Recent progress of the R&D and design for high temperature blanket and biomass hybrid concept

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S. Konishi, K. Ibano, F. Okino, K. Noborio, T. Shibata, Y. Yamamoto and R. Kasada
Kyoto University
Background

Kyoto University pursues the Biomass Hybrid concept from various aspects.

Particular interest is on Socio-Economics and possible scenario for early introduction of Fusion, with minimal extrapolation of the current technology.

Safety, environment and the adoption to the future energy system are our current concern.

Contents

- LiPb blanket and tritium recovery / SiC study
- zero-carbon electricity system with Micro DC grid.
- Tritium in the environment
High Plasma Q not required

Driven and pulsed operation is acceptable

High output temperature is required for gasification efficiency is required

High temperature blanket To be developed.

Electricity generation
Q=20, $\eta_e=0.33$

$\eta_f=2.7 - 0.6$

Break-even Q=1, $\eta=1$

Negative power

Biomass Hybrid Concept

Net 6P_f

Net 8P_f

ITER

DEMO

GNOME

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Droplet and Diffusion

\[ \frac{M_t}{M_\infty} = 1 - \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp \left( -Dn^2 \pi^2 t / \alpha^2 \right) \]

The droplet diameter is a key factor for optimum design of the extraction system.
A: Tritium balance study
To explicate the recovery rate of Biomass Gasification fusion reactor GNOME

B: Tentative observation of droplet formation
from 1mm dia. nozzle by an experimental setup (one point data)
Tritium Balance in plant

Net TBR 1.05

Plasma

Consumption 4.5E-04

[\text{mol/s}]

Recovered tritium

IHX permeability, tritium confinement of Entire power plant needs maturity and Demonstration for social understanding.

Recovered tritium

IHX permeation, tritium confinement of Entire power plant needs maturity and Demonstration for social understanding.

IHX

Permeation 2.3E-8

Recovery System 1

Tritium Recovery System 1

Recovery 4.7E-04

Recovery 2.3E-08

Reactor

Permeation 2.5E-10

Recovery System 2

Pb

0.652 m$^3$/s

LiPb

0.724 m$^3$/s

Plants

Biomass

Recovered tritium
Tritium Recovery Process

\[ \Phi = 4 \text{mm} \]

\[ M(\infty) = 1 - \sum_{n=1}^{\infty} \frac{6}{n^2 \pi^2} \exp\left[ -\frac{n^2 \pi^2 D}{r^2} t \right] \]

\[ M(t) [\text{mol}] : \text{gas release} \]
\[ M_\infty [\text{mol}] : \text{dissolved tas} \]
\[ D [\text{m}^2 \text{s}^{-1}] : \text{diffusion coefficient} \]
\[ t [\text{s}] : \text{time} \]
\[ r_0 [\text{m}] : \text{radius of the droplet} \]
\[ l [\text{m}] : \text{depth} \]

Vacuum Sieve Tray

Inventory control

Tritium in hydrogen product

requirement

at 500°C

H = 1.2m

\( \Phi = 4.6 \text{ m} \)

\( \Phi = 4 \text{ mm} \)

Vac. 

Vacuum Sieve Tray

Institute of Sustainable Science

Institute of Advanced Energy, Kyoto University
Tritium Recovery Process

- Tritium concentration in product hydrogen (Bq/m$^3$)
- Tritium permeability through IHX [mol Pa$^{-1/2}$ s$^{-1}$ m$^{-1}$]
  - Regulation for HTO
  - Target recovery ratio >35% in the LiPb stream

- Recovery ratio determined from the contamination of product.
- Requirement is a function of permeability through IHX

Natural background

SiC fiber

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Institute of Advanced Energy, Kyoto University
Water ($H_2O$) vs. Liquid Pb-17Li

Boundary equilibrium equation

\[-p_d' + \frac{1}{Fr} z' + \frac{2}{Re} n \cdot E' \cdot n = \frac{1}{We} (\nabla' \cdot n)\]

<table>
<thead>
<tr>
<th></th>
<th>Density $\rho$ [Kg/m$^3$]</th>
<th>Viscosity $\mu$ [Pa·s]</th>
<th>Surface tension $\sigma$ [N/m]</th>
<th>Temperature $T$ (°C)</th>
<th>Velocity $V$ [m/sec]</th>
<th>Length $L$ [m]</th>
<th>Reynolds number $\rho \ U L / \mu$</th>
<th>Froude number $U^2 / g L$</th>
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Both $Surface$ $tension$ $regime$ material
Deducing formula

\[ r = a + \alpha \cos kz, \]

Energy minimum by Euler-Lagrange-Equation

\[
\frac{\partial L}{\partial q} - \frac{d}{dt} \left( \frac{\partial L}{\partial \dot{q}} \right) = 0
\]

\[ U = \sigma (s - s_0) = -\sigma \frac{\pi \alpha^2}{2a} \left( 1 - a^2 k^2 \right) \]

\[ T = \frac{1}{2} \rho \int_{V} (\nabla \phi) \cdot (\nabla \phi) \, dV \]

\[ = \frac{1}{2} \pi \rho a^2 \frac{I_0(ka) \dot{\alpha}^2}{kaI_1(ka)} \]
Deducing formula

\[ \alpha = a_0 e^{qt} \]

Fastest grow rate at \( ka=0.6970 \) overwhelm

\[ d_{\text{droplet}} \approx 1.89D_0 \]
Experimental Result

droplet dia. vs. nozzle

![Diagram showing droplet diameter vs. nozzle](image-url)
Liquid metal Pb-17Li droplet

A: Theoretically deduced droplet size formula is

\[ d_{\text{droplet}} \approx 1.89D_0 \]

B: Effective range is less than \( \phi 2.2 \text{mm} \)

Both good accordance with the experimental results and well applicable for extraction system design engineering
SiC cooling panel
- Actively cooled SiC panel to control heat transfer
- Isolate outer RAFM vessel structure
- Obtain high temperature LiPb for heat

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### Blanket parameters

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<th>Parameter</th>
<th>Value</th>
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<td>He temperature at SiC channel</td>
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<td>Thermal conductivity of SiC</td>
<td>20 W m⁻¹ K⁻¹</td>
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Fabrication R&D for SiC cooling panels

Institute of Advanced Energy, Kyoto University
LiPb circulated >900 °C

Loop operated >900 °C
Only in the test vessel

SiC module

IHX heat transfer from LiPb to He

Installed in 900 °C vessel
Hydrogen permeation through SiC

In CVD SiC, diffusion in grain boundary weems major path.

In Hexoloy(a), diffusion in bulk is regarded as major path.
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Tritium in power system is the major issue from TBM to DEMO.
### Blanket and tritium flow

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<th>breeder</th>
<th>coolant</th>
<th>Tritium recovery</th>
<th>IHX</th>
<th>Generation</th>
<th>Detritiation</th>
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<td>physical</td>
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<td>hybrid</td>
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</table>

**Primary coolant issue:** accidental release
In the case of BWR..

- Reactor Building (R/B)
- Dry Well
- Pressure Containment Vessel (PCV)
- Spent Fuel Pool
- Reactor Pressure Vessel (RPV)
- Suppression Chamber

Source: http://nei.cachefly.net/static/images/BWR_illastration.jpg
<table>
<thead>
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<th>Breeder</th>
<th>Coolant</th>
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<td>g-g IHX</td>
<td>Brayton</td>
<td>hybrid</td>
</tr>
<tr>
<td></td>
<td>Metal</td>
<td>Physical</td>
<td>Metal-gas IHX</td>
<td>hybrid</td>
<td></td>
</tr>
</tbody>
</table>

Secondary coolant issue: permeation in normal operation.
Emission controlled by confinement and active detritiation both in Normal and accidental Condition.
Yearly change of tritium concentration

Change on the tritium concentration in the atmosphere during prolonged operation is analyzed.

Emission rate: $1.35 \times 10^{14}$ Bq/year

- Tritium concentration increase for about 60 years on land.
- Tritium concentration on the sea surface is low and does not show accumulation.
Environmental models convert emission to dose.

Major dose from normal operation comes from ingestion.

\( \mu \text{Sv} \) per person, per year per 1 gram emission.

Particular concern is a damage for sales of food products.
Annual emission **accumulates** in the environment.

Emission rate: $1.35 \times 10^{14}$ Bq/year

- **Considerably increases** for 20 years
- **Still negligible from dose, but easy to detect.**
  - If 100 plants operated 100 years?
With accumulation, dose is still below 10 mSv/year
• However, 15 times larger than the first year.
Coastal siting absorbs tritium by isotopic dilution

Tritium concentration distribution

- Inland tritium also decreases by the tritium migration
- Existence of sink prevents environmental accumulation.
Inland tritium continue to accumulate until balance with decay.

Little accumulation observed on the coast.
Off-shore location

Off shore siting is even more effective.

Coastal model

Off shore model

Tritium concentration distribution

Emission at 5 km from the coast decreases Atmospheric tritium to 1/10.
Tritium can be well controlled but normally discharged at below legal limits. (annual, single plant.)

Water detritiation requires further development and significant cost is anticipated.

- Tritium in the environment and foods can easily be detected.
- Annually controlled emission can be accumulated and spreads.
- Releases from multiple sources can be summed.

Canadians report tritium control experience in normal operation of Heavy Water Reactors (expensive coolant with minimal loss with reasonable efforts) to be 1000Ci/y order /unit.

→ Fusion should be as clean as fission with minimal cost.
Electric grid capacities

Eastern Grid ~500GW
Texas Grid ~53GW
Western Grid ~140GW

UTPTE ~270GW

Vietnam ~8GW
West Japan ~100GW
East Japan ~80GW
West Japan ~100GW
Thailand ~20GW

Extremely large Grids in a country
Internationally connected Grids
Delicately controlled grids

- these are all exceptional in the future energy market.

Electric grid is a national security issue and cannot be easily integrated.

Stability of the grid is region specific.
All the generators on the grids are synchronized → Exactly same amount generated as demanded.

Sudden increase of demand or unstable generator

- Demands exceed generation capacity
- Frequency drops (~0.1%)
- Load to the generators
- Generator disconnected

Chain reaction kills the grid.

→ unstable renewables can initiate the blackout.
For near term, leveling of the load is important.

Local generators, cogeneration and batteries preferred.

Increased renewable jeopardizes grid

For future, substitute of fire power needed.

→ load leveling power is preferred. Can fusion be a base load?
- unpredictable change of generating power of renewable is large
- time constant of seconds
- controlled power to compensate this change needed
- connecting to grid decreases amplitude but not time constant
- fire power can provide only slow change (~5%/min)
Future low carbon Systems

Fusion (to come)

Nuclear (??)

Fire (fade out)

Large scale grid

Local systems

Solar cell

Fuel cells

Battery

PHV, EV

Electricity must be powered by Carbon-free sources

Both large grid and local systems are needed.

Battery, generators and fuel cells Stabilizes fluctuation by renewables.

Large scale supply of fuels for Fuel cells needed.
# Carbon-free electricity systems

<table>
<thead>
<tr>
<th></th>
<th>Power [kW]</th>
<th>Max.power[kW]</th>
<th>capacity[kWh]</th>
<th>units</th>
<th>area[m²]</th>
<th>Vol.[m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar</td>
<td>633</td>
<td>566.2</td>
<td>–</td>
<td>–</td>
<td>4740</td>
<td>–</td>
</tr>
<tr>
<td>battery</td>
<td>364.7</td>
<td>420</td>
<td>2625</td>
<td>7</td>
<td>–</td>
<td>16.7</td>
</tr>
<tr>
<td>Fuel cell</td>
<td>–</td>
<td>988</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>5.6</td>
</tr>
<tr>
<td><strong>計</strong></td>
<td>998</td>
<td>1974</td>
<td>2625</td>
<td>7</td>
<td>4740</td>
<td>22.2</td>
</tr>
</tbody>
</table>

**SOFC+NaS+Solar①, Summer, Fine**

**SOFC+NaS+Solar①, Summer, Rain**

## Graphs

- **SOFC+NaS+Solar①, Summer, Fine**
  - Large scale grid
  - SOFC
  - NaS-2
  - NaS-1
  - Solar

- **SOFC+NaS+Solar①, Summer, Rain**
  - Large scale grid
  - SOFC
  - NaS-2
  - NaS-1
  - Solar

---

*Note: The table and graphs are showing the electrical energy [kWh/h] over time [h] for different settings and conditions. The graphs illustrate the energy output from various sources such as large scale grid, SOFC, NaS-2, NaS-1, and solar.*
Future Energy Systems

Institute of Sustainable Science

Fusion

Fuel (H₂ / CO)

Load following power

NUCLEAR

FIRE

0 6 12 18 24(h)

Large scale grid

DC Microgrid

Solar cell

Fuel Cells

Battery

Electricity will be powered by Carbon-free sources

Day peak will be supplied by Battery and fuel cells.
Fusion and grid

Indirectly supplied by fusion

Large-scale power generation

Fusion will be started by night sources

Fusion reactor (2 GW)

~ 400 MW

Office

Office

Large scale grid

DC Microgrid

DC Microgrid

DC Microgrid

Institute of Advanced Energy, Kyoto University

Fusion will be started by night sources

Charge of NaS

SOFC

Fission, Hydro

H₂ 16 GL/day

16 GL/day

2.9 GL/day

6.7 GL/day \times 10^4 Microgrid

6.5 GL/day

Time [h]

Electrical Energy [MWh]

0
100
200
300
400
500
600
700

AC

DC

Indirectly supplied by fusion
• Micro Grid can be cheaper than large Grid for long runs.
• Combination of generation technology is needed to stabilize the supply.
• Carbon-free system can be made before 2050.

Cost of micro grid electricity

2025cost (NEDO)

<table>
<thead>
<tr>
<th>generator [10^5 ¥/kW]</th>
<th>SOFC</th>
<th>Solar</th>
<th>NaS</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>12</td>
<td>29</td>
<td></td>
</tr>
</tbody>
</table>

- Electrical Energy [kWh/h]

- Large scale grid

- SOFC+NaS+Solar②, Summer, Fine

- Commercial electricity

- Cumulative cost [10^8 ¥/system]

- Year from the introduction

- Time [h]
Fusion – biomass hybrid may demonstrate fusion energy earlier than pure fusion electricity.
- Small power generation has better market chance.
- Cost requirements for the product (hydrogen, oil) may be easier (eventually. Depends on oil price and carbon tax)
- Fusion-fuel cell combination may be a preferred option.

High temperature blanket/divertor are realistic challenge
- SiC-LiPb blanket being developed.
- Low pressure system is preferred from safety aspects

Tritium self sufficiency and environmental effect is concerned.
- Tritium recovery from breeder needs demonstration (TBM)
- Demonstrated safety will be important to launch DEMO
- Environmental tritium contamination needs social understanding
Fuel production from biomass continued to be studied.

Fukushima accident required additional consideration for fusion safety.

High temperature, low pressure LiPb blanket has preferred safety features.

Public is aware of existing radioactive contamination.

Energy security with renewables will be a major concern in the future.

Fusion needs an adequate position in the future energy system.