SOMBRERO is an attractive conceptual IFE power plant of relatively simple design

- SOMBRERO is a conceptual design for a 1000 MW$_e$ laser-driven IFE power plant

- Safety and environmental attractiveness has been given strong emphasis since the original report

- Design uses a low activation material (C/C composite) for chamber structures

- Blanket consists of a moving bed of solid Li$_2$O particles flowing in a He carrier gas through the chamber
LLNL is conducting safety analyses for SOMBRERO

- Recent work has pointed out the need to address key safety issues
  - tritium retention in C/C composites (seems to be more important than reported originally)
  - graphite oxidation with air (appears to be significant even at $T < 1000 \, ^\circ C$)
  - discussions with U. Wisconsin and INEEL colleagues have been great help

- We have performed a worst case accident analysis for SOMBRERO
  - need to be conservative at this early stage
  - similar analysis will be performed for more credible, less severe accidents

- Accident consists of
  - total loss of flow accident (LOFA) in the 4 circuits of the coolant loop
  - simultaneous loss of vacuum accident (LOVA) with air ingress produced by 1 m² breach in confinement

- Our goal is to meet DOE requirement of accident dose $\leq 1$ rem (10 mSv) for no public evacuation
Codes and methodologies

- Codes traditionally used for MFE safety studies have been adopted and adapted for IFE safety analysis.

  - **CHEMCON** heat transfer code:
    - simulates time-temperature excursions of components due to radioactive afterheat and carbon oxidation (oxidation package has been enhanced).
    - time-temperature histories are then used to evaluate mobilization fractions during the transient.

  - **MELCOR** thermal hydraulics code:
    - uses the calculated radioactive source term available for mobilization.
    - models thermal-hydraulics and aerosol and fusion products transport and release.
    - new module introduced by INEEL allows simulation of HTO transport and condensation.
Time-temperature history of reactor components

• There are various energy sources to be considered during the accident:
  – **fusion reactions** will stop due to graphite evaporation increasing the pressure of the building and stopping beam propagation (shutdown)
  – **radioactive decay heat** from activated structures is low enough to allow a rapid cooling of FW/blanket structures (T < 1000 °C in less than 1 minute)
  – **oxidation heat** from exothermic graphite/air reaction must be considered

• 1D cylindrical CHEMCON model used to calculate heat transfer and graphite oxidation

• Preliminary calculations showed that the FW burnt in only 2 hours (the whole FW/blanket structure in about a day and a half)

• Oxidation should be limited by the partial pressure of oxygen in the surroundings of the FW/blanket
  – chamber/confinement initially at vacuum and oxygen must travel through the building
  – oxygen must diffuse across CO gas layer generated by the oxidation
Time-temperature history of reactor components (cont)

- Iterative process and feedback is needed using the CHEMCON (oxidation code) to get the CO source and MELCOR (thermal-hydraulics code) to get the oxygen partial pressure.

- Convergent solution shows that FW burns in ~7 hours (oxidation rate is still significant at $T < 1000 \, ^\circ C$).

Time-temperature evolution of reactor components due to decay heat

Time-temperature evolution of reactor components due to oxidation and decay heat
Activation products source term

- Assuming that oxidation takes place, the radioactivity source terms available for mobilization are:
  - total mass of carbon from FW/blanket structures (due to graphite oxidation with air)
  - fraction of Li₂O inventory present in the chamber in the moment of the accident (1/3 of the total 2000 tonnes)
  - we assume 1 kg of tritium trapped in the FW (instead of 10 g from original report), getting a total of 1.173 kg of tritium in all reactor structures which will be mobilized during the accident
  - the chamber gas (Xe in the SOMBRERO report) with all its activation products

- If oxidation could be avoided (thus eliminating a significant temperature excursion) then only the chamber gas and 0.173 kg of tritium would be mobilized during the accident
Radioactivity release and off-site doses: with oxidation

<table>
<thead>
<tr>
<th>Radioactive source</th>
<th>Mobilized activity (Bq)</th>
<th>Release fraction (%)</th>
<th>Dose at site boundary (rem)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C_FW</td>
<td>6.1E+14</td>
<td>100</td>
<td>0.05</td>
</tr>
<tr>
<td>C_blanket</td>
<td>1.4E+15</td>
<td>100</td>
<td>0.12</td>
</tr>
<tr>
<td>Li$_2$O</td>
<td>5.8E+18</td>
<td>1.5E-04</td>
<td>0.00</td>
</tr>
<tr>
<td>HTO</td>
<td>4.2E+17</td>
<td>19</td>
<td>0.78</td>
</tr>
<tr>
<td>Xe/Xe*/Kr</td>
<td>1.4E+16/1.4E+16/8.8E+15</td>
<td>100/100/100</td>
<td>4.69/0.24/0.11</td>
</tr>
<tr>
<td>Total with Xe/Xe*/Kr</td>
<td>6.2E+18/6.2E+18/6.2E+18</td>
<td>100/100/100</td>
<td>5.64/1.19/1.06</td>
</tr>
</tbody>
</table>

Xe* = Xe with clean up of iodine and cesium activation products

- The total dose is dominated by the activated Xe chamber gas, which contributes 4.69 rem to the global result
- Design using Xe would lead to a dose of 5.64 rem if the iodine and cesium activation products are included in the release (would be 1.19 rem if these isotopes can be removed by the chamber vacuum system)
- For a modified Sombrero using Kr, we calculate a total off-site dose of 1.06 rem
Radioactivity release and off-site doses: with oxidation (cont)

- DOE requires dose ≤ 1 rem (10 mSv) for no public evacuation

- Assuming Xe* (with clean up) or Kr is used as the chamber gas, the dose is dominated by the tritium

- Reducing the temperature of the concrete building by increasing its thermal conductivity will enhance HTO condensation on walls

- Two options are proposed:
  - increasing steel content in concrete form 2.8 % to 5% vol. would reduce the tritium release to 14% and the final dose to 1 rem case of Xe*, and 0.87 rem case of Kr
  - using concrete with 3% vol. aluminum would give a tritium release fraction of 11% and a total dose of 0.81 rem case of Xe*, and 0.68 rem case of Kr

- Any of these design modifications results in dose ≤ 1 rem, no evacuation plan would be needed
Radioactivity release and off-site doses: without oxidation

<table>
<thead>
<tr>
<th>Radioactive source</th>
<th>Mobilized activity (Bq)</th>
<th>Release fraction (%)</th>
<th>Dose at site boundary (rem)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTO</td>
<td>6.2E+16</td>
<td>2.8</td>
<td>0.02</td>
</tr>
<tr>
<td>Xe/Xe*/Kr</td>
<td>1.4E+16/ 1.4E+16/ 8.8E+15</td>
<td>100/100/100</td>
<td>4.69/0.24/0.11</td>
</tr>
<tr>
<td>Total with Xe/Xe*/Kr</td>
<td>7.6E+16/ 7.6E+16/ 7.1E+16</td>
<td></td>
<td>4.71/0.26/0.13</td>
</tr>
</tbody>
</table>

Xe* = Xe with clean up of iodine and cesium activation products

- In this case the only radioactive source terms are the chamber gas and the 172.6 g of tritium trapped in structures other than the carbon FW/blanket

- Design using Xe results in 4.71 rem if the non-xenon activation products were included in the release (only 0.26 rem if the iodine and cesium isotopes were removed by the chamber vacuum system)

- For a modified version using Kr instead of Xe, the final off-site dose is 0.13 rem
Conclusions

- Assuming oxidation of carbon structures, dose is **5.64 rem** in the case of Xe as chamber gas and **1.06 rem** if Kr is used instead.

- Simple modifications in the confinement building material would reduce the dose below **1 rem** for case with Kr or Xe* (with iodine and cesium removal) evacuation plan not needed.

- If oxidation does not take place then the dose would be **0.26 rem** in the case of Xe* (with iodine and cesium removal) and **0.13 rem** if Kr was used would not require an evacuation plan.

- Oxidation could be avoided
  - passive safety feature should be easy to implement (inert gas released from tank by rupture disk failure when a differential pressure is reached)
  - protective coatings for C/C composites (Si-B-C coatings)
  - alternative materials for FW and/or blanket structures
Future work in SOMBRERO safety analysis

• Tritium inventory:
  – tritium trapped in FW/blanket may be greater than 1 kg according to available data (need more accurate estimation)
  – use of steam in the He carrier gas may reduce tritium inventory but needs to be evaluated

• Oxidation prevention:
  – passive safety feature could prevent oxygen from reaching carbon structures
  – protective coatings for carbon composites may be appropriate for oxidation protection of FW and blanket
  – alternate materials for FW and/or blanket structures should be considered

• We plan to complete our safety analysis including alternate severe accidents as well as other more credible, less severe scenarios