Nuclear Fusion (核融合) as Clean Energy Source for Mankind

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政大「物理與生活」通識課程
Taiwan Energy Supply & Demand

- Taiwan total oil and natural gas reserve is estimated at ~500 million Barrels of Oil Equivalent (BOE)

- Taiwan consumes ~600 million BOE energy in 2000. 98% of Taiwan energy supply is imported – almost completely relying on world energy supply.

- Taiwan electricity supply: ~75% by fossil energy resources (coal 43%, natural gas 19%, oil 6%, cogeneration 7%); ~21% by nuclear fission power

- How will Taiwan get adequate energy supply?
  - Taiwan government aims to achieve ~30% energy supply from renewables (wind power, solar power, hydropower, geothermal, ocean wave & tidal power, biomass) by 2050
  - How about the other 70%?
World Population & Energy Demand

1 ton of oil equiv. = 7.4 barrels of oil equiv.
At our rate of energy use, experts predict an energy shortage in about 30-40 years.
World Energy Supply & Demand

• World energy use is ~ $3T in 2004. More than 90% of energy use is supplied by fossil energy resources (coal, oil, natural gas)

• Running out of fossil fuel (oil first)

• Fossil energy consumption has severe impact on climate and environment (CO$_2$, air pollution, global warming)

• Energy & environment problems are worsened by growing world population; world energy need will double by 2050; CO$_2$ concentrations will double by 2100

• Nuclear fusion is a climate and environment friendly option for replacing fossil fuels!
## Fossil Fuel Energy Sources - Advantages and Disadvantages

<table>
<thead>
<tr>
<th></th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coal</strong></td>
<td>• Abundant</td>
<td>• Burns dirty</td>
</tr>
<tr>
<td>(220 Years)</td>
<td>• Flexible fuel source with many derivatives</td>
<td>• Causes acid rain</td>
</tr>
<tr>
<td></td>
<td>• Transportable</td>
<td>• air pollution, CO2</td>
</tr>
<tr>
<td><strong>Oil</strong></td>
<td>• Flexible fuel source with many derivatives</td>
<td>• Finite supply</td>
</tr>
<tr>
<td>(35 Years)</td>
<td>• Transportable</td>
<td>• Causes air pollution</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Produces CO2</td>
</tr>
<tr>
<td><strong>Natural Gas</strong></td>
<td>• Burns cleanly</td>
<td>• Finite supply</td>
</tr>
<tr>
<td>(60 Years)</td>
<td>• Transportable</td>
<td>• Produces CO2</td>
</tr>
</tbody>
</table>
In US ~93% of coal is used for electricity generation; worldwide ~ 66% for electricity use (~75% by 2025)!

### Coal Consumption (Billion Tons)

<table>
<thead>
<tr>
<th>Region</th>
<th>2004</th>
<th>2025</th>
</tr>
</thead>
<tbody>
<tr>
<td>N. America</td>
<td>1.1</td>
<td>1.6</td>
</tr>
<tr>
<td>Developing Asia</td>
<td>2.1</td>
<td>3.9</td>
</tr>
<tr>
<td>W. Europe</td>
<td>0.6</td>
<td>0.4</td>
</tr>
<tr>
<td>E. Europe</td>
<td>0.8</td>
<td>0.6</td>
</tr>
<tr>
<td>Total (world)</td>
<td>~5</td>
<td>~7</td>
</tr>
</tbody>
</table>

### CO₂ Emission (Tons/MW)

- Current Chinese plants: 1.15
- Current US plants: 1.05
- State of the art: 0.8
- US DOE 2020 goal: 0.55 (~ same as gas turbine)

Present CO₂ levels higher than at any time during the past 420,000 years

- Even with the adoption of all new technologies for fossil electrical energy production, CO₂ concentrations will double by 2100
- CO₂ increases can be avoided only by non-fossil energy sources

Figure from Sir David King, 31st EPS Presentation, “The challenge of climate change: Developing our low carbon energy”, 28, June 2004, London, UK
# Non-fossil Energy Source Advantages and Disadvantages

<table>
<thead>
<tr>
<th>Energy Sources</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| Fission (Nuclear Power) (45 Years) (2700 Years-Breeder) | • Clean, no CO₂  
• Does not produce immediate pollution | • Waste disposal is difficult  
• Safety concerns |
| Hydroelectric (mostly utilized) | • Clean, no CO₂ | • Dam construction destroys habitats  
• Geographically limited |
| Wind (low utilization) | • Clean, no CO₂ | • Huge numbers of windmills required for adequate power generation  
• Geographically limited |
| Geothermal (low utilization) | • Clean, no CO₂ | • Geographically limited |
| Solar (under utilized) | • Clean, no CO₂ | • Huge number of solar cells required for adequate power generation  
• Geographically limited |
Taiwan government aims to achieve ~30% energy supply from renewables by 2050.

> 70% energy must be supplied by fossil fuel and nuclear energy (fission & fusion). However, fossil fuel will run out first.

Fusion is a viable clean energy source!
Nuclear Fusion

Fastest fusion reaction is:
\[ D + T \rightarrow n \ (14 \text{ MeV}) + ^4\text{He} \ (\alpha\text{-particle, } \ 3.5 \text{ MeV}) \]

\[ E = mc^2 \ (\text{Mass lost fraction } \approx 0.38\%) \]
Energy gain \( \approx 450 \)
20\% goes to sustain fusion
80\% goes to generate electricity

Needs a plasma at
\[ T_{\text{ion}} \approx 10 \text{ keV} \ (10^8 \text{ K}) \]
Different Fusion Reactions

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Ignition Temperature (millions of °C)</th>
<th>Output Energy (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D + T</td>
<td>220</td>
<td>17,600</td>
</tr>
<tr>
<td>D + $^3$He</td>
<td>350</td>
<td>18,300</td>
</tr>
<tr>
<td>D + D</td>
<td>400</td>
<td>$\sim$4,000</td>
</tr>
</tbody>
</table>

$^3$He supply is very limited, but can be mined from the Moon.
ADVANTAGES OF FUSION

• Abundant Supply of Fuel (deuterium and tritium)
• No Risk of Nuclear Accident
  – No reactor meltdown possible
  – Large uncontrolled release of energy impossible
• Minimal or No High Level Nuclear Waste
  Careful material selection should minimize waste caused by neutron activation
• No Air Pollution of Greenhouse Gases
  Reaction product is Helium and neutron
Abundant Supply of Fusion Fuel

- Deuterium isotope ≈ 1/7000 of hydrogen atoms in water and can be extracted at a negligible cost (≈ $1/gr).

- Deuterium in 1 gallon of water has the same energy as 300 gallons of gasoline, if burned in a fusion D-T reactor.

- Tritium is not present in Nature (13 year half-life), but slightly more than 1 tritium atom can be created for each DT neutron in a lithium “breeding blanket.”

\[
\begin{align*}
\text{Li}^6 + n & \rightarrow T + \text{He}^4 \quad (7\% \text{ natural Li}) \\
\text{Li}^7 + n & \rightarrow T + \text{He}^4 + n \quad (93\% \text{ natural Li})
\end{align*}
\]
<table>
<thead>
<tr>
<th>Fuel</th>
<th>Coal Plant</th>
<th>D-T Fusion Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
<td>9,000 T. COAL</td>
<td>1.0 LB D$_2$</td>
</tr>
<tr>
<td>Waste</td>
<td>30,000 T. CO$_2$</td>
<td>3.0 LB Li$^6$ (1.5 LB T$_2$)</td>
</tr>
<tr>
<td>Waste</td>
<td>600 T. SO$_2$</td>
<td></td>
</tr>
<tr>
<td>Waste</td>
<td>80 T. NO$_2$</td>
<td>4.0 LB He$^4$</td>
</tr>
</tbody>
</table>
Fusion energy release from 1 gm of DT fuel equals the energy from 2400 gallons of oil
Fusion Power Plant

- Fusion reactions occur in the hot plasma fuel.
- Fast neutrons from fusion reactions heat the moderator.
- Cool fluid.
- Hot fluid.
- Heat Exchanger.
- Turbine Generator.
- Electrical Power Output.
To overcome repulsive electrical force of like charged particles, very high temperature is required.

- 100,000,000°C Hydrogen Nuclei Fuse
- 16,000,000°C Sun Center
- 100,000°C Lightning Bolt
- 10,000°C Fluorescent Light Plasma
- 6000°C Sun Surface
- 3,400°C Tungsten Melts
- 1,500°C Iron Melts
- 100°C Water Boils
- 23°C Room Temperature
- 0°C Ice
- -78°C Dry Ice
- -200°C Liquid Nitrogen
- -269°C Liquid Helium
- -273°C Absolute Zero
Three Basic Ways to Achieve Fusion

- **Magnetic Confinement**: Ion gyroradius $\approx 1$ cm, $T_i = 20$ keV, $B = 20$ kG

- **Gravitational Confinement**: Difficult to heat D-T fuel to 20 keV in a very small space and short time

- **Inertial Confinement**: Difficult to heat D-T fuel to 20 keV in a very small space and short time
Main Criteria in Fusion Research

• The fusion power created must be larger than the power required to keep the D-T fuel at high temperature in sufficiently long time

  ➔ near-term scientific goal of a “burning plasma”

• The mechanical structure of the device must be capable of withstanding damage due to plasma bombardment and radiation damage due to 14 MeV neutrons

  ➔ long-term engineering goal of improved materials
Requirements for Fusion Burning

“Burning” means self-heating by alpha particles produced in DT reaction. To maintain self-sustained burning, it requires

\[
\text{alpha heating rate} > \text{plasma energy loss rate}
\]

or,

\[
\text{constant} \cdot n^2 T^2 > 3 n T / \tau_E
\]

[where \(\tau_E\) is the plasma energy confinement time]

Thus, the condition to achieve self-sustained burning is

\[
n \cdot T \cdot \tau_E > (10^{14} \text{ cm}^{-3}) \cdot (20 \text{ keV}) \cdot (5 \text{ sec})
\]
What Have We Done in Magnetic Confinement Research in Past 50 Years?

Model A Stellarator of 1953 (with Lyman Spitzer)
\[ n \approx 10^{13} \text{ cm}^{-3} \]
\[ T \approx 10 \text{ eV} \]
\[ \tau_E \approx 10 \mu\text{sec} \]

JET Tokamak in 2003:
\[ n \approx 10^{14} \text{ cm}^{-3} \]
\[ T \approx 20 \text{ keV} \]
\[ \tau_E \approx 1 \text{ sec} \]
\[ nT\tau_E \text{ still needs a factor } \approx 5 \text{ from burning condition} \]
Early Ideas for Magnetic Fusion Research

- Magnetic mirror
- Linear pinch
- Field reversed configuration
- Stellarator
The Winner so Far: the Tokamak

Tokamak = toroidal magnetic chamber (Russian acronym)
Present World Magnetic Fusion Devices

- JET (EU)
- W-7X (Germany)
- LHD (Japan)
- JT-60 (Japan)
- NSTX (US)
- KSTAR (Korea)
- NST (Japan)
- ITER
- Tore-Supra (France)
- SST-1 (India)
- EAST (China)
- DIII-D (US)
DIII-D with Plasma and No Plasma
World Fusion Energy R&D History and Strategy

Basic science
- Study of magnetically confined plasmas

Scientific demonstration of fusion plasmas
- Plasma conditions close to break-even
  - Japan, EU, and US devices

Engineering demonstration of fusion reactor (ITER)
- Experimental reactor for output power of 0.5GW, energy multiplier of Q > 10, and sustaining time > 400 sec.
- US priority investment on science infrastructure
- ITER for the next 20 years

Fusion reactor
- Commercialized fusion energy via "FAST TRACK" in advanced countries
  - Fast Track: 35 years plan for commercial fusion reactor based on unified version of the DEMO PROTO
  - Japan, EU, and US devices

Timeline:
- 1960
- 1980
- 2000
- 2020
- 2035
Progress of World Fusion Research

Equivalent Fusion Power Output (Watts in Log Scale)

- Projected (World-Wide)
- Achieved (World-Wide)

Year

History of $nT\tau_E$ in Tokamaks

- $T \approx 20$ keV achieved
- $n \approx 10^{14}$ cm$^{-3}$ achieved
- $\tau_E \approx 1$ sec achieved
- (but not quite simultaneously)

$nT\tau_E$ still needs a factor of $\approx 5$ to create burning plasma

(improvements came mainly from increase in machine size)
ITER – A Burning Plasma Fusion Reactor

Site: France
Construction: 2007-2017

Design Goals:
• $Q \approx 10$ (burning plasma)
• 0.5 GW fusion power
• 500 sec long pulse

• 10B Euro ITER agreement was signed by 7 parties (EU, Japan, USA, Russia, China, Korea, India) in 2005.
• Taiwan 4th Nuclear Power Plant costs ~ $6B for 2.7 GW power
## ITER Construction & Operation

<table>
<thead>
<tr>
<th>Agreement</th>
<th>2007</th>
<th>2017</th>
<th>2025</th>
<th>2035</th>
<th>Transfer to Host</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITER Legal Entity</td>
<td>-2</td>
<td>0</td>
<td>8</td>
<td>18</td>
<td>28</td>
</tr>
<tr>
<td>Start Construction</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>33</td>
</tr>
<tr>
<td>First Plasma</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>End Operation</td>
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<tr>
<td>Build Tokamak Complex</td>
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<tr>
<td>Start Assembly</td>
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<tr>
<td>Component Fabrication</td>
<td></td>
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<tr>
<td>Test and Commissioning</td>
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<tr>
<td>Initial Operation</td>
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<tr>
<td>Subsequent Operation</td>
<td></td>
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<tr>
<td>Deactivation</td>
<td></td>
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</tbody>
</table>
**Major Fusion Science Areas**

- Macroscopic Stability
- Wave-Particle Interactions
- Microturbulence & Transport
- Plasma-Wall Interactions

**Integrated Predictive Model**

**GOAL:** Reliable predictions of complex properties of high temperature plasmas

**Benefits**

- Innovations for better designs
- Progress to Fusion Power
- Cost-effective harvesting of physics from facilities

*All with strong coupling to experiments*
\( \alpha \) interaction with thermal plasmas is a strongly nonlinear process.

Must develop efficient methods to control profiles for burn control!

\( \Rightarrow \) Need nonlinear kinetic-fluid simulation codes!
Disparate Spatial & Temporal Scales in Fusion Plasmas Present Major Challenge to Theory & Simulations

- Huge range of spatial and temporal scales
- Overlap in scales and nonlinearity often mean simplified ordering and theory not possible
Major Fusion Technology Challenges

• Materials development
  – Survive high heat flux (10 MW/m²)
  – Retain strength despite neutron activation
  – Minimize production of activated wastes

• Develop safe and efficient Tritium handling techniques
  – Develop breeding technologies for Tritium from Lithium blankets
  – Minimize Tritium inventory for improved safety

• Reduce size, cost, and complexity to make competitive with other energy sources
Fusion Research Spending

• **ITER**
  – Agreement signed in June 2005 with construction cost ~$13B over 10 yrs, to be built in France
  – Participants: EU(40%), Japan(10%), US(10%), Korea (10%), Russia(10%), China(10%), India(10%) representing > 1/2 of world population

• 2006 US annual magnetic fusion budget ~ $300M
  – One space shuttle launch costs ~$500M
  – Japan & EU each spends more than US
  – Developing nations increase fusion funding greatly since 2000

• Korea’s fusion investment
  – K-STAR tokamak built mainly by Korean industries. Total investment ~ $1B during 1995-2005 including industry investment

• Taiwan’s fusion & plasma science investment: none or negligible now! Now is the time for Taiwan to participate and grow!
Korea Jump-Starts Fusion Program in 1995

- Approval of the KSTAR project in 1995
- Mid-entry strategy

Graph showing the equivalent fusion power output (in Watts) from 1970 to 2010, with projected and achieved data for various fusion experiments around the world and in Korea.
Korean fusion energy R&D history and strategy

- Basic fusion plasma research
  (Universities and national Institutes)
  - 1970-1990

- G-5 level fission reactor technology
  (Korean standard fission reactor design)
  - 1995.12-2007.8

- Assembly of the KSTAR device
  initiated by Mid-entry strategy:
  - 2008

- ITER junior partner
  - 2010

- Operation

- Operation

- 2017

- 2020
Fusion Energy R&D

Fusion is large scale, high efficiency next generation clean energy source

- High oil price & fossil fuel issue
- Natural disaster due to environment & climate change
- Advancement of technology & industrial structure for 21st C
- Basic science and technology for fusion energy
- Efficient large scale energy source
- Environmentally friendly and clean energy source
- High-value-added new industries

Advanced science and state-of-the-art technology
Fusion Energy Research in Taiwan

• Present Taiwan’s fusion & plasma science investment: none or negligible!
• Can Taiwan continue to ignore fusion research when nations representing more than 1/2 of world population are working on fusion energy research?
  – Assuming that ITER succeeds in producing output energy 5 - 10 times of the input energy, it’d be too late for Taiwan to catch up in fusion technology if Taiwan does not have a fusion energy research program now.
• If Korea can afford to work on fusion energy research, why can’t Taiwan?
  – YES! Taiwan can afford to initiate a moderate fusion energy research program.
Establish a Moderate Taiwan Fusion Energy R&D Program

• **Initial Phase: Start a Taiwan Fusion Facility with fusion plasma science program:**
  – develop expertise & manpower in fusion-related plasma theory and modeling, and small basic plasma experiments
  – establish international collaborations in tokamak fusion theory and experiments (e.g., with US, Japan, Korea)
  – participate in KSATR experiments (e.g., US contributes $4M and Japan contributes $6M to KSTAR in plasma diagnostics, particle heating source in exchange of participating in KSTAR experiments)
In conclusion, it is very important to initiate a modest fusion energy research program in Taiwan!

For training scientific and engineering personnel in anticipation of success of ITER & future fusion devices

Thank you!