Materials Development and Design Effort for V/Li Blanket in Japan

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US/Japan Workshop on Power Plant Studies and Related Advanced Technologies
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V/Li Research in Japan

- Collaboration by Materials, Blanket and Design people is increasing on V/Li system in Japan

  - Progress in the development of vanadium alloys by NIFS/Universities
  - Enhanced development of Li technology in relation to IFMIF-Key Technology Development
  - Enhanced participation to ITER-TBM by NIFS/Universities, presently V/Li is the candidate being examined by NIFS/Universities
  - MHD coating development needs collaboration with design group and the collaboration is being enhanced
Production and Characterization of High Purity V-4Cr-4Ti (NIFS-HEATs)

- NIFS-HEAT-1 has been tested by Japanese Universities
- NIFS-HEAT-2 was distributed for international collaboration

April 98

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<thead>
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<tr>
<td>Development of high purity V</td>
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<td>Development of alloying method</td>
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<tr>
<td>NIFS-HEAT-1 (30 kg)</td>
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<td>NIFS-HEAT-2 (166 kg)</td>
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NIFS-HEAT-2 ingots

Products

Specimens distributed

NIFS-HEAT-2 ingots
Merit of Purification

- Some properties (welding, working, radiation response (in limited cases)) were improved by reduction of O and N
- Feasibility of economical recycling was demonstrated by reducing Al, Nb, Ag, Mo
Fabrication Technology  (Tubing, welding)

- Plates, wires, tubes were successfully fabricated
- Good property of laser-weldment

Specimen: 50 X 8 X 3 mm

Absorbed energy, $E_u / J \text{ cm}^{-2}$

Test temperature, $T / K$

$E_u = 150 \text{ J cm}^{-2}$

As-weld NH2 plate

Before weld NH2 plate

$2TR \times 180^\circ$

$\phi 10 \times 0.5t \times 100$

$\phi 4.57 \times 0.25t \times 400$

NH2 $26 \times 26 \times 140 \text{ mm}$, Pre-heating

Machining

Mandrel 3-directional roll

Intermediate annealing

$3 TR \times 180^\circ$

$T = 3 \text{ mm}$
Creep Properties of NIFS-HEAT

- One of the concerns by the purification was the creep strength.
- Creep strength of NIFS-HEATs was similar to other V-4Cr-4Ti.

Significant progress was made in developing vanadium alloys with improved engineering maturity and feasibility for economical recycling.
Status of V-Alloy Development

Key-Issues

- Massive production
- high purity
- low activation
- Fabrication tech.
- Welding
- MHD coating
- Radiation effects (He)

Feasibility almost demonstrated

Progress being made but further efforts necessary for feasibility

Systematic efforts necessary
IFMIF Key Technology Verification

IFMIF Key Technology Verification studies were carried out in Japan in FY 2000~2002, sharing responsibility by JAERI and NIFS/Universities.

Li related Target research was carried out mainly by NIFS/Universities.

### IFMIF Schedule

**Key Element Technology (KEP)**
- Phase (KEP) **2000-2002**
- Transition **2003-2004**
- Engineering Validation and Engineering Design Activity (EVEDA) **2005-2009**
- Construction **2010-2016**
- Operation **2017**
Li Target Test (Osaka University)

- A test station was installed to 200L Li loop of Osaka Univ. for Target test
- Free surface test successfully carried out in FY2002
- Li and relating device technologies were enhanced
Li Impurity Control (U. Tokyo)

- V-10Ti and Cr were shown to be effective getter material for hot N trap
- Control of N is essential for T recovery with Y
- T recovery study with Y in progress (U. Tokyo, Kyushu U.)

S. Tanaka 2002
Li Loop Experiment Planned in EVEDA

- Full-size test loop will be constructed for validation of continuous operation
- Impurity control system will be installed based on KEP results
- The technology will be applied to Li blanket
ITER-TBM Past Proposals

- From Japan, only solid breeders were proposed to ITER via JAERI
- A NIFS-collaboration activity started in 2002, in which liquid blanket test module is explored

<table>
<thead>
<tr>
<th>Party</th>
<th>Proposed TBM-type</th>
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<td>JAPAN</td>
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<td>EU</td>
<td>Solid - Helium</td>
</tr>
<tr>
<td></td>
<td>Li-Pb - Water</td>
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<tr>
<td>Russia</td>
<td>Solid - Helium</td>
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<td>US</td>
<td>Solid - He</td>
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<td>Lithium</td>
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<td></td>
<td>1995</td>
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NIFS Collaboration Activity for ITER-TBM

- Li/V as a reference and Flibe as a back-up
- Support from JAERI
- First output expected in 2004

<table>
<thead>
<tr>
<th>Subject</th>
<th>University</th>
<th>NIFS</th>
<th>Initial Activity</th>
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<tbody>
<tr>
<td>Thermal-structural Analysis</td>
<td>Hashizume Horiike</td>
<td>Imagawa Nagasaka</td>
<td>Thermal-structural analysis MHD-reduction</td>
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<td>Neutronics</td>
<td>Iguchi</td>
<td>T. Tanaka</td>
<td>T-production Nuclear Heat, After Heat, Activation</td>
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<td>T-recovery</td>
<td>S. Tanaka Fukada</td>
<td>Suzuki</td>
<td>Hot trap Cold trap</td>
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<td>Materials</td>
<td>Matsui Abe</td>
<td>Nagasaka</td>
<td>Design data</td>
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<td>Flibe-module concept</td>
<td>Terai</td>
<td>Sagara</td>
<td>Concept exploration</td>
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<td>Design Integration</td>
<td>Matui JAERI</td>
<td>Muroga Sagara</td>
<td>Reporting</td>
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</table>
Roadmap for Materials and Blanket Development in Japan (Fast Option)

Approximate calendar year

- **2015**
- **2020**
- **2030**
- **2040**

**Materials and Blanket System Development**
- **Reference Material (RAFM) and System**
- **Advanced Materials (V-alloy, SiC/SiC --) and System**

**Power Generation Plant**
- **Design**
- **Construction**
- **Operation**
  - (Licencing)
  - (Blanket test)

**ITER**

**Fast Power Generation Option** (Mostly JAERI responsibility)

**Advanced Option** (Mostly NIFS/University responsibility)
Purpose of Li/V ITER-TBM
(current discussion in NIFS collaboration)

- Feasibility of no-Be and natural Li blanket
  - Use of $^7$Li reaction for enhancing TBR in contrast to Russian Be+$^6$Li enriched TBM
- Validation of neutronics prediction
- Technology integration for V-alloy, Li and T
ITER with Li/V self-cooled blanket - MCNP calculation by T. Tanaka (NIFS) -

A : Standard ITEF-FEAT blanket
B : ITER with V/Li full blanket

Input geometry for MCNP calculation (Dimensions from ITER Nuclear Analysis Report)
ITER with Li/V self-cooled blanket - *Local TBR* -

<table>
<thead>
<tr>
<th>Contribution of $^7$Li (%)</th>
<th>Inboard</th>
<th>Outboard</th>
<th>Total</th>
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<td>Li/V blanket</td>
<td>0.30</td>
<td>0.92</td>
<td>1.22</td>
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<tr>
<td>Coolant in filler</td>
<td>0.029</td>
<td>0.15</td>
<td>0.18</td>
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<tr>
<td>Total</td>
<td>0.33</td>
<td>1.1</td>
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(*JENDL 3.2*)

Significant contribution of $^7$Li to TBR
Neutron spectrum at first wall of Standard and V/Li Blanket

Comparison of Neutron Flux at Outboard First Wall

Cross Section for Tritium Production (JENDL 3.2)

- Significant difference between thermal neutron component in ITER-FEAT and ITER-Li/V
- Thermal neutron should be shielded in the TBM area of ITER-FEAT for the purpose of simulating V/Li blanket condition
Russian Li/V self-cooled test blanket module - Structure -

- Structure of Russian Li/V TBM

- 6Li enriched coolant (7.5 % ==> 90%)
- Li layer x 2, Be multiplier ==> 6Li (n, α) T
- Maximize the 6Li reaction to demonstrate DEMO reactor breeding tritium by 6Li

(Unit : mm)
Russian Li/V self-cooled test blanket module - Tritium production -

Tritium production rate in Li layers and contribution of $^6$Li and $^7$Li

Total: 0.09 (g/FPD)

Total TPR
TPR from $^6$Li
TPR from $^7$Li

Tritium production rate (g/FPD/cm³)

Position (mm)
Tentative design of Li/V self-cooled TBM by NIFS/Universities

Verification of
(1) Coolant circulation
(2) MHD coating

Verification of
(1) Neutron transport
(2) Tritium production from $^7$Li

Inlet/outlet pipes

$Li : \sim 0.027 \, m^3$

Tentative design of Li/V TBM

- Verification of TPR for $^7$Li
- Thick Li tanks for verification of neutron transport

Diagram showing
- Plasma
- V-4Cr-4Ti
- Li layer
- SS(60%), H$_2$O(40%)
- SS316 TBM frame
- SS(60%), H$_2$O(40%)

(Unit : mm)
Tentative design of Li/V self-cooled TBM  - Tritium production -

For verification of tritium production from $^7$Li (n, n$\alpha$)T reaction
- Reduction of thermal neutrons by B$_4$C shielding

![Diagram showing Tritium production rate in Li layers and Contribution of $^7$Li to tritium production.](image)
Changes in contribution of $^7$Li by $B_4C$ covering

- Contribution of $^7$Li to TPR can be adjusted by thickness of $B_4C$ shield
MHD Coating – Necessity–

Pressure Drop: proportional to
Flow length, Velocity, $B^2$, Duct thickness, Conductivity of Li and Duct

MHD Pressure Drop

- Load to pumping system
- Force to structures

Insulator coating inside the ducts a possible solution
MHD Coating Candidates
(1)–Free Energy

Stable ceramics in a quite reducing condition

Selection from the free energy data

CaO, Y_2O_3, Er_2O_3, CaZr(Sc)O_3, AlN, BN
MHD Coating Candidates (2)– Bulk Compatibility

- Potential candidates
  - $\text{Y}_2\text{O}_3$
  - $\text{Er}_2\text{O}_3$
  - AlN with N control
  - CaZr(Sc)O$_3$ ($\sim$700°C)
  - others

Japan-US JUPITER-II Collaboration (Pint, Suzuki et al. 2002)
MHD Coating Development
Present Efforts

- Development of coating technology
  - RF-sputtering
  - EB-PVD
  - Arc Plasma Deposition

- Characterization of the coating
  - Resistivity
  - High temperature stability
  - Compatibility with Li
  - Radiation induced conductivity

- In-situ coating technology

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Japan-US JUPITER-II Collaboration (Suzuki, Pint et al. 2003)
The in-situ coating method has advantages as,

- possibility of coating on the complex surface after fabrication of component
- potentiality to heal the cracks without disassembling the component
- CaO coating has been explored
Problems of the CaO Coating and New Effort on Er$_2$O$_3$

- It was found that the CaO coating, after formation, dissolved at high temperature (600, 700°C)
  - CaO bulk is inherently not stable in pure Li at high temperature, continuous supply of oxygen is necessary to maintain the coating
- Er$_2$O$_3$ is much more stable at high temperature
  - It is expected Er$_2$O$_3$, once formed, be stable in Li for a long time
  - Er$_2$O$_3$ is stable in air, combination of dry-coating and in-situ coating is more feasible
In-situ Er$_2$O$_3$ Coating on V-4Cr-4Ti

Er$_2$O$_3$ layer was formed on V-4Cr-4Ti by oxidation, anneal and exposure to Li (Er) at 600°C.

The coating was stable to 300 hrs.

The resistivity was $\sim 10^{13}$ ohm-cm.

XPS depth profile after exposure to Li (Er) at 600°C for 100 hr.

Yao. 2003
Need for Collaboration with Design People

- Requirement to the coating performance depends strongly on the design
  - System design is necessary to quantify the requirement to the coating
  - Clever design would make the requirement lenient
- New idea of coating will be obtained by collaboration with design
  - Laminar coating structure, etc.
For a single pipe, with a perfect insulating coating, the allowable crack fraction was $<10^{-7}$.

For a real coating, $10^{-2}$ is achievable, while $10^{-4}$ might be achievable.

If we start with a poor coating, the allowable fraction can be higher, maybe $10^{-4}$, with a higher MHD pressure drop.

There are other ways to increase the allowable crack fraction, such as change the aspect ratio of the channel, change the boundary conditions of the flow channel.

The boundary condition of the flow channel, such as the contact resistance between the fluid and the wall, may have major impact on the crack fraction.

The change of the designs may have major impact on the crack allowance.
Impact of Sze Summary on the Coating Development in Japan

- Experimental examination of the resistance between the (flowing) Li and the wall covered with cracked coatings at high temperature is of high priority.

- The goal of the in-situ healing may be set to increase the resistivity of cracked area from complete conduction by 4 order of magnitude

  
  Allowable crack fraction : $10^{-7}$
  
  Realistic crack fraction : $10^{-3}$

- Increased collaboration between materials and design people in Japan
Design Effort to Reduce Requirement to the Coating

- Optimization of channel structure for reducing the requirement to the coating
  - Coating may be necessary only on limited flat surfaces
  - Insulator ribs may be inserted instead of coated ribs/walls

- Other suggestions on laminar coating structure, enhanced heat transfer, etc

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<th>( \sigma_{\text{insulator}} / \sigma_{\text{HT-9}} )</th>
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<td>48.1</td>
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(Hashizume)
Summary

- Collaboration by Materials, Blanket and Design people are increasing on V/Li system in Japan
  - Progress in developing vanadium alloys toward engineering maturity
  - Enhanced Li technology by IFMIF-KEP
  - Increased accessibility for the liquid blanket people to ITER-TBR
  - Collaboration on MHD-coating development by materials and design people

- One of the goals of the collaboration is to propose V/Li ITER-TBM

- The collaboration is enhancing research for other advanced blanket systems (Flibe --)

- The collaboration covering Material, Blanket and Design people in the US will accelerate the progress, and should be enhanced in the framework of JUPITER-II