The Future of Fusion

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Contents

• Energy Needs in 21st Century
• Lessons learned from past
• Possible approaches for Accelerating Fusion Energy
• Summary
Energy Needs over the World

World average 2.4 kW per person
USA: 10.5 kW
UK: 5.2 kW
JP: 6.3 kW
China: 1.5 kW (growing 10% / y)
India: 0.7 kW
Bangladesh: 210 Watts

Energy Needs in China

Anticipation of Energy Demand in China before 2050

Renewable and nuclear energy were promoted significantly in China for reducing CO2 of 40% in 2020.
Fukushima Nuclear accident make a strong impact to nuclear energy
More urgent need for fusion energy.

2005—2050, average annual growth rate is 1.3%
Can Fusion Play a Role in This Century

**How?**
- 5 % of total primary energy
- Fusion power plant in 2100

**When?**
- 2019-2038 ITER
- 2030-2050 DEMO
- 2040-2060 Proto-Type
- 2050-- First Power Plant

**Country** | **GW plant**
--- | ---
China | 150
India | 150
EU | 50
US | 50
Japan | 30
KOREA | 20
Total: 450 GW plant

**How much?**
- 2060: 5-7 GW power plant
- 2070: 35
- 2080: 70
- 2090: 150
- 2100: 300 (x3=450!)
Lessons learned from past
Lessons learned from past T3, T7, TFR, JT-60, JET (16MW), TFTR, ITER

Projected Fusion-Reactor Development Program
Wash-1267, July 1973
Lessons learned from past

- TFTR construction began in 1976, 4.5 years
- JET 1977, 5.5 y
- JT-60 1978, 4.5
- T-15 1979, Single party efforts

ITER
1986, start
1986-1998, 4 parties
1999-2005, 7 parties
2005-2007, site decision,
2007.10.24, ITER-IO
2007.10-2019.11, construction
## GAP Analysis: > 50 years to power Plant

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**Timeline:**
- **10 year** to Build ITER
- **10 years** to Run ITER
- **10 years** to Build + IFMIF
- **10 years** to Run + IFMIF
- **10 years** to Build DEMO
- **10 years** to Run DEMO
- **10 years** to Build proto-type
Lessons learned from past

- How long will it take? Next 50 years
- Why’s it taking so long?
  Technical difficulties, limited financial and human resources, risk, politics..
- Do we really need another (moving) 50 years?
  It took only 8 years for US landing on moon in 60s!

ITER is on the right track now
Do we make things more simple or more complicated

It is time from the Era of Fusion Science to Fusion Energy
Next step: European Union

Towards a demonstration fusion reactor (DEMO)

ITER is not an end in itself: it is the bridge toward a first demonstration fusion power plant that produces electrical power.

The strategy to achieve this long-term aim includes a number of different elements: firstly, the development of ITER, research into special materials, development and use of existing fusion devices.

This will be followed by a demonstration fusion reactor (DEMO).

The expectation is that after DEMO, the first commercial fusion power stations can be constructed.

Safety & Environment

With Courtesy from EU-DA
Road Map to Fusion DEMO Reactor

Scientific & Technological Feasibility

- Realization of Burning Plasma and Long-duration burning
- Formation of Fusion Technology Basis for DEMO Development

Achievement of Break-Even Plasma Condition

The latter half the 2000's
~ The latter half of the 2030's

Technological Demonstration & Economic Feasibility

- Demonstration of Electric Power
- Improvement of Economic Efficiency

After 2050

Prospect of Practical use

< Issues addressed in ITER project >
- Establishment of control technology towards steady-state sustainment of burning plasmas
- Demonstration of feasibility of fusion blanket for tritium breeding and collection, heat removal and generation of electricity

< Issues addressed in Broader Approach activities >
- Development of high performance plasmas for reducing electricity cost
- Development of fusion reactor materials used under high neutron flux environment etc

With Courtesy from JA-DA
Fusion Eng. Research Project has started towards steady-state helical DEMO reactor

2010
Step by step advancement of reactor design
Conceptual design → Basic design → Improved basic design

- Establishment of engineering base
  - Large-scale high-field superconducting magnet
  - Long-life liquid blanket
  - Low activation structural materials
  - High heat flux plasma facing wall
  - Tritium control

2016
Full-scale, full-condition testing

2022
Engineering design

2027
Construction

2036FY
Licensing

Operation

With universities

Sagara- 2/24

With Courtesy from Prof. Sagara
Fusion Energy Development Roadmap in Korea

Role of KSTAR and ITER

2010’ KSTAR
- High-Beta, Steady-state
- Integrated Control
- Optimum Fusion Reaction
- ITER Operation Scenario Study & Component Test
  - ITER Pilot Plant

2020’ ITER
- Tritium Fuel Cycle
- Reactor Engineering
- DT Burning Plasma
- Blanket, Divertor
- Joint Big Science Experiment

2030’ DEMO
- Reactor System Optimization
- Socio-economic Studies
- Based on Results of KSTAR & ITER Operation
- Electricity Production

2040’ Fusion Plant
- Completion of Fusion Plant Engineering
- Commercialization of Fusion Energy
- Massive Electricity Production

With Courtesy from H-C-Kim
R&D and Test Facilities Plan to be Proposed

With Courtesy from H-C-Kim
Indian Fusion Road Map

2 x 1GWe Power plant by 2060

EFBR
Indigenous Fusion Experiment

ITER Participation 2005
Scientific and technological feasibility of fusion energy

SST-1 2004
Steady State Physics and related technologies

ADITYA Tokamak

With Courtesy from IN-DA
Charting the Roadmap to Fusion Energy: Options for a Nuclear Next Step

Requires a technical evaluation of missions, requirements, and prerequisites for Demo and next-step facilities.
Development Path -

**Full-system demonstration, “LIFE.1” in 2020s**
- Conservative design maximizing use of near turn solutions
- Fully integrated development and vendor readiness program
- Steady state, integrated fusion operations (~500 MWth)
- Define the plant availability growth program
- Materials / structure qualification for commercial plant

**Commercial GWe plants, “LIFE.2” from 2030s**
- Deliver baseload power to grid at relevant size (~ 1GWe)
- Uses systems and materials qualified on LIFE.1
- Defines capital and operating costs for rollout

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With Courtesy from M. Dunne

SPL1-2 E. I. Moses Monday
Options for next step-Important issues

ARIES-Team:

- ARIES-I first-stability tokamak (1990)
- ARIES-III D-\(^3\)He-fueled tokamak (1991)
- ARIES-II and -IV second-stability tokamaks (1992)
- Pulsar pulsed-plasma tokamak (1993)
- Starlite study (1995) (goals & technical requirements for power plants & Demo)
- ARIES-RS reversed-shear tokamak (1996)
- ARIES-AT advanced technology and advanced tokamak (2000)
- ARIES-CS Compact Stellarators (2007)

With Courtesy from Farrokh Najmabadi

- SS operability of a fusion energy facility, including plasma control, reliability of components, availability, inspectability and maintainability of a power plant relevant device.
- Net electricity generation.
- Complete T fuel cycle.
- Power and particle management.
- Necessary date for safety & licensing of a fusion facility.
- Large industrial involvement.
- Cost
Road Map

US: ITER—IFMIF+CTF(FNF)—DEMO—Power Plant
EU&JP: ITER—IFMIF—DEMO—Power Plant
KO: ITER—DEMO—Power Plant

Risks are always there. No single device can solve all S&T problems.
Learning by Doing.
Make Next Step forward is most important.
How to Speed up fusion energy development

- Decision
  Technical solution
  Cost (size)
  World political and economic environments
  International cooperation

- Construction
  Availability of technology
  Personnel
  Financial resources
  Structure of management

- Operation
  Scientific mission
  Structure of management

ITER

- Decision
  1985-2007
  8m → 6m → cheaper?
  By full agreement

- Construction
  R&D still needed
  No enough expertise
  IC-IO-DA
  ~10 years?

- Operation
  Q=10
  20 years

Decision + Technical solution + Personnel
Wide International Cooperation

Take full advantage by using existing facilities

JET, JT-60U, JT-60SA
ASDEX-U, DIII-D, HL-2A(M),
C-Mod
EAST, KSTAR, Tore-Supra
MAST, NSTX,
SST-1, HT-7,
TCV, TEXTOR, FTU
LHD, W7-X

Facilities for engineering:
ST magnets
H&CD facilities
Remote Handling
T-plant
IFMIF (?)
14 MeV neutron Source

Build Necessary test facilities for next step
in different countries, such as CTF.

One party dominate cooperation mechanism is better for next step
EDEMO / Pilot plant (20 years)
Electricity generation with reduced mission

Electricity generation
No need real steady state
Burning plasma control
Sufficient T Breeding
As a CTF
H₂ production
Testing tokamak system availability (reliability, buildability, operability and maintainability)
P_{fusion} ~ 200MW, t = a few hours to weeks

Based on existing technologies:

Option 1: Pure Fusion
A FDF-class with SC coils
A ST-type compact device

Option 2: Fusion – Fission hybrid
Fusion: Q=1-3, Pth=50-100MW
Fission: M=20-30, Pt = 0.3-1.5GW

Or:
ITER-type machine with different blanket: Pt = 5GW, Pe=1.5GW

15:30 SO2B-1 A. Sykes Tuesday
16:20 SO2B-3 T. P. Intrator Tuesday
Efforts Made in China

G-IV Reactor:
- Fast Breeder
  - 65MW (now)
  - \( \rightarrow \) 800MW (2015)
- HTGR
  - 10MW (now)
  - \( \rightarrow \) 200MW (2015)

ADS-NWT Road Map

- ADS Testing Reactor
  - Reactor: \(~100\text{MW}\)
  - Accelerator: 0.6-1GeV/\(~10\text{mA}\)

- ADS DEMO
  - Reactor: \(~1000\text{MW}\)
  - Accelerator: 1.5-2GeV/\(>10\text{mA}\)

Z-pinch and Laser hybrid reactor configurations also proposed

DO WE FUSION HAVE ENOUGH ROOM
CN-MCF Near Term Plan (2020)

ITER construction

- ASIPP: Feeders (100%), Correction Coils (100%), TF Conductors (7%), PF Conductors (69%), Transfer Cask System (50%), HV Substation Materials (100%), AC-DC Converter (62%)
- SWIP: Blanket FW (10%), Shield (40%), Gas Injection Valve Boxes + GDC Conditioning System (88%), Magnetic Supports (100%),
- Diagnostics (3.3%)

Enhance Domestic MCF
Upgrade EAST, HL-2M
ITER technology
TBM
University program
DEMO design (Wan)
DEMO Material
Education program (2000)

Can start construct CN next step device around 2020
Present state:

- ASIPP: HT-7/EAST (150 students), ITER (80 students)
- SWIP (60)
- School of Physics (USTC, 25)
- School of Nuclear Science (USTC-ASIPP, >50)
- CN-MOE-MCF center (10 top universities) 50

Total about 450 students, 150/y, 20-30% remain in fusion

Targets and efforts

- 2000 young fusion talents
- MOST, MOE, CAS, CNNC have lunched a national fusion training program for next 10 years.
  - Basic training in 10 Univ.
  - Join EAST/HL-2A experiments
  - small facilities in Univ.
  - Foreign Labs & Univ.
  - Annual summer school, workshop
China Fusion Engineering Testing Reactor

Main functions
Q=1-5
T> 8 hour, SSO
Component testing
T breeding (TBR>1),
different TBM configuration
Qeng>1
T fuel recycling
RH validation
RAMI validation (weeks)
Hybrid blanket testing (spent fuel burner, transmutation)

R=5m;
a=1.5m;
k=1.75;
BT=5T;
Ip=8-10MA;
ne=1-4x10^{20} m^{-3};
Beta N : 3-5
Pth: 100MW-1GW

TWO Steps in one machine
Step 1: ITER-SS-H mode
    ARIES-RS
Step 2: AT H-mode
    ARIES-AT
Efforts from China

China needs fusion more urgent and would like to be the first user of fusion energy

I. Very Strong Supports from top leaders to public

II. Start MCF program with strong evolvement with industry

III. Finding possible near term application
Summary

- Fusion development comes to a new era with significant progress during past 50 years.
- It is too long to wait for another 50 year to get electricity by fusion.
- A much more aggressive approach should be taken with better international collaboration towards the early use of fusion energy.
- Decision should be made quickly. A EDEMO/Pilot plant might be a better approach to start.