Study of irradiation effects in materials with high-neutron-flux fission reactors

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The Oarai Branch, Institute for Materials Research, Tohoku University
Future Scope of the Oarai Branch (tentative proposal)

JAEA Irradiation Division

The Oarai Branch

Coordination of individual proposals
Capsule design
Irradiation technology
Advanced PIEs
Cooperation with other institutions

Proposal of new projects
Structuring researchers

Project oriented studies

University researchers
(focused on fundamental studies)

Variety of interests
New ideas which are not validated yet
### Outline of Research Reactors in Japan

<table>
<thead>
<tr>
<th>Reactor</th>
<th>JMTR</th>
<th>JRR-3</th>
<th>JRR-4</th>
<th>NSRR</th>
<th>HTTR</th>
<th>JOYO</th>
<th>KUR</th>
<th>YAYOI</th>
<th>UTR</th>
<th>KINKI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor Power</td>
<td>50 (MW)</td>
<td>20 (MW)</td>
<td>3.5 (MW)</td>
<td>2.3 (GW) (Pulse)</td>
<td>30 (MW)</td>
<td>140 (MW)</td>
<td>5 (MW)</td>
<td>2 (kW)</td>
<td>1 (W)</td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>Tank</td>
<td>Pool</td>
<td>Pool</td>
<td>TRIGA ACPR</td>
<td>Tank</td>
<td>Fast Na Cool</td>
<td>Tank</td>
<td>Tank</td>
<td>Pool</td>
<td></td>
</tr>
<tr>
<td>Coolant</td>
<td>Light water</td>
<td>Light water</td>
<td>Light water</td>
<td>Light water</td>
<td>He</td>
<td>Na</td>
<td>Light water</td>
<td>Air</td>
<td>Light water</td>
<td></td>
</tr>
<tr>
<td>Operation</td>
<td>30d/cy (6cy/y)</td>
<td>26d/cy (6cy/y)</td>
<td>4daily/cy (40cy/y)</td>
<td>7MWd/y</td>
<td>about 3 month/y</td>
<td>60d/cy (about 7 month/y)</td>
<td>about 2 month/y</td>
<td>about 4 month/y (daily)</td>
<td>about 4 month/y (daily)</td>
<td></td>
</tr>
</tbody>
</table>
Facilities of JOYO
(Highest neutron flux in Japan)
### Specifications of Joyo MK-III Core

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reactor Power</strong></td>
<td>140 MWt</td>
</tr>
<tr>
<td><strong>Fast Neutron Flux</strong></td>
<td>$4.0 \times 10^{19} \text{n/m}^2 \cdot \text{s}$</td>
</tr>
<tr>
<td><strong>Flow of Primary Coolant</strong></td>
<td>2700 t/h</td>
</tr>
<tr>
<td><strong>Coolant Temperature</strong></td>
<td>350°C / 500°C</td>
</tr>
<tr>
<td><strong>Core Height</strong></td>
<td>500 mm</td>
</tr>
<tr>
<td><strong>Type</strong></td>
<td>U, Pu Mixed Oxide</td>
</tr>
<tr>
<td><strong>Pu Content</strong></td>
<td>Inner: 23 wt% or less&lt;br&gt;Outer: 30 wt% or less</td>
</tr>
<tr>
<td><strong>Uranium Enrichment</strong></td>
<td>Approximately 18 wt%</td>
</tr>
<tr>
<td><strong>Maximum Number of Fuel S/A</strong></td>
<td>85</td>
</tr>
<tr>
<td><strong>Reflector/Shielding S/A</strong></td>
<td>Stainless Steel/B$_4$C</td>
</tr>
<tr>
<td><strong>Number of Irradiation S/A</strong></td>
<td>Maximum 21</td>
</tr>
<tr>
<td><strong>Subassembly Pitch</strong></td>
<td>81.5 mm</td>
</tr>
<tr>
<td><strong>Operation Days</strong></td>
<td>60 days/cycle</td>
</tr>
</tbody>
</table>

**Core Configuration**

- **Inner S/A**
- **Outer S/A**
- **Control Rod**
- **Reflector**
- **Irradiation S/A**
- **Shielding S/A**
Facilities of JMTR (multipurpose Japanese main materials-testing reactor)

- Connected by Canal
  - Easy Transfer of Irradiated Materials
  - Re-instrumentation
  - Coupling Irradiation
- Easy access to its core (easy instrumentation)
- Designated solely to materials(fuel) testing
(little disturbance from other users)
### Outline of JMTR

#### Specifications of JMTR

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor Power</td>
<td>50 MWt</td>
</tr>
<tr>
<td>Fast Neutron Flux (Max)</td>
<td>$4 \times 10^{18} \text{n/m}^2 \cdot \text{s}$</td>
</tr>
<tr>
<td>Thermal Neutron Flux (Max)</td>
<td>$4 \times 10^{18} \text{n/m}^2 \cdot \text{s}$</td>
</tr>
<tr>
<td>Flow of Primary Coolant</td>
<td>6000 m$^3$/h</td>
</tr>
<tr>
<td>Coolant Temperature</td>
<td>49°C/56°C</td>
</tr>
<tr>
<td>Core Height</td>
<td>750 mm</td>
</tr>
<tr>
<td>Fuel</td>
<td>ETR type, 19.8% $^{235}$ U</td>
</tr>
<tr>
<td>Irradiation Capability (Max)</td>
<td>60 capsules</td>
</tr>
<tr>
<td>Fluence/$\gamma$ (Max)</td>
<td>$3 \times 10^{25} \text{n/m}^2 \cdot \gamma$</td>
</tr>
<tr>
<td>dpa of Stainless Steel (Max)</td>
<td>4 dpa</td>
</tr>
<tr>
<td>Diameter of Capsule</td>
<td>30 - 65 mm</td>
</tr>
<tr>
<td>Temp. Control (Max)</td>
<td>2000°C</td>
</tr>
</tbody>
</table>

- **Hydraulic Rabbit**
- **Low $\gamma$ Area**
- **Shroud Facility**
- **Core Configuration**

- Standard Fuel Element
- Fuel Follower / Control Rod
- Aluminum Reflector Element
- Beryllium Reflector Element
- Beryllium Frame
- Gamma-ray Shield Plate
JRR-3
Open type reactor (mainly for beam-type uses)

ISTC/JWS-32 in Oarai, 17 Nov., 2004
Layout of JRR-3 In-situ experiment
Main activities of the Oarai Branch

LWR related materials study

Fundamental studies related with radioisotopes

In-situ type experiments

Development of new materials at High dpa

Development of radiation resistant materials for advanced nuclear systems

Evaluation of life of structural materials in LWRs

Utilization of radiation energy and RI

New analyzing techniques, new functional materials utilizing radiation energy

Fundamental studies

mechanisms

Interaction between materials and radiations

Irradiation and instrumentation technologies

Temperature regulation

In-situ measurements

Multi-layers multi-divided

Advanced PA and 3DAP

Optical in-situ measurements
High-accuracy Temperature Control System

Pool
Guide Tube
RPV
Capsule
Core
Gas Gap
Heater
T/C
Sample
Temp. Controller
Vacuum Line
Capsule
Temp.
Power Supply
Heater (Feedback Control)
He gas
Heater
Vacuum Pump
Gas Pressure
(Feedforward control)
Valve
Quick Response by Vacuum Pump
Computer
Reacto Signal
Gas Pressure
Computer Control
Gas Pressure
Computer Control
A Result of High-accuracy Temperature Control

Irradiation Temperature

- Advanced Control
- Manual Control

Constant temperature control at reactor start up (JMTR)

- ±2.4 °C
- ±8 °C

Reactor power

- 45MW
- 50MW

Operating Time (h)

- March, 1, 14:00
- March, 3, 14:00

± 12 h

±8 °C

290 °C

280 °C
Multi-temperature Multi neutron fluence control irradiation rig in JMTR
Importance of Temperature Control being Independent of Reactor Power

(Fundamental and Systematic Studies in JMTR and Validation in HFIR under Japan/USA Collaboration)  

After Muroga et al.
Material Testing Rig with Temperature Control in JOYO (High flux fast reactor)

Special Feature
- Irradiation Temperature Control (Accuracy: ±4 deg. C)
- Heated by gamma ray or Electronic Heating
- Breach Detection for In-pile Creep Rupture Test by
  - Ultra High Sensitivity Tagging Gas (Xe, Kr) Analysis
  - Radioactivity Measurement of Cover Gas
  - Detection of Sodium Temperature Fluctuation by Thermocouple
- Reassembling and Reloading Capability
In-situ Measurement Technology

**Development Radiation-resistant Optical Fiber as New Instrument**

**Optical Property Measurement of Diagnostic Windows for Fusion Reactor**

**Electrical Properties of Ceramics as Insulator for Cable**

- **Radiation Induced Conductivity (S/m)**
- **Dose Rate (Gy/s)**
- **Heater**
- **Sapphire**
- **KU-Quarts**
- **S2**
- **KU1**

**ISTC/JWS-32 in Oarai, 17 Nov., 2004**
Temperature dependence of electrical conductivity of BaCe$_{0.9}$Y$_{0.1}$O$_{3-d}$
In-situ irradiation studies on ITER-related components

- Radiation induced degradation behaviors of electrical insulating ability of ceramics (Radiation induced electrical conductivity (RIC) and Radiation induced electrical degradation (RIED)).
- Performance of fused silica (SiO$_2$) core optical fibers, other optical materials under fusion relevant irradiation conditions.
- Radiation induced electro-motive-force (RIEMF) in mineral insulating cables (MI-cables) and other metals/ceramics systems.
- Performance of components whose major constituents are functional materials, such as a bolometer (electrically conductive metallic meander and electrically and thermally insulating substrate), a magnetic sensor and a JxB sensor (windings of electrically conductive wires and electrical insulators).
ISTC/JWS-32 in Oarai, 17 Nov., 2004

**Engineering aspects**

- **Stage I**: Validation of materials in a specific environment.
- **Stage II**: Irradiation studies with charged particles and 14MeV neutrons under well-defined parameters.
  - Aiming for more comprehensive understandings in materials behavior in more universal environments.
- **Stage III**: Controlled and well-monitored irradiations.
  - Advancement of computer simulation and multi-scale modeling.
- **Stage IV**: Controlled and well-monitored irradiation in higher flux neutron irradiation to validate multi-scale modeling and to establish comprehensive understandings of materials behavior in universal neutron environments.

**Aspects from Material Science**

- General interests in interactions between materials and neutrons.
  - Validation of materials in a specific environment.

General interests in interactions between materials and neutrons.
ISTC/JWS-32 in Oarai, 17 Nov., 2004

Engineering aspects

Validation of materials in a specific environment

Aspects from Material Science

General interests in interactions between materials and neutrons

MONJU

Irradiation studies with charged particles and 14MeV neutrons under well defined parameters

Stage I

Aiming for more comprehensive understandings in materials behavior in more universal environments

Stage II

JRR-3

Controlled and well-monitored irradiations

Stage III

JOYO

Advancement of computer simulation and multi-scale modeling

Stage IV

JMTR

Controlled and well-monitored irradiation in higher flux neutron environment to validate multi-scale modeling and to establish comprehensive understandings of materials behavior in neutron environments
ISSUES to be addressed for high fluence irradiation in fission reactors

• Fuel conversion to LEU (Low Enriched Uranium)
  • Sustain reactor reactivity high enough to meet with various and complicated material irradiation
  • Satisfy safety issues and versatile operation modes
    • Adaption of advanced fuel such as U-Mo
    • Restructure of core
  • Multipurpose operation (reason to exist(survive))
    • Sometimes purposes conflict with each other
    • Operation mode
      • Steady state, as long as possible, keeping the same conditions for RI production and neutron dopings but changing conditions every time satisfying various demands from materials tests.
      • Intermission interval as short as possible for RI production and neutron dopings, but interval long enough to accommodate complicated instrumentations for advanced materials irradiation
Sophisticated instrumentation and control of irradiation conditions in high flux neutron fields

High gamma-ray dose rate associated with neutrons
Mixed spectrum reactor (10W/g for $10^{18}$n/m²s)

Difficult to irradiate materials below 300°C under well-controlled irradiation conditions
Even now, it is difficult in the core region of JMTR (12W/g)
Difficult of instrumented irradiation (in-situ measurements)
ITER-EDA, JUPITER program in HFIR

Next generation materials testing reactors need to overcome the issue
Sodium cooled fast reactor may be one solution
low gamma-ray dose rate associated with fast neutron flux
Summing ups

- The Oarai Branch of Tohoku University is planning to extend its activity of utilizing reactors around Oarai as well as overseas, under collaboration and cooperation with the JEAE.

- Its unique feature of advanced technology of microstructural analyses will be more emphasized to make a rigid basis for hot laboratory linkage around Oarai.

- The international collaboration will be essential for the future activity of the Oarai Branch, in the fields of utilization of fission reactors for materials studies.