Recent Developments in the HIBALL Conceptual Reactor Design

HIBALL Team

June 1982

FPA-82-3

Presentation at KfK-Karlsruhe, FRG, 3-4 June 1982
MAJOR ACTIVITIES ON HIBALL
FROM JANUARY – MAY 1982

• Beam Line Neutronics (March Meeting)

• Cost Optimization (March Meeting)

• Improvements in Evaporation/Condensation Model

• Sabot Heating Calculations

• Analysis of Upper Blanket Design

• Pb–Li Droplet Formation on Cavity Roof

• Shock Effects on Upper Roof

• T₂ Extraction, Confinement, and Inventory

• Mechanical Properties Tests of SiC Fibers

• Presentations: Darmstadt, FRG and Ottawa, Canada
$t = 0$

TARGET EXPLOSION

$t = 10^{-8}$ sec

Target generated x-rays

$t \sim 10^{-4}$ sec

Target debris

$10^{-4} \text{sec} \leq t \leq 5 \cdot 10^{-4} \text{sec}$

Vapor

$5 \cdot 10^{-4} \text{sec} \leq t \leq 2 \cdot 10^{-3} \text{sec}$

Radiant heat

$2 \cdot 10^{-3} \text{sec} \leq t \leq 0.3\text{sec}$

Condensation

0 to 5 meters
IMPROVED MODELING OF TARGET CHAMBER GAS CONDENSATION

• SELF-CONSISTENT ANALYSIS OF RADIATION TRANSPORT, CONDENSATION AND EVAPORATION

• MOMENTUM AND ENERGY EXCHANGE BETWEEN VAPOR AND FILM ON TUBES

• TRANSITION BETWEEN VISCOUS AND MOLECULAR FLOW

• SAHA AND CORONAL IONIZATION CONSIDERED

• IMPROVED TREATMENT OF LINE RADIATION

N.B. ALL OF THESE IMPROVEMENTS ARE INCLUDED IN THE CODES CONRAD AND MIXERG.
PARTICLE DENSITY vs. TIME

Mo = 13 kg

Improved

HIBALL-1

4 x 10^{10} \text{ cm}^{-3}

TIME (sec)
CONденSATION CONCLUSIONs

• CONRAD predicts 0.3 s needed to clear cavity of vapor.

• CONRAD underestimates temperature of gas during condensation phase.

• 0.3 s is an upper bound on condensation time.
Figure III-5-4 Scheme of Hiball-I Pneumatic Injection System and Design Parameter Values, Pellet Velocity = 200 m/s
HEATING OF SABOT AND TARGET WHILE IN INJECTOR GUN BARREL

• FRICTIONAL HEATING POWER

\[ q_f = f \cdot p \cdot v \]

\[ f = 0.05 \text{ (Teflon on steel)} \]

\[ p = 10^5 \text{ N/m}^2 \]

\[ v = 100 \text{ m/s} \]

\[ q_f = 51.3 \text{ W/cm}^2 \]

• ACCELERATION TIME = 20 ms

• THE TARGET MUST RECEIVE VERY LITTLE HEAT FROM THE SABOT BECAUSE HEATING OF THE TARGET BY THE TARGET CHAMBER IS NEAR THE CRITICAL LEVEL.
• axially symmetric pellet storage
  contact between pellet and sabot:
  $a_1$: compensation of inertial force
  – tensile stresses of materials
  (acceleration $1000 \text{ g} - a_1 \text{ some mm}^2$)
  $a_2, a_3$ (annular): very small – small heat transfer

• material: plastics
  e.g.: Teflon (reference material)
  thermal properties at cryogenic temperatures are available
HEATING OF TARGET & SABOT IN INJECTOR

\[ q'' = 51.3 \text{ W/cm}^2 \]

FRICIONAL HEATING

70
60
50
40
30
20
10
0

TEMPERATURE (°K)

0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0

RADIUS (cm)

P₁
P₂
P₃

Teflon
Lead-Bismuth
Void
SABOT SUMMARY

CONCLUSION

• TARGET IS INSULATED FROM FRICTIONAL HEAT BY SABOT

OTHER ISSUES

• TEFLOM MAY BE TOO EXPENSIVE

• SURVIVABILITY OF SABOTS
PROBLEMS OF CAVITY UPPER BLANKET DESIGN

1 STRESS OF SiC FABRIC DUE TO BREEDING MATERIAL PRESSURE

2 FORMATION AND RELEASE OF DROPLETS FROM UPPER BLANKET

3 SHOCK EFFECTS ON UPPER BLANKET
HYDROSTATIC LOADING

LOCAL PRESSURE

PRESSURE PROFILE

2 PSI

20.17 PSI
MAXIMUM STRESS STATE

SILICON CARBIDE SHELL

PRINCIPAL STRESSES
UPPER BLANKET PROFILE COMPARISONS

SINGLE LOBE
RADIUS: 1.25 m = 49.0 in
STRESS: 172 MPa = 25.0 ksi

DOUBLE LOBE
RADIUS: 0.375 m = 14.8 in
STRESS: 51.7 MPa = 7.5 ksi

TRIPLE LOBE
RADIUS: 0.25 m = 9.8 in
STRESS: 34.5 MPa = 5.0 ksi
## Upper Blanket Design Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module Structural Material</td>
<td>SiC</td>
</tr>
<tr>
<td>Number of Modules</td>
<td>30</td>
</tr>
<tr>
<td>Length of Module (cm)</td>
<td>680</td>
</tr>
<tr>
<td>Width of Module at Fabric Termination (cm)</td>
<td>130</td>
</tr>
<tr>
<td>Depth of Cylindrical Portion (cm)</td>
<td>16.3</td>
</tr>
<tr>
<td>Front SiC Fabric Thickness (cm)</td>
<td>0.1</td>
</tr>
<tr>
<td>Maximum Pressure of Fabric (atm)</td>
<td>1.37</td>
</tr>
<tr>
<td>Maximum Hoop Stress (MPa)</td>
<td>22.8</td>
</tr>
<tr>
<td></td>
<td>(ksi)</td>
</tr>
</tbody>
</table>
DROP RELEASE DUE TO GRAVITY

### Gravitational Force

\[ F_g = \frac{4}{6} \pi r^3 \rho g \]

### Adhesive Force

\[ F_a = \Gamma 2 \pi r \]

**Where** \( \Gamma \) **is surface tension**

Taking \( \Gamma = 450 \text{ dynes/cm} \)

And equating \( F_g = F_a \)

We get \( r = 0.38 \text{ cm} \)

\[ \delta \leq r \]

\[ \delta = 0.1 - 0.3 \text{ cm} \]
ALLOWABLE SEEPAGE RATE

\[ F_a = \rho g x \sin \theta \]

\[ F_r = -\mu \frac{dV}{dx} \]

\[ V(x) = \frac{\rho g \delta^2}{2\mu} \left[ 1 - \left( \frac{x}{\delta} \right)^2 \right] \sin \theta \]

VOLUMETRIC FLOW RATE AT ANY RADIUS \( r \)

\[ Q(r) = \frac{\rho g \delta_r^3 \sin \theta (2\pi r)}{3 \mu} \]

AT \( R = 5 \text{ m}, \theta = 7^\circ \) AND TAKING \( \mu = 0.017 \frac{\text{gm}}{\text{sec.cm}} \)

<table>
<thead>
<tr>
<th>( \delta_R ) (cm)</th>
<th>( Q_R ) (cm³/sec.)</th>
<th>( Q/A ) (cm³/sec.cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.7 x 10⁵</td>
<td>0.09</td>
</tr>
<tr>
<td>0.2</td>
<td>5.6 x 10⁵</td>
<td>0.71</td>
</tr>
<tr>
<td>0.3</td>
<td>18.9 x 10⁵</td>
<td>2.4</td>
</tr>
</tbody>
</table>
SHOCK EFFECTS ON UPPER BLANKET

1 PRESSURE INCREASE

2 RELEASE OF DROPLETS FROM UPPER BLANKET

POSSIBLE SOLUTIONS

INTRODUCTION OF FREE SURFACES WITHIN THE BREEDING MATERIAL BY:

a) Injecting Gas Bubbles (He or other gas)
b) Injecting LiPb Vapor
In-Situ Boiling LiPb

UTILIZING A PERFORATED PLATE TO HELP DAMP THE SHOCK
INTERESTING OBSERVATIONS ON DROPLETS

1 Unlike the case in HYLIFE, where drops are the result of jet disassembly, in HIBALL the drops originate on the upper blanket and fall down by gravity.

2 No matter where on the upper blanket the droplet originates, it will take at least one second before it will intersect a beam path. Thus it will be exposed to 5 shots and may be:
   a) fragmented
   b) evaporated
   c) accelerated radially and trapped on the inport units

3 Only 3.2% of the cavity area contains beam paths.
CONCLUSIONS

A SOLUTION TO ALL THE PROBLEMS OF THE PROPOSED UPPER BLANKET DESIGN WILL REQUIRE AN EXTENSIVE ANALYTICAL AND EXPERIMENTAL PROGRAM

ANALYTICAL

• SHOCK EFFECTS AND CONSEQUENCES

• EFFECT OF DROPLET RELEASE

EXPERIMENTAL

• FABRIC STRUCTURE FOR DESIRED SEEPAGE

• WETTING CHARACTERISTICS

• COMPATIBILITY
TRITIUM ISSUES

• Review of the tritium extraction scheme for HIBALL

• Containment Issues

  Review of tritium permeation into the steam cycle

  Use of double-walled tubes to prevent tritium losses in the heat exchanger

  Secondary containment of liquid metal piping in reactor buildings

• Inventory Concerns

  Target factory

  Review of overall inventory
## TRITIUM EXTRACTION

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tritium removal method</td>
<td>Vacuum pumping from the reactor chamber</td>
</tr>
<tr>
<td>Tritium breeding rate</td>
<td>$2.94 \times 10^{-3}$ mol T$_2$/s</td>
</tr>
<tr>
<td>Tritium partial pressure above 17Li : 83Pb</td>
<td>$10^{-4}$ torr</td>
</tr>
<tr>
<td>Tritium solubility at $10^{-4}$ torr</td>
<td>$5.1 \times 10^{-4}$ wppm</td>
</tr>
<tr>
<td>% tritium extracted</td>
<td>9.2</td>
</tr>
<tr>
<td>Extraction rate</td>
<td>$3.6 \times 10^5$ l/s</td>
</tr>
<tr>
<td>Pumping rate to remove cavity gases (700 K and $10^{-4}$ torr)</td>
<td>$\sim 4 \times 10^6$ l/s</td>
</tr>
<tr>
<td>Tritium inventory in 17Li : 83Pb (4 cavities)</td>
<td>10 g</td>
</tr>
</tbody>
</table>
TRITIUM PERMEATION IN HEAT EXCHANGER

PERMEATION RATE FOR HT–9

clean, single-walled tubing with 1 mm thickness
Tritium Partial Pressure = 10^{-4} torr

\[ P_T = 2.26 \times 10^4 \exp(-\frac{11100}{RT}) \text{ Ci/d x Area (m}^2\text{)} \]

<table>
<thead>
<tr>
<th></th>
<th>PREBOILER</th>
<th>BOILER</th>
<th>SUPERHEATER</th>
</tr>
</thead>
<tbody>
<tr>
<td>AREA, m²</td>
<td>1.52x10⁴</td>
<td>2.0x10⁴</td>
<td>4.72x10⁴</td>
</tr>
<tr>
<td>AVG. TEMP., °C</td>
<td>310</td>
<td>352</td>
<td>428</td>
</tr>
<tr>
<td>PERMEATION, Ci/d</td>
<td>2.4x10⁴</td>
<td>5.9x10⁴</td>
<td>3.7x10⁵</td>
</tr>
</tbody>
</table>

PERMEATION RATE = 4.5x10⁵ Ci/d

TRITIUM BARRIER REQUIREMENT ~ 10⁵ to limit losses in the heat exchanger to < 10 Ci/d
EXTRACTION & CONTAINMENT PARAMETERS AS A FUNCTION OF TRITIUM PARTIAL PRESSURE

VACUUM PUMPING
BREEDING RATE
(1 CAVITY) = 7.4x10^-4 mol/s
TEMPERATURE = 500°C
COST = $ 0.19/ℓ/s
• With no diffusion barrier, T leakage rate is $4.5 \times 10^5$ Ci/d.  
(For single wall.)

• A diffusion barrier of $10^5$ is needed.

• The total tritium leakage is the summation of diffusion across the gap and diffusion across the contact point.

• A diffusion barrier of $10^5$ to $10^6$ is available across the gap with oxide coatings.
B. THE TRITIUM DIFFUSION ACROSS THE GAP

1. THE EFFECT OF THE THICKNESS $\delta$ OF THE 1 TORR O$_2$ LAYER.

THE PERMEATION PROBLEM OF FIG. 3A IS SIMPLIFIED THROUGH B TO C, BECAUSE IT CAN BE SHOWN THAT THE DIFFUSION RATE OF T$_2$ ALONG THE Y DIRECTION IS MUCH SMALLER THAN THE CAPTURE RATE OF T$_2$ BY O$_2$ TO FORM T$_2$O. SO, THE EQUATIONS FOR T$_2$ CONCENTRATION AND BOUNDARY CONDITIONS ARE AS FOLLOWS:

$$D_1 \frac{d^2c_1}{dx^2} - \frac{v}{x} c_1 = 0$$

$$D_2 \frac{d^2c_2}{dx^2} = 0$$

AT $x = 0$ \hspace{1cm} $D_1 \frac{dc_1}{dx} = J_0$

$x = \delta$ \hspace{1cm} $-D_1 \frac{dc_1}{dx} = -D_2 \frac{dc_2}{dx}$

$\kappa_s (c_1 RT)^{1/2} = c_2$

$x = L$ \hspace{1cm} $c_2 = 0$

WHERE $v$ - VELOCITY OF T$_2$

$\lambda$ - MEAN FREE PATH OF T$_2$ COLLISION WITH O$_2$

$J_0$ - THE T$_2$ CURRENT PENETRATING THE 1ST WALL AND IS CALCULATED TO BE $1.9 \times 10^{-13}$ GMOL T$_2$/CM$^2$ SEC AT T = 400°C.

WITH THE FOLLOWING PARAMETERS,

$v = 1.4 \times 10^5$ CM/SEC, $D_1 = 4$ CM$^2$/SEC, $D_2 = 4.18 \times 10^{-5}$ CM$^2$/SEC

$\lambda = 1.87 \times 10^{-2}$ CM, $\kappa_s = 1.24 \times 10^{-6}$ GMOL T$_2$/(CM$^3$ X ATM$^{1/2}$)

THE SOLUTION OF THE PROBLEM IS

$c_1(x) = 3.58 \times 10^{-17} e^{-1370x} + (e^{-1370x} + e^{1370x}) B$

$c_2(x) = E (1 - \frac{x}{\delta + \delta})$

FOR DIFFERENT VALUES OF $\delta$, THE COEFFICIENTS B, E, CURRENT J AND PERMEATION P ARE LISTED IN TABLE 1 AND SHOWN IN FIGURE 4.
TABLE 1

<table>
<thead>
<tr>
<th>δ CM</th>
<th>0.0025</th>
<th>0.001</th>
<th>0.0025</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>3.61 x 10^{-17}</td>
<td>2.44 x 10^{-18}</td>
<td>3.68 x 10^{-20}</td>
</tr>
<tr>
<td>E</td>
<td>3.05 x 10^{-12}</td>
<td>1.34 x 10^{-12}</td>
<td>4.69 x 10^{-13}</td>
</tr>
<tr>
<td>J G MOL T_2/CM^2 X SEC</td>
<td>1.27 x 10^{-15}</td>
<td>5.55 x 10^{-16}</td>
<td>1.9 x 10^{-16}</td>
</tr>
<tr>
<td>P = J/J_0</td>
<td>0.67 x 10^{-2}</td>
<td>2.92 x 10^{-3}</td>
<td>10^{-3}</td>
</tr>
</tbody>
</table>

2. THE EFFECT OF PERMEATION BARRIER FACTOR \( F \) FROM OXIDIZED COATING.

Suppose the coating reduces the permeation by a factor of \( F \), i.e.,

\[
J_{O2} = \frac{1}{F} J
\]

It acts as if the coating increases the thickness of HT-9 to \( F \times 0.1 \) cm; consequently, the arrangement can be treated as in Figure 5.

It is easy to see that the total permeation will be reduced by a factor of

\[
F^{-1} = \frac{1}{\sqrt{F} (2F - 1)}
\]

with \( \frac{1}{\sqrt{F}} \) being the contribution by the first coating.

Conclusions, \( J_0 = 3.5 \times 10^5 \) Ci/day, so, it should be reduced by a factor of 10^5. This can be done with either

(i) \( \delta = 0.0025 \) cm and \( F = 16 \) or
(ii) \( \delta = 0.001 \) cm and \( F = 30 \).

According to the experiments, these values of \( F \) are quite reasonable.
TRITIUM RELEASE FROM PIPES IN BUILDING

Building Volume \( \sim 10^6 \text{ m}^3 \)
Temperature \( \sim 300 \text{ K} \)

<table>
<thead>
<tr>
<th>TRITIUM PRESSURE</th>
<th>TRITIUM CONCENTRATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>IN BLDG. (torr)</td>
<td>(( \mu \text{ Ci/m}^3 ))</td>
</tr>
<tr>
<td>(10^{-8})</td>
<td>32</td>
</tr>
<tr>
<td>(10^{-6})</td>
<td>(3.2 \times 10^3)</td>
</tr>
<tr>
<td>(10^{-4})</td>
<td>(3.2 \times 10^5)</td>
</tr>
</tbody>
</table>

40 \( \mu \text{ Ci/m}^3 \) – maximum permissible concentration for worker exposure for 40 h work week without protective clothing (HTO fraction must be \(< 12\%\) by volume)

- Tritium building pressure is expected to be slightly less than the partial pressure in the pipes at steady state

- To maintain this tritium level in the buildings would require a separate extraction system that removes tritium from \(17\text{Li : 83Pb}\) to \(10^{-8}\text{ torr} \) (\(5.1 \times 10^{-3}\ \text{ wppb}\))

- Secondary containment of piping must be used: Aluminum sleeves with slow purge gas
TRITIUM INVENTORY IN TARGET FACTORY

- Model developed by J.W. Sherohman at Lawrence Livermore National Laboratory. Some modifications of the model were developed at UW to give a reduced inventory.

Inventory consists of three parts:

- Filling Process
- Storage
- Recovery Process

Parameters:

- amount of tritium in target
- target injection rate
- time of slowest step for a process
- the number of steps in a process
- the point at which the tritiated fuel is added in the production line
- the efficiency of each step in the production line
MODIFICATIONS

ORIGINAL MODEL

- Each step in the fill and recovery process remains completely filled and is dependent on the time for the slowest step in the production line.

MODIFICATIONS

1. Allow each step to finish in its respective time interval and then remain empty until the slow step is complete.

2. Allow materials from inefficient recovery steps to be recycled back into the previous step for further removal. This may eliminate the need for a redundant recovery system.
TRITIUM INVENTORY IN THE FILL PROCESS

![Graph showing tritium inventory over time for two processes. The graph includes a reference process and a modified production process. The time axis is logarithmic, and the inventory axis is also logarithmic. The intersection point of the two lines indicates a time of 1 hour.]

FIG. 1 A COMPARISON OF THE TRITIUM INVENTORY FOR TWO PRODUCTION PROCESSES.
TRITIUM INVENTORY IN RECOVERY PROCESS

TRITIUM INVENTORY (kg) vs. INJECTION RATE (kg/hr)

Reference process

Modified process

Modified process without redundant recovery

$t_c$ (hr) for reference process

$\sum t_k$ (hr) for modified processes

FIG. 3 A COMPARISON OF THE TRITIUM INVENTORY FOR THREE RECOVERY SCHEMES.
TRITIUM INVENTORY IN TARGET FACTORY

HIBALL PARAMETERS
8000 MW
FUELING RATE = 0.048 g/s
BURN FRACTION = 0.3

ASSUMED PARAMETERS
EFFICIENCIES = 90%
FILL STEPS = 10
RECOVERY STEPS = 5
TRITIUM FILL = STEP # 6
STORAGE = 1 day
$t_i \neq t_c = 1$ hour

TOTAL INVENTORY (kg)

10^3
10^2
10^1
10^0

$10^0$  $10^1$  $10^2$
$t_c$ - TIME FOR PROCESS
SLOW STEP (hr)

Reference process

Modified process (with redundant recovery)
## HIBALL TRITIUM INVENTORY

### FUEL CYCLE (kg):

<table>
<thead>
<tr>
<th>Component</th>
<th>kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryopumps</td>
<td>0.37</td>
</tr>
<tr>
<td>Fuel Cleanup</td>
<td>0.041</td>
</tr>
<tr>
<td>Isotopic Separation</td>
<td>0.083</td>
</tr>
</tbody>
</table>

#### SUBTOTAL

0.49 kg

### BLANKET (kg):

<table>
<thead>
<tr>
<th>Component</th>
<th>kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li$<em>{17}$Pb$</em>{83}$ (cavity and reflector)</td>
<td>0.010</td>
</tr>
<tr>
<td>SiC tubes</td>
<td>0.012</td>
</tr>
</tbody>
</table>

#### SUBTOTAL

0.025 kg

### TOTAL REACTOR INVENTORY (kg):

0.52 kg

### Storage (1 d fuel supply) (kg)

4.1 kg

### Target Factory (kg)

- Slow step 1 h – 5 kg
- Slow step 24 h – 10-50 kg

- 10 kg
AREAS TO BE ADDRESSED IN HIBALL STUDY
JUNE – DECEMBER 1982

• Neutronics Analysis of Final Focussing Magnets

• Neutron Dumps in Beam Lines

• Mechanical Properties of SiC Fabric

• Incorporate New (?) Accelerator Scenario in Cost Optimization

• Continue Cavity Environment Analysis

• Address Alternate Use of Fusion Energy

• Present HIBALL at Winter ANS Meeting, Washington DC, November 1982