# Recent Developments in the HIBALL Conceptual Reactor Design

**HIBALL Team**

**June 1982**

**FPA-82-3**

Presentation at KfK-Karlsruhe, FRG, 3-4 June 1982

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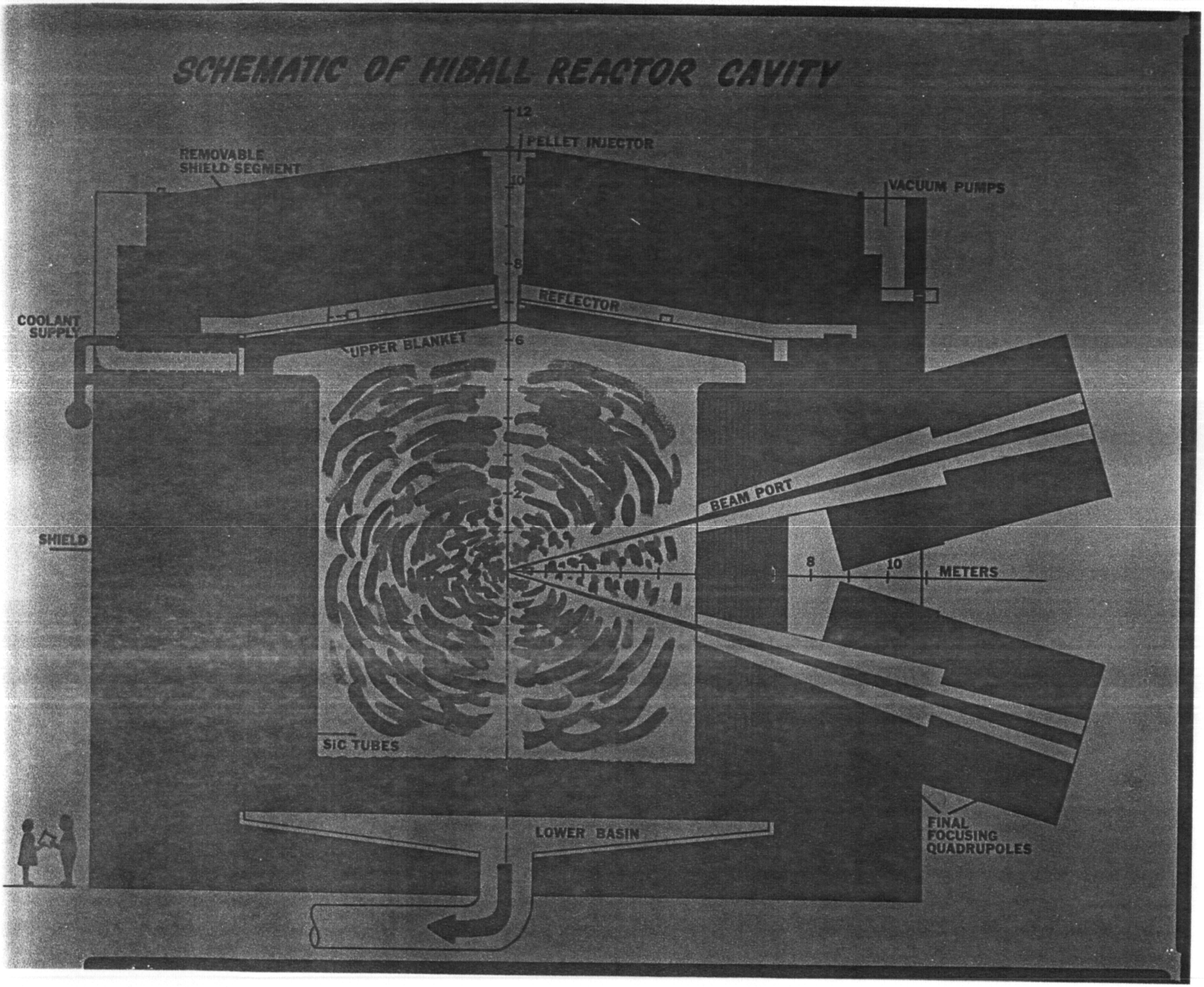
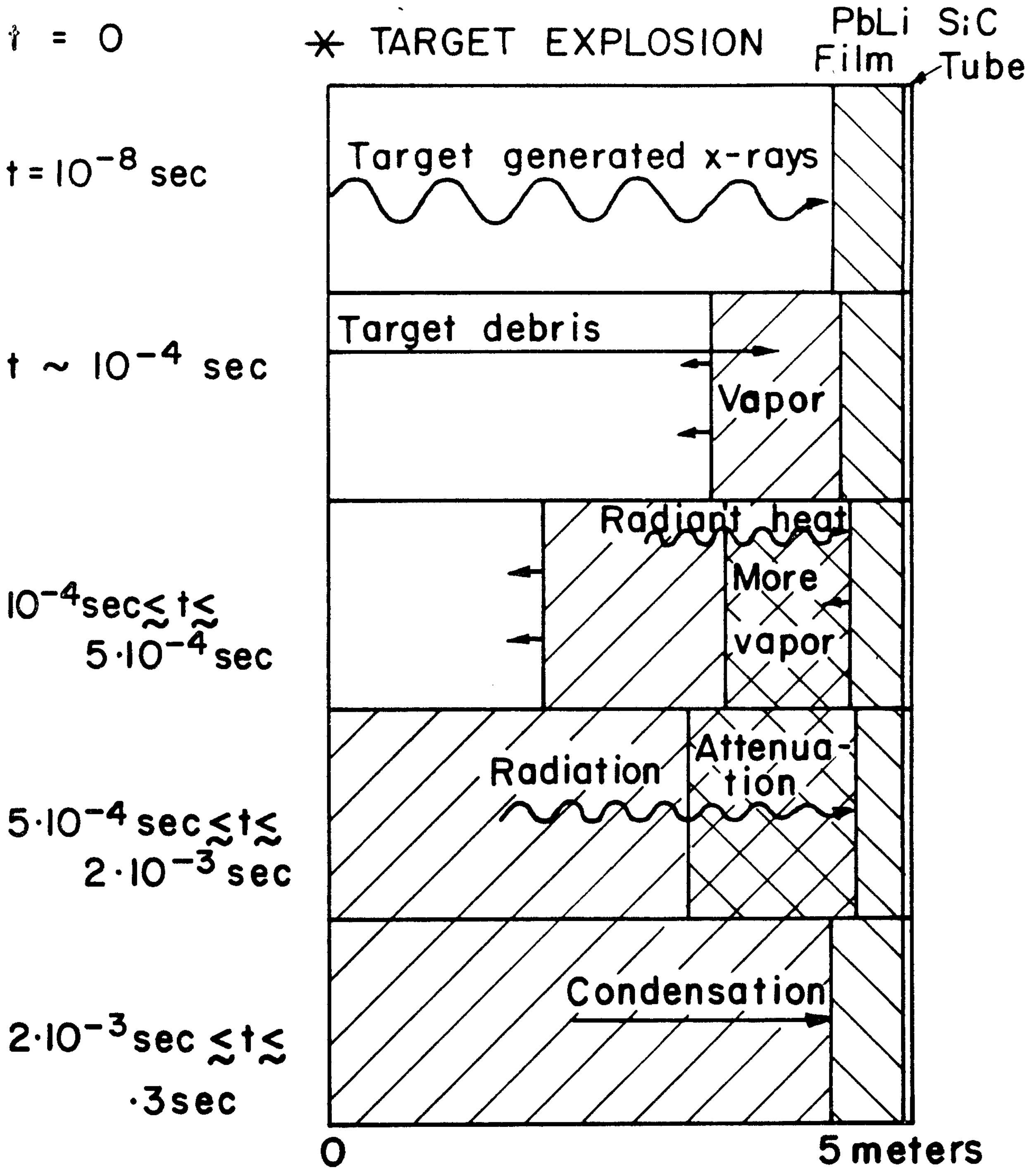
# MAJOR ACTIVITIES ON HIBALL FROM JANUARY – MAY 1982

- 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
- $T_2$ Extraction, Confinement, and Inventory
- Mechanical Properties Tests of SiC Fibers
- Presentations: Darmstadt, FRG and Ottawa, Canada



SCHEMATIC OF HIBALL REACTOR CAVITY
12
10
8
6
2
PELLET INJECTOR
REMOVABLE SHIELD SEGMENT
VACUUM PUMPS
REFLECTOR
COOLANT SUPPLY
UPPER BLANKET
BEAM PORT
SHIELD
8
10
METERS
SiC TUBES
LOWER BASIN
FINAL FOCUSING QUADRUPOLES

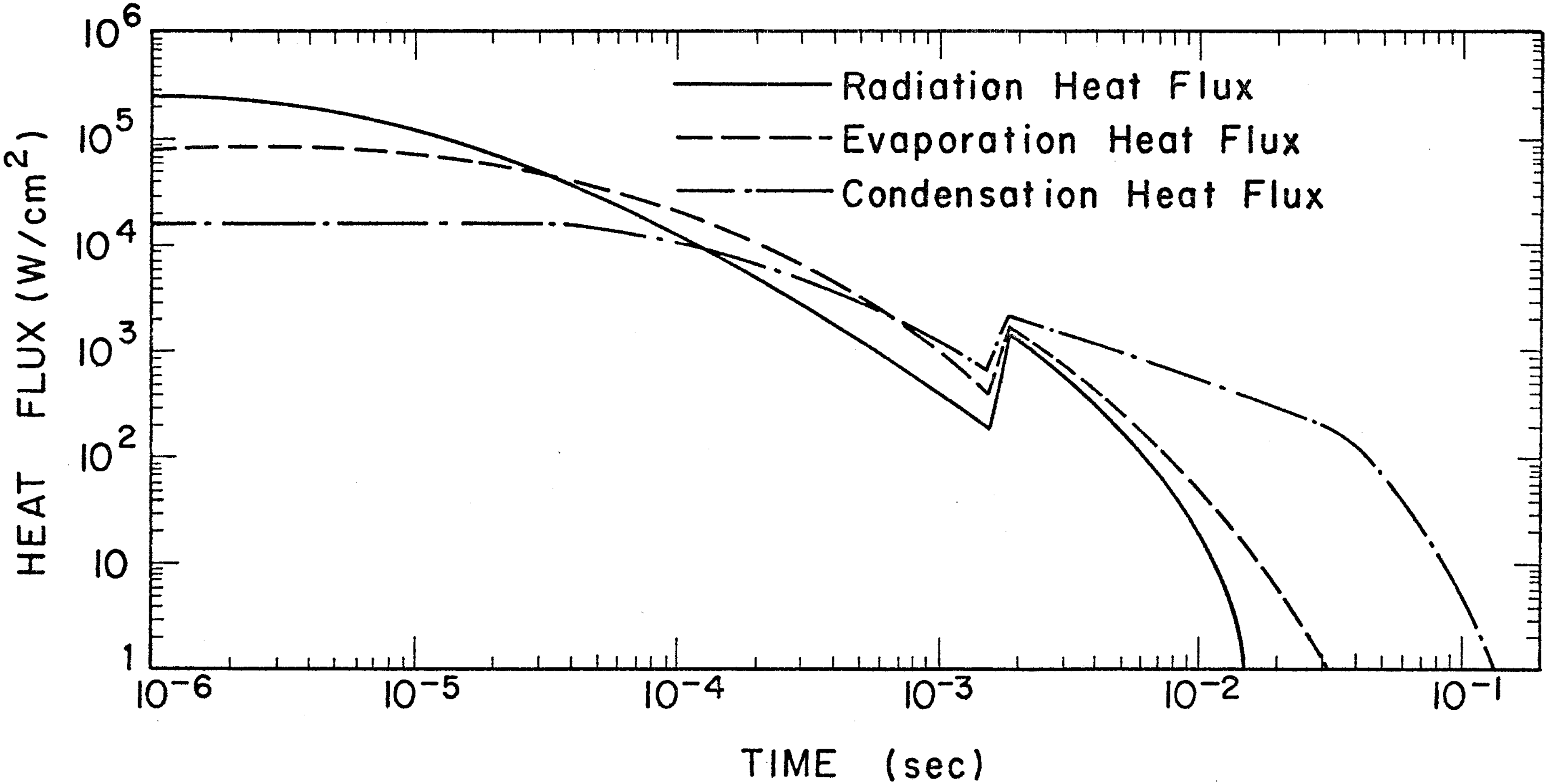


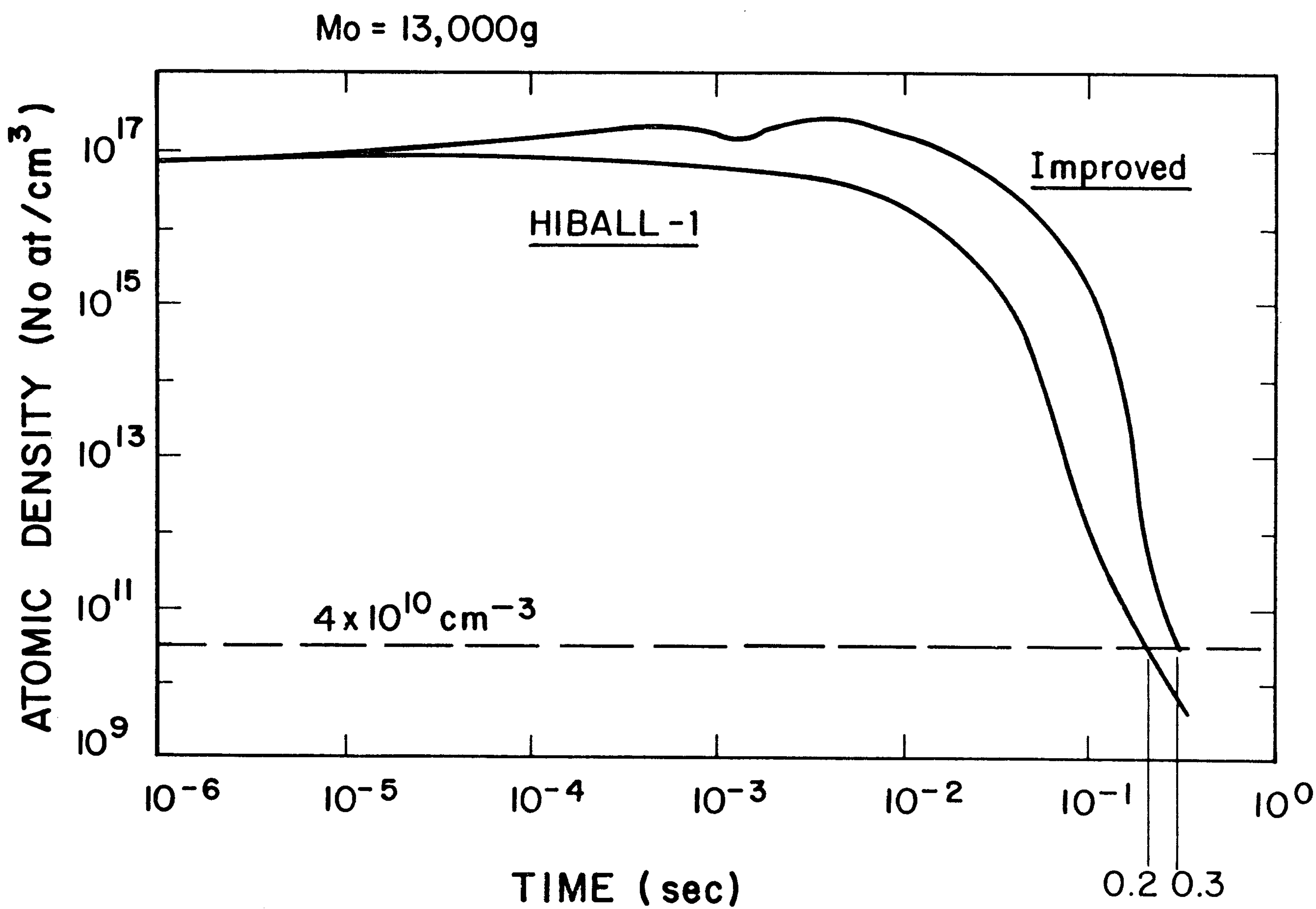
t = 0
TARGET EXPLOSION
PbLi Film
SiC Tube
t = 10^-8 sec
Target generated x-rays
t ~ 10^-4 sec
Target debris
Vapor
10^-4 sec ≲ t ≲ 5·10^-4 sec
Radiant heat
More vapor
5·10^-4 sec ≲ t ≲ 2·10^-3 sec
Radiation
Attenuation
2·10^-3 sec ≲ t ≲ .3 sec
Condensation
0
5 meters

# IMPROVED MODELING OF TARGET CHAMBER GAS CONDENSATION

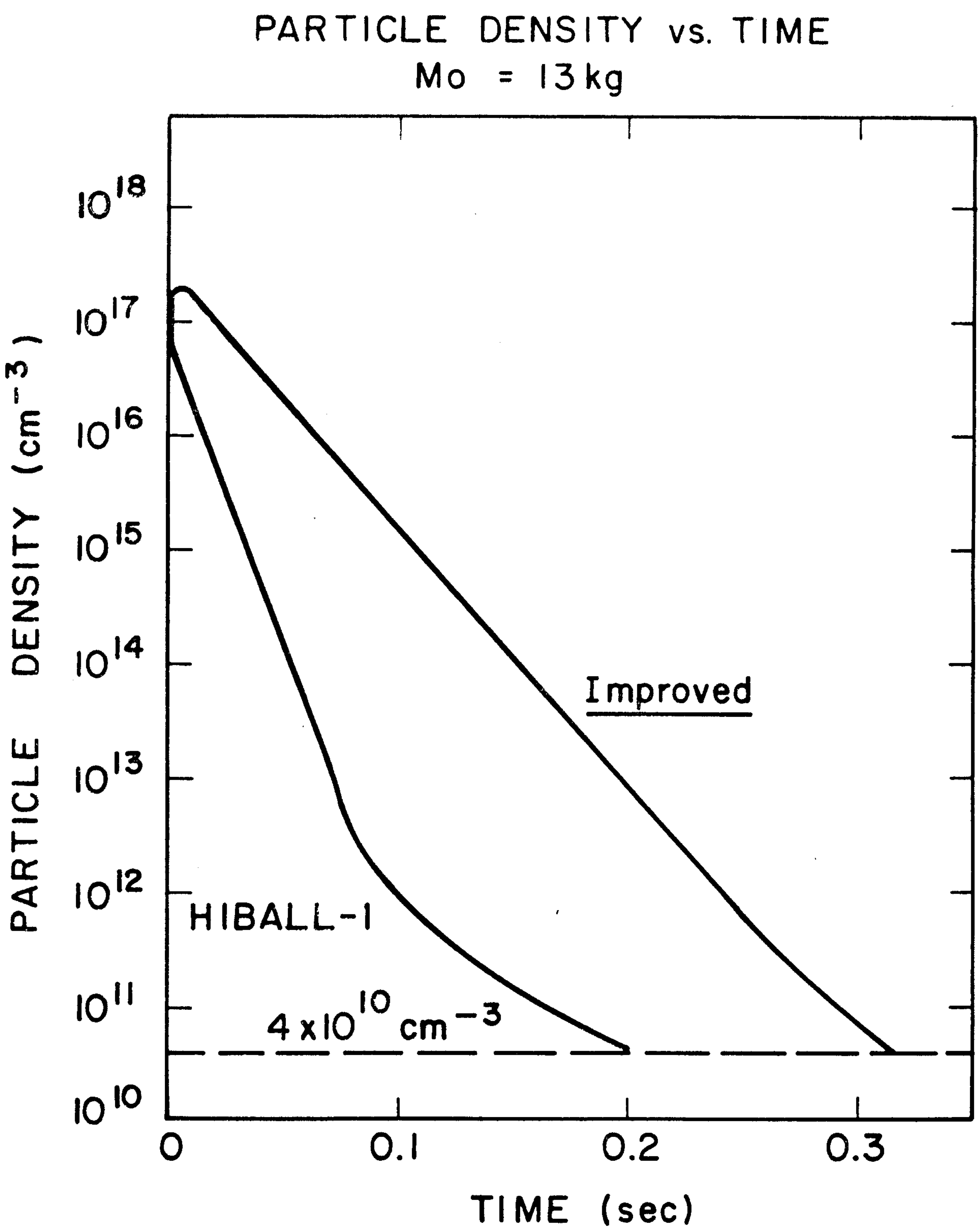
- SELF–CONSISTENT ANALYSIS OF RADIATION TRANSPORT, CONDENSATION AND EVAPORATION
- MOMENTUM AND ENERGY EXCHANGE BETWEEN VAPOR AND FILM ON TUBES
- TRANSITION BETWEEN VISCOUS AND MOLECULAR FLOW
- SAHA AND CORONAL IONIZATION CONSIDERED
- IMPROVED TREATMENT OF LINE RADIATION

N.B. ALL OF THESE IMPROVEMENTS ARE INCLUDED IN THE CODES CONRAD AND MIXERG.


Radiation Heat Flux
Evaporation Heat Flux
Condensation Heat Flux
HEAT FLUX (W/cm²)
10⁶
10⁵
10⁴
10³
10²
10
1
10⁻⁶
10⁻⁵
10⁻⁴
10⁻³
10⁻²
10⁻¹
TIME (sec)



Mo = 13,000g
ATOMIC DENSITY (No at/cm³)
Improved
HIBALL-1
4 x 10¹⁰ cm⁻³
10¹⁷
10¹⁵
10¹³
10¹¹
10⁹
10⁻⁶
10⁻⁵
10⁻⁴
10⁻³
10⁻²
10⁻¹
10⁰
0.2
0.3
TIME (sec)



PARTICLE DENSITY vs. TIME
Mo = 13 kg
PARTICLE DENSITY (cm⁻³)
10^18
10^17
10^16
10^15
10^14
10^13
10^12
10^11
10^10
Improved
HIBALL-I
4 x 10^10 cm^-3
0
0.1
0.2
0.3
TIME (sec)

# CONDENSATION 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.

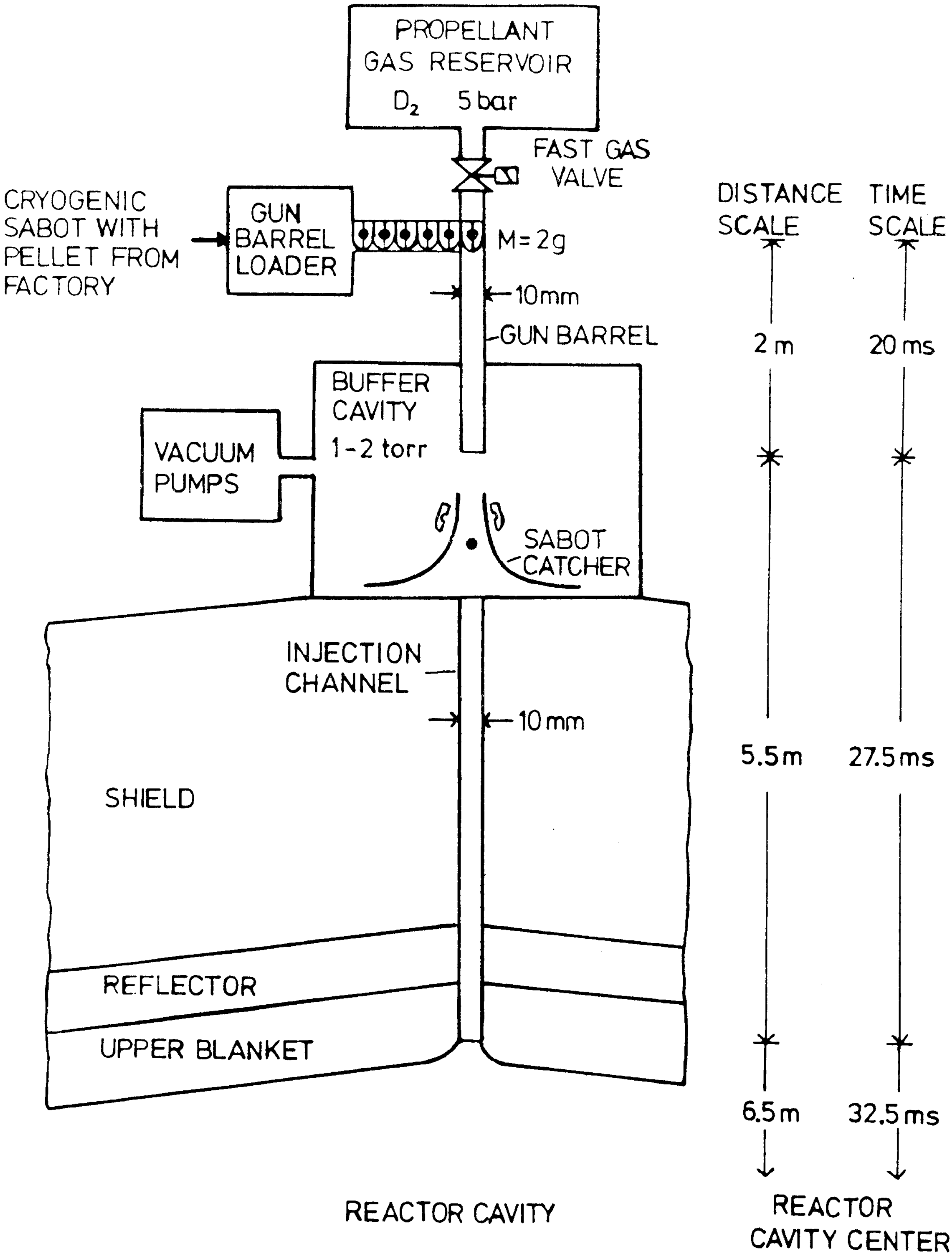



FIGURE III 5-4 SCHEME OF HIBALL-I PNEUMATIC INJECTION SYSTEM AND DESIGN PARAMETER VALUES, PELLET VELOCITY = 200 m/s

# HEATING OF SABOT AND TARGET WHILE IN INJECTOR GUN BARREL

- **FRICTIONAL HEATING POWER**

$$q_f = f \bullet p \bullet v$$

$$f = 0.05 \quad \textbf{(Teflon on steel)}$$

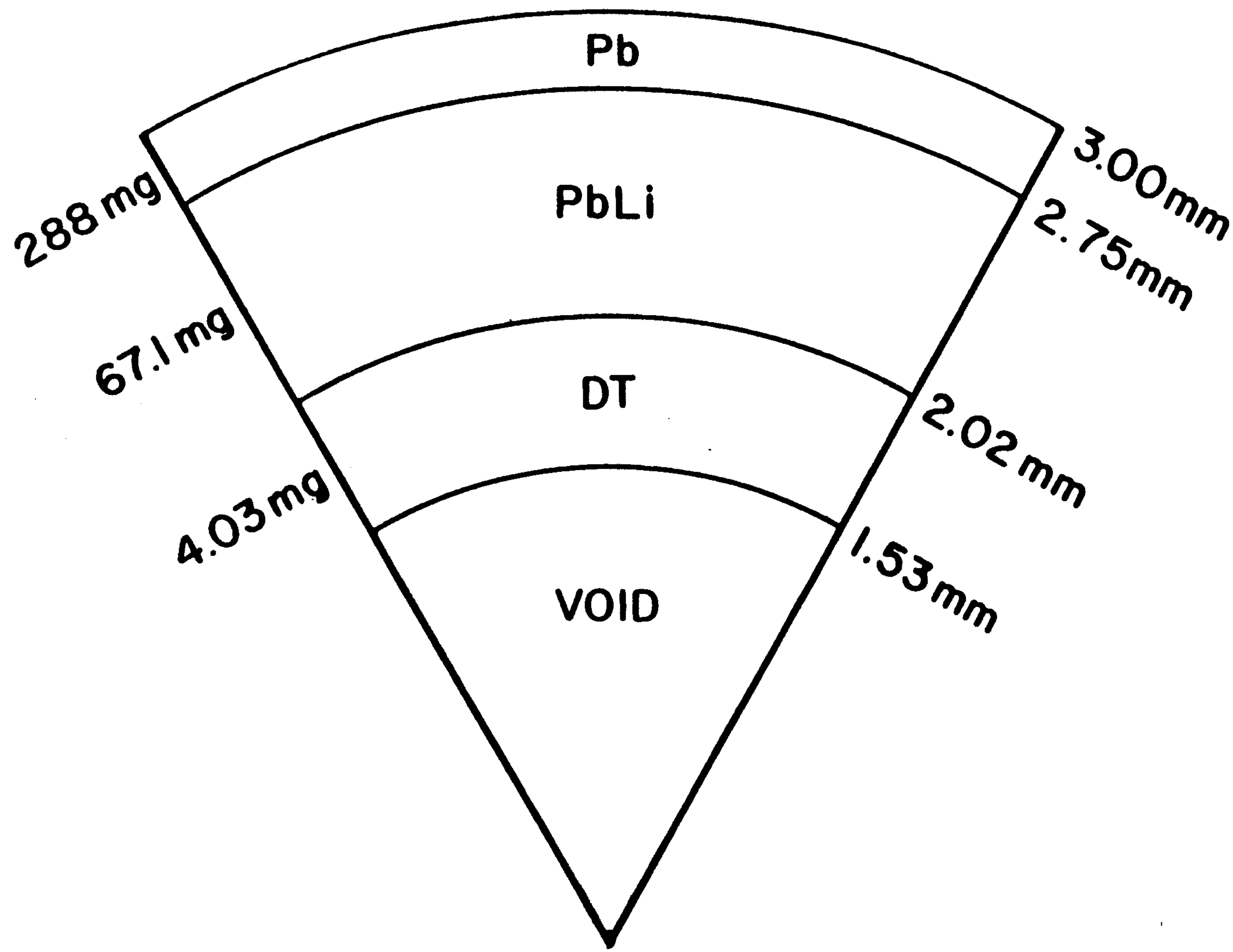
$$p = 10^5 \ \text{N/m}^2$$

$$v = 100 \ \text{m/s}$$

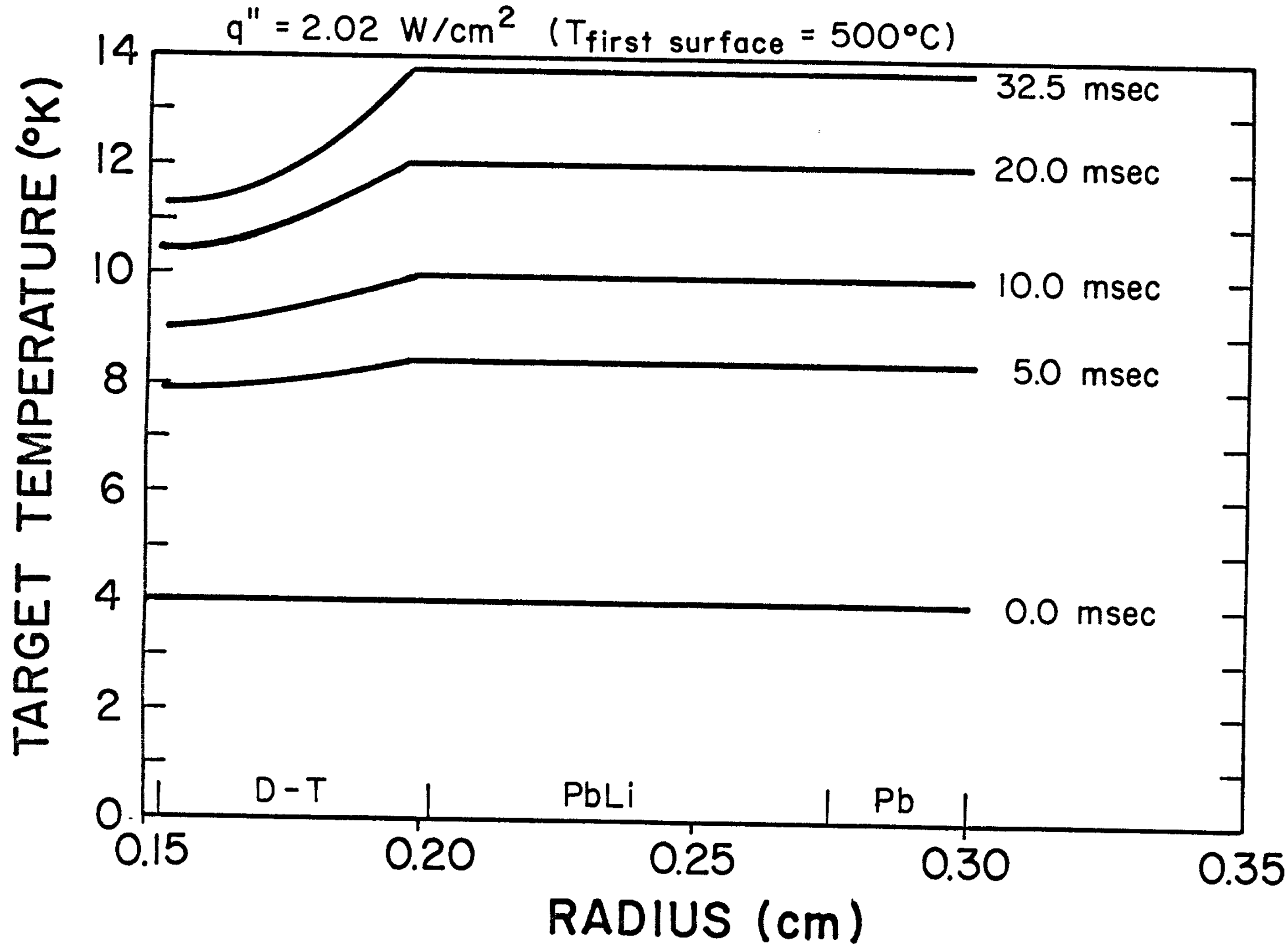
$$q_f = 51.3 \ \text{W/cm}^2$$

- **ACCELERATION TIME = 20 ms**

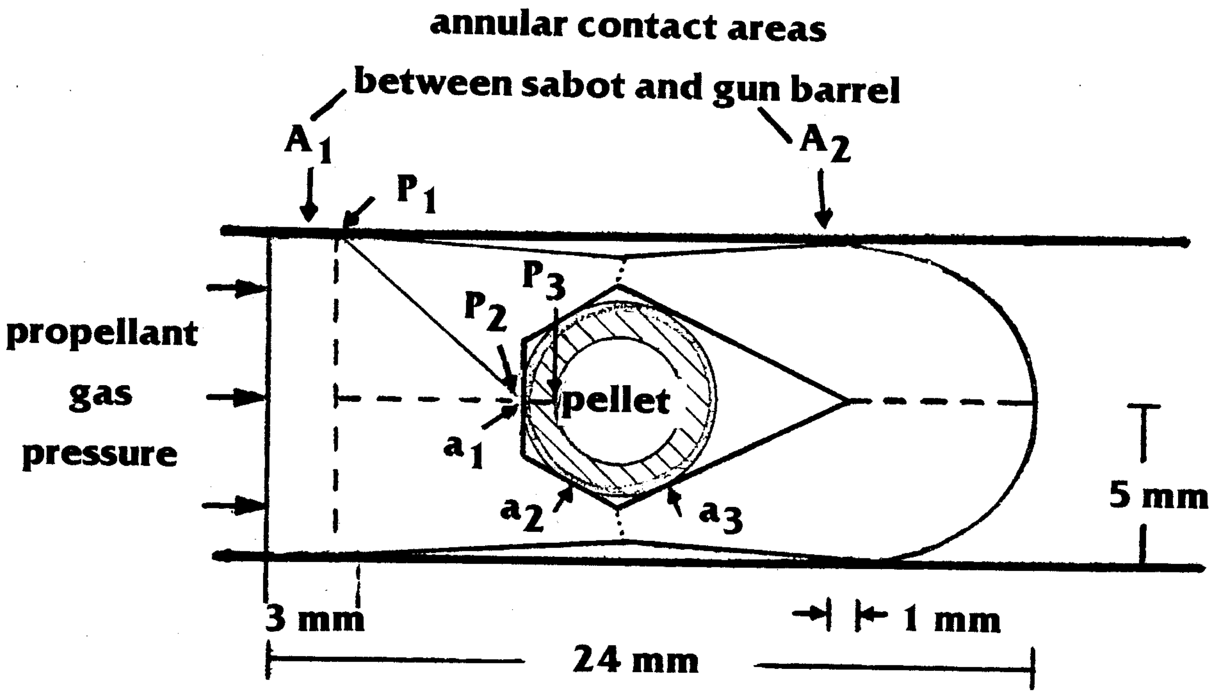
- **THE TARGET MUST RECEIVE VERY LITTLE HEAT FROM THE SABOT BECAUSE HEATING OF THE TARGET BY THE TARGET CHAMBER IS NEAR THE CRITICAL LEVEL.**




HIBALL CRYOGENIC
TARGET


q" = 2.02 W/cm2 (Tfirst surface = 500°C)
32.5 msec
20.0 msec
10.0 msec
5.0 msec
0.0 msec
D-T
PbLi
Pb
TARGET TEMPERATURE (°K)
RADIUS (cm)
14
12
10
8
6
4
2
0
0.15
0.20
0.25
0.30
0.35

# SABOT DESIGN (PNEUMATIC INJECTION)




- axially symmetric pellet storage

  contact between pellet and sabot:

  $a_1$: compensation of inertial force

  – tensile stresses of materials

  (acceleration 1000 g – $a_1$ some $mm^2$)

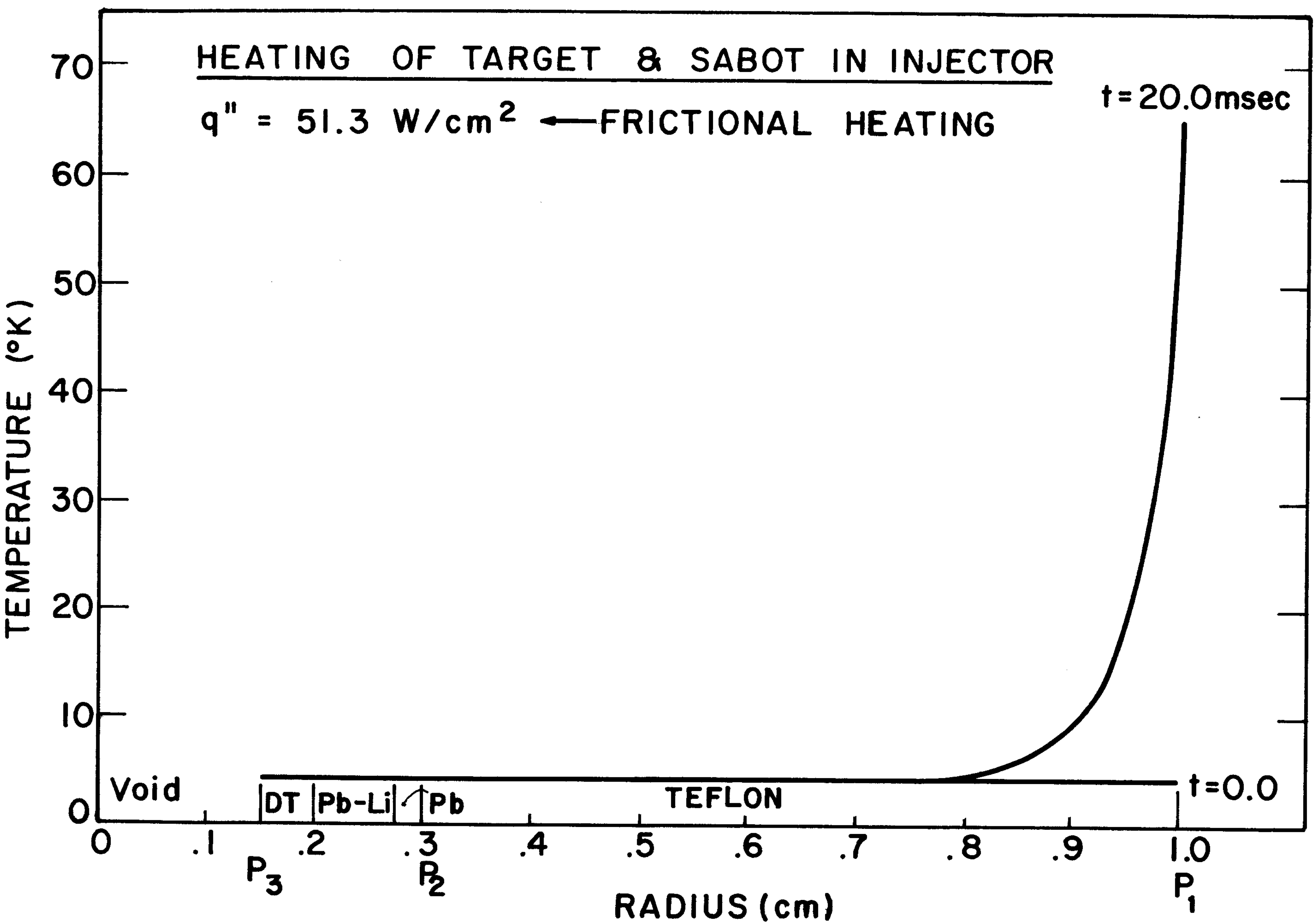
  $a_2$, $a_3$ (annular) : very small – small heat transfer

- material: plastics

  e.g.: Teflon (reference material)

  thermal properties at cryogenic

  temperatures are available



HEATING OF TARGET & SABOT IN INJECTOR
q" = 51.3 W/cm2 ←FRICTIONAL HEATING
t=20.0msec
t=0.0
Void
DT
Pb-Li
Pb
TEFLON
TEMPERATURE (°K)
70
60
50
40
30
20
10
0
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
P3
P2
P1
RADIUS (cm)

# SABOT SUMMARY

## CONCLUSION

- TARGET IS INSULATED FROM FRICTIONAL HEAT BY SABOT

## OTHER ISSUES

- TEFLON MAY BE TOO EXPENSIVE

- SURVIVABILITY OF SABOTS

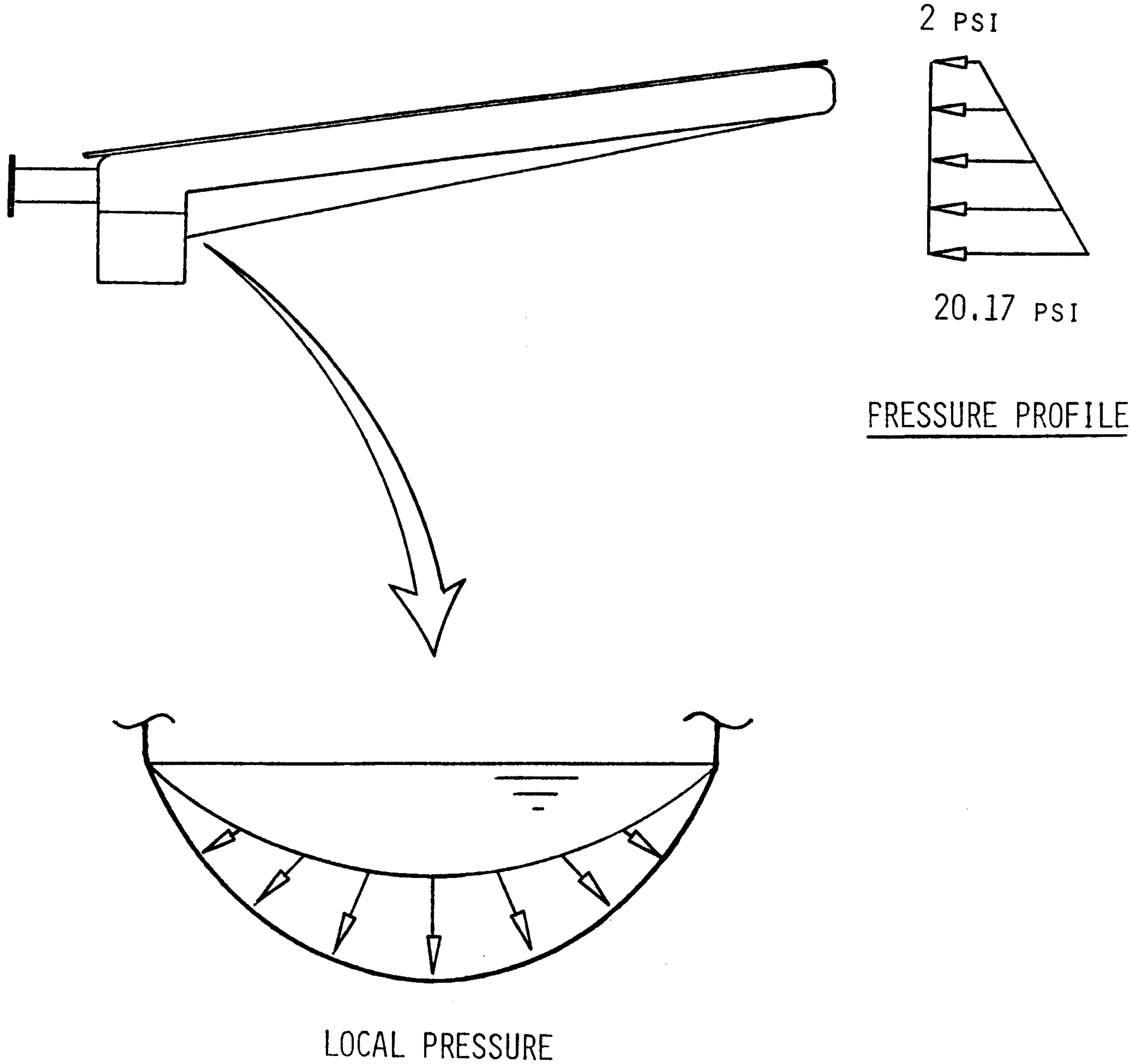
# PROBLEMS OF CAVITY UPPER BLANKET DESIGN

1 STRESS OF SiC FABRIC DUE TO BREEDING MATERIAL PRESSURE

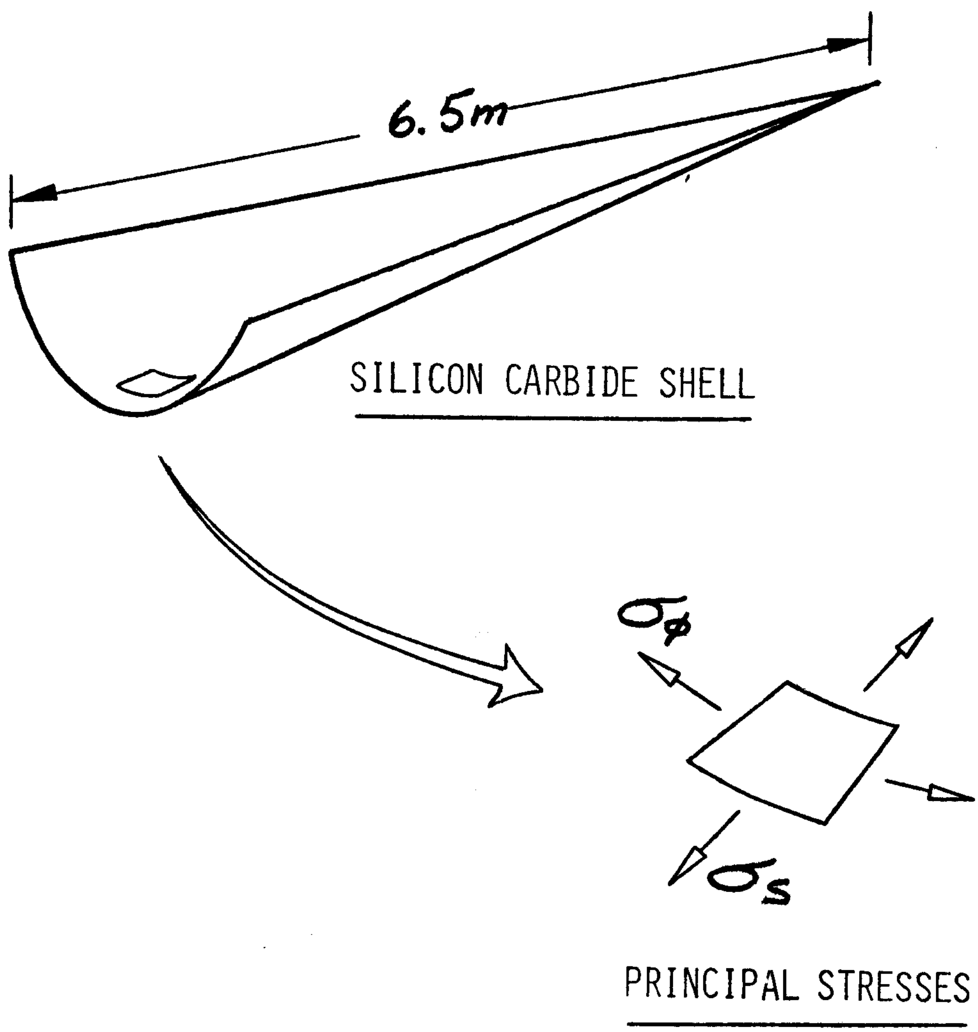
2 FORMATION AND RELEASE OF DROPLETS FROM UPPER BLANKET

3 SHOCK EFFECTS ON UPPER BLANKET

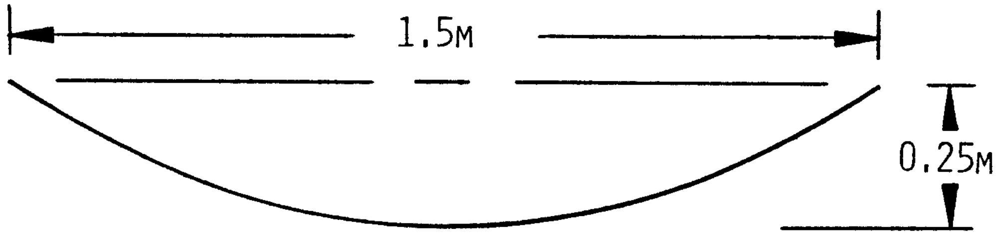
# HYDROSTATIC LOADING



MAXIMUM STRESS STATE



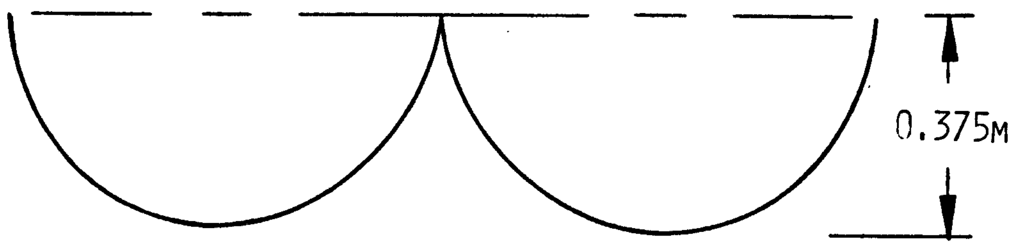
# UPPER BLANKET PROFILE COMPARISONS




## SINGLE LOBE

RADIUS: 1.25 M = 49.0 IN

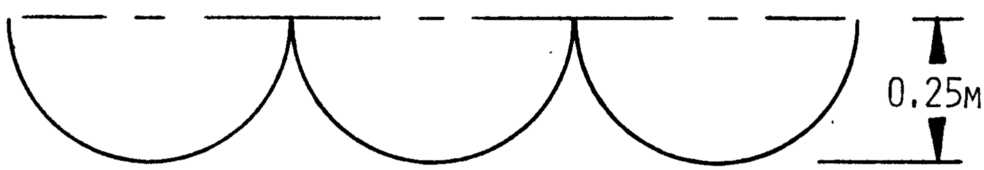
STRESS: 172 MPA = 25.0 KSI




## DOUBLE LOBE

RADIUS: 0.375 M = 14.8 IN

STRESS: 51.7 MPA = 7.5 KSI

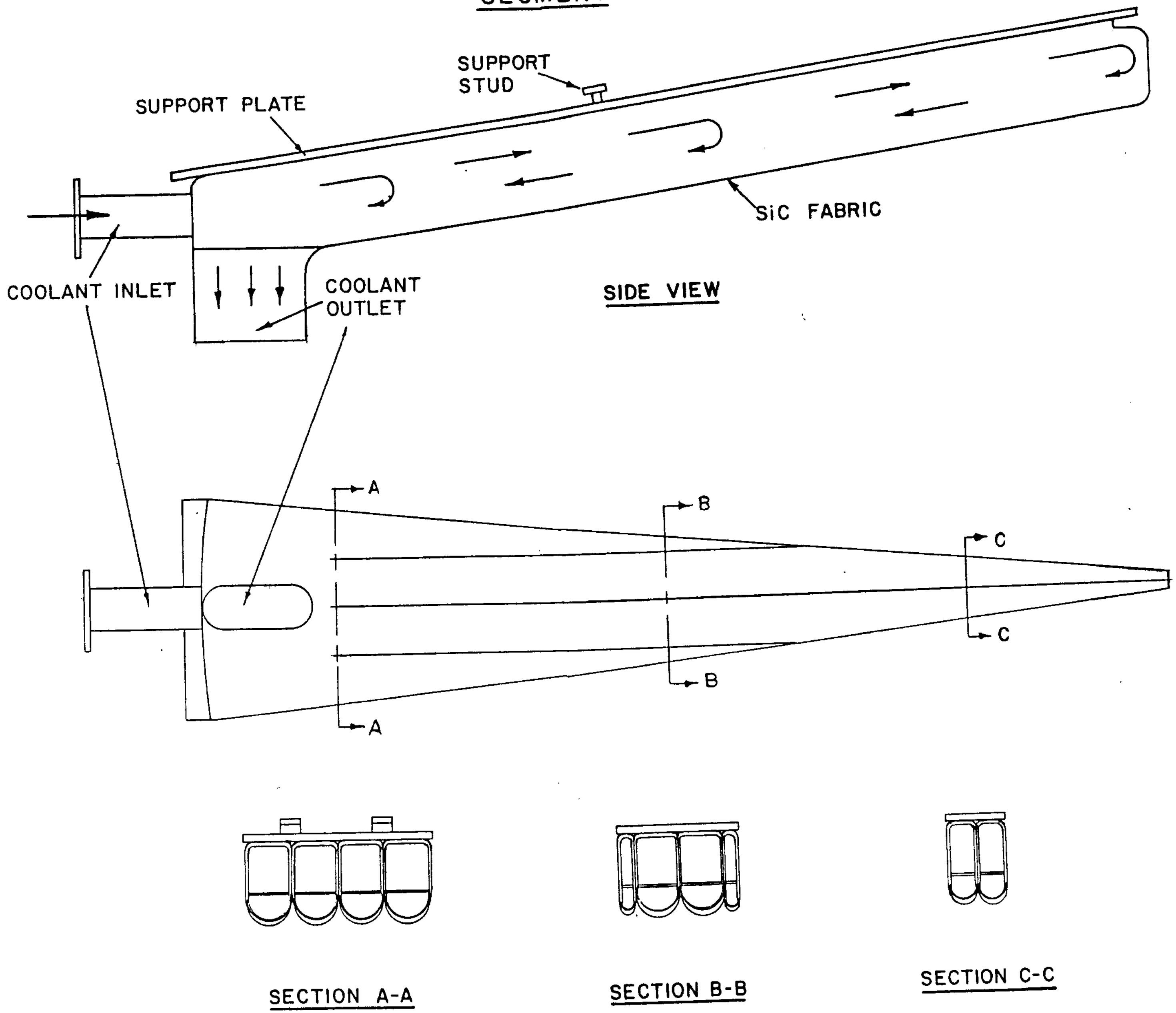



## TRIPLE LOBE

RADIUS: 0.25 M = 9.8 IN

STRESS: 34.5 MPA = 5.0 KSI

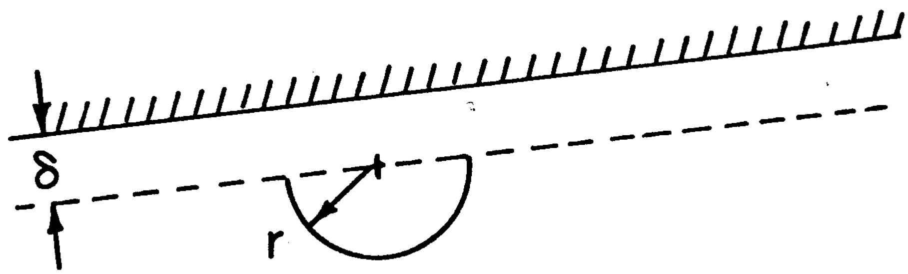
## DESIGN OF AN UPPER BLANKET SEGMENT



# UPPER BLANKET DESIGN PARAMETERS

| | |
|---|---|
| Module Structural Material | SiC |
| Number of Moduels | 30 |
| Length of Module (cm) | 680 |
| Width of Module at Fabric Termination (cm) | 130 |
| Depth of Cylindrical Portion (cm) | 16.3 |
| Front SiC Fabric Thickness (cm) | 0.1 |
| Maximum Pressure of Fabric (atm) | 1.37 |
| Maximum Hoop Stress (MPa) | 22.8 |
| (ksi) | 3.3 |

# 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 $\Gamma = 450$ dynes/cm

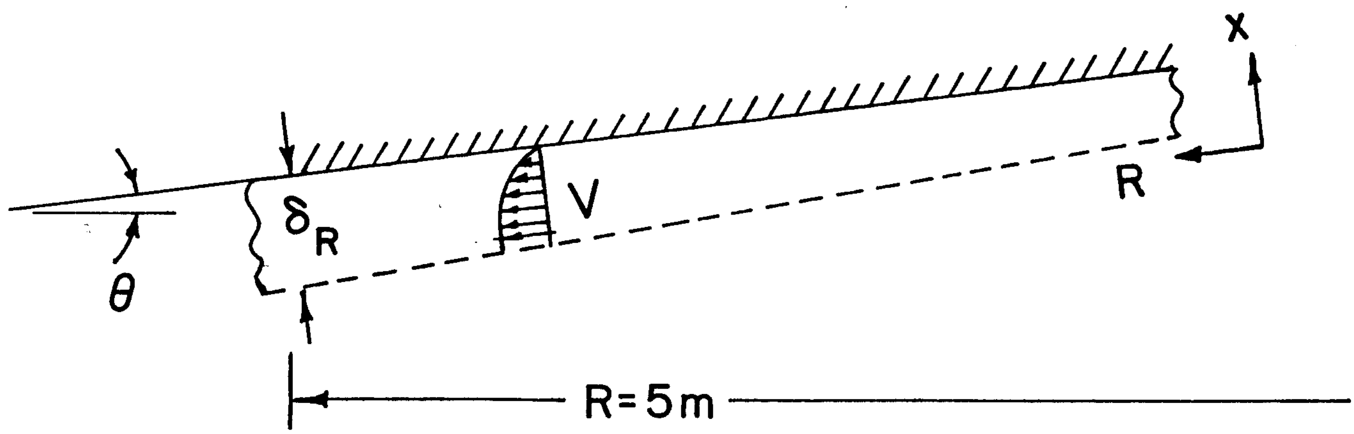
AND EQUATING $F_g = F_a$

WE GET $r = 0.38$ cm

$\delta \leq r$

$\delta = 0.1 - 0.3$ cm

# ALLOWABLE SEEPAGE RATE




ACCELERATING FORCE $F_a = \rho g x \sin\theta$

RETARDING FORCE $F_r = -\mu \frac{dV}{dx}$

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

VOLUMETRIC FLOW RATE AT ANY RADIUS r

IS: $Q(r) = \frac{\rho g \delta_r^3 \sin\theta \; (2\pi r)}{3\mu}$

AT R = 5m, $\theta = 7°$ AND TAKING $\mu = 0.017 \frac{gm}{sec.\,cm}$

| $\delta_R$ (cm) | $Q_R$ ($cm^3$/sec.) | Q/A ($cm^3$/sec.$cm^2$) |
|---|---|---|
| 0.1 | $0.7 \times 10^5$ | 0.09 |
| 0.2 | $5.6 \times 10^5$ | 0.71 |
| 0.3 | $18.9 \times 10^5$ | 2.4 |

# 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

| | |
|---|---|
| Tritium removal method | Vacuum pumping from the reactor chamber |
| Tritium breeding rate | $2.94 \times 10^{-3}$ mol $T_2$/s |
| Tritium partial pressure above 17Li : 83Pb | $10^{-4}$ torr |
| Tritium solubility at $10^{-4}$ torr | $5.1 \times 10^{-4}$ wppm |
| % tritium extracted | 9.2 |
| Extraction rate | $3.6 \times 10^{5}$ ℓ/s |
| Pumping rate to remove cavity gases (700 K and $10^{-4}$ torr) | $\sim 4 \times 10^{6}$ ℓ/s |
| Tritium inventory in 17Li : 83Pb (4 cavities) | 10 g |

# TRITIUM PERMEATION IN HEAT EXCHANGER

## PERMEATION RATE FOR HT–9

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

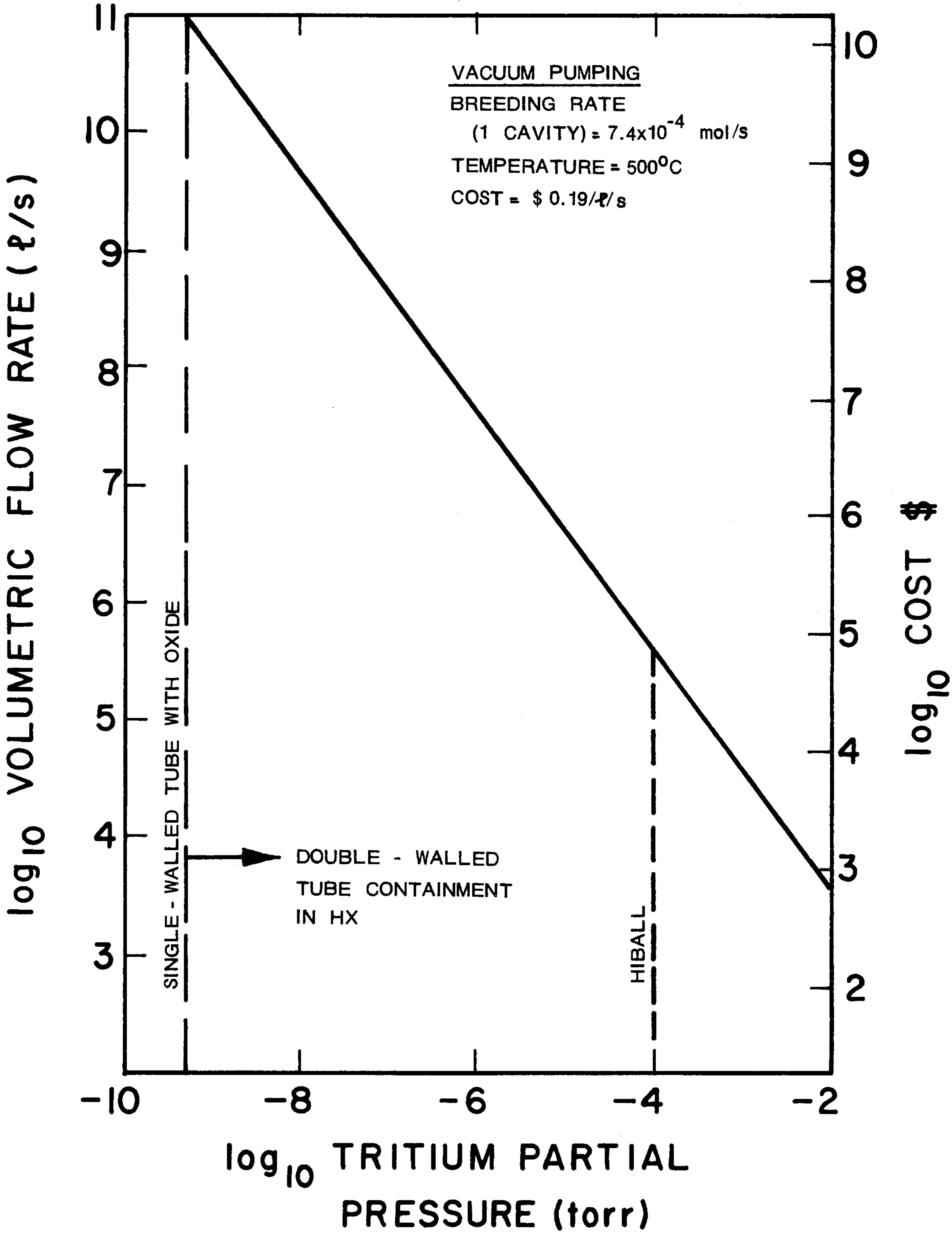
$$P_T = 2.26\times10^{4}\ \exp(-11100/RT)\ \text{Ci/d} \times \text{Area}\ (m^2)$$

| | PREBOILER | BOILER | SUPERHEATER |
|---|---|---|---|
| AREA, $m^2$ | $1.52\times10^4$ | $2.0\times10^4$ | $4.72\times10^4$ |
| AVG. TEMP., $^oC$ | 310 | 352 | 428 |
| PERMEATION, Ci/d | $2.4\times10^4$ | $5.9\times10^4$ | $3.7\times10^5$ |

**PERMEATION RATE = $4.5\times10^5$ Ci/d**

**TRITIUM BARRIER REQUIREMENT ~ $10^5$**
**to limit losses in the heat exchanger to < 10 Ci/d**

## EXTRACTION & CONTAINMENT PARAMETERS AS A FUNCTION OF TRITIUM PARTIAL PRESSURE



# TRITIUM DIFFUSION THROUGH A DOUBLE-WALLED HX

- 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 $T_2O$. SO, THE EQUATIONS FOR $T_2$ CONCENTRATION AND BOUNDARY CONDITIONS ARE AS FOLLOWS:

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

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

$$\text{AT } x = 0 \qquad - D_1 \frac{dc_1}{dx} = J_o$$

$$x = \delta \qquad - D_1 \frac{dc_1}{dx} = - D_2 \frac{dc_2}{dx}$$

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

$$x = L \qquad c_2 = 0$$

WHERE $v$ - VELOCITY OF $T_2$

$\lambda$ - MEAN FREE PATH OF $T_2$ COLLISION WITH $O_2$

$J_o$ - THE $T_2$ CURRENT PENETRATING THE 1ST WALL AND IS CALCULATED TO BE $1.9 \times 10^{-13}$ GMOL $T_2/\text{CM}^2$ 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

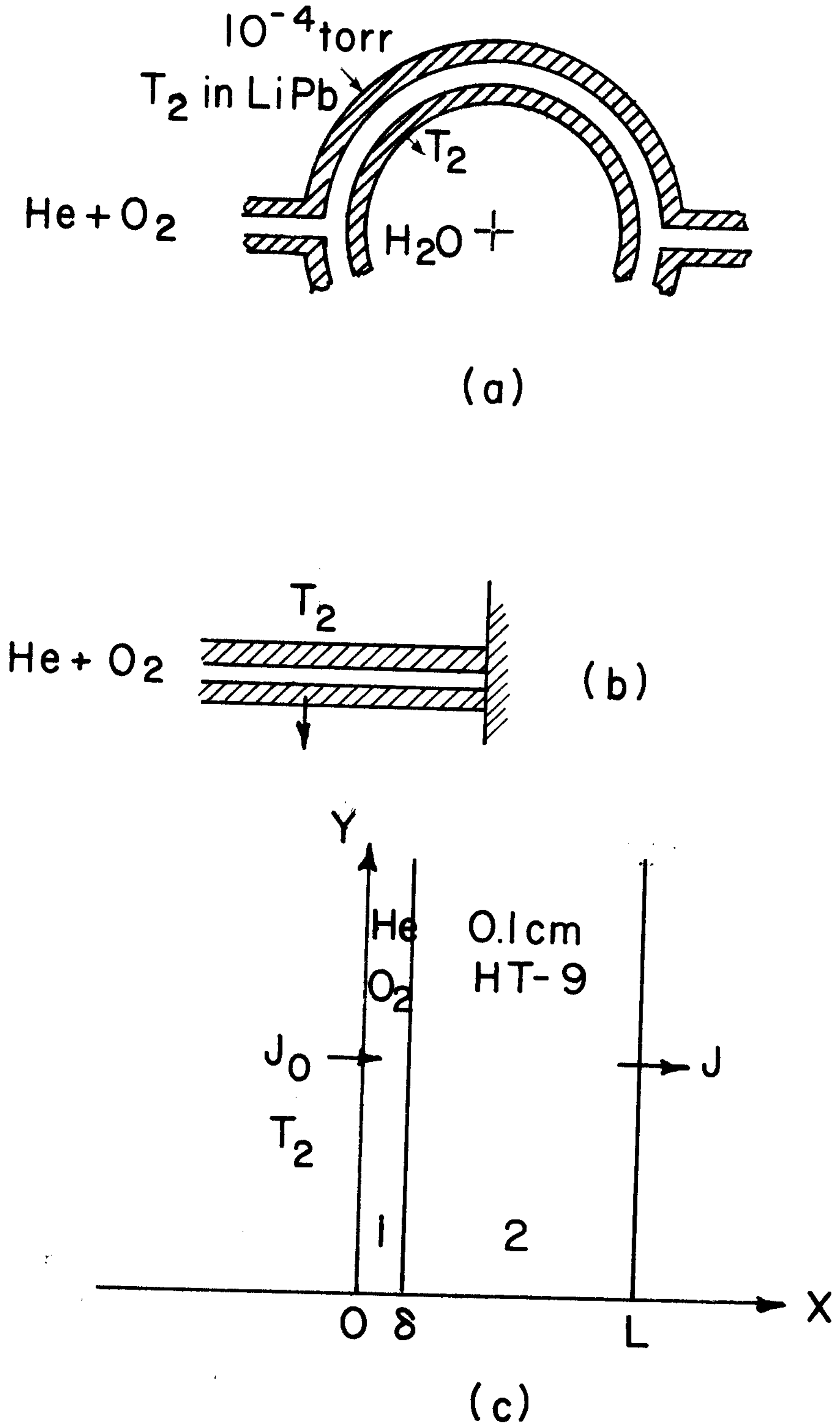
$\lambda = 1.87 \times 10^{-2}$ CM, $\kappa_s = 1.24 \times 10^{-6}$ GMOL $T_2/(\text{CM}^3 \times \text{ATM}^{1/2})$

THE SOLUTION OF THE PROBLEM IS

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

$$c_2(x) = E \left(1 - \frac{x}{0.1+\delta}\right) .$$

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



10^-4 torr
T2 in LiPb
T2
He + O2
H2O
(a)
T2
He + O2
(b)
Y
He
O2
0.1 cm
HT-9
J0
J
T2
1
2
0
δ
L
X
(c)

TABLE 1

| $\delta$ CM | .00025 | .001 | .0025 |
|---|---|---|---|
| B | $3.61 \times 10^{-17}$ | $2.44 \times 10^{-18}$ | $3.68 \times 10^{-20}$ |
| E | $3.05 \times 10^{-12}$ | $1.34 \times 10^{-12}$ | $4.69 \times 10^{-13}$ |
| J GMOL $T_2/CM^2 \times$ SEC | $1.27 \times 10^{-15}$ | $5.55 \times 10^{-16}$ | $1.9 \times 10^{-16}$ |
| $P \equiv J/J_0$ | $0.67 \times 10^{-2}$ | $2.92 \times 10^{-3}$ | $10^{-3}$ |

2. THE EFFECT OF PERMEATION BARRIER FACTOR F FROM OXIDIZED COATING. SUPPOSE THE COATING REDUCES THE PERMEATION BY A FACTOR OF F, I.E.,

$$J_{O_2} = \frac{1}{F} J .$$

IT ACTS AS IF THE COATING INCREASES THE THICKNESS OF HT-9 TO F x 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

$$F^{-1} = \frac{1}{\sqrt{F}\,(2F - 1)}$$

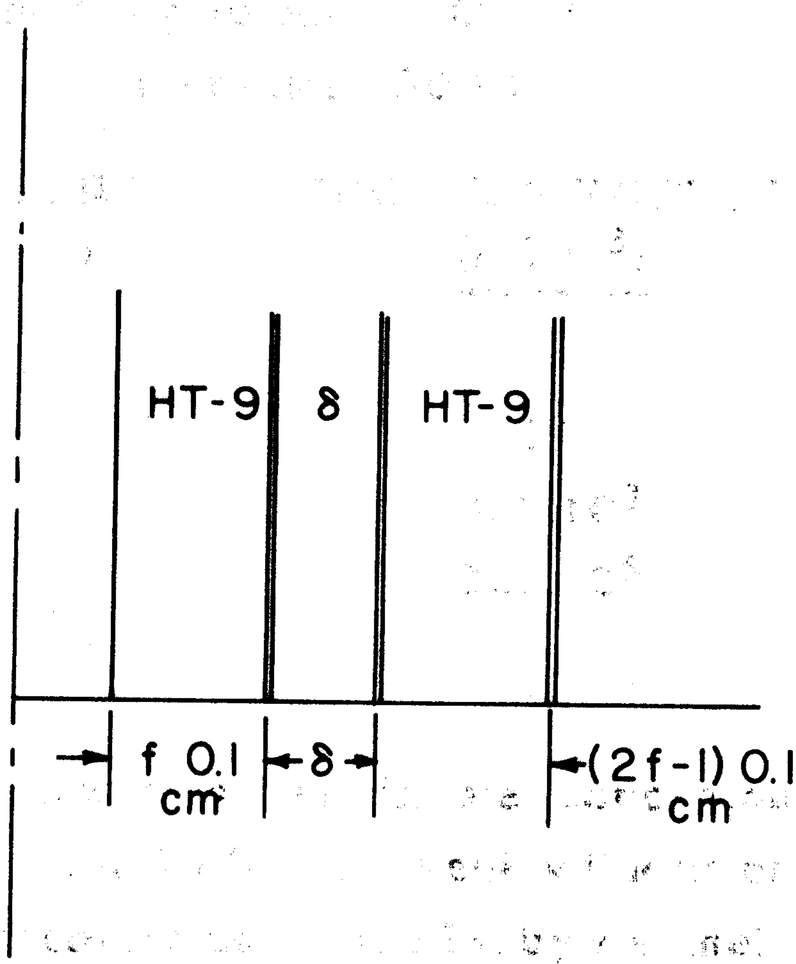
WITH $\frac{1}{\sqrt{F}}$ BEING THE CONTRIBUTION BY THE FIRST COATING.

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.



HT-9
δ
HT-9
f 0.1 cm
δ
(2f-1) 0.1 cm

# TRITIUM RELEASE FROM PIPES IN BUILDING

**Building Volume ~ $10^6$ m$^3$**

**Temperature ~ 300 K**

| TRITIUM PRESSURE IN BLDG. (torr) | TRITIUM CONCENTRATION ($\mu$Ci/m$^3$) |
|---|---|
| $10^{-8}$ | 32 |
| $10^{-6}$ | $3.2 \times 10^3$ |
| $10^{-4}$ | $3.2 \times 10^5$ |

**40 $\mu$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 17Li : 83Pb to ~ $10^{-8}$ torr ($5.1 \times 10^{-3}$ 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.

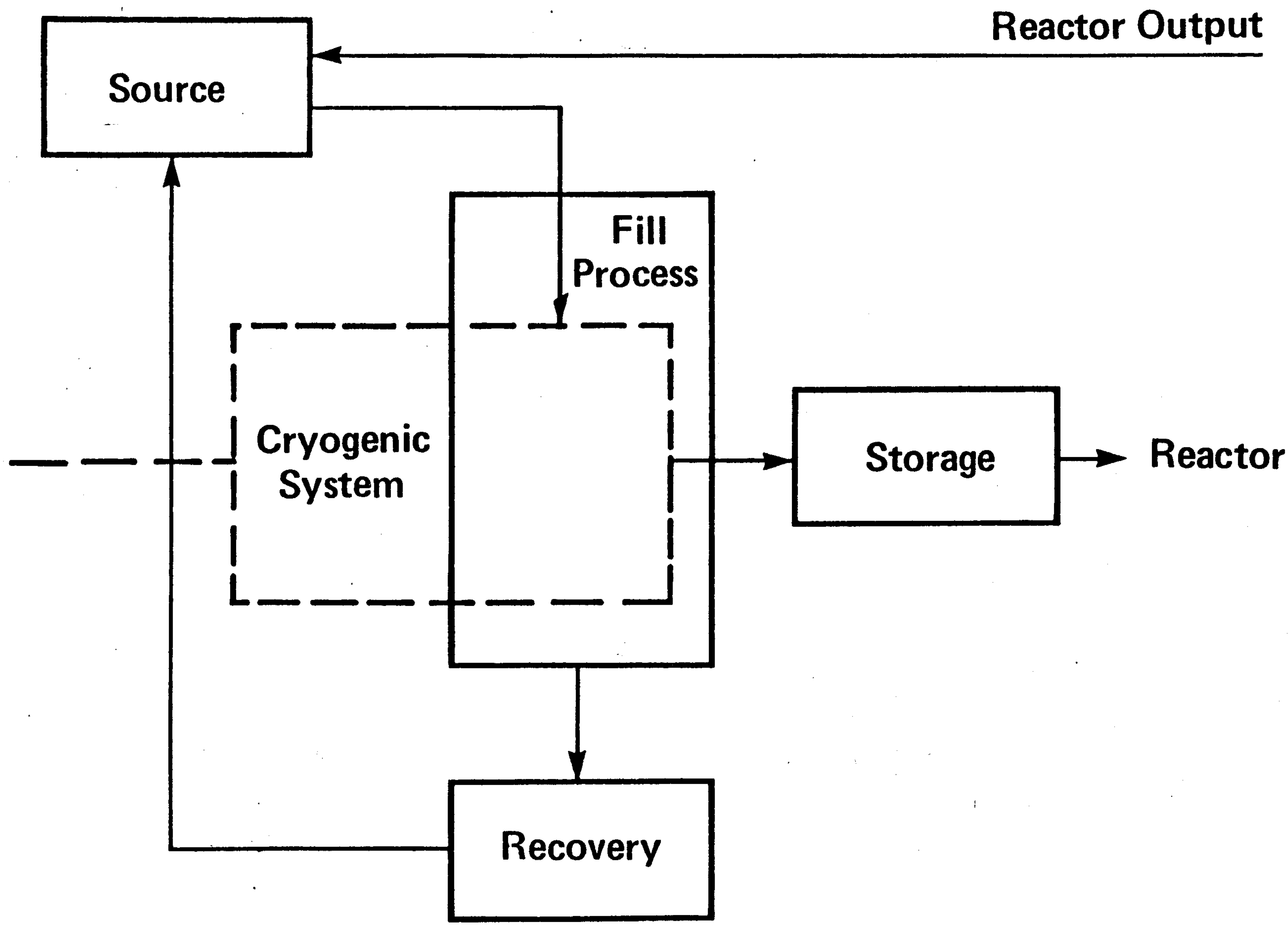
**Inventory consists of three parts:**

- 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

# TARGET FACTORY – FLOW DIAGRAM



# 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

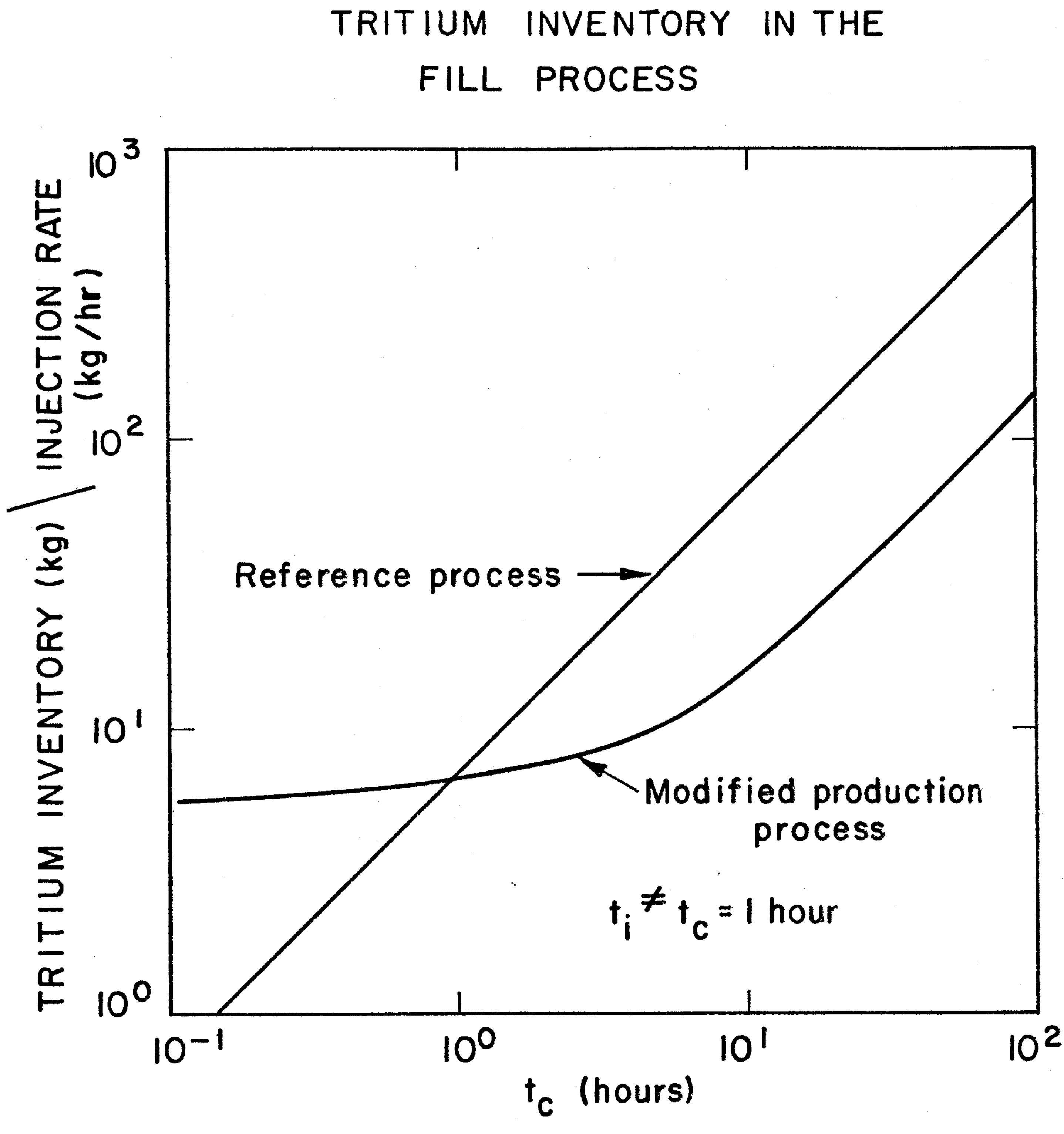



FIG. 1 A COMPARISON OF THE TRITIUM INVENTORY FOR TWO PRODUCTION PROCESSES.

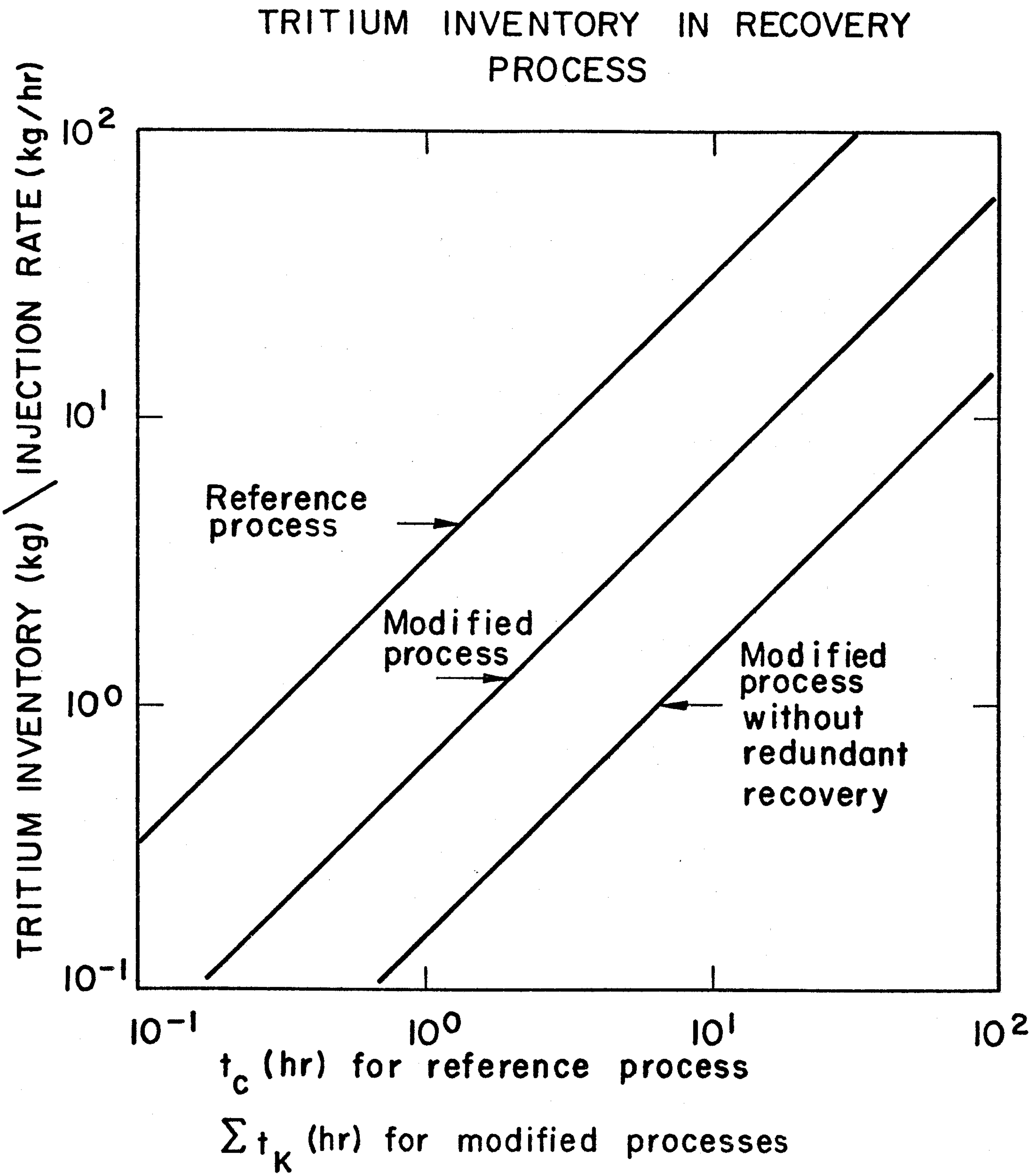
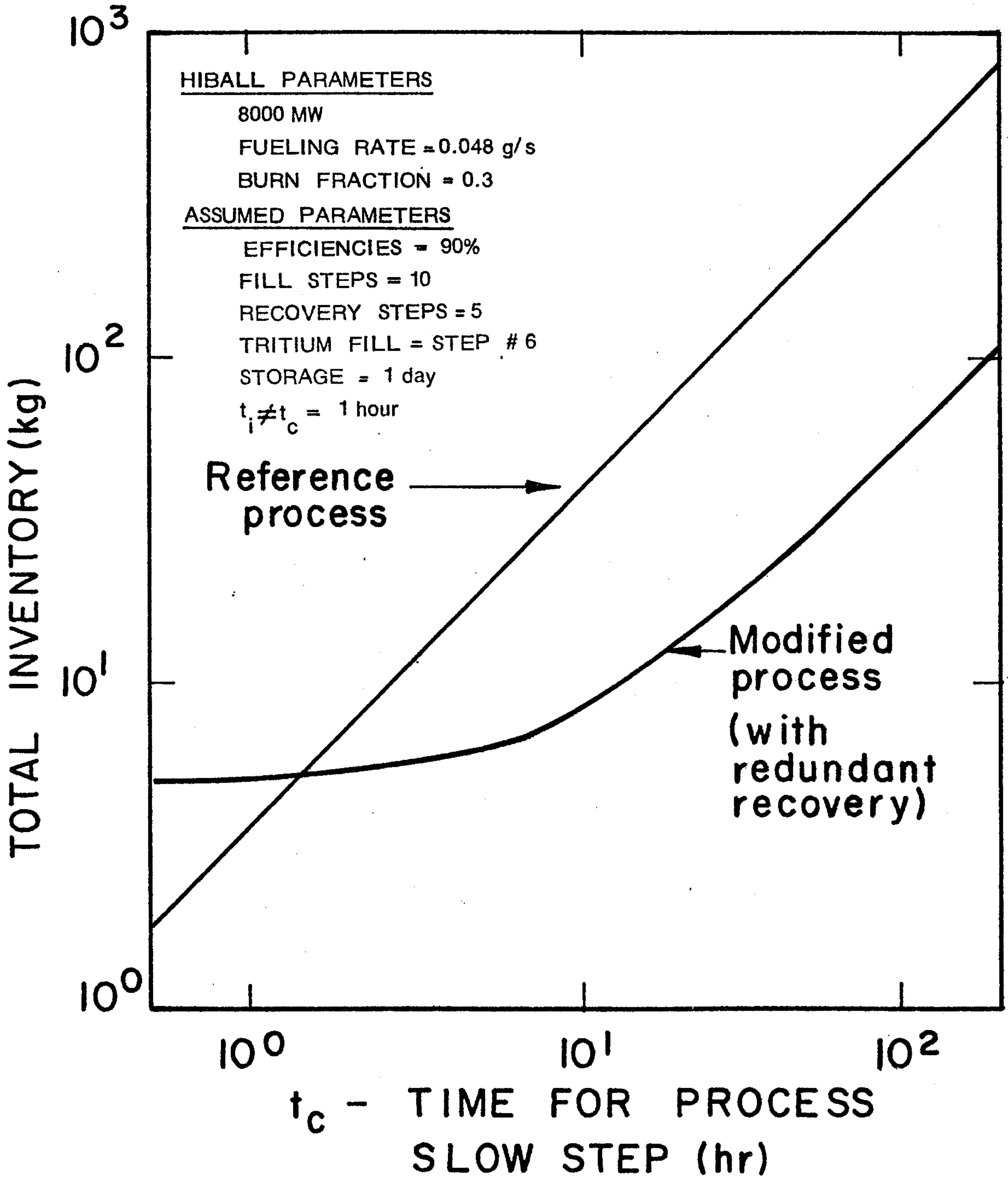



FIG. 3 A COMPARISON OF THE TRITIUM INVENTORY FOR THREE RECOVERY SCHEMES.

# TRITIUM INVENTORY IN TARGET FACTORY



# HIBALL TRITIUM INVENTORY

| | | |
|---|---|---|
| **FUEL CYCLE (kg):** | | |
| Cryopumps | 0.37 | |
| Fuel Cleanup | 0.041 | |
| Isotopic Separation | 0.083 | |
| **SUBTOTAL** | | 0.49 |
| **BLANKET (kg):** | | |
| $Li_{17}Pb_{83}$ (cavity and reflector) | 0.010 | |
| SiC tubes | 0.012 | |
| **SUBTOTAL** | | 0.025 |
| **TOTAL REACTOR INVENTORY (kg):** | | 0.52 |
| Storage (1 d fuel supply)(kg) | | 4.1 |
| Target Factory (kg) | | ~10 |
| Slow step 1 h – 5 kg | | |
| Slow step 24 h – 10-50 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