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 subcommittees 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
  Professor, Institute of Advanced Energy, Kyoto University)
Katsunori Abe          Professor, Graduate School of Engineering, Tohoku University
Kunihiro 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)

<table>
<thead>
<tr>
<th>Design Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma Current $I_p$</td>
</tr>
<tr>
<td>Toroidal Field Coil $B_t$</td>
</tr>
<tr>
<td>Major Radius $R$</td>
</tr>
<tr>
<td>Aspect Ratio $A$</td>
</tr>
<tr>
<td>Elongation $\kappa_{35}$</td>
</tr>
<tr>
<td>Normalized Beta $\beta_N$</td>
</tr>
<tr>
<td>Fusion Output $P_F$</td>
</tr>
<tr>
<td>Current Drive Power $P_{CD}$</td>
</tr>
<tr>
<td>Net Electric Output Power $P_{E}$</td>
</tr>
<tr>
<td>Fusion Gain $Q$</td>
</tr>
<tr>
<td>Averaged Neutron Wall Load $P_{\text{neut.}}$</td>
</tr>
</tbody>
</table>
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

Vanadium ($V_2O_5$) and Uranium (Yellow Cake)
Fossil Resources (Reserves and Resource Base)

Resource life
For reserve
- Coal: 231 years
- Nat. Gas: 63 years
- Oil: 44 years
For resource base
- Nat. Gas: 452 years
- Oil: 242 years

Saturation at 12 billion persons assumed (1.67 TOE /person)

Demand of Fossil Energy
(assumed 90% of total demand)

~$30/bbl (Oil)
$10~15/bbl (Coal)
$15~30/bbl (Coal)
~$30/bbl (Oil)

Shortage due to the Restriction of Coal Use
Shortage due to Reserves

Past → Future

Present

Energy

Year

1900 1950 2000 2100 2200 2300 2400

Oil/Natural gas
Nuclear/Renewable
Coal
Fusion is environmentally attractive with its low CO₂ 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.

- Radiological toxic hazard potential of T is less than 1/1000 of that of I-131.
- CO₂ emission is less than 1/10.

Latent risk of the radiation exposure

I-131 in 3GW LWR

4.5kg of T
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.

- Burn-up ashes from the coal-fired plant
- Fusion reactor
- Boiling water reactor

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

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)
1) If fusion power plants are forced to be competitive only for the COE issue, a COEn of 0.5~0 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 CO2 sequestration systems will need cost than the fusion plants. Furthermore, the cost of CO2 sequestration will be reduced in future.
# Target for Commercial Use

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>COE</td>
<td>designed value of 10yen/kWh or less 15yen/kWh as upper limit</td>
</tr>
<tr>
<td>Stability</td>
<td>less than 1%</td>
</tr>
<tr>
<td>Forced outage</td>
<td>0.5/unit year (including disruption-induced outage)</td>
</tr>
<tr>
<td>Load-following</td>
<td>at least partial load operation in case of emergency</td>
</tr>
<tr>
<td>Site requirement</td>
<td>near high demand area if possible</td>
</tr>
<tr>
<td>Generation capacity</td>
<td>&lt;2GW/unit</td>
</tr>
<tr>
<td>Capacity factor</td>
<td>ideal design value of 85%, initial target 70%</td>
</tr>
</tbody>
</table>
Overall Assessment

Fusion can be a balanced energy source

**Coal thermal plant with CO2 sequestration**
- Economy: Inverse CO2En (linear scale)
- Safety laxity: inverse movable BHP in reactor
- CO2 reduction effect: inverse emission unit
- Fuel resource: R/P ratio
- Radiological Risk of waste: BHP 20 year after decommissioning

**LWR with sea water uranium**
- Economy: Inverse CO2En (linear scale)
- Safety laxity: inverse movable BHP in reactor
- CO2 reduction effect: inverse emission unit
- Fuel resource: R/P ratio
- Radiological Risk of waste: BHP 20 year after decommissioning

**Fusion Reactor**
- Economy: Inverse CO2En (linear scale)
- Safety laxity: inverse movable BHP in reactor
- CO2 reduction effect: inverse emission unit
- Fuel resource: R/P ratio
- Radiological Risk of waste: BHP 20 year after decommissioning

**Fusion can be a balanced energy source**

Virtually unlimited
- Based on values for ABWRs
- Target for demo reactor
- Target for commercial reactor

**Safety laxity**
- Fusion reactor: 1.5
- Fusion reactor: 1.0
- Fusion reactor: 0.5
- Fusion reactor: 0.001
- Fusion reactor: 0.01
- Fusion reactor: 0.1
- Fusion reactor: 1
- Fusion reactor: 10
- Fusion reactor: 100
- Fusion reactor: 1000

**CO2 reduction effect**
- Fusion reactor: 1.5
- Fusion reactor: 1.0
- Fusion reactor: 0.5
- Fusion reactor: 0.001
- Fusion reactor: 0.01
- Fusion reactor: 0.1
- Fusion reactor: 1
- Fusion reactor: 10
- Fusion reactor: 100
- Fusion reactor: 1000

**Fuel resource**
- Fusion reactor: Virtually unlimited
- Fusion reactor: Based on values for LWRs

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Chapter 2 Development Strategy based on ITER Project

2.1 Approach - Integration and Phased Development

2.2 ITER as an Experimental Reactor
   2.2.1 ITER
   2.2.2 What will be realized on ITER
   2.2.3 Significance and cost sharing philosophy
   2.2.4 Value of hosting ITER to Japan
   2.2.5 Tokamak research insupport of ITER

2.3 From ITER to DEMO

2.4 Summary-Placement of ITER in development strategy
Fusion energy development and scenarios toward the fusion power plant

- **Second phase**
  - JT-60
  - Development of major components with enlarged sizes and improved performances
  - Test using Experimental Reactor
  - Long-term development necessary for a fusion reactor

- **Third phase**
  - Experimental Reactor (ITER)
  - Ignition & Long-burn

- **Fourth phase**
  -Prototype Reactor
  - Economic aspects
  - Review
  - Decision system of prototype reactor

- Economic aspects

- **Prototype Reactor**

- **Experimental Reactor** (ITER)

- **Joint Venture**

- **Prototype Reactor**

- **JT-60**

- **Tokamak**

- **Helical device, Reverse field pinch, Mirror, Inertial confinement**

- **Advanced confinement**
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

<table>
<thead>
<tr>
<th>Item</th>
<th>ITER</th>
<th>Prototype reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy amplification factor (inductive)</td>
<td>10 - 20</td>
<td></td>
</tr>
<tr>
<td>Energy amplification factor (steady state)</td>
<td>5</td>
<td>30 - 50</td>
</tr>
<tr>
<td>Plasma pressure</td>
<td>Several atm</td>
<td>~10 atm</td>
</tr>
<tr>
<td>Maximum magnetic field</td>
<td>12 T</td>
<td>16 T</td>
</tr>
<tr>
<td>Normalized beta</td>
<td>~2.5</td>
<td>~3.5</td>
</tr>
<tr>
<td>Blanket</td>
<td>Test module</td>
<td>Blanket for power generation</td>
</tr>
<tr>
<td>Structural material</td>
<td>SS316</td>
<td>Low activation ferritic steel, etc.</td>
</tr>
<tr>
<td>Neutron fluence</td>
<td>0.3 MWa/m²</td>
<td>&lt;10 MWa/m²</td>
</tr>
</tbody>
</table>

Power flow in SSTR
(Generated electric power 1.08GW)

- Plant efficiency: 30%
- Thermal power: 3.7 GW
- Generated power: 1.28 GW
- Steam turbine
- Generator
- N-NB current drive equipment
- Efficiency 50%
- Plasma thermal power: 0.7 GW
- Blanket power: 300 GW
- Station power: 80 MW
- Circulating power: 120 MW
- Fusion plasma
- Plasma current: 12 MA
- Fusion building
- Q = 50
- Reduced plasma current
- Plant efficiency
- Station power
- Efficiency 50%
- N-NB current drive equipment
- Plasma current
- High plasma pressure and high bootstrap currents
- Steady state fusion power plant

Steady state fusion power plant

Thermal power 3.7 GW

Generated power 1.28 GW

Efficiency 34.5%

Nominal generated power 1.08 GW
Chapter 3 Technical Issues and Future Prospects

3.1 Fusion plasma technology
3.2 Fusion reactor technology
3.3 Blanket and material development
3.4 Safety related technology
3.5 Operation and maintenance
3.6 View from Industry
3.7 Competitiveness in the Market
3.8 Summary-Technological Prospects
Demonstration in model coil

Current status

Magnetic field (T)

ITER-TF(12.5T, 60kA)

ITER-CS(13T, 40kA)

US-DPC

DPC-U

DPC-EX

LCT

LHD

TMC

Tore Supra

TRIAM

TMC

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

FY1999-2002
1 Niobium Aluminum Conductor development
2 Development of 20-K operation high temperature superconductor
3 Optimization of design technique from limitation experiment results of CS model coil

Target for Demo reactor TF coil (16.5T, 80kA)

Target for Demo reactor coil (16.5T, 80kA)

Demonstration in model coil

Current status

Coil for magnetic levitation train

DPC-U

DPC-EX

LCT

LHD

TMC

TRIAM

Tore Supra

TMC

Figs. 3.2.3-2 Development Step of Conductor for Demo Reactor Coil
Development of Structural Materials and their Target Performances in Feasible Temperature and Neutron Fluence
Figure 3.3.2-5 A schedule of fusion materials development
Fusion Safety

Inherent safety of fusion

- low fuelling
- poor confinement

Operable region

Shutdown

- excess fuelling
- instability by over pressure

Containment/confinement concept

Building

- Clean-up system
- Vacuum Vessel
- Tritium Plant
- Stack

Fuelling

Exhaust

Clean-up system

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SSTR: 400 modules

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

Period of exchange 28 days 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 design guideline, a "single step to DEMO," can be realized. Major issues of concern 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 DEMO beyond have been identified. However, performance of these materials should be 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 will 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.