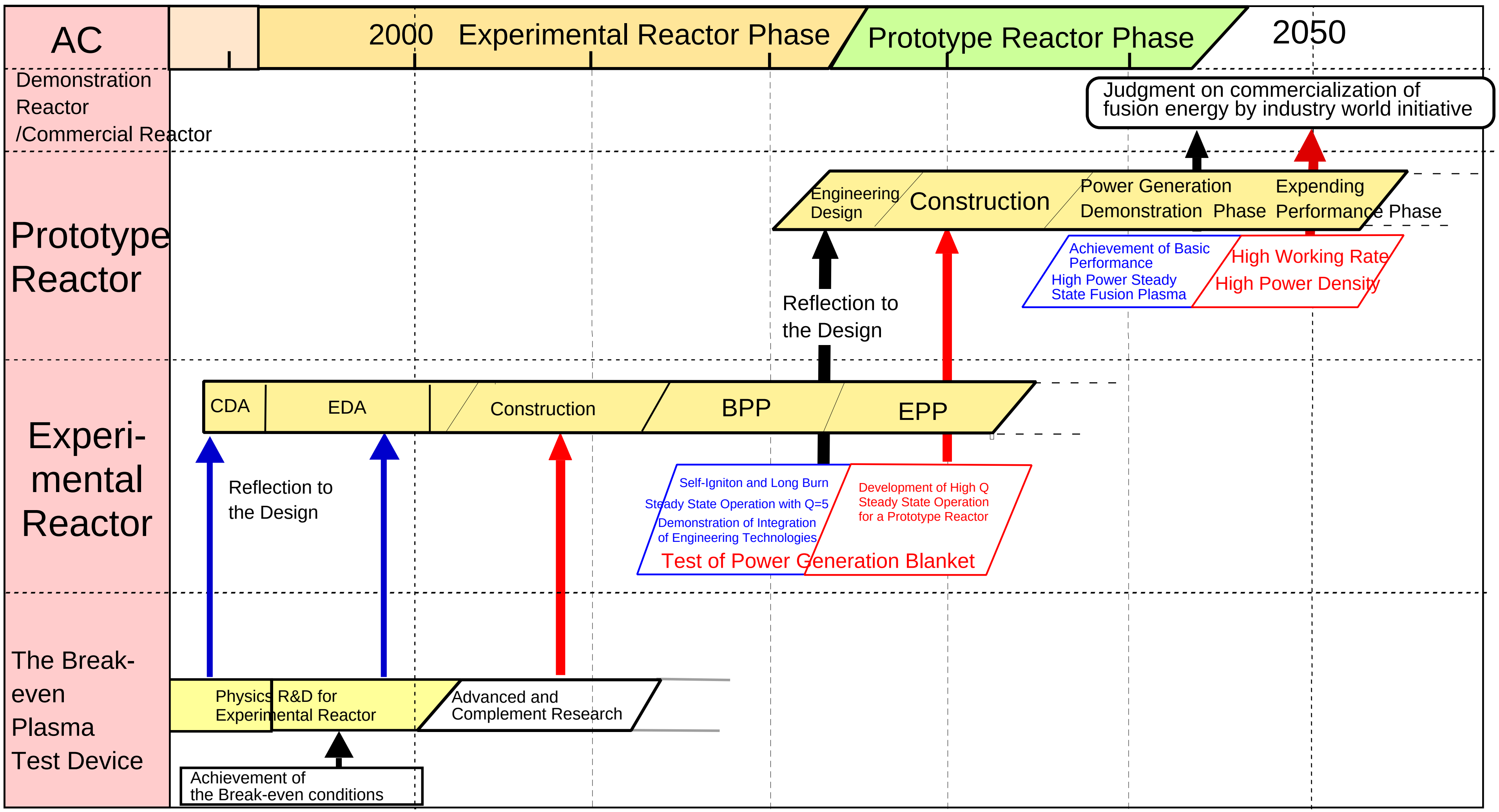
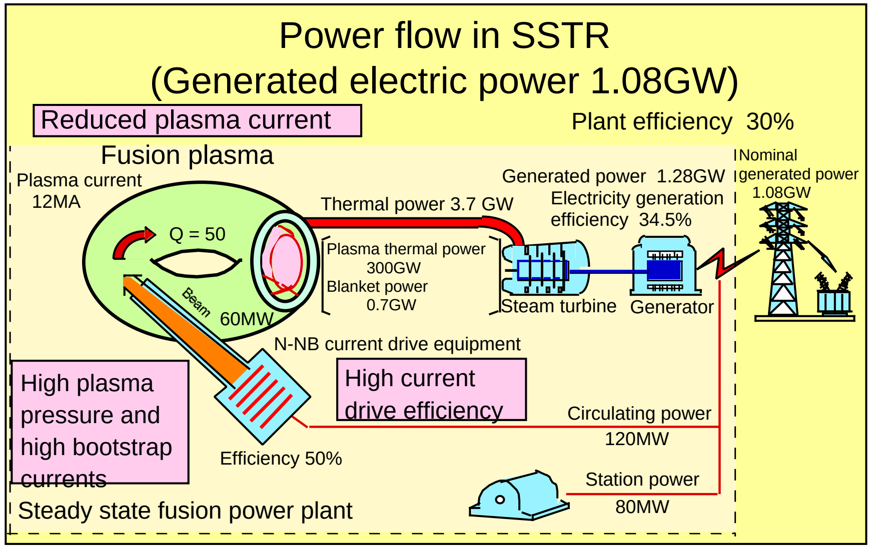
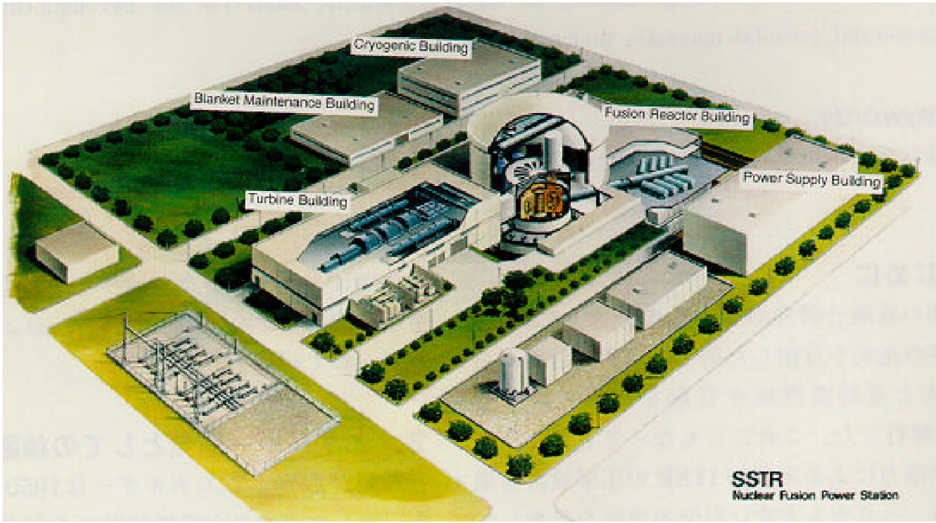



**fig2.1.2-2 : An example of Development Program on a Tokamak Fusion Reactor**

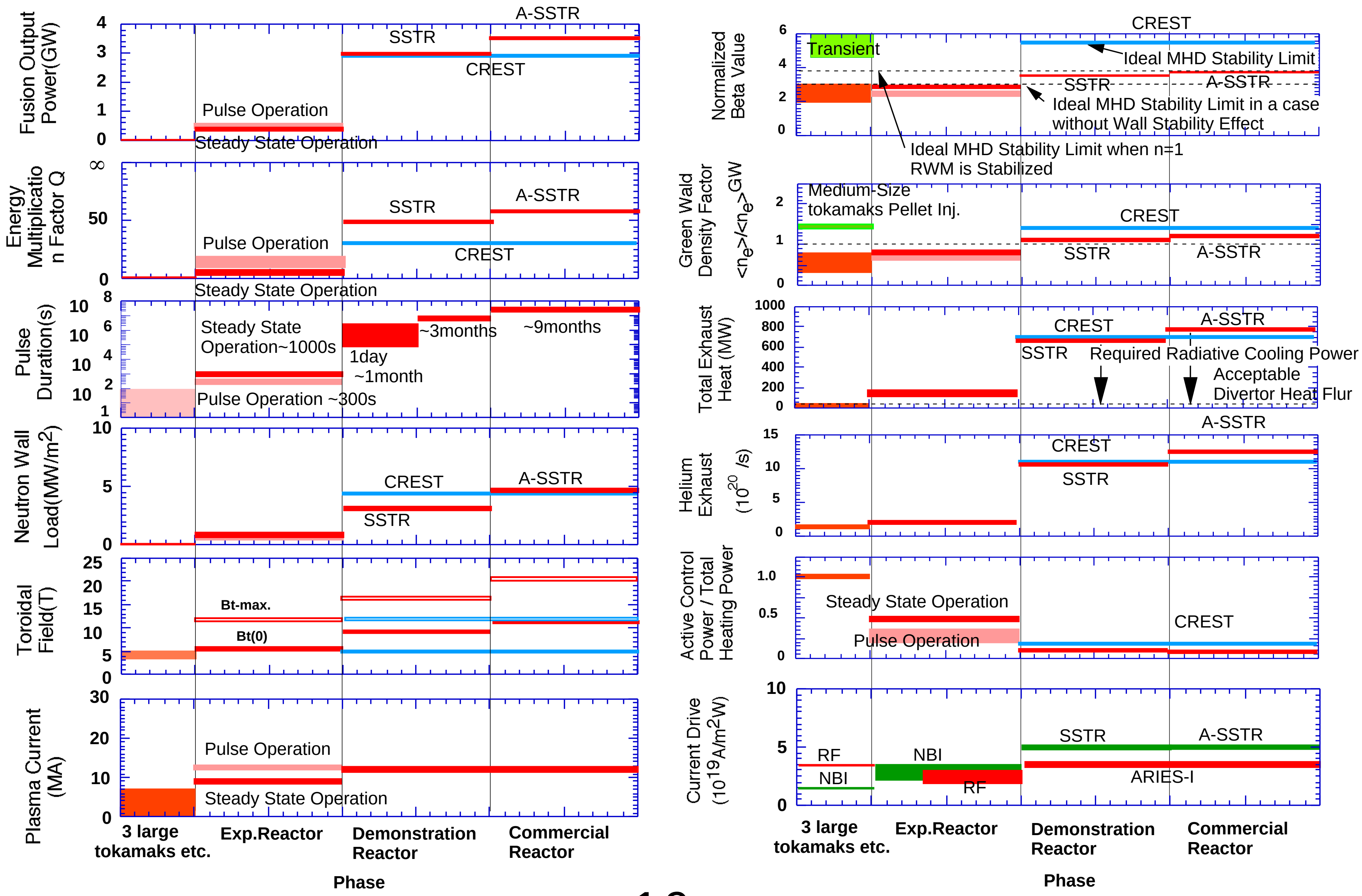
Table 2.3.2-1 Parameter gaps from experimental reactor ITER to a prototype reactor

| Item | ITER | Prototype reactor |
|---|---|---|
| Energy amplification factor (inductive) | 10 - 20 | |
| Energy amplification factor (steady state) | 5 | 30 - 50 |
| Plasma pressure | Several atm | ~10 atm |
| Maximum magnetic field | 12 T | 16 T |
| Normalized beta | ~2.5 | ~3.5 |
| Blanket | Test module | Blanket for power generation |
| Structural material | SS316 | Low activation ferritic steel, etc. |
| Neutron fluence | 0.3 MWa/m$^2$ | <10 MWa/m$^2$ |



# Chapter 3 Technical Issues and Future Prospects


Fusion Output Power(GW)
A-SSTR
SSTR
CREST
Pulse Operation
Steady State Operation
Energy Multiplication Factor Q
Pulse Duration(s)
Steady State Operation~1000s
~3months
~9months
1day
~1month
Pulse Operation ~300s
Neutron Wall Load(MW/m2)
Toroidal Field(T)
Bt-max.
Bt(0)
Plasma Current (MA)
3 large tokamaks etc.
Exp.Reactor
Demonstration Reactor
Commercial Reactor
Phase
Normalized Beta Value
Transient
Ideal MHD Stability Limit
Ideal MHD Stability Limit in a case without Wall Stability Effect
Ideal MHD Stability Limit when n=1 RWM is Stabilized
Green Wald Density Factor
Medium-Size tokamaks Pellet Inj.
Total Exhaust Heat (MW)
Required Radiative Cooling Power
Acceptable Divertor Heat Flur
Helium Exhaust
Active Control Power / Total Heating Power
Current Drive
RF
NBI
ARIES-I

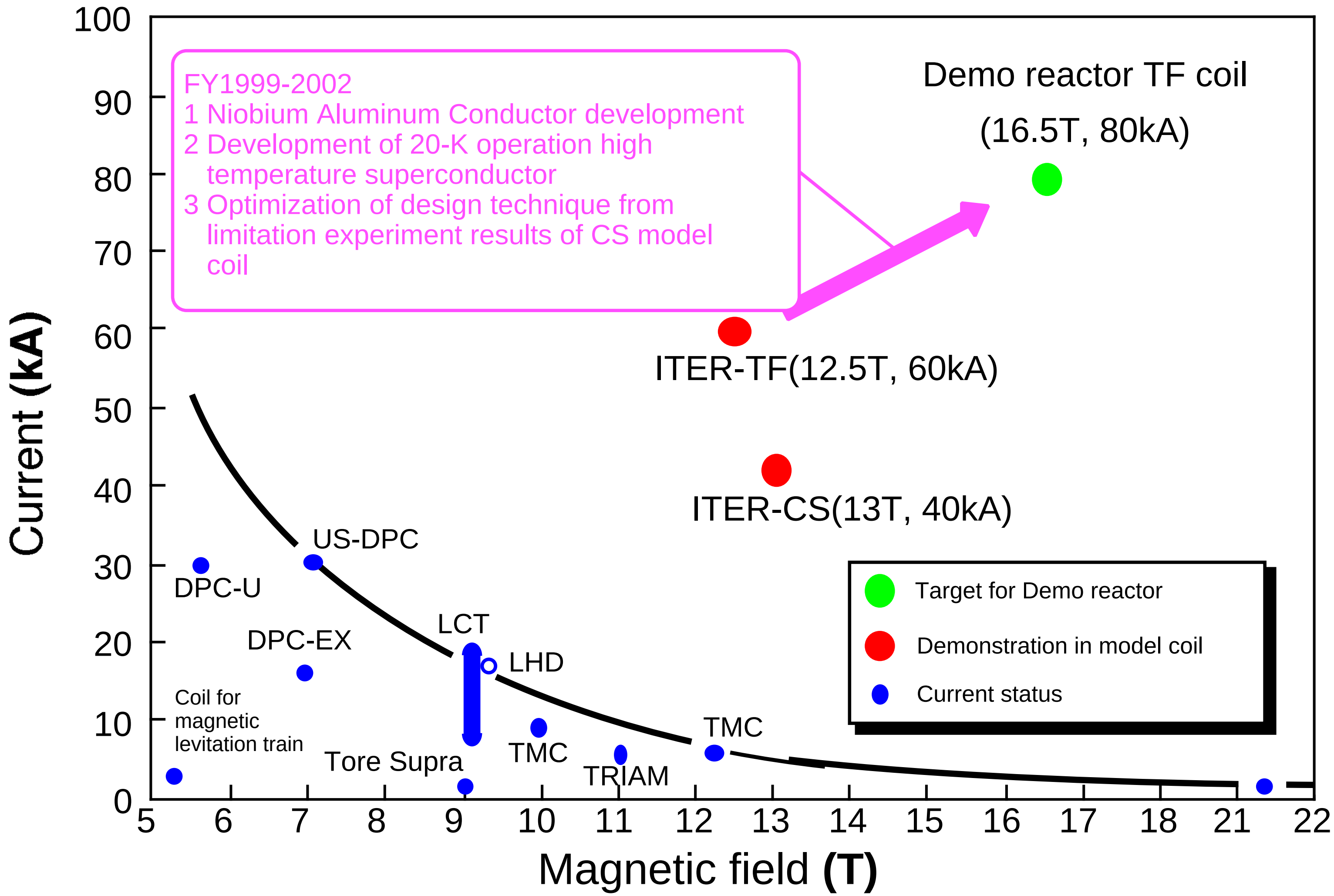



Fig. 3.2.3-2 Development Step of Conductor for Demo Reactor Coil

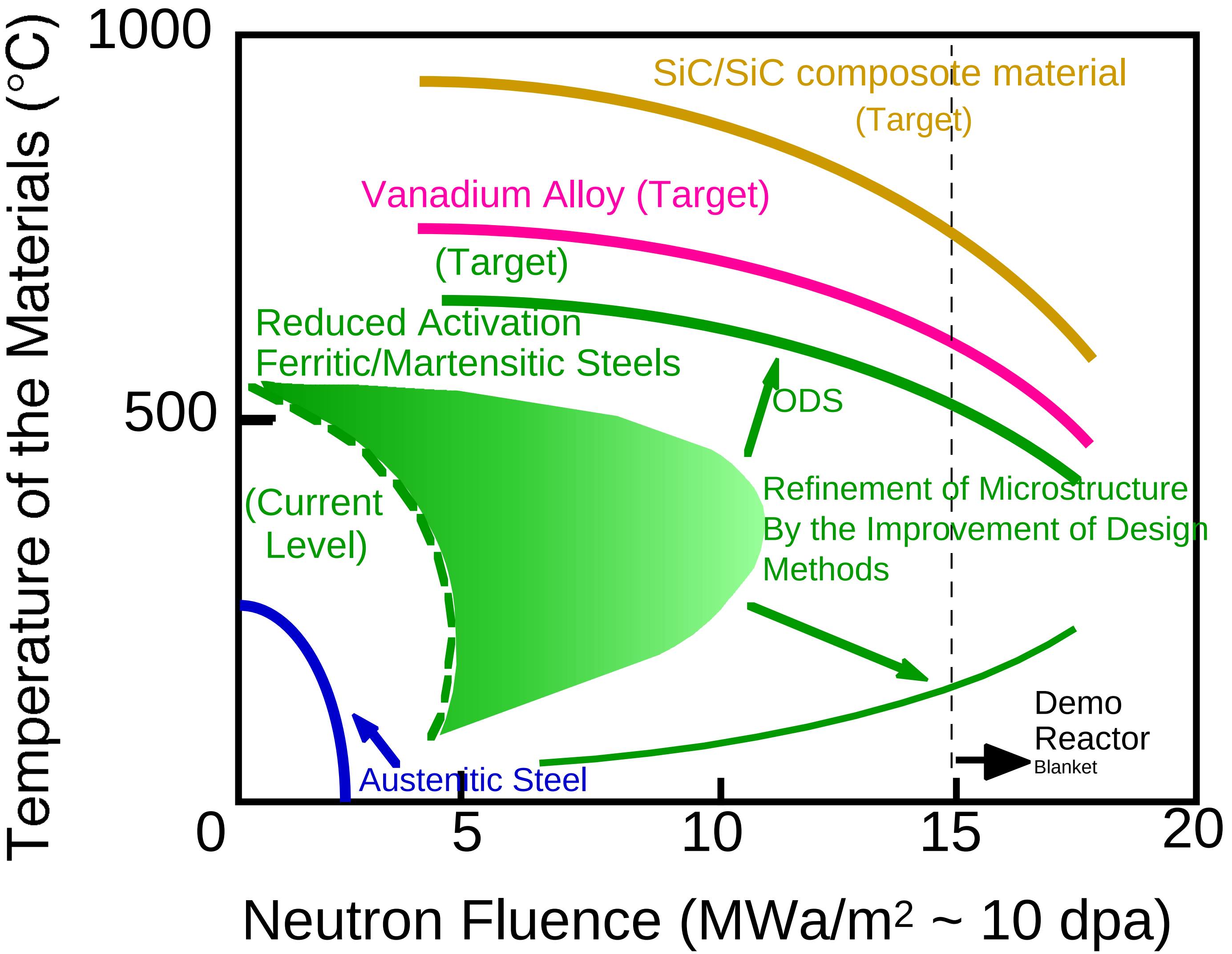
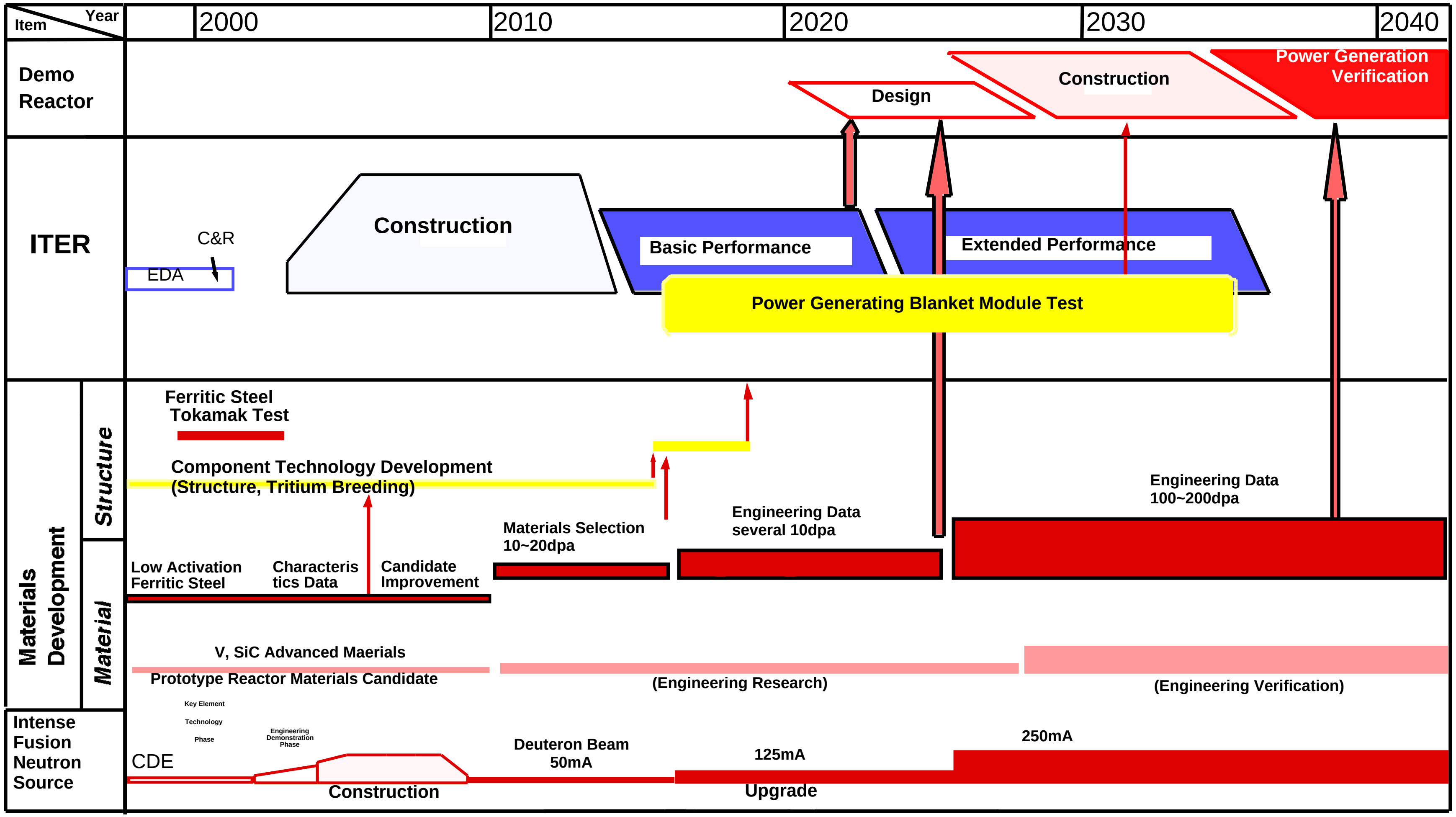



Fig.3.3.2-4 Development of Structural Materials and
their Target Performances in Feasible Temperature and Neutron Fluence

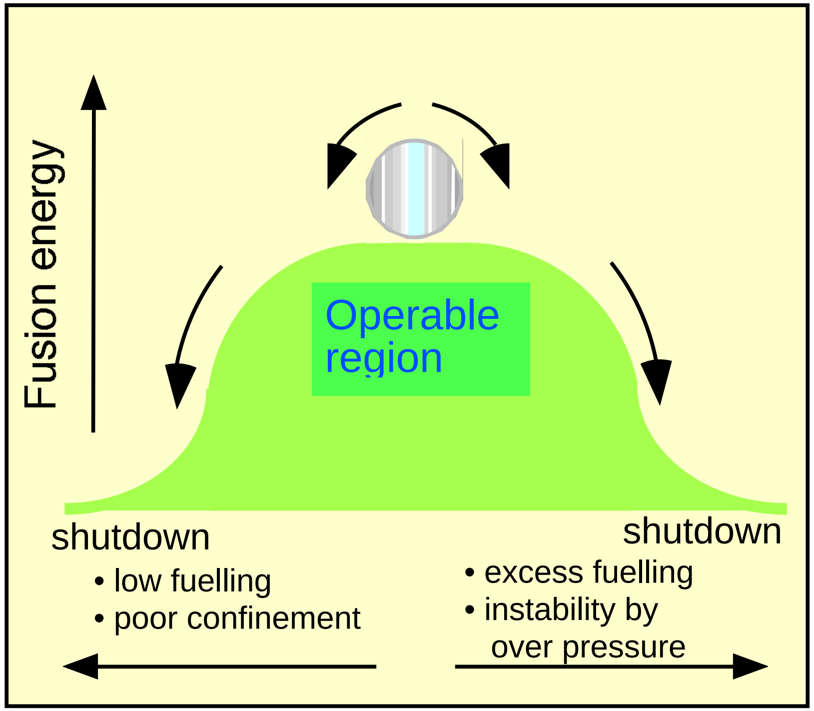



* dpa: integrated neutron damage parameter to study the effect of neutron irradiation on the materials characteristics

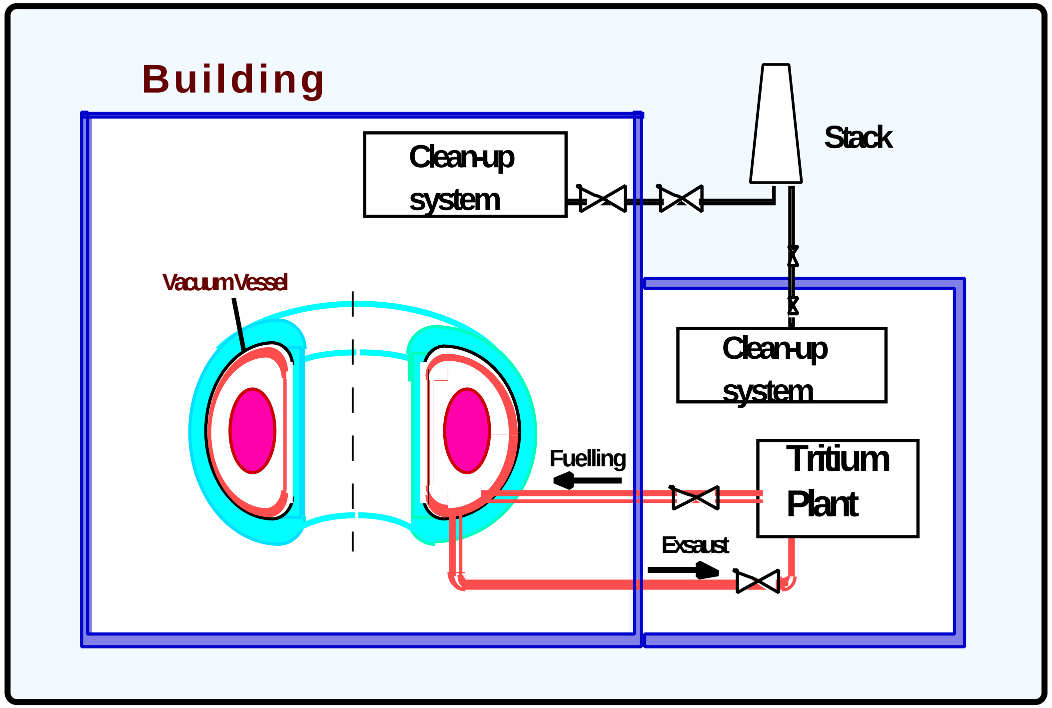
Figure 3.3.2-5 A schedule of fusion materials development

# Fusion Safety

## Inherent safety of fusion




## Containment/confinement concept

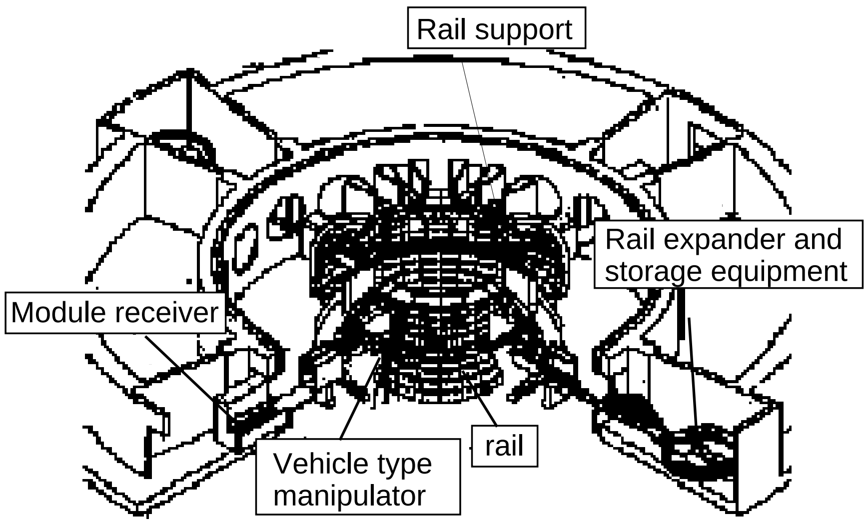


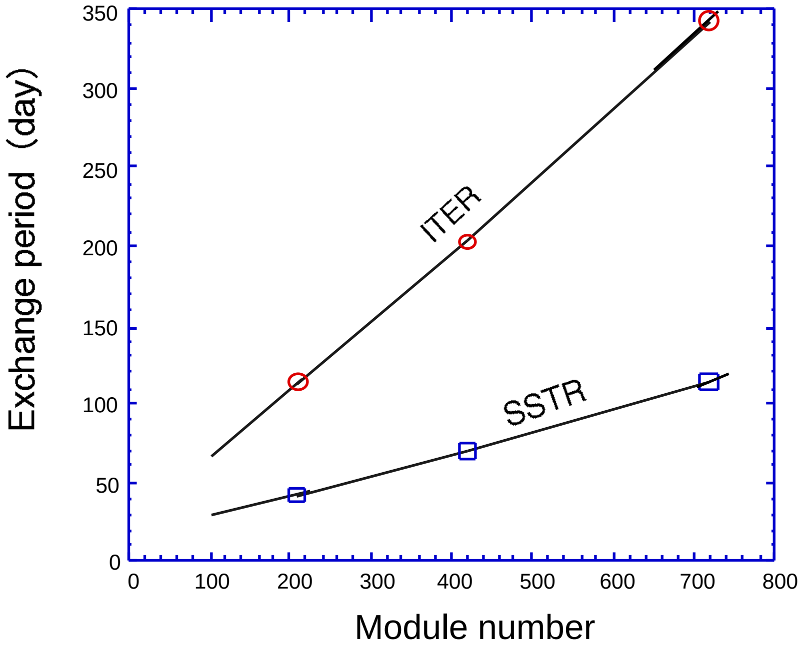
# Operation and Maintenance

SSTR: 400 modules

200 modules will be changed every 3 years if RAF neutron fluence can be increased to 200dpa.

Period of exchange 28days for 200 modules with improvement from ITER technology.



## 5.4 Control of burning plasma and technologies addressed in ITER

Control of burning plasma

Self-heating power produced by the fusion reaction will be applied to the burning plasma itself, while only plasma heating from the external sources has been examined in experiments to date.

It is difficult to predict burning plasma behavior with the present knowledge base since fusion self-heating simulation using external power is difficult. Therefore, without understanding this burning plasma behavior, it is difficult to clearly predict the technical feasibility of fusion energy.

Nonetheless, fusion energy development can be achieved by advancement of existing technologies if the control of burning plasma becomes possible. Thus, the understanding and control of burning plasma is the last big challenge of fusion energy research.

New developments for DEMO

Technologies required for DEMO should be developed in parallel with those needed for ITER.By confirming them in ITER, one major ITER desi guideline, a "single step to DEMO," can be realized. Major issues of conce are discussed below.

(1) Development of steady-state operation scheme

The basic principle of steady-state operation in tokamaks has been proven at a number of research institutions in Japan and other countries.

It is important to fully develop steady-state operation methods through the most productive use of existing tokamak devices and to apply their performances to ITER operation, especially to the burning plasma in ITER.

At the same time, it is important to establish operational methods that avoid plasma disruptions, which preclude steady-state operation.

(2) Development of high-temperature blanket test modules

The blanket plays three important roles, neutron shielding, tritium breeding, and extraction of high-temperature thermal energy. The latter will produce for generation of electricity.

To accomplish the technologies relevant to these roles, a high-temperature blanket is required. Developed in ITER, its design will be available for DEMO.

(3) Neutron irradiation test

Development of reduced activation materials that allow intense high-energy neutron irradiation and high-temperature operation is required to enhance safety and economics of fusion.

Leading candidates for blanket structural materials to be used in DEM beyond have been identified. However, performance of these materials shoul confirmed by neutron irradiation tests, as the material database has not been satisfactorily completed at present. Neutrons produced in ITER can be used for irradiation tests at low fluence and for component tests.

5.9 Conclusion of Part 1

The technical feasibility of fusion energy will be confirmed by demonstrating control of burning fusion plasma, by establishing the technical feasibility of an integrated fusion device, and by accomplishing safety and reliability in ITER.

Furthermore, a high-performance fusion reactor will be realized by establishing steady-state operation. Most major technologies required for the DEMO reactor and beyond can be developed as an extension of ITER.

Therefore, the prospects of fusion development for the DEMO reactor beyond will become clearer during the ITER program, as compared to the present situation where clarification of physical phenomena receives more emphasis.

In addition, it is possible that the construction cost of the DEMO reactor w be lower than that of ITER due to development of materials, technological innovations, and the progress of plasma physics. A similar possibility could apply to a commercial fusion power station that would follow DEMO.