# Comparative Assessment of the World Major Fusion Programs on Fusion Nuclear Technology and Materials

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# BACKGROUND

- A comparative assessment of the world's four major research efforts on magnetic confinement fusion, including a comparison of the capabilities of the Soviet Union, the European Community (Western Europe), Japan and the United States of America
- The assessment was carried out by a panel of experts. It was conducted by FASAC (SAIC) for the Office of Energy Research
- The results of the assessment are contained in a report published by FASAC
- Important background material for this assessment includes three recent FASAC reports:
  - Soviet Magnetic Confinement Fusion Research (Davidson, et al., 1987)
  - West European Magnetic Confinement Fusion Research (Hazeltine, et al., 1989) and
  - Japanese Magnetic Confinement Fusion Research (Davidson, et al., 1989)

# COMPARATIVE ASSESSMENT OF WORLD RESEARCH EFFORTS ON MAGNETIC CONFINEMENT FUSION

The assessment covered six areas:

- Tokamak Confinement
- Alternate Confinement Approaches
- Plasma Technology and Engineering
- Fusion Nuclear Technology and Materials
- Plasma Confinement Theory
- Fusion Computations

The focus of this presentation is:

Fusion Nuclear Technology and Materials

# FUSION NUCLEAR TECHNOLOGY (FNT) AND MATERIALS

FNT and Materials

Includes components and technical disciplines related to:
    Fusion Energy Conversion and Recovery
    Tritium Fuel Breeding and Processing
    Radiation Protection

Main Areas

- Blanket
  - Liquid Metals
  - Solid Breeders
- Tritium Systems
- Neutronics
- Structural Materials
- Plasma-Facing Components

# IMPORTANCE OF FUSION NUCLEAR TECHNOLOGY PROGRAM

- Resolve some of the most critical unresolved feasibility issues for fusion

- Substantially enhance the potential competitiveness of fusion reactors

  - Economics
  - Safety and Environment

- Selection of nuclear concepts can significantly impact plasma engineering, and vice-versa

- Near-term fusion devices that burn tritium (e.g. ITER) will have new, challenging nuclear issues
  - e.g., **blanket** to produce tritium

- FNT development requires a long lead time

- Blanket R&D involves many technical disciplines with broad scientific and technological applications outside fusion

  - Advanced engineering materials
  - Thermodynamics and advanced power conversion
  - Nuclear Physics
  - Thermal-hydraulics, liquid metal magnetohydrodynamics
  - Corrosion
  - Radiation effects

# Comparison of Funding for FNT and Materials
## (Approximation based on 1987 - 1989*)

| | Annual Funding: Million Dollar/Year | | | |
|---|---|---|---|---|
| | W. Europe | Japan | USSR(a) | USA |
| Blanket and Breeding Materials | 31 | 14.6 | | 4.9 |
| Tritium | 10.3 | 7 | | 2 |
| Safety/Environment | 8.9 | (b) | | 2.1 |
| Structural Materials | 29 | 12 | | 8.7 |
| Plasma-Interactive Materials | 8 | 7 | | 6.9 |
| Total (M$/yr) | 87.2 | 40.6 | | 24.7 |

(a) No sufficient data on USSR Program
- Manpower comparable to other programs
- Direct funding is much less than the other 3 programs

(b) Part of other programs

* For 1990:
* About the same in EC, Japan
* USA: about 15% lower

# Fusion Nuclear Technology and Materials:

## Ranking of World Fusion Programs
## 1990 ( → 1995*)

| | United States | Western Europe | Japan | Soviet Union |
|---|---|---|---|---|
| Blanket | | | | |
| Solid Breeder | 3 | 1 | 2 → 1 | 4 |
| Liquid Metals | 3 → 4 | 1 | 4 → 3 | 2 |
| Tritium Systems | 1 → 2 | 2 → 1 | 3 | 4 |
| Neutronics | 2 → 3 | 3 → 2 | 1 | 4 |
| Neutron-Interactive Materials | 1 → 3 | 3 → 1 | 2 → 1 | 4 |
| Plasma-Facing Components | 1 → 3 | 1 | 1 | 4 |

1 = best; 2 = second best; 3 = third best; 4 = weakest

* Projections assuming continuation of present levels of effort

# FNT AND MATERIALS COMPARISON

## GENERAL REMARKS

- THE US PROGRAM WAS THE WORLD LEADER IN THE 1970'S AND EARLY 1980'S IN TERMS OF FUNDING, MANPOWER, INGENUITY, TECHNICAL PLANNING, AND PRODUCTIVITY.

  DURING THAT PERIOD EC AND JAPAN LAGGED CONSIDERABLY BEHIND.

- DURING THE MID TO LATE 1980'S EC AND JAPAN EXPANDED THEIR PROGRAMS SEVERAL FOLDS, CONSTRUCTED NEW FACILITIES, AND SHARPLY IMPROVED AND FOCUSED THEIR TECHNICAL PROGRAM.

  DURING THAT PERIOD, THE US PROGRAM FUNDING SHARPLY DECLINED.

- INTERNATIONAL COLLABORATION ON FNT AND MATERIAL R&D IS EXCELLENT.

- ROLE OF INDUSTRY:

  EC, JAPAN - STRONG
  USA - WEAK
  USSR - EXTREMELY WEAK

- ROLE OF UNIVERSITIES:

  JAPAN - MAJOR ROLE (COMPARABLE IN SIZE TO JAERI)
  US - STRONG ROLE
  EC - WEAK
  USSR - WEAK

# MAJOR FUNCTIONS OF THE BLANKET

- Breed Tritium
- Convert kinetic energy to usable heat
- Partial shielding

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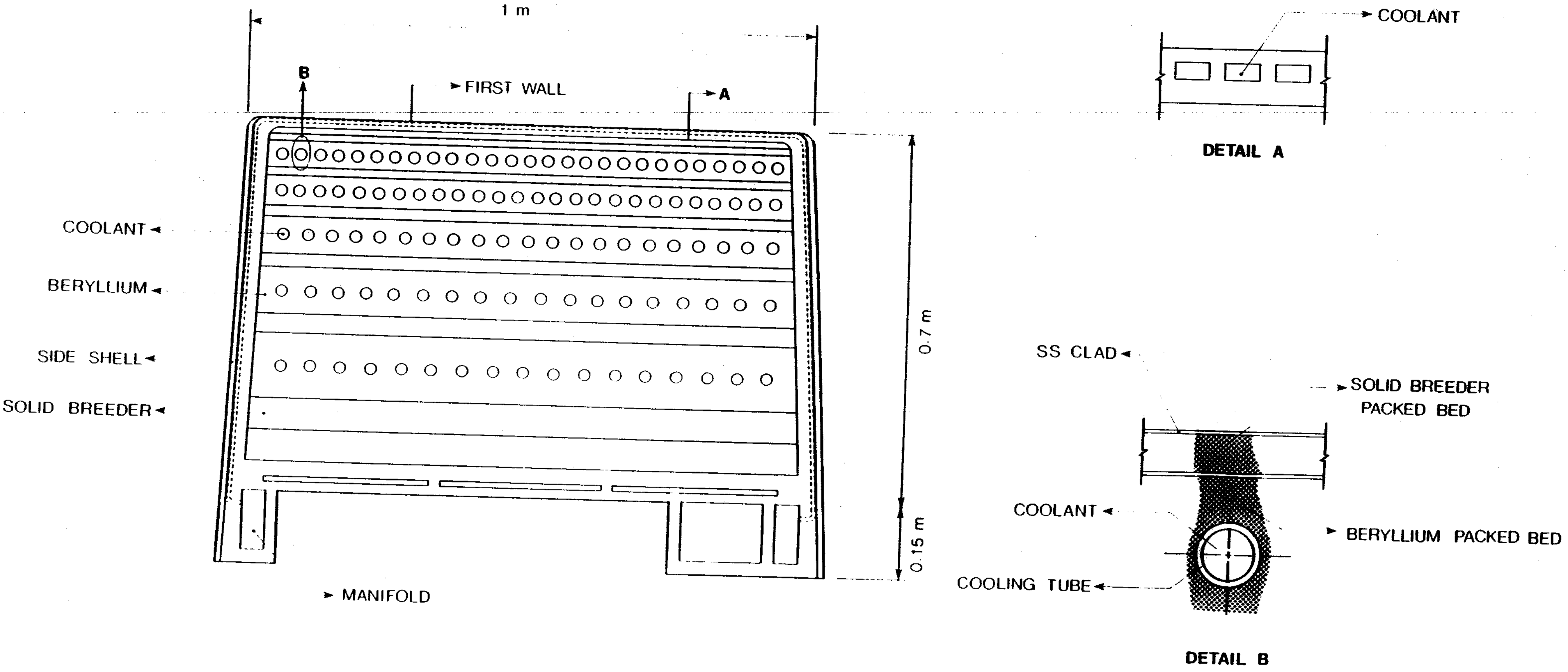
# BLANKET OPTIONS

- At present, two major options are being pursued worldwide
- These involve breeding material in either liquid or solid physical form
- The two classes of blankets have different critical feasibility issues

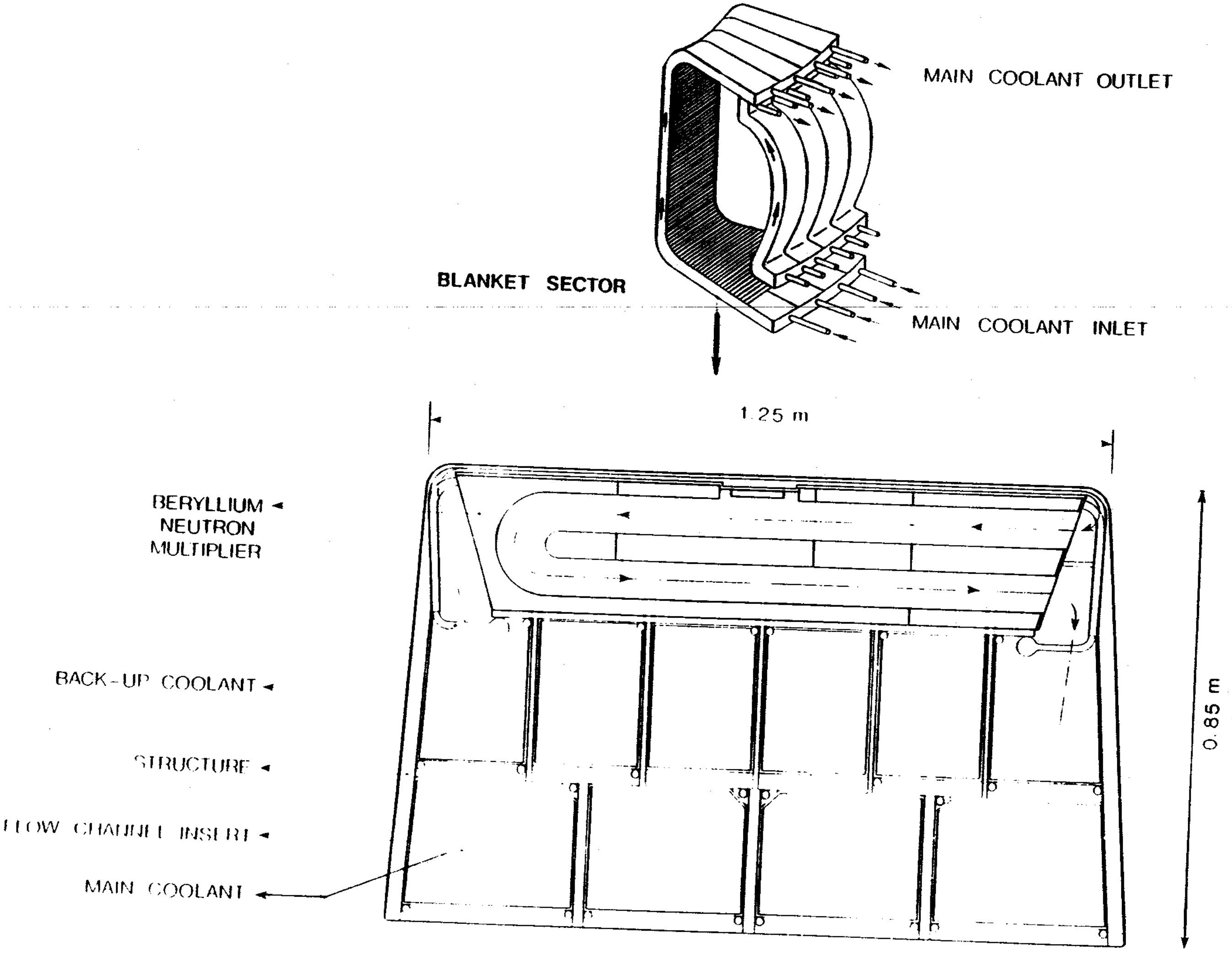
# EXAMPLE OF A SOLID BREEDER BLANKET



# CRITICAL ISSUES FOR SOLID BREEDER BLANKETS

- Tritium Self-Sufficiency
- Breeder/multiplier tritium inventory, recovery, and containment
- Breeder/multiplier/structure mechanical interactions
- Operation under off-normal and accident conditions
- Structure mechanical behavior; failure modes and reliability
- Corrosion and mass transfer

# EXAMPLE OF A LIQUID METAL BLANKET



# CRITICAL ISSUES FOR LIQUID METAL BLANKETS

- Tritium fuel self-sufficiency
- Magnetohydrodynamic efforts
  - fluid flow and pressure drop
  - heat transfer
- Material interactions
  - corrosion/mass transport
  - chemical reactions
- Structural response in the fusion environment
  - irradiation effects on material properties
  - response to complex loading conditions
  - failure modes
- Tritium recovery and control

# LIQUID METAL BLANKET

Key areas of research: MHD pressure drop, corrosion; experimental and modeling activities

**EC**

- Strongest of the 4 world program
- Experimental facilities at KfK (West Germany)
- Very good capabilities for construction and operation of facilities
- Modeling capabilities good, improving

**USSR**

- Second strongest
- Large pool of manpower
- Powerful MHD facilities at Leningrad Polytechnic Institute and in Riga
- Broad theoretical expertise; modeling capabilities weak but improving
- Lower quality of construction, instrumentation and data acquisition capabilities
    - lower confidence in experimental results

**USA**

- Small and shrinking program overall
- One MHD facility; small corrosion loops
- No significant component development work
- Modeling capabilities good and improving

**JAPAN**

- JAERI has no Liquid Metal program
  Liquid Metal activities only in Japanese Universities
- Good facilities and large manpower in Universities
- Research is generally broad but without depth; no focus
- Capabilities for numerical modeling and component construction could expand rapidly

# Comparison of Liquid-Metal Blanket Programs

| | EC | Japan | USSR | USA |
|---|---|---|---|---|
| 1. Program Size | | | | |
| a. manpower | | | | |
| design, theory and modeling | 2 | 4 | 1 | 3 |
| experimental | 3 | 2 | 1 | 4 |
| b. experimental facilities | 1 | 4 | 2 | 4 |
| 2. Skills and Capabilities | | | | |
| a. theory | 4 | 3 | 1 | 2 |
| b. modeling | 2 | 4 | 3 | 1 |
| c. facility operation | 1 | 4 | 3 | 2 |
| d. fabrication of components | 1 | 2 | 4 | 3 |
| **3. Overall Ranking** | **1** | **4** | **2** | **3** |

1= best 2= second best 3= third best 4= weakest

# SOLID BREEDER BLANKETS

Key Areas of Research: Tritium recovery experiments in fission reactors; Property measurements; Compatibility; Modeling

## EC

- Strongest; clear world leader
- Largest in funding and manpower
- Powerful facilities, primarily fission reactors
- Produces best experimental results
- Comprehensive: covers all important areas
- Excellent R & D plan (many parts borrowed from US earlier plans)

## Japan

- Second strongest
- Expanding rapidly
- Highly focused program; one material: Li2O
- Weak on fission reactor testing capability
  Participates in International Collaboration: BEATRIX
- Experiment in local fission reactor (JMTR) is part of national priority to develop tritium production capability

## USA

- "Was" the leader in late 1970's to early 1980's
- Now smallest effort in funding, manpower and experiments
- Powerful fission reactor testing capabilities
- Best modeling effort
- Effective use of resources, presence of facilities and broad technological experience
  - still desirable international partner
  - future?

## USSR

- Excellent tritium recovery experiments in late 1970's to early 1980's
- Has not made significant contribution in the past several years
  - Classification problem?

# TRITIUM PROCESSING

## USA

- World leader now
  - TSTA at LANL is a unique integrated facility
  - Experience from other programs
- International collaboration activities with Japan and Europe

## EC

- Largest program in terms of funding
- Two large-scale facilities being constructed (scheduled operation 1990)
  - At KfK
  - ETHEL at Ispra
- French extensive experience not yet fully shared with the rest of EC
- Program at KfK is producing some of the best R & D results
- JET will be the FIRST operating tokamak to be integrated with a tritium processing loop

## Japan

- Strong effort
- Tritium handling technology targeted for extensive R & D effort
- TPL constructed at JAERI 3-gram level operation in 1988
- Still several years behind US and EC
- Pays for participating in TSTA operation

## USSR

- No significant contribution
- Soviet experts to international meetings/activities (e.g. ITER) appear not to have "hands on" experience

# Neutronics

## Key Areas

- Tritium breeding, nuclear heating, radioactivity after heat, radiation shielding
- Methods, codes, nuclear data, integral experiments

## JAPAN

- Largest world program
- Constructed largest 2 facilities in the early 1980's
  - FNS at JAERI
  - OKTAVIAN at Osaka University
- Design adapted many US technologies; many scientists trained in US and Germany

## US

- No neutronics facility is now in operation
- Relies on collaborative program with JAERI
- Strong analysis and computational capabilities
- Broad base of experience from fission and weapons programs

## EC

- Funding larger than US, smaller than Japan
- Remains somewhat behind US
  - Transport codes from US
  - Nuclear data effort comparable
- Limited program on neutronics integral experiments

## USSR

- Large manpower
- Most of the technology imported from the west
  - Transport codes
  - Nuclear data
- Sophistication of analysis limited by lack of fast, large computers
- Experimental facilities in East Germany

# MATERIALS

## US

- Funding declined sharply over the past several years; now much smaller than EC and Japan
- Still maintains technological edge:
  - previous investment
  - effective use of resources
  - more attention to long-term material needs
  - better neutron irradiation facilities

## Japan

- Tremendous growth in the past several years
- Major area of strength:
  - Non-neutron testing capabilities
- Major weakness:
  - lack of neutron irradiation facilities
    (uses facilities in USA, Europe)
  - innovation
  - theory and modeling of radiation effects

## EC

- Large program
- Balance between theory and experiments
- Balance between long-term and near-term
- Emphasis on NET and <u>testing</u> in NET
- Excellent neutron irradiation facilities

## USSR

- Effort fragmented, uncoordinated
- Approach is to use existing materials
  - Reason? :
    - Hybrids?
    - Lack of resources?

# MATERIALS

| Comparison Area | Western Europe | Japan | USSR | USA |
|---|---|---|---|---|
| • Metallic Structural Materials | - Ferritic and austenitic steels<br>- Vanadium alloys<br>(Verv good) | - Ferretic and austenitic steels<br>- Vanadium alloys<br>- Molybdenum alloys<br>- Titanium alloys<br>(Excellent) | - Austenitic steels<br>(Good) | - Ferritic and austenitic steels<br>- Vanadium alloys<br>(Very Good) |
| • Innovative Materials | - Low activation<br>- Recycle<br>(Good) | - Low activation<br>(Good) | - None<br>(Poor) | - Low activation<br>(Excellent) |
| • Ceramic Structural Materials | - None<br>(Poor) | - SiC/SiC composites<br>- Al/SiC composites<br>(Excellent) | - None<br>(Poor) | - None<br>(Poor) |
| • PFC Materials | - Graphite<br>- TiC coatings<br>(Good) | -Graphites<br>-TiC coatings<br>-W-Re coatings<br>(Excellent) | - Graphites<br>(Good) | - W-Re coatings<br>- TiC coatings<br>- Graphites<br>(Excellent) |
| • Emphasis | Near-term | Balanced, near & long-term | Near-term | Balanced, near & long-term |
| **Overall Ranking** | 3 | 2 | 4 | 1 |

# Plasma - Facing Components

- Programs in Europe, Japan and US are comparable in size, scope and focus
- Soviet program is weak
  - One innovative area: free surface
- Major strength areas:

US: test stand capabilities
special material development
balanced modeling and experimental effort

EC: testing capabilities in existing tokamaks

Japan: fundamenal studies

# Ranking by Area in Fusion Nuclear Technology and Materials Research

If projected to 5 years from now, assuming continuation of current funding.

| | EC | Japan | USSR | USA |
|---|---|---|---|---|
| Blanket | | | | |
| Solid Breeder | 1 | 1 | 4 | 3 |
| Liquid Metals | 1 | 3 | 2 | 4 |
| Tritium Systems | 1 | 3 | 4 | 2 |
| Neutronics | 2 | 1 | 4 | 3 |
| Materials (neutron-interactive) | 1 | 1 | 4 | 3 |
| Plasma-Facing Components | 1 | 1 | 4 | 3 |

1= best 2= second best 3= third best 4= weakest

# Ranking by Area in Fusion Nuclear Technology and Materials Research

(now)

| | EC | Japan | USSR | USA |
|---|---|---|---|---|
| **Blanket** | | | | |
| Solid Breeder | 1 | 2 | 4 | 3 |
| Liquid Metals | 1 | 4 | 2 | 3 |
| Tritium Systems | 2 | 3 | 4 | 1 |
| Neutronics | 3 | 1 | 4 | 2 |
| Materials (neutron-interactive) | 3 | 2 | 4 | 1 |
| Plasma-Facing Components | 1 | 1 | 4 | 1 |

1= best 2= second best 3– third best 4= weakest

# OUTLOOK

- THE WORLD LEADERSHIP OF FUSION NUCLEAR TECHNOLOGY AND MATERIALS RESEARCH WILL BE:

  A COMPETITION BETWEEN WESTERN EUROPE AND JAPAN.

  DURING THE PAST SEVERAL YEARS, EC AND JAPAN SUBSTANTIALLY INCREASED THE FUNDING AND SIZE OF THEIR PROGRAMS, THEY CONSTRUCTED NEW FACILITIES, THEY ARE NOW PRODUCING SOME OF THE BEST R&D RESULTS, AND THEY PLAN AN ADDITIONAL EXPANSION OF THEIR EFFORT.

- THE PRESENT US COMPETITIVE POSITION MAY RAPIDLY DETERIORATE.

  THE US PROGRAM DECLINED SHARPLY OVER THE PAST SEVERAL YEARS. THE PRESENT RELATIVE STRENGTH RESULTS FROM PREVIOUS INVESTMENT, EFFECTIVE MANAGEMENT OF RESOURCES, AND BROAD TECHNOLOGICAL CAPABILITIES FROM OUTSIDE FUSION. NEW INVESTMENT IS REQUIRED TO MAINTAIN RELATIVE STRENGTH.

# OUTLOOK (CONT'D)

- THE US HAS BENEFITTED FROM INTERNATIONAL COLLABORATION. THE US HAS BEEN A DESIRABLE PARTNER. HOWEVER, IF PRESENT TRENDS CONTINUE, THE US ABILITY TO NEGOTIATE INTERNATIONAL COLLABORATIVE AGREEMENT MAY SUFFER CONSIDERABLY.

- THE SOVIET PROGRAM IS NOW THE WEAKEST OF THE FOUR MAJOR WORLD PROGRAMS.

  IT IS LIKELY TO REMAIN SO FOR THE NEXT SEVERAL YEARS.

- FOR THE SOVIET PROGRAM TO BE MORE EFFECTIVE, IT REQUIRES:

  1) BETTER TECHNICAL MANAGEMENT AND COORDINATION AMONG ORGANIZATIONS;

  2) INVESTMENT IN NEW FACILITIES, WITH STATE-OF-THE-ART TECHNOLOGY; AND,

  3) BETTER COMPUTATION CAPABILITY.

## Table I.1
## COMPARATIVE RANKING OF WORLD FUSION PROGRAMS IN SELECTED TECHNICAL AREAS
### 1990 ( → 1995 *)

| | United States | Western Europe | Japan | Soviet Union |
|---|---|---|---|---|
| Tokamak Confinement | | | | |
| Large Tokamaks | 2 → 3 | 1 | 2 | 4 |
| Medium-Size Tokamaks | 1 | 1 | 4 | 3 |
| Diagnostics | 1 → 2 | 2 → 1 | 3 | 4 → 3 |
| Data Interpretation | 1 | 1 | 4 | 1 |
| ITER Physics | 1 | 2 | 3 | 3 |
| ITER Engineering Design | 2 | 1 | 2 | 4 |
| Alternate Confinement Approaches | | | | |
| Stellarators | 2 → 3 | 2 | 1 | 4 |
| Reversed-Field Pinches | 1 → 2 | 1 | 3 | - |
| Mirrors | - | - | 2 | 1 |

* Projections, assuming continuation of present levels of effort.
1 = best, 2= second best, 3 = third best , 4 = weakest.

## Table I.1
## COMPARATIVE RANKING OF WORLD FUSION PROGRAMS IN SELECTED TECHNICAL AREAS
## 1990 ( → 1995 *)

| | United States | Western Europe | Japan | Soviet Union |
|---|---|---|---|---|
| Plasma Technology and Engineering | | | | |
| Neutral Beams | 1 → 2 | 1 → 2 | 1 | 4 |
| Ion Cyclotron Systems | 2 | 1 | 2 | 4 |
| Lower Hybrid Systems | 3 | 2 → 1 | 1 | 4 |
| Electron Cyclotron Systems | 1 → 2 | 3 → 2 | 4 | 1 |
| Pellet Fueling | 1 | 2 → 1 | 3 | 4 |
| Magnets | 3 | 1 | 1 | 4 |
| Industrial Capability | 3 | 1 | 1 | 4 |
| Fusion Nuclear Technology and Materials | | | | |
| Blanket | | | | |
| Solid Breeder | 3 | 1 | 2 → 1 | 4 |
| Liquid Metals | 3 → 4 | 1 | 4 → 3 | 2 |
| Tritium Systems | 1 → 2 | 2 → 1 | 3 | 4 |
| Neutronics | 2 → 3 | 3 → 2 | 1 | 4 |
| Neutron-Interactive Materials | 1 → 3 | 3 → 1 | 2 → 1 | 4 |
| Plasma-Facing Components | 1 → 3 | 1 | 1 | 4 |

* Projections, assuming continuation of present levels of effort.
1 = best, 2= second best, 3 = third best , 4 = weakest.

## Table I.1

## COMPARATIVE RANKING OF WORLD FUSION PROGRAMS IN SELECTED TECHNICAL AREAS

### 1990 ( → 1995 *)

| | United States | Western Europe | Japan | Soviet Union |
|---|---|---|---|---|
| Plasma Confinement Theory | | | | |
| Major Disruptions | 1 → 2 | 1 | 4 | 3 → ? |
| Enhanced Confinement | 1 | 3 → 2 | 2 → 3 | 4 → 3 |
| Transport | 1 | 2 → 1 | 4 | 3 |
| Magnetohydrodynamics | 2 | 1 | 4 | 3 → ? |
| Fusion Computations | | | | |
| Scientific Computations | 1 | 2 | 3 → 4† | 3 → 2† |
| Data Acquisition Systems | 1 | 2 → 1 | 2 → 3† | 4 → 3† |
| Engineering Computations | 1 | 3 → 2 | 1 → 2 | 4 |

* Projections, assuming continuation of present levels of effort.

† Assumes acquisition by Soviet Union of modern computational hardware, other factors constant.

1 = best, 2= second best, 3 = third best , 4 = weakest.

# CONCLUSIONS

- Before the mid-1990s, the upgraded large-tokamak facilities, JT-60U (Japan) and JET (Western Europe), are likely to explore plasma conditions and operating regimes well beyond the capabilities of the TFTR tokamak (United States).

- If present trends continue in the areas of fusion nuclear technology and materials, and plasma technology development, the capabilities of Japan and Western Europe in these areas will surpass those of the United States by a substantial margin before the mid-1990s.

- The Soviet fusion effort is presently the weakest of the four programs in most areas of the assessment. (Electron cyclotron heating, plasma confinement theory, and mirror research are notable exceptions.)

# CONCLUSIONS

- If present trends continue, the United States, once the world leader in fusion research, will soon lose its position of eminence to the West European and Japanese fusion programs.

- The deterioration of the United States' leadership position in fusion is not a consequence of shortcomings in US scientific and engineering talent, or in US technical accomplishments, which are substantial by any measure. Rather, it reflects an apparent decrease, during the 1980s, in the national priority assigned by the US government to fusion energy development, as well as to the development of other advanced energy technologies.

# ASCENDANCY OF WEST EUROPEAN AND JAPANESE FUSION PROGRAMS

- By contrast, Japan and Western Europe have assigned fusion R&D relatively high priority.
- In the case of Japan, national energy circumstances dictate the prudent development of long-term options that would assure the eventual "energy independence" of Japan from the rest of the world; also, the Japanese government views fusion as an important vehicle for the development of advanced technological capabilities.
- In the case of Western Europe, fusion has been viewed as a timely and important R&D area in which to "internationalize" scientific and technological development within the European Community, thereby reducing the cost burden on any one nation.

# OBSERVATION

- IN ORDER FOR THE UNITED STATES TO BE VIEWED BY WESTERN EUROPE OR JAPAN AS A DESIRABLE PARTNER FOR COLLABORATION ON THE CONSTRUCTION AND OPERATION OF AN ITER-CLASS DEVICE, THE PANEL BELIEVES THAT A RENEWED COMMITMENT BY THE US GOVERNMENT TO DEVELOP FUSION AS A PRACTICAL ENERGY SOURCE IS ESSENTIAL.

- SUCH A RENEWED COMMITMENT IS ALSO ESSENTIAL FOR THE RESTORATION OF THE US FUSION PROGRAM TO A POSITION OF INTERNATIONAL PARITY, IF NOT UNDISPUTED LEADERSHIP.