Materials Challenge for
Clean Nuclear Fusion Energy

Development of Low Activation
Structural Materials

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Roadmap of Fusion Energy Development for Japan

Development of Low Activation Vanadium Alloys for Nuclear Fusion Reactors

2020

ITER

D-T

ITER

DEM0

Operation

Operation

Power Generation

Materials Performance under Irradiation

Fission reactors and charged particle irradiation

IFMIF : International Fusion Materials Test Facility
Nuclear fusion is a clean energy source from the CO₂ emission standpoints

One of the very limited candidates of major energy source in the future

From radiological standpoint, nuclear fusion is a clean energy source relative to nuclear fission

No high level radioactive waste is produced

Neutron-induced radioactivity of the components (low to middle level waste) and tritium are the only radiological issues

Neutron-Induced radioactivity is an issue for:

(1) Maintenance of in-vessel components (lifetime of maintenance tools)

(2) Waste disposal or reuse

(3) Potential hazard
Structural Materials for Fusion Blankets

Blanket is the key component of fusion reactors

- Energy conversion (neutron to heat)
- Tritium production (Li + n → T)

The structural materials need to have high temperature strength, resistance to neutron irradiation and compatibility with coolants.
The Concept of Low Activation Materials

“Low Activation Materials” is defined as:

The materials in which neutron irradiation-induced radioactivity decrease to a level where economical waste disposal or recycling in the next fusion plant (possible zero emission) is feasible in <50 years of cooling.

Use of Low Activation Materials can increase largely the attractiveness of fusion system as a clean energy source.
Element Restriction for Low Activation

There is strong element restriction for low activation materials:

Ni, Cu, Al, Mo, Nb cannot be used as alloying elements.
Al, Ag, Nb Mo should be strictly controlled to ~ppm levels.

None of the commercially-established materials can be used for the low activation structural components.

Classification of the elements by the restriction for low activation:

- **no limit**
- **design dependent**
- **<0.1%**
Radioactivity of Fusion Candidate Materials

Three candidate materials are under development for fusion application as low activation materials:

- Reduced activation Ferritic/Martensitic steel
- Vanadium alloys
- SiC/SiC composites

The candidate materials satisfy the recycling limit.
“Low Activation” would also be the Future Key Phrase for Nuclear Fission Systems

Disposal of Light Water Reactor in-vessel components
The activity can be reduced by three orders using low activation materials
Low Activation Concrete is already investigated in nuclear fission community
Reduction of Eu and Co levels for satisfying clearance level

Radioactivity after 60 y operation of PWR
Radioactivity of concrete after 20 y operation
High operation temperature is essential for high conversion efficiency. Plant efficiency is influenced also by other factors (e.g. net working rate).
History of Vanadium Alloys for Fusion Reactors

Vanadium alloys were once candidates of FBR core materials in 1970s

V-Nb-Cr, V-Nb-Mo, V-Cr-Zr (JP-NIMS), V Ti-Cr, V-Cr-Fe (US), V-Ti-Si (Germany)

The programs were concluded because of insufficient compatibility with Na

Vanadium alloys attracted attention for fusion reactors from 1980s

Low activation property -- potentiality for recycling

High temperature strength, high thermal stress factor

Fusion materials programs identified V-4Cr-4Ti as the leading candidate

Industrial infrastructure of vanadium alloys are still quite limited
Impurity Reduction is the Key Issue for V-Alloys

Vanadium is a reactive metal, whose properties are influenced heavily by C, N, O impurities

C, N, O impurities need to be controlled

Contamination from the environment may be an issue

Vanadium alloys must satisfy low activation criteria

Nb, Mo, Al, Ag need to be controlled to 1~10 ppm

Cross contamination by sharing facilities for other purposes may be an issue

NIFS has promoted a program for development of high purity V-4Cr-4Ti

The effect of O, N and C levels on Elongation
Commercial Production Process of Metal Vanadium

Development of Low Activation Vanadium Alloys for Nuclear Fusion Reactors

Ores

Spent catalyst from oil desulphurization → Dissolution → Precipitation ($\text{NH}_4\text{VO}_3$) → Thermal decomposition → Aluminothermic reduction (Thermit) → Electron beam melting → V$_2$O$_5$ → V-Al-O → V

(Cross Contamination)

C N Nb, Mo

O Al
**Improvement of the Process**

### Development of Low Activation Vanadium Alloys for Nuclear Fusion Reactors

<table>
<thead>
<tr>
<th>Intermediates</th>
<th>Conventional process</th>
<th>Improved process</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>N</td>
</tr>
<tr>
<td>Ammonium Vanadate</td>
<td>12</td>
<td>41</td>
</tr>
<tr>
<td>(Calcination)</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V$_2$O$_5$</td>
<td>100-150</td>
<td>20-90</td>
</tr>
<tr>
<td>(Themic reduction)</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al</td>
<td>20-80</td>
<td>10</td>
</tr>
<tr>
<td>(Themic reduction)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V-Al-O</td>
<td>180</td>
<td>300-400</td>
</tr>
<tr>
<td>(EB refining)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metal V</td>
<td>300</td>
<td>400-710</td>
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</table>
Production of Purified Metal Vanadium

Metal Vanadium with <100wppm O and <200ppm N were produced by improving the production process.

O and N levels of metal V produced

125 kg ingots of purified V
Alloying Technology

Development of Low Activation Vanadium Alloys for Nuclear Fusion Reactors

Alloying to V-4Cr-4Ti was carried out by EB and VAR methods.

Special cares were taken to avoid contamination with O and N from atmosphere and with Nb and Mo by cross-contamination.
### Resulting Purity of the Alloys

Purification of metal vanadium resulted in low O level relative to US alloys. US alloy had high Nb level because the infrastructure was common to Nb production system.

This is a valuable lesson for future manufacturing of low activation V-alloys.

#### Chemical compositions of V-4Cr-4Ti ingots produced by NIFS and USDOE Programs

<table>
<thead>
<tr>
<th>ID</th>
<th>As</th>
<th>Zr</th>
<th>Nb</th>
<th>P</th>
<th>S</th>
<th>Ca</th>
<th>Co</th>
<th>Ag</th>
<th>Sn</th>
<th>Sb</th>
<th>Ti</th>
<th>W</th>
<th>Mo</th>
<th>Ta</th>
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</thead>
<tbody>
<tr>
<td>NIFS-HEAT-1</td>
<td>1</td>
<td>&lt;10</td>
<td>1.4</td>
<td>16</td>
<td>9</td>
<td>3</td>
<td>2</td>
<td>&lt;0.05</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>4.13</td>
<td>&lt;1</td>
<td>23</td>
<td>58</td>
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<tr>
<td>NIFS-HEAT-2</td>
<td>&lt;1</td>
<td>2.5</td>
<td>0.8</td>
<td>7</td>
<td>3</td>
<td>12</td>
<td>0.7</td>
<td>&lt;0.05</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>3.98</td>
<td>&lt;1</td>
<td>24</td>
<td>13</td>
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<tr>
<td>US832665</td>
<td>1.4</td>
<td>&lt;46</td>
<td>60</td>
<td>33</td>
<td>16.5</td>
<td>&lt;0.26</td>
<td>0.30</td>
<td>0.078</td>
<td>0.24</td>
<td>0.17</td>
<td>4.05</td>
<td>25</td>
<td>315</td>
<td>&lt;19</td>
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<tr>
<td>US832864</td>
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<td>&lt;30</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.8</td>
<td></td>
<td></td>
<td>&lt;50</td>
</tr>
</tbody>
</table>
V-4Cr-4Ti Products

Various high purity products were manufactured.
V-4Cr-4Ti Tubing by Drawing

Development of Low Activation Vanadium Alloys for Nuclear Fusion Reactors

O impurity before fabrication ~400 ppm

Quality of tubes increased by reducing O levels

O impurity before fabrication ~130 ppm
Welding – Impurity Control is the Key Issue

Welding can result in contamination with C, N, O by two ways
(a) Contamination of the weld joints with C, N, O from atmosphere during the welding
(b) In V-4Cr-4Ti, large fraction of C, N, O are stored in Ti-CON precipitates. Welding results in contamination of matrix with C, N, O

(a) is avoidable by highly controlling the welding atmosphere
(b) can be avoided only by reducing the original level of C, N, O in the material

![Image of Ti-C, N, O precipitates in Base Metal and Weld Metal]
TIG Welding with Ultra-High Purity Wire

Ultra-high purity wires were used for TIG welding for the purpose of reducing impurity level of weld joints.

With the decrease in the oxygen level in the weld joint, DBTT decreased.

Absorbed energy of Charpy tests for weld joints

DBTT of weld joints as a function of oxygen level

<table>
<thead>
<tr>
<th>Alloy Name</th>
<th>O level (appm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>US-Large Heat (US)</td>
<td>310</td>
</tr>
<tr>
<td>NIFS-HEAT-1 (NH1)</td>
<td>180</td>
</tr>
<tr>
<td>High Purity Wire (HP)</td>
<td>36</td>
</tr>
</tbody>
</table>
Irradiated Vanadium alloys showed plastic instability

Interaction of dislocations with radiation-induced defect clusters (black dot images by TEM) is thought to be the key process

Atom Probe Elemental Mapping showed the black dots are decorated with Ti, O and TiO.

Elemental mapping of radiation-induced defect clusters by Atom Probe

(Rice 1998)  Change of tensile property and typical microstructure after deformation in V-4Cr-4Ti irradiated at low temperature

(Nita 2003)
**Enhanced Uniform Elongation in V-Cr-Ti-Si,Al,Y**

Uniform elongation after irradiation decreased to ~ 0 after irradiation at <400°C

However, the uniform elongation recovered by addition of Si, Al, Y.

Si, Al and Y can scavenge impurity O in V-4Cr-4Ti matrix and suppress the formation of the “decorated” defect clusters.

*Uniform elongation of V-4Cr-4Ti after neutron irradiation*

(Abe, Satou 2003)
Nano Structural Materials for Fusion

Development of Low Activation Vanadium Alloys for Nuclear Fusion Reactors

Nano oxide dispersion strengthened (ODS) materials are under development for fusion as advanced options:

- Enhanced high temperature strength
- Improved radiation damage resistance because of high density of defect sinks
- ODS low activation steel: Fe-9Cr-W
- Collaboration with FBR and SCWR
- ODS vanadium alloys
- ODS Cu alloys: Heat sink materials

![Tensile Stress vs Temperature Graph](image)

- 9CrODS steel
- Ferritic steel

![Uniform Elongation Graph](image)

- 9Cr Ferritic Steel vs. 9Cr ODS steel

![Nano Structural Materials for Fusion](image)

- W, Be, C
- CuCrZr to ODS-Cu
- Steels

ITER First Wall

ODS V-alloys
Summary

Development of Low Activation Vanadium Alloys for Nuclear Fusion Reactors

Materials development is the key to successful development of fusion energy. Use of “low activation” structural materials can largely increase the attractiveness of fusion reactors as a clean energy source.

High temperature operation is essential for high efficiency energy conversion.

Vanadium alloys are attractive candidate low activation structural materials for fusion reactors because of low activation and high temperature strength.

Control of both potentially-radioactive impurities (Nb, Mo, Al, Ag) and interstitial impurities (C, N, O) is essential for vanadium alloy development.

Nano Structural Materials are longer-term advanced options to enhance the operation temperature window and radiation resistance of structural components.