U.S. Solid Breeder Blanket and Neutronics Experiments and Facilities

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**Present U.S. Solid Breeder Experimental Activities**

- Carried out mostly in collaboration with other countries

- Primary organizations: ANL, HEDL
  Support: ORNL, GA, UCLA

- Fabrication
  - BEATRIX/FUBR-1B
  - LBM

- Irradiation
  - Completed: TRIO, FUBR-1A
  - Active: FUBR-1B/BEATRIX
    - First Insertion: Fall 85 to Fall 86
    - Second Insertion: Spring 87 for ~2 yrs

- Material Characterization
  - $\text{Li}_2\text{O}$, LiAlO$_2$ (at ANL)

- Tritium Oxidation Experiments (ANL)
## Solid Breeder Blanket

<table>
<thead>
<tr>
<th>Issues</th>
<th>Ongoing Research</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Tritium self-sufficiency</td>
<td>a</td>
</tr>
<tr>
<td>- Tritium release and recovery</td>
<td>b</td>
</tr>
<tr>
<td>- Tritium permeation and processing</td>
<td>b</td>
</tr>
<tr>
<td>- Hydrogen thermodynamic/chemistry studies</td>
<td>b</td>
</tr>
<tr>
<td>- Compatibility with multiplier and structural materials</td>
<td>c</td>
</tr>
<tr>
<td>- Materials fabrication</td>
<td>c</td>
</tr>
<tr>
<td>- Breeder/multiplier chemical and mechanical integrity</td>
<td>c</td>
</tr>
</tbody>
</table>

- **a**  U.S./Japan neutronics experiment, Nuclear Technology Program
- **b**  Experimental program
- **c**  Low level of effort being maintained
<table>
<thead>
<tr>
<th>Reactor</th>
<th>Site</th>
<th>Neutron Flux n/cm²·s</th>
<th>Experiment Size cm OD x cm</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFTF</td>
<td>HEDL</td>
<td>$5 \times 10^{15}$ (fast)</td>
<td>$10 \times 91$</td>
<td>Operational; Suitable for T-Recovery Experiments</td>
</tr>
<tr>
<td>EBR-II</td>
<td>ANL-W</td>
<td>$2 \times 10^{15}$ (fast)</td>
<td>$6 \times 33$</td>
<td></td>
</tr>
<tr>
<td>HFIR</td>
<td>ORNL</td>
<td>$1.3 \times 10^{15}$ (fast) $0.2 \times 10^{15}$ (thermal)</td>
<td>$3 \times 51$</td>
<td>Presently used (structural, other materials)</td>
</tr>
<tr>
<td>ORR</td>
<td></td>
<td>$0.5 \times 10^{15}$ (fast)</td>
<td>$8 \times 38$</td>
<td>Scheduled for shutdown</td>
</tr>
<tr>
<td>Others</td>
<td></td>
<td>A number of reactors not presently utilized</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
International Collaboration - BEATRIX

• Involves the exchange of materials and shared irradiation testing among partners - Belgium, Canada, England, France, West Germany, Italy, Japan, the Netherlands, and USA.

• Allows comparison of materials preparation and fabrication methods, irradiation techniques, and tritium extraction methods.

• Irradiation experiments are of two types: closed-capsule tests to evaluate lifetime and open-capsule tests to evaluate purge flow tritium recovery.
Closed-Capsule Tests

- Closed-capsule tests are being done in mixed-spectrum reactors (HFR, OSIRIS, and NRX) and in a hard-spectrum reactor (EBR-II)

<table>
<thead>
<tr>
<th>Laboratory</th>
<th>Reactor</th>
<th>Experiment</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Westinghouse/Hanford</td>
<td>EBR-II</td>
<td>FUBR-1B</td>
<td>((\text{Li}_2\text{O}, \text{LiAlO}_2, \text{Li}_2\text{SiO}_3, \text{Li}_4\text{SiO}_4, \text{Li}_2\text{ZrO}_3))</td>
</tr>
<tr>
<td>ECN/Petten</td>
<td>HFR</td>
<td>EXOTIC</td>
<td>((\text{Li}_2\text{O}, \text{LiAlO}_2, \text{Li}_2\text{SiO}_3))</td>
</tr>
<tr>
<td>CEA/Saclay</td>
<td>OSIRIS</td>
<td>ALICE</td>
<td>((\text{LiAlO}_2))</td>
</tr>
<tr>
<td>KfK/Karlsruhe</td>
<td>OSIRIS</td>
<td>DELICE</td>
<td>((\text{Li}_2\text{SiO}_3, \text{Li}_4\text{SiO}_4))</td>
</tr>
<tr>
<td>AECL/Chalk River</td>
<td>NRX</td>
<td>CREATE</td>
<td>((\text{Li}_2\text{O}, \text{LiAlO}_2))</td>
</tr>
</tbody>
</table>

- The most detailed experiment is FUBR-1B because it involves five different materials supplied by six different partners in three different configurations
## FUBR-1B/BEATRIX TEST MATRIX
(Second Insertion - May 1987 for about 2 years)

<table>
<thead>
<tr>
<th>Capsule</th>
<th>Material</th>
<th>Source</th>
<th>Density (% TD)</th>
<th>Diameter (Inch)</th>
<th>Goal (C)</th>
<th>Time Exposure (EFPD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S3T</td>
<td>LiAlO₂</td>
<td>WHC</td>
<td>80%</td>
<td>0.913</td>
<td>1150</td>
<td>900</td>
</tr>
<tr>
<td>S3B</td>
<td>LiAlO₂</td>
<td>WHC</td>
<td>80%</td>
<td>0.648</td>
<td>900</td>
<td>900</td>
</tr>
<tr>
<td>S4T</td>
<td>LiAlO₂</td>
<td>Saclay</td>
<td>74%</td>
<td>0.913</td>
<td>1120</td>
<td>600</td>
</tr>
<tr>
<td>S4B</td>
<td>Li₄SiO₄</td>
<td>Karlsruhe</td>
<td>89%</td>
<td>0.647</td>
<td>1000</td>
<td>600</td>
</tr>
<tr>
<td>S5T</td>
<td>Li₂ZrO₃</td>
<td>WHC</td>
<td>89%</td>
<td>0.913</td>
<td>1240</td>
<td>600</td>
</tr>
<tr>
<td>S5B</td>
<td>Li₂O</td>
<td>JAERI</td>
<td>90%</td>
<td>0.647</td>
<td>930</td>
<td>600</td>
</tr>
</tbody>
</table>

### S7A PINS

<table>
<thead>
<tr>
<th>Capsule</th>
<th>Material</th>
<th>Source</th>
<th>Density (% TD)</th>
<th>Diameter (Inch)</th>
<th>Goal (C)</th>
<th>Time Exposure (EFPD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B4T</td>
<td>Li₂O</td>
<td>WHC</td>
<td>80%</td>
<td>0.375</td>
<td>700</td>
<td>900</td>
</tr>
<tr>
<td>B4C</td>
<td>Li₂O</td>
<td>WHC</td>
<td>80%</td>
<td>0.375</td>
<td>900</td>
<td>900</td>
</tr>
<tr>
<td>B4B</td>
<td>Li₂O</td>
<td>WHC</td>
<td>80%</td>
<td>0.375</td>
<td>900</td>
<td>900</td>
</tr>
<tr>
<td>B5T</td>
<td>LiAlO₂</td>
<td>WHC</td>
<td>80%</td>
<td>0.375</td>
<td>700</td>
<td>900</td>
</tr>
<tr>
<td>B5C</td>
<td>LiAlO₂</td>
<td>WHC</td>
<td>80%</td>
<td>0.375</td>
<td>900</td>
<td>900</td>
</tr>
<tr>
<td>B5B</td>
<td>LiAlO₂</td>
<td>WHC</td>
<td>80%</td>
<td>0.375</td>
<td>900</td>
<td>900</td>
</tr>
<tr>
<td>B8T</td>
<td>Li₂O</td>
<td>JAERI</td>
<td>89%</td>
<td>0.375</td>
<td>700</td>
<td>600</td>
</tr>
<tr>
<td>B8C</td>
<td>Li₂O</td>
<td>JAERI</td>
<td>89%</td>
<td>0.375</td>
<td>900</td>
<td>600</td>
</tr>
<tr>
<td>B8B</td>
<td>Li₂O</td>
<td>JAERI</td>
<td>89%</td>
<td>0.375</td>
<td>900</td>
<td>600</td>
</tr>
<tr>
<td>B9T</td>
<td>Li₂O</td>
<td>Springfield</td>
<td>83%</td>
<td>0.372</td>
<td>700</td>
<td>600</td>
</tr>
<tr>
<td>B9C</td>
<td>Li₂O</td>
<td>JAERI</td>
<td>45%</td>
<td>0.410</td>
<td>700</td>
<td>600</td>
</tr>
<tr>
<td>B9B</td>
<td>Li₂O-sc</td>
<td>JAERI</td>
<td>100%</td>
<td>0.314</td>
<td>500</td>
<td>600</td>
</tr>
<tr>
<td>B10T</td>
<td>LiAlO₂</td>
<td>Saclay</td>
<td>74%</td>
<td>0.375</td>
<td>700</td>
<td>600</td>
</tr>
<tr>
<td>B10C</td>
<td>LiAlO₂</td>
<td>Saclay</td>
<td>73%</td>
<td>0.375</td>
<td>900</td>
<td>600</td>
</tr>
<tr>
<td>B10B</td>
<td>LiAlO₂</td>
<td>Saclay</td>
<td>75%</td>
<td>0.375</td>
<td>500</td>
<td>600</td>
</tr>
<tr>
<td>B11T</td>
<td>Li₂SiO₃</td>
<td>Karlsruhe</td>
<td>81%</td>
<td>0.375</td>
<td>700</td>
<td>600</td>
</tr>
<tr>
<td>B11C</td>
<td>Li₄AlO₂</td>
<td>Casaccia</td>
<td>85%</td>
<td>0.375</td>
<td>700</td>
<td>600</td>
</tr>
<tr>
<td>B11B</td>
<td>Li₄SiO₄</td>
<td>Karlsruhe</td>
<td>92%</td>
<td>0.375</td>
<td>500</td>
<td>600</td>
</tr>
<tr>
<td>B12T</td>
<td>Li₂ZrO₃</td>
<td>Springfield</td>
<td>81%</td>
<td>0.370</td>
<td>700</td>
<td>600</td>
</tr>
<tr>
<td>B12C</td>
<td>Li₄AlO₂</td>
<td>Casaccia</td>
<td>81%</td>
<td>0.375</td>
<td>700</td>
<td>600</td>
</tr>
<tr>
<td>B12B</td>
<td>Li₄SiO₄</td>
<td>Karlsruhe</td>
<td>36%</td>
<td>0.410</td>
<td>500</td>
<td>600</td>
</tr>
</tbody>
</table>

B is bottom, C is center, and T is top capsule in each pin.
Open-Capsule Tests

- Purge flow tests are being performed in HFR, SILOE, and NRU

- Complementary data will be obtained on tritium release behavior under irradiation

<table>
<thead>
<tr>
<th>Laboratory</th>
<th>Reactor</th>
<th>Experiment</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECN/Petten</td>
<td>HFR</td>
<td>EXOTIC</td>
<td>(Li$_2$SiO$_3$, Li$_2$Si$_2$O$_5$, Li$_2$ZrO$_3$, Li$_4$SiO$_4$)</td>
</tr>
<tr>
<td>CEA/Saclay</td>
<td>SILOE</td>
<td>LILA*</td>
<td>(γ-LiAlO$_2$, Li$_2$ZrO$_3$)</td>
</tr>
<tr>
<td>KfK/Karlsruhe</td>
<td>SILOE</td>
<td>LISA</td>
<td>(Li$_2$SiO$_3$, Li$_4$SiO$_4$)</td>
</tr>
<tr>
<td>JAERI/Tokai</td>
<td>JRR2</td>
<td>VOM-23H</td>
<td>(Li$_4$SiO$_4$, γ-LiAlO$_2$)</td>
</tr>
<tr>
<td>AECL/Chalk River</td>
<td>NRU</td>
<td>CRITIC**</td>
<td>(Li$_2$O)</td>
</tr>
</tbody>
</table>

* U.S. material provided by ANL (Li$_2$ZrO$_3$)

** U.S. collaboration through ANL
Hydrogen Studies at ANL

- Measure adsorption/desorption of H₂O and He from ceramic breeder in non-irradiated environment.

- Early 1986 to Fall 1987: \( \gamma \)-LiAlO₂

- Starting Fall 1987: Li₄SiO₄ or Li₂ZrO₃ depending on comparative analysis of the two candidate solid breeders
  - thermodynamic calculations at ANL
  - UCLA comparative study of solid breeders
MOTA Experiment
(Materials Open Test Assembly)

• Current operation in FFTF reactor (at HEDL) includes structural and high heat flux fusion material testing

• Plan is to start in-situ tritium recovery experiment in MOTA around 1990 with international collaboration
Tritium Oxidation
(Applicable to Solid Breeders and Liquid Breeders)

• The rate of tritium release is highly dependent on the form of the tritium
  - $T_2O$, Low Release
  - $T_2$, High Release

• Experimental data from TRIO showed a high fraction of release in the $T_2$ form

• It has been assumed in design studies that almost all the tritium is in the water vapor form

• The concerns raised with possible high levels of tritium release warranted an experiment aimed at assessing tritium oxidation rates for expected fusion conditions
Tritium Oxidation Experiment
(cont'd.)

Two competing reactions are possible at the steel surface:

- The combination of tritium atoms and oxygen to form water
- The combination of tritium atoms to form tritium gas

To determine the conditions which favor oxidation, an experimental matrix is being examined in which different parameters are varied:

- Oxygen concentration (<1 to 1000 ppm);
- Tritium atom concentration \((10^{-4}) \text{ to } 1 \text{ Pa})
- Temperature \((350 \text{ to } 550^\circ \text{ C})
- Residence time \((2 \text{ to } 30 \text{ sec})
- Hydrogen concentration \((0-50 \text{ ppm})
- Time (days)
Experimental Apparatus

Loop C
Analytical Loop
(O2/He Circulated)

Loop A
Source Loop
(T2/He Circulated)

Loop B
Reference Loop
(Tritium Calibrated)

Diagram showing the flow of gases and components in the experimental apparatus, including Ion Chamber, Glycol Traps, CuO Bed, 3 L Reservoir, O2 Monitor, 316 SS Reaction Surface, and Tritium/Helium Preparation.
Summary of Tritium Oxidation

- Significant dependence on oxygen was observed:
  - The ratio of HTO/HT is < 1 at oxygen concentrations < 1 ppm
  - The ratio of HTO/HT is > 10 at oxygen concentrations > 50 ppm

- Oxidation rate is a function of:
  - Temperature in the range 350-550° C
  - Residence time in the range 2 to 30 seconds

- Experiment started in 1986 and experimental matrix will be about 60% completed by the end of fiscal 1987
Comparative Study of Solid Breeders (1986)

Lead Organization: UCLA

Objectives

- Provide a consistent comparison of the effect of solid breeder material choice on blanket attractiveness

- Evaluate impact of uncertainties in solid breeder properties and behavior on blanket feasibility and attractiveness

- Provide guidance to the test program on the choice of experimental parameters and solid breeders

Materials and Configurations Considered

<table>
<thead>
<tr>
<th>Without a Multiplier</th>
<th>Homogeneous Solid Breeder/Multiplier Mixture</th>
<th>With a Separate Be Multiplier Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li₂O</td>
<td>LiAlO₂/Be</td>
<td>Li₂O</td>
</tr>
<tr>
<td>Li₂ZrO₃</td>
<td>LiAlO₂/BeO</td>
<td>LiAlO₂</td>
</tr>
<tr>
<td>Li₈ZrO₆</td>
<td>Li₂O/Be</td>
<td>Li₅AlO₄</td>
</tr>
<tr>
<td>Li₂Be₂O₃</td>
<td>Li₂O/BeO</td>
<td>Li₂SiO₃</td>
</tr>
<tr>
<td>Li₇Pb₂</td>
<td></td>
<td>Li₄SiO₄</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Li₂ZrO₃</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Li₈ZrO₆</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Li₂TiO₃</td>
</tr>
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</table>
## Comparative Study of Solid Breeders

**Performance Parameters**

<table>
<thead>
<tr>
<th>Category</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutronics:</td>
<td>Tritium Breeding Ratio, Energy Multiplication, Maximum Li Burnup</td>
</tr>
<tr>
<td>Thermomechanics:</td>
<td>Clad Stress and Deflection, Breeder Thermal Stress</td>
</tr>
<tr>
<td>Tritium:</td>
<td>Tritium Inventory and Permeation</td>
</tr>
<tr>
<td>Activation:</td>
<td>Waste Disposal Rating, Biological Hazard Potential, Recycling Hazard, Afterheat</td>
</tr>
<tr>
<td>Economics:</td>
<td>Material Cost, Net Thermal Efficiency, Power Leakage from Blanket</td>
</tr>
</tbody>
</table>
Table 1.2-6 Blanket Performance Summary

<table>
<thead>
<tr>
<th>Solid Breeder</th>
<th>Effective TBR&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Power Multi.</th>
<th>$\dot{q}$&lt;sup&gt;b&lt;/sup&gt; (W/cm&lt;sup&gt;3&lt;/sup&gt;)</th>
<th>Peak Li Burnup (at. %)</th>
<th>Gross $\eta_{el}$ (%)</th>
<th>Power Leakage (MW)</th>
<th>Blanket SB &amp; M Cost ($M$)</th>
<th>Blanket Total T Inventory (g)</th>
<th>Breeder Permeation Rate (g T/d)</th>
<th>Breeder Power Ratio (%)</th>
<th>Pumping Power Ratio (%)</th>
<th>Dose Rate at 1 m&lt;sup&gt;c&lt;/sup&gt; (REM/hr-g)</th>
<th>Afterheat Time to Reach $T_{max}$ (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cases Without a Multiplier</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Li&lt;sub&gt;2&lt;/sub&gt;O</td>
<td>1.08 (nat)</td>
<td>1.22</td>
<td>41.8</td>
<td>2.9</td>
<td>39.4</td>
<td>5.6</td>
<td>28</td>
<td>5.6</td>
<td>1.4</td>
<td>5.4</td>
<td>0.0029</td>
<td>183</td>
<td></td>
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<tr>
<td>Li&lt;sub&gt;2&lt;/sub&gt;TiO&lt;sub&gt;3&lt;/sub&gt;</td>
<td>0.93 (29)</td>
<td>1.02</td>
<td>35.5</td>
<td>6.1</td>
<td>37.8</td>
<td>4.1</td>
<td>90</td>
<td>85.8</td>
<td>1.8</td>
<td>6.0</td>
<td>24.1</td>
<td>0.048</td>
<td></td>
</tr>
<tr>
<td>Li&lt;sub&gt;2&lt;/sub&gt;Be&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;</td>
<td>0.98 (nat)</td>
<td>1.12</td>
<td>41.4</td>
<td>3.7</td>
<td>38.6</td>
<td>4.2</td>
<td>54</td>
<td>85.2</td>
<td>2.0</td>
<td>5.3</td>
<td>24.1</td>
<td>0.047</td>
<td></td>
</tr>
<tr>
<td>Li&lt;sub&gt;7&lt;/sub&gt;Pb&lt;sub&gt;2&lt;/sub&gt;</td>
<td>1.09 (nat)</td>
<td>1.31</td>
<td>47.6</td>
<td>5.4</td>
<td>39.7</td>
<td>3.4</td>
<td>135</td>
<td>552,000</td>
<td>2.4</td>
<td>4.1</td>
<td>0.031</td>
<td>56</td>
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<tr>
<td>Li&lt;sub&gt;7&lt;/sub&gt;Be&lt;sub&gt;2&lt;/sub&gt;</td>
<td>1.22 (29)</td>
<td>1.18</td>
<td>33.7</td>
<td>5.0</td>
<td>39.1</td>
<td>14.9</td>
<td>110</td>
<td>1,590</td>
<td>2.9</td>
<td>5.6</td>
<td>2.64</td>
<td>0.024</td>
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<tr>
<td>Cases With a Homogeneous SB/M Mixture</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LiAlO&lt;sub&gt;2&lt;/sub&gt;/Be</td>
<td>1.51 (36)</td>
<td>1.51</td>
<td>43.9</td>
<td>46.8</td>
<td>41.4</td>
<td>7.1</td>
<td>104</td>
<td>230</td>
<td>2.2</td>
<td>3.1</td>
<td>1.86</td>
<td>5.4</td>
<td></td>
</tr>
<tr>
<td>LiAlO&lt;sub&gt;2&lt;/sub&gt;/BeO</td>
<td>1.09 (40)</td>
<td>1.36</td>
<td>43.5</td>
<td>35.3</td>
<td>40.3</td>
<td>6.1</td>
<td>96</td>
<td>76.5</td>
<td>1.3</td>
<td>3.6</td>
<td>1.27</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Li&lt;sub&gt;2&lt;/sub&gt;O/Be</td>
<td>1.57 (nat)</td>
<td>1.52</td>
<td>45.9</td>
<td>19.5</td>
<td>41.2</td>
<td>4.7</td>
<td>73</td>
<td>8.1</td>
<td>2.3</td>
<td>3.1</td>
<td>0.0033</td>
<td>420</td>
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<tr>
<td>Li&lt;sub&gt;2&lt;/sub&gt;O/BeO</td>
<td>1.14 (14)</td>
<td>1.36</td>
<td>43.7</td>
<td>14.3</td>
<td>40.3</td>
<td>3.8</td>
<td>81</td>
<td>9.5</td>
<td>1.6</td>
<td>3.7</td>
<td>0.027</td>
<td>940</td>
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<tr>
<td>Cases With a Separate Be Multiplier Region</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Li&lt;sub&gt;2&lt;/sub&gt;O</td>
<td>1.24 (20)</td>
<td>1.42</td>
<td>81.6</td>
<td>15.8</td>
<td>40.7</td>
<td>1.2</td>
<td>68</td>
<td>43.9</td>
<td>1.2</td>
<td>3.5</td>
<td>0.0029</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>LiAlO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>1.09 (62)</td>
<td>1.39</td>
<td>64.9</td>
<td>37.8</td>
<td>40.4</td>
<td>2.5</td>
<td>75</td>
<td>36.4</td>
<td>1.1</td>
<td>3.6</td>
<td>7.1</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>Li&lt;sub&gt;5&lt;/sub&gt;AlO&lt;sub&gt;4&lt;/sub&gt;</td>
<td>1.17 (30)</td>
<td>1.40</td>
<td>72.6</td>
<td>23.2</td>
<td>40.6</td>
<td>2.5</td>
<td>68</td>
<td>23</td>
<td>1.9</td>
<td>3.3</td>
<td>7.1</td>
<td>0.51</td>
<td></td>
</tr>
<tr>
<td>Li&lt;sub&gt;2&lt;/sub&gt;SiO&lt;sub&gt;3&lt;/sub&gt;</td>
<td>1.10 (50)</td>
<td>1.37</td>
<td>68.5</td>
<td>31.2</td>
<td>40.4</td>
<td>2.6</td>
<td>78</td>
<td>9.6</td>
<td>1.7</td>
<td>3.4</td>
<td>0.14</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>Li&lt;sub&gt;2&lt;/sub&gt;SiO&lt;sub&gt;4&lt;/sub&gt;</td>
<td>1.14 (33)</td>
<td>1.38</td>
<td>70.0</td>
<td>24.9</td>
<td>40.5</td>
<td>2.5</td>
<td>71</td>
<td>9.2</td>
<td>1.5</td>
<td>3.5</td>
<td>0.14</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>Li&lt;sub&gt;2&lt;/sub&gt;ZrO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>1.17 (58)</td>
<td>1.27</td>
<td>67.1</td>
<td>31.8</td>
<td>39.7</td>
<td>2.4</td>
<td>97</td>
<td>47</td>
<td>1.3</td>
<td>3.9</td>
<td>24.1</td>
<td>0.041</td>
<td></td>
</tr>
<tr>
<td>Li&lt;sub&gt;2&lt;/sub&gt;TiO&lt;sub&gt;3&lt;/sub&gt;</td>
<td>1.22 (26)</td>
<td>1.34</td>
<td>74.6</td>
<td>21.2</td>
<td>40.3</td>
<td>2.1</td>
<td>91</td>
<td>45.4</td>
<td>1.6</td>
<td>3.5</td>
<td>24.1</td>
<td>0.036</td>
<td></td>
</tr>
<tr>
<td>Li&lt;sub&gt;2&lt;/sub&gt;TiO&lt;sub&gt;3&lt;/sub&gt;</td>
<td>1.12 (51)</td>
<td>1.39</td>
<td>65.5</td>
<td>32.9</td>
<td>40.6</td>
<td>3.2</td>
<td>77</td>
<td>4.1</td>
<td>1.1</td>
<td>3.6</td>
<td>5.6</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> 6Li enrichment corresponding to optimum TBR is shown in parentheses; (nat) is for natural lithium (7.25% 6Li).

<sup>b</sup> At 0.5 cm from tip of breeder plate.

<sup>c</sup> After 3-year irradiation and 10-hour cooling.

For the separate multiplier cases, the dose rate for Be is 0.0034 REM/hr-g and is due entirely to impurities.

For the homogeneous SB/M mixture cases, the dose rate for the multiplier (0.0034 REM/hr-g for Be and = 0.03 REM/hr-g for BeO) have been included in these figures.
Summary of Experiments

• Phase I
  - Late 1984 to March 1986
  - Open Geometry
    \( \text{Li}_2\text{O} \) assembly
    Be added later

• Phase II
  - August 1986 to October 1987
  - Closed Geometry
    \( \text{Li}_2\text{O} \) assembly/\( \text{Li}_2\text{CO}_3 \) container
    Be multiplier

• Phase III
  - Begins Late 1987
  - Important Engineering Features
  - New Important Material
EXPERIMENTAL SYSTEM FOR PHASE-2 OF US/JAERI PROGRAM ON BLANKET NEUTRONICS

SCHEMATIC OF REACTOR MODEL

SIMULATED BLANKET TESTING ZONE (Li₂O)
ENCLOSURE (Li₂CO₃)
ROTATING NEUTRON TARGET
ACCELERATOR BEAM DUCT
SUPPORT

TESTING ZONE

D-T PLASMA
BLANKET
PHASE I

BLANKET TEST ASSEMBLIES INVESTIGATED

• Reference System

SINGLE-REGION Li₂O BREEDER
60 cm Li₂O

• First Walled System

<table>
<thead>
<tr>
<th>No first wall</th>
<th>/60 cm Li₂O*</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 cm SS</td>
<td>/60 cm Li₂O</td>
</tr>
<tr>
<td>0.5 cm SS / 0.5 cm PE</td>
<td>/60 cm Li₂O</td>
</tr>
<tr>
<td>1.5 cm SS</td>
<td>/60 cm Li₂O</td>
</tr>
<tr>
<td>1.5 cm SS / 0.5 cm PE</td>
<td>/60 cm Li₂O</td>
</tr>
</tbody>
</table>

• Be Neutron Multiplier System

<table>
<thead>
<tr>
<th>5 cm Be</th>
<th>/60 cm Li₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 cm Be</td>
<td>/60 cm Li₂O</td>
</tr>
<tr>
<td>5 cm Li₂O / 5 cm Be</td>
<td>/60 cm Li₂O**</td>
</tr>
<tr>
<td>10 cm Li₂O</td>
<td>/60 cm Li₂O</td>
</tr>
</tbody>
</table>

*: IDENTICAL WITH REFERENCE SYSTEM
**: BE SANDWICHED SYSTEM
+: TYPE 316 STAINLESS STEEL
++: POLYETHYLENE AS SIMULANT OF WATER
MEASURED ITEMS AND METHODS APPLIED

TRITIUM PRODUCTION RATES

On-line Type (JAERI)
  T6: Paired Li Glass Scintillation Counters
  T7: Micro Spherical NE213 Spectrometer
  - INDIRECT METHOD -

Irradiation Type
  T6 : Li$_2$O Pellet/Liq. Scint.* (JAERI)
  T7 : Li Metal Foil/Liq. Scint. (ANL)
  TN

NEUTRON SPECTRUM

On-line Type
  Fast Neutron: NE213 Spectrometer
  0.5 MeV < E < 15 MeV (JAERI)
  Slow Neutron: Proton Recoil Spectrometer**
  5 keV < E < 2 MeV (ANL)

Irradiation Type (JAERI)
  Activation Foils: Al, Au, Co, In, Nb, Ni
  Spectral Indices: Ti, Zn, Zr

* Liquid Scintillation Counting Method
** Input Source Spectrum only
Assemblies for the Experiments on Neutron Multiplier Effect

Reference
\[
\text{Li}_2\text{O} \ 60 \text{ cm Li}_2\text{O}
\]
Ass'y O
(Previous Experiments)

Be
Be in the front (I)
\[
\text{Be} \ 5 \text{ cm Li}_2\text{O} \ 60 \text{ cm}
\]
Ass'y I

Be in the front (II)
\[
\text{Be} \ 10 \text{ cm Li}_2\text{O} \ 60 \text{ cm}
\]
Ass'y II

Be Sandwiched
\[
\text{Li}_2\text{O} \ 5 \text{ cm Be} \ 5 \text{ cm Li}_2\text{O} \ 60 \text{ cm}
\]
Ass'y III

Reference Prime
\[
\text{Li}_2\text{O} \ 10 \text{ cm Li}_2\text{O} \ 60 \text{ cm}
\]
Ass'y IV
Tritium Production Rate From $^6\text{Li}$, $^7\text{Li}$, in the Beryllium-Sandwiched System

- (US)$_C^c$ / (US)$_E^c$ corr. - Li-Metal Detectors
- (JAERI)$_C^c$ / (US)$_E^c$ corr. - Li-Metal Detectors
- (US)$_C^c$ / (JAERI)$_E^c$ corr. - $\text{Li}_2\text{O}$ Pellets Detectors
- (JAERI)$_C^c$ / (JAERI)$_E^c$ corr. - $\text{Li}_2\text{O}$ Pellets Detectors

Calculated to Measured Value, C/E

Distance from the Front Surface of the $\text{Li}_2\text{O}$ Assembly, cm
TRITIUM PRODUCTION RATES FROM Li-6, USING FOILS
IN THE CENTRAL DRAWER (PHASE-II REFERENCE CASE)

legend
○ = MCNP-3A
△ = DOT-4.3

Distance from Front Surface of the Li2O Assembly, (cm)

Calculated to Experimental Value, C / E
TRITIUM PRODUCTION RATE FROM Li–6, T6, USING Li–GLASS DETECTOR IN THE CENTRAL DRAWER (PHASE–II REFERENCE CASE)
ADVANCED LINE SOURCE FOR TRITIUM BREEDING EXPERIMENTS

TARGET ASSEMBLY

ANNULAR TEST MODULES

DIRECTON OF MOTION

DETECTOR

PEDESTAL

POSITION SENSING DEVICE

DRIVE CONTROL

MOVABLE CARRIAGE

RAILS
Approx. Level of Effort
(man years/year)

- Solid Breeder ~ 6.0
  - Experiments (irradiation, characterization)
  - Including Part of Modelling

- Oxidation Kinetics ~ 2.3

- Neutronics ~ 4.5
  - Experiments
  - Pre- and Post-Experiment Analysis
Comparative Study of Solid Breeders

Results and Conclusions

• A neutron multiplier is needed for all solid breeders, except possibly for Li$_2$O

• Cases with a homogeneous mixture of Be and solid breeder have superior neutronics performance to those with separate Be and solid breeder regions

• Be is superior to BeO based on improvement of tritium breeding and energy production, and lower tritium diffusive inventory in multiplier

• Li$_2$O is the most attractive solid breeder with or without a multiplier

• Li$_4$SiO$_4$ and Li$_2$SiO$_3$ (to a lesser extent) appear to be the most attractive ternary ceramics

• Li$_2$Be$_2$O$_3$ and Li$_7$Pb$_2$ are not particularly attractive; Li$_2$Be$_2$O$_3$ has a large tritium diffusive inventory (assuming BeO-like tritium diffusion) and a marginal tritium breeding ratio; and Li$_7$Pb$_2$ has a low energy multiplication, relatively high tritium inventory and a limited operating temperature range
Comparative Study of Solid Breeders

Recommendations for Test Program

Materials:
- \( \text{Li}_2\text{O} \) without a multiplier
- \( \text{Li}_2\text{O} \), \( \text{Li}_4\text{SiO}_4 \) and \( \text{Li}_2\text{SiO}_3 \) with Be
  (\( \text{LiAlO}_2 \) should also be considered because of chemical stability considerations)

Configurations:
- Homogeneous mixtures of beryllium and solid breeder should be included in the test matrix in addition to the separate breeder and multiplier configuration
- Sphere-pac form is more attractive than sintered block form

Properties:
Experimental effort should be pursued to reduce the large uncertainties in tritium-related properties. These properties are important for designs as well as breeder comparisons

Test Conditions:
- Better definition of burnup limits is required
- Tests should also include temperature gradients to determine the importance of cracking and/or breeder mass transfer
Present U.S. Neutronics Activities

- Almost all activities are part of international agreements

- US—Japan cooperation
  —Facility: FNS at JAERI, Japan (14 MeV neutron source, neutronics mockup facility)
  —US organizations: UCLA, ANL, ORNL
  —Focus: Tritium breeding, nuclear heating with candidate materials and representative configurations

- LBM at LOTUS
  —Test module constructed by GA
  —Neutronics experiments at LOTUS in Switzerland

- Activities on data and method improvements
U.S./JAERI Collaboration
Program on Fusion Neutronics

*Joint Effort* (Annex II) to perform and analyze integral
neutronics experiments

*Facility*

- Fusion Neutron Source (FNS) at JAERI, Japan

- FNS was constructed with capabilities specifically
  suited for fusion

*Objectives*

1. Contribute to resolving tritium self-sufficiency issue

   - Evaluate uncertainty in state-of-the-art tritium
     breeding estimates by comparing calculations and
     experiments

   - Identify and improve deficiencies in nuclear data,
     calculations and modelling

2. Develop the neutronics technology necessary for the
next fusion device (components and testing modules),
e.g., experimental measurement techniques for neutron
spectra