BLANKET/SHIELD ENGINEERING LIMITS BASED ON CONVENTIONAL DESIGN STUDIES

MOHAMED A. ABDOU
UCLA

MFAC PANEL X MEETING
JANUARY 30, 1985
UCLA

<u>CONTRIBUTORS</u>

P. GIERSZEWSKI
K. TAGHAVI
M. TILLACK
A. MAJID

CONVENTIONAL DESIGN STUDIES

UWMAK Series

STARFIRE, ANL/DEMO

BCSS

MARS

Parts of FINESSE

OUTLINE

- RADIATION SHIELD
- BLANKET/FIRST WALL
  - THERMOMECHANICAL AND MATERIALS CONSTRAINTS
  - TRITIUM BREEDING
- MASS UTILIZATION
- BLANKET EXTERNAL TO COILS

INTRODUCTORY POINTS

- KEY DEVICE PARAMETERS THAT AFFECT FIRST WALL/BLANKET/SHIELD:
  - NEUTRON WALL LOAD
    MOST NEUTRONICS PARAMETERS ARE APPROXIMATELY LINEAR WITH NEUTRON WALL LOAD (FLUX, HEATING, ACTIVATION BURNUP, ETC.)
  - SURFACE HEAT LOAD AT FIRST WALL
  - PLASMA PARTICLE FLUX, ENERGY AT FIRST WALL
  - MAGNETIC FIELD

- THERE IS A STRONG CORRELATION BETWEEN FIRST WALL BLANKET AND IMPURITY CONTROL SYSTEM CONDITIONS AND DESIGNS:
  - α-POWER IS SHARED BETWEEN FIRST WALL AND "LIMITER/DIVERTOR" TYPE
  - COMPATIBILITY OF MATERIAL CHOICE, E.G., LITHIUM IN BLANKET PRACTICALLY RULES OUT WATER IN LIMITER/DIVERTOR
  - "BLANKET/SHIELD" AND "IN-VESSEL COMPONENT" CONSTRAINTS SHOULD BE VIEWED TOGETHER

RADIATION SHIELDING

BULK SHIELD

- FOR TYPICAL OPTIMIZED SHIELD:

  INCREASING P_{NW} BY A FACTOR OF 10 REQUIRES INCREASING Δ_{BS} BY 15 CM (OR 6.5 CM FOR A FACTOR OF 2 IN P_{NW})

- IN TYPICAL TOKAMAKS (R ~ 5-6 M):

  A 1 CM INCREASE IN Δ^{I}_{BS} REDUCES POWER BY 1%

- THE INCREASE IN Δ_{BS} AT HIGH P_{NW} IS AN ADDED PENALTY:

  IT DOES NOT BY ITSELF ELIMINATE THE ADVANTAGE OF HIGHER P_{NW}. IT ONLY REDUCES THE MAGNITUDE OF THE ADVANTAGE (UNLESS A TECHNOLOGICAL CONSTRAINT IS REACHED, E.G., B_{MAX}).

PENETRATION SHIELD

- AFFECTED BY P_{NW}
- HOWEVER, THE KEY FACTORS ARE THE CHARACTERISTICS OF PENETRATIONS (E.G., SIZE, SHAPE, LOCATION)

DEPENDENCE OF BLANKET DESIGN ON POWER DENSITY

- **CONCLUSION FROM PREVIOUS STUDIES**

  - THE UPPER END OF "OPTIMUM" PARAMETERS ARE:

    $P_{NW} \sim 5$ MW/M^2
    $Q_S \sim 1$ MW/M^2
    FIRST WALL EROSION < 1 MM/Y

  - REASONS:

    LIMITATIONS ON ABILITY TO PRODUCE
    LIMITATIONS ON ABILITY TO USE

- **THIS PRESENTATION**

  - EXPLANATION OF USE LIMITATIONS

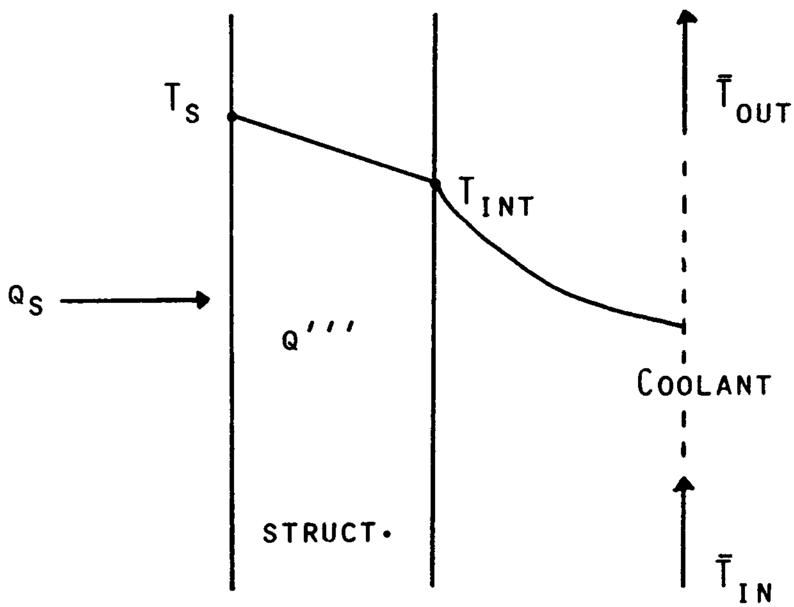
  - PRELIMINARY THOUGHTS ON HOW TO OVERCOME SOME OF THE LIMITATIONS

BLANKET EXAMPLES

SELF-COOLED LIQUID METALS

SOLID BREEDERS

LIQUID METAL BLANKETS



$\bar{T}_{IN} > T_{IN}^{MIN}$ (MELTING, PINCH POINTS)

$\bar{T}_{OUT} > T_{OUT}^{MIN}$ (THERMAL EFFICIENCY)

$T_{INT} = \bar{T}_{OUT} + \Delta T_{FILM} < T_{INT}^{MAX}$ (COMPATIBILITY)

$T_S = \bar{T}_{OUT} + \Delta T_{FILM} + \Delta T_S < T_S^{MAX}$ (STRUCTURE LIMIT)

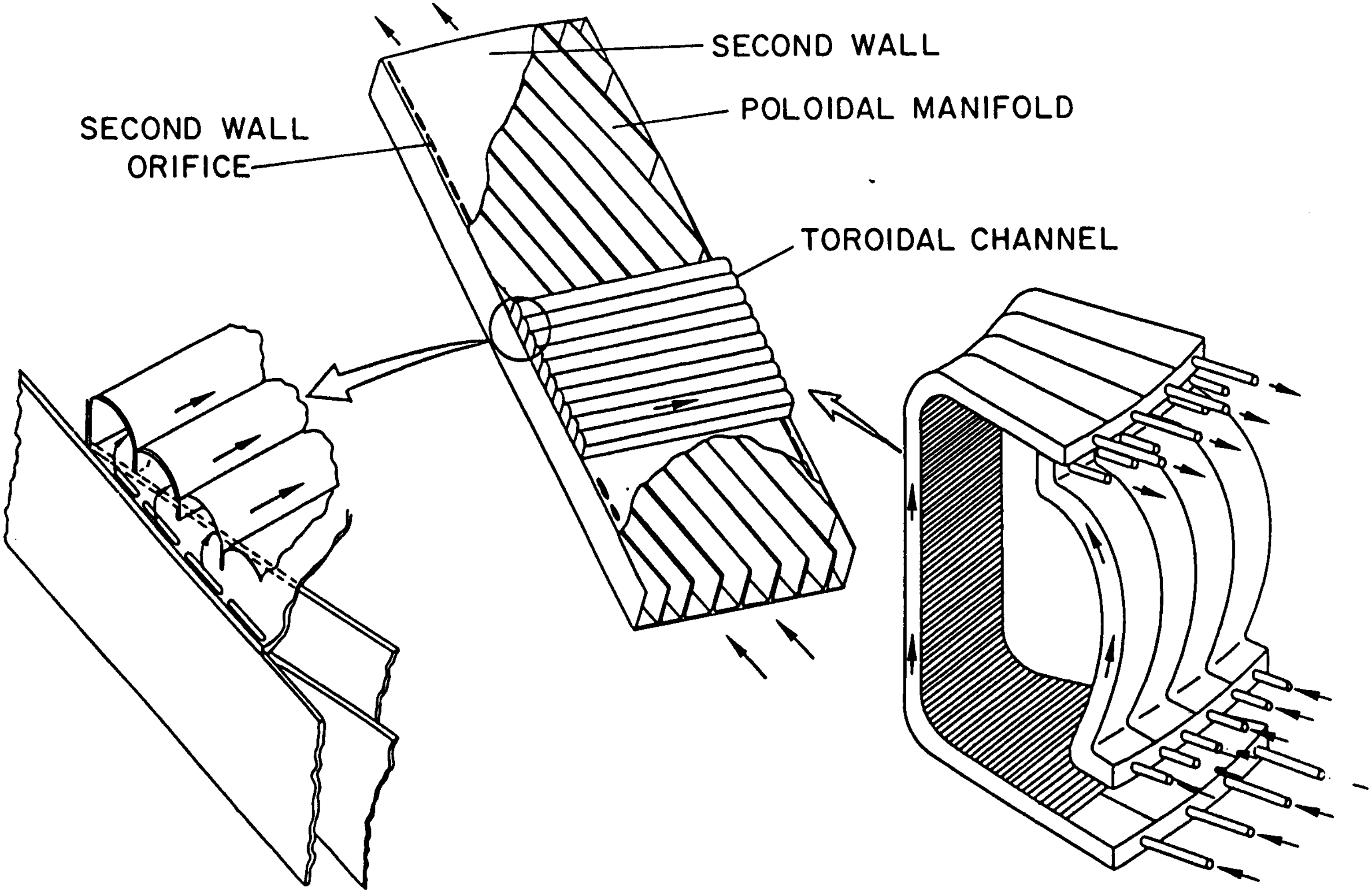
MHD

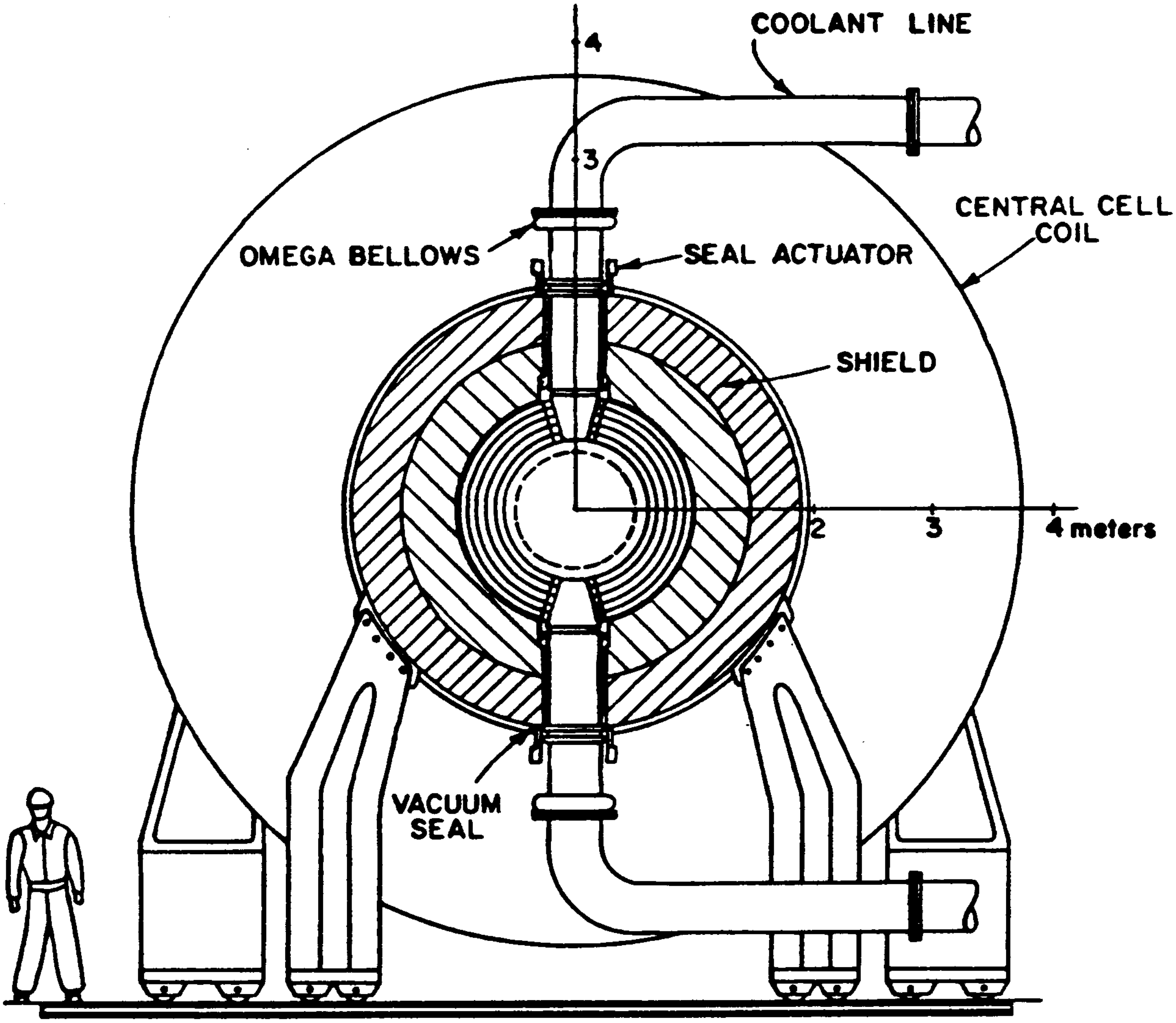
$$\Delta P \sim \ell v B^2 \sigma_W T_W / A$$

$$\ell^2 B^2 \sigma_W \left(\frac{Q_S + Q''' T}{\rho C_P \Delta_B \overline{\Delta T_C}} \right) < S_{ALLOW}$$ (FEASIBILITY CONDITION)

POLOIDAL BLANKET/MANIFOLD FLOW

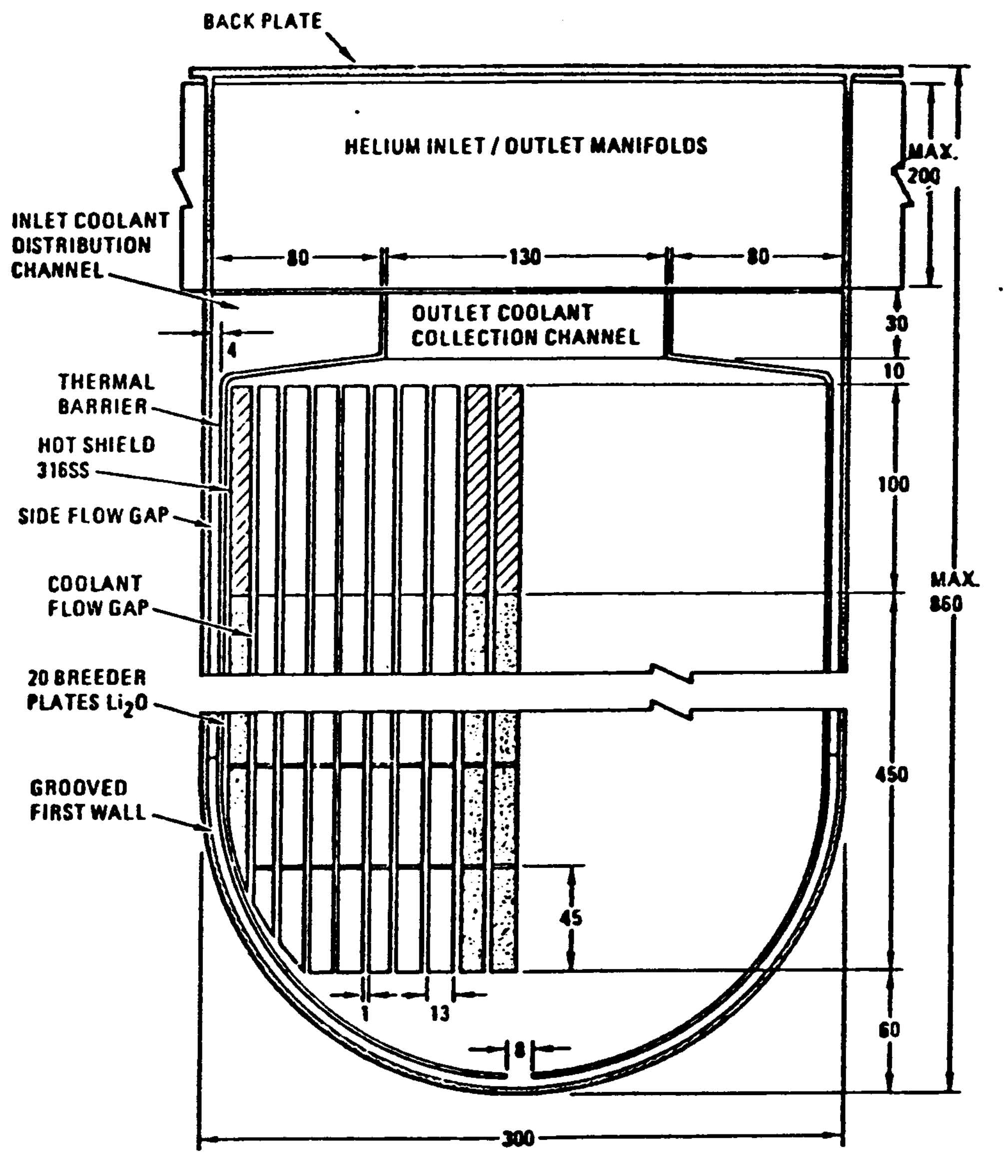
TOROIDAL FIRST WALL FLOW





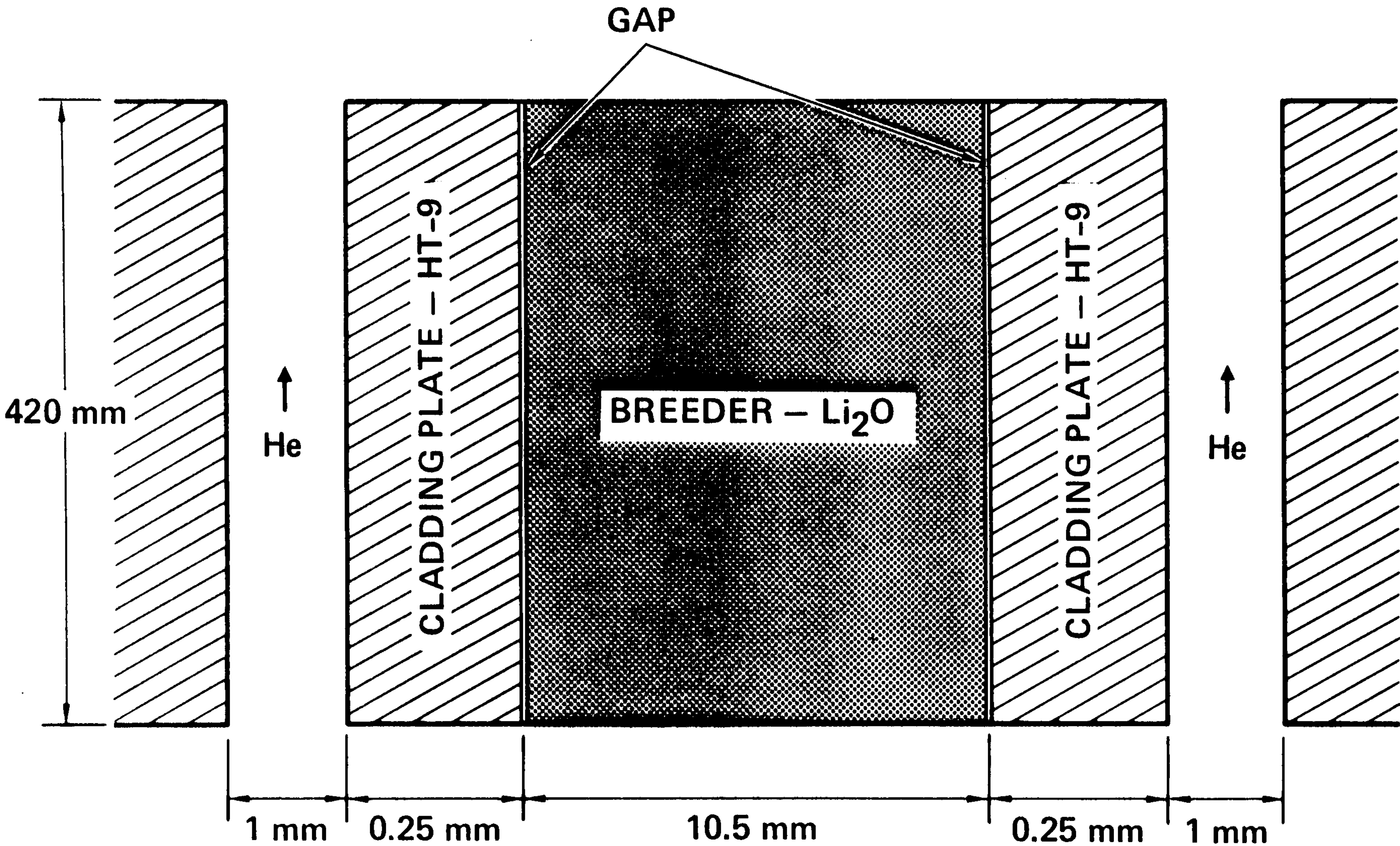
CROSS SECTION OF TMR CENTRAL CELL

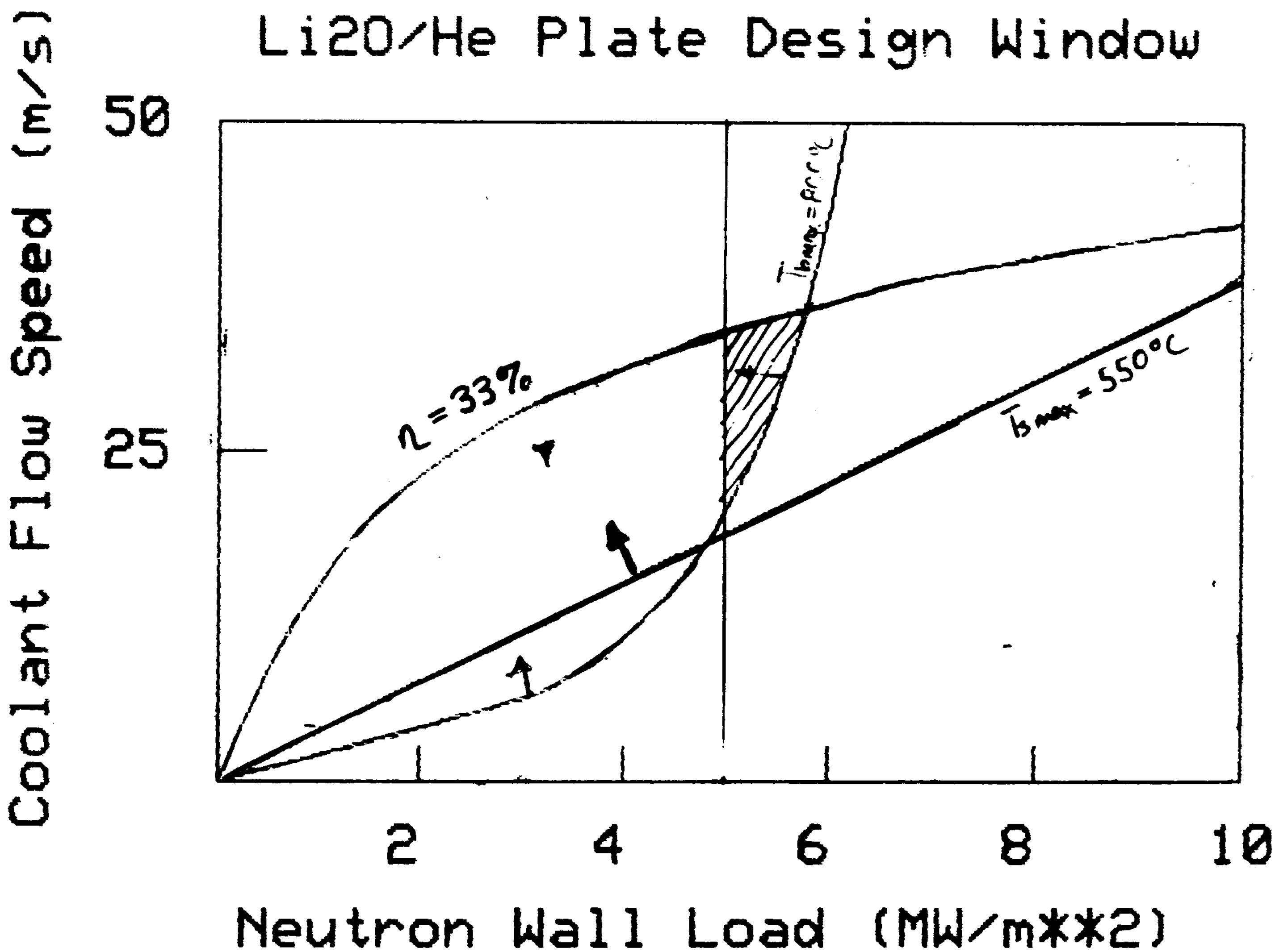
BLANKET MODULE CROSS SECTION (AN EXAMPLE)



ALL DIMENSIONS IN mm

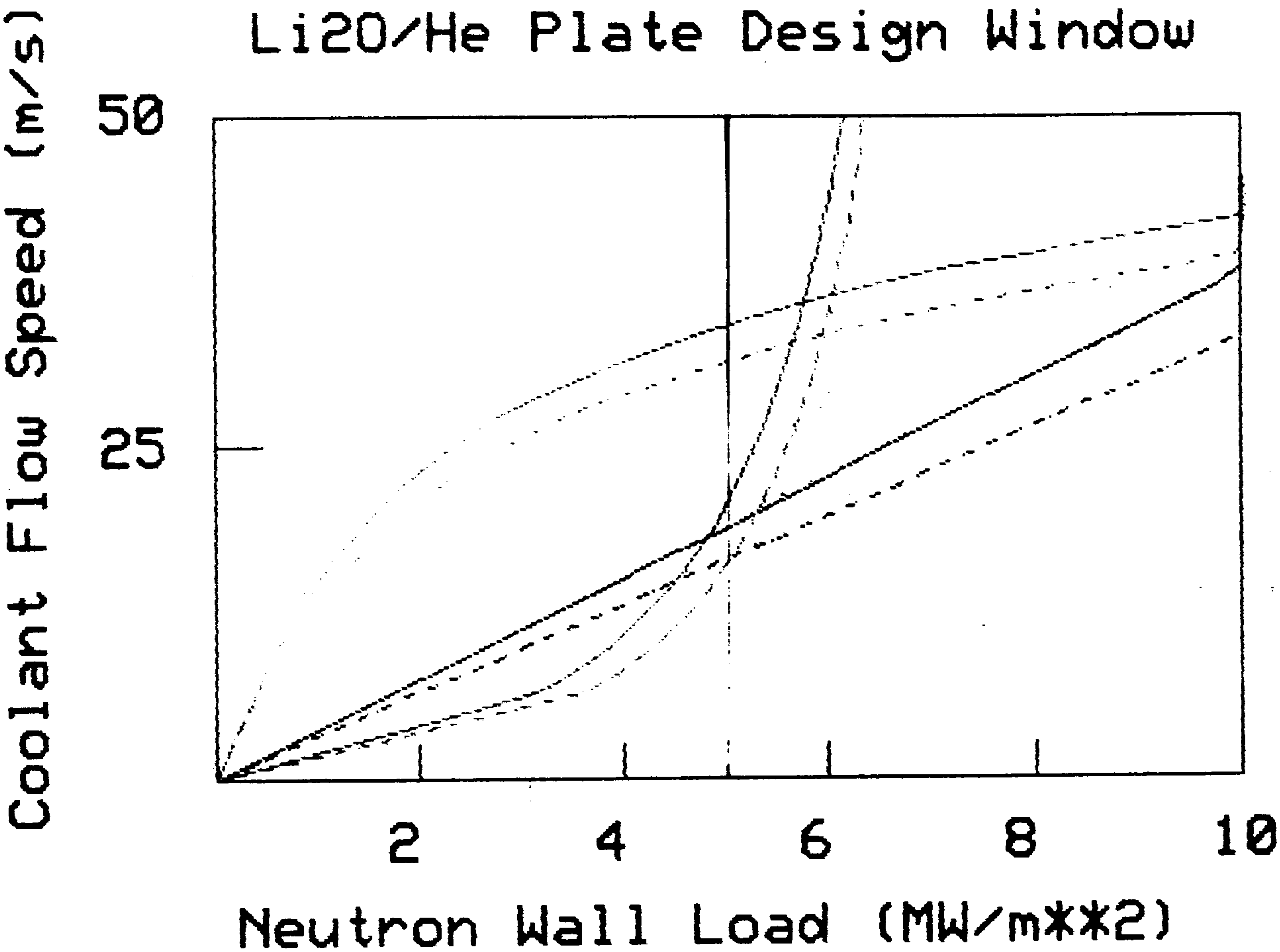
BLANKET MODEL





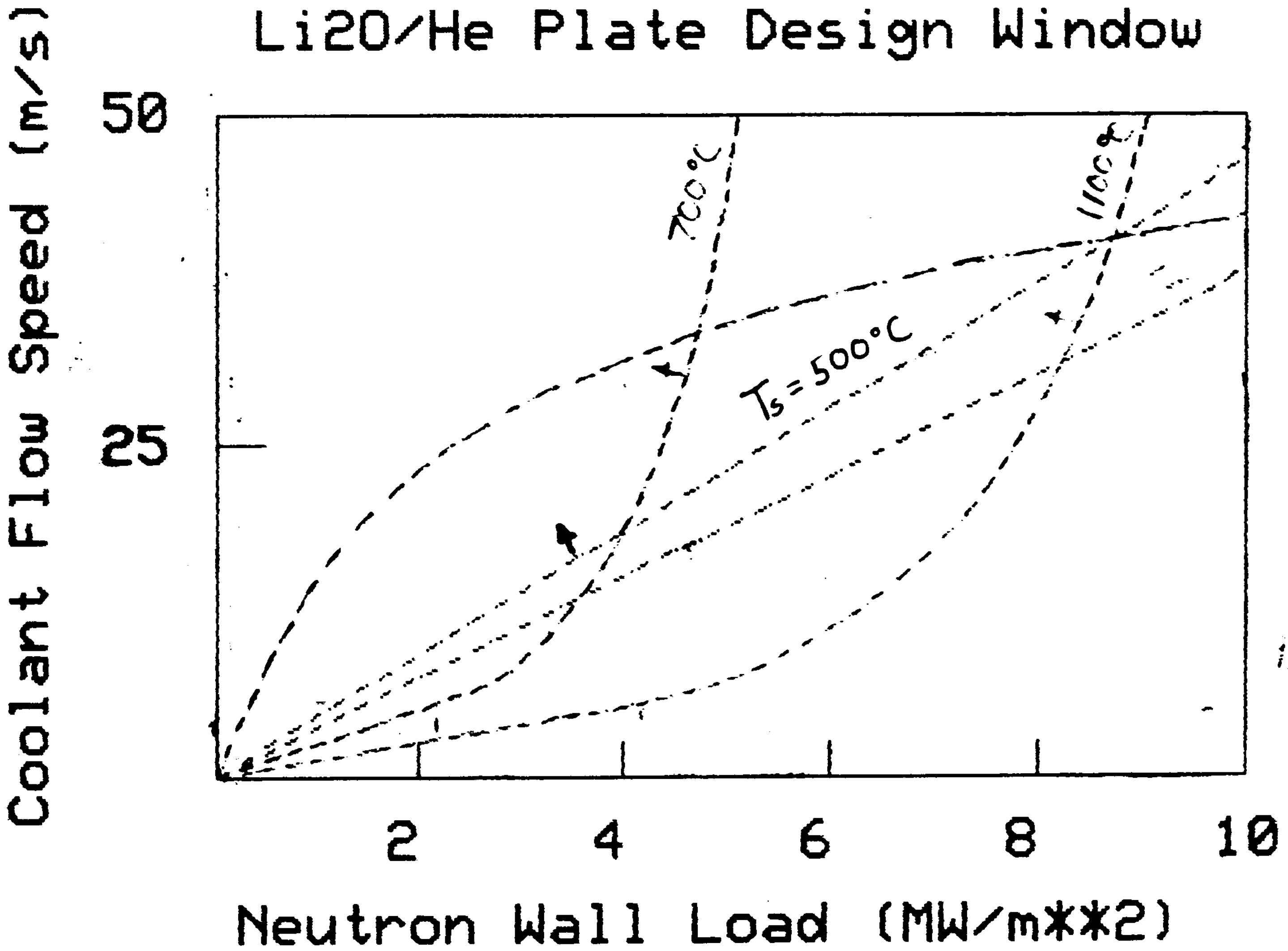
REFERENCE DESIGN WINDOW

No Surface Heat Flux Effects



DESIGN WINDOW CHANGE WITH NO SURFACE HEAT FLUX

Effect of Uncertainties on Design Window



TRITIUM BREEDING RATIO (TBR)

T_R = REQUIRED TBR

T_A = ACHIEVABLE TBR

FUEL SELF SUFFICIENCY: $T_A > T_R$

REQUIRED TBR

- T_R DEPENDS ON REACTOR PLASMA, ENGINEERING PARAMETERS
- EXAMPLES OF DESIGN LIMITATIONS:

  TRITIUM FRACTIONAL BURNUP IN PLASMA > 5%
  BLANKET TRITIUM INVENTORY < 5 KG

ACHIEVABLE TBR

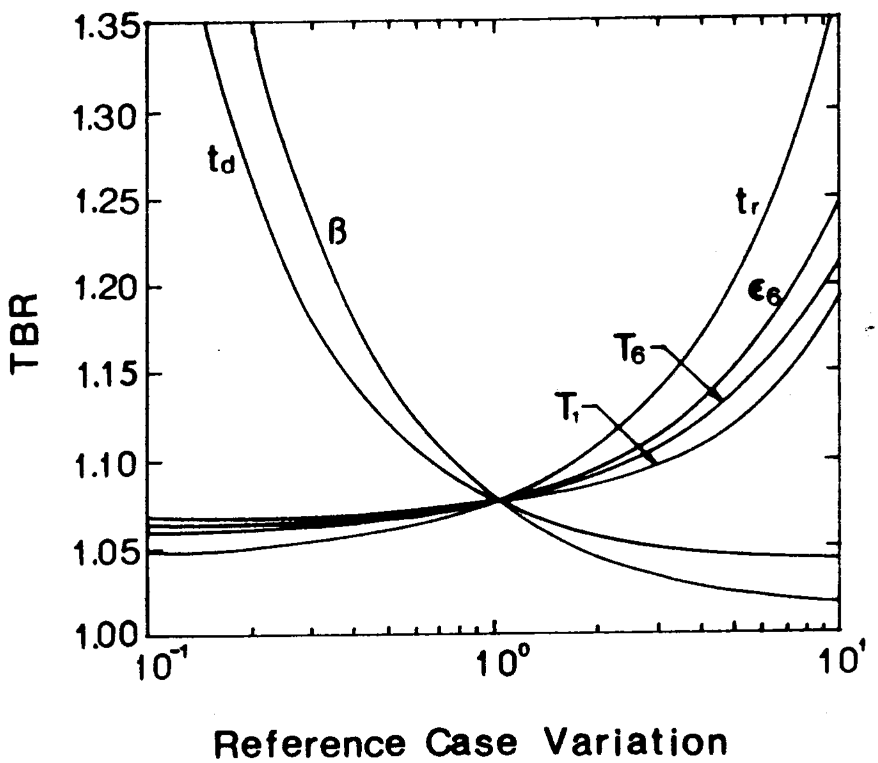
- PRESENT CONCEPTS ARE LIMITED IN THE MAXIMUM ACHIEVABLE TBR
- EXAMPLES OF DESIGN LIMITATIONS:

  AMOUNT OF STRUCTURE
  BLANKET COVERAGE

IMPACT OF HIGH POWER DENSITY ON TBR

- WILL INCREASE THE DIFFICULTY OF T_A
- CAN BE ACCEPTABLE IF IT RESULTS IN LOW T_R

DEPENDENCE OF REQUIRED TBR ON PLASMA, ENGINEERING PARAMETERS



Reference Case

β = 5%

T_1 = 10 D

T_R = 2 D

T_D = 5 Y

T_6 = 1 D

ϵ_6 = 0.1%

Notation

β = TRITIUM FRACTIONAL BURNUP IN PLASMA

T_D = DOUBLING TIME

T_1 = TRITIUM MEAN RESIDENCE TIME IN BLANKET

T_6 = TRITIUM MEAN RESIDENCE TIME IN PLASMA EXHAUST PROCESSING

T_R = NUMBER OF DAYS OF TRITIUM RESERVE

ϵ_6 = TRITIUM EXTRACTION INEFFICIENCY IN PLASMA EXHAUST PROCESSING

Table 2.X2 Results of Tritium Breeding Requirements, Potential and Uncertainties for Candidate Blanket Concepts in Tokamaks

	Concept	T_c	$1+G_o$	Δ_G^2	Δ_S^2	Δ_p^2	$\sum\Delta_i^2$	$T_c-(1+G_o)-\sqrt{\sum\Delta_i^2}$
A	$LiAlO_2$/DS/HT-9/Be	1.24	1.073	.05	.0094	.0009	.0603	-.0779
B	Li/Li/HT-9	-	-	-	-	-	-	-
C	LiPb/LiPb/V	-	-	-	-	-	-	-
D	Li/Li/V	1.28	1.068	.05	.0094	.0041	.1635	-.192
E	Li_2O/He/He/HT-9	1.11	1.067	.05	.0094	.0029	.1623	-.360
F	$LiAlO_2$/He/HT-9/Be	1.04	1.067	.05	.0094	.0009	.1603	-.427
G	Li/He/HT-9	1.16	1.068	.05	.0094	.0030	.1624	-.311
H	Flibe/He/HT-9/Be	1.17	1.067	.05	.0094	.0017	.1611	-.298
I	$LiAlO_2$/H_2O/HT-/Be	1.16	1.071	.05	.0094	.0009	.1603	-.311

Table 2.X3 Results of Tritium Breeding Requirements, Potential and Uncertainties for Candidate Blanket Concepts in Mirrors

	Concept	T_c	$1+G_o$	Δ_G^2	Δ_S^2	Δ_p^2	$\sum\Delta_i^2$	$T_c-(1+G_o)-\sqrt{\sum\Delta_i^2}$
A	$LiAlO_2$/DS/HT-9/Be	1.29	1.069	.05	.0094	.0009	.0603	-.0779
B	Li/Li/HT-9	1.14	1.068	.05	.0094	.0035	.1629	-.332
C	LiPb/LiPb/V	1.18	1.067	.05	.0094	.0024	.1618	-.289
D	Li/Li/V	1.19	1.068	.05	.0094	.0041	.1635	-.282
E	Li_2O/He/HT-9	1.14	1.067	.05	.0094	.0029	.1623	-.330
F	$LiAlO_2$/He/HT-9/Be	1.16	1.067	.05	.0094	.0009	.1603	-.307
G	Li/He/HT-9	1.17	1.067	.05	.0094	.0030	.1624	-.300
H	Flibe/He/HT-9/Be	1.29	1.067	.05	.0094	.0017	.1611	-.178
I	$LiAlO_2$/H_2O/HT-9/Be	1.22	1.070	.05	.0094	.0009	.1603	-.250

BLANKET/SHIELD AND MASS UTILIZATION

BLANKET

- PRESENT BLANKET CONCEPTS HAVE TYPICAL BLANKET THICKNESS:
  $\Delta_B \sim 70\text{-}100$ CM

- THERE ARE APPROACHES TO REDUCE Δ_B TO ~ 20 CM
  (IMPROVE BLANKET MASS UTILIZATION BY A FACTOR OF 3-5)

  EXAMPLE

  5 CM BE, 10 CM ENRICHED LI, 5 CM SS
  (HIGHER MASS UTILIZATION, HIGHER ENERGY MULTIPLICATION)

- SUCH CONCEPTS WERE PUT ASIDE IN THE PAST BECAUSE OF DIFFICULT ENGINEERING PROBLEMS (HEAT REMOVAL, MATERIAL LIMITS, ETC.) AT $P_{NW} = 5$ MW/M^2

- SUCH CONCEPTS SHOULD BE REVISITED (FOR TOKAMAKS AND MIRRORS IN PARTICULAR)

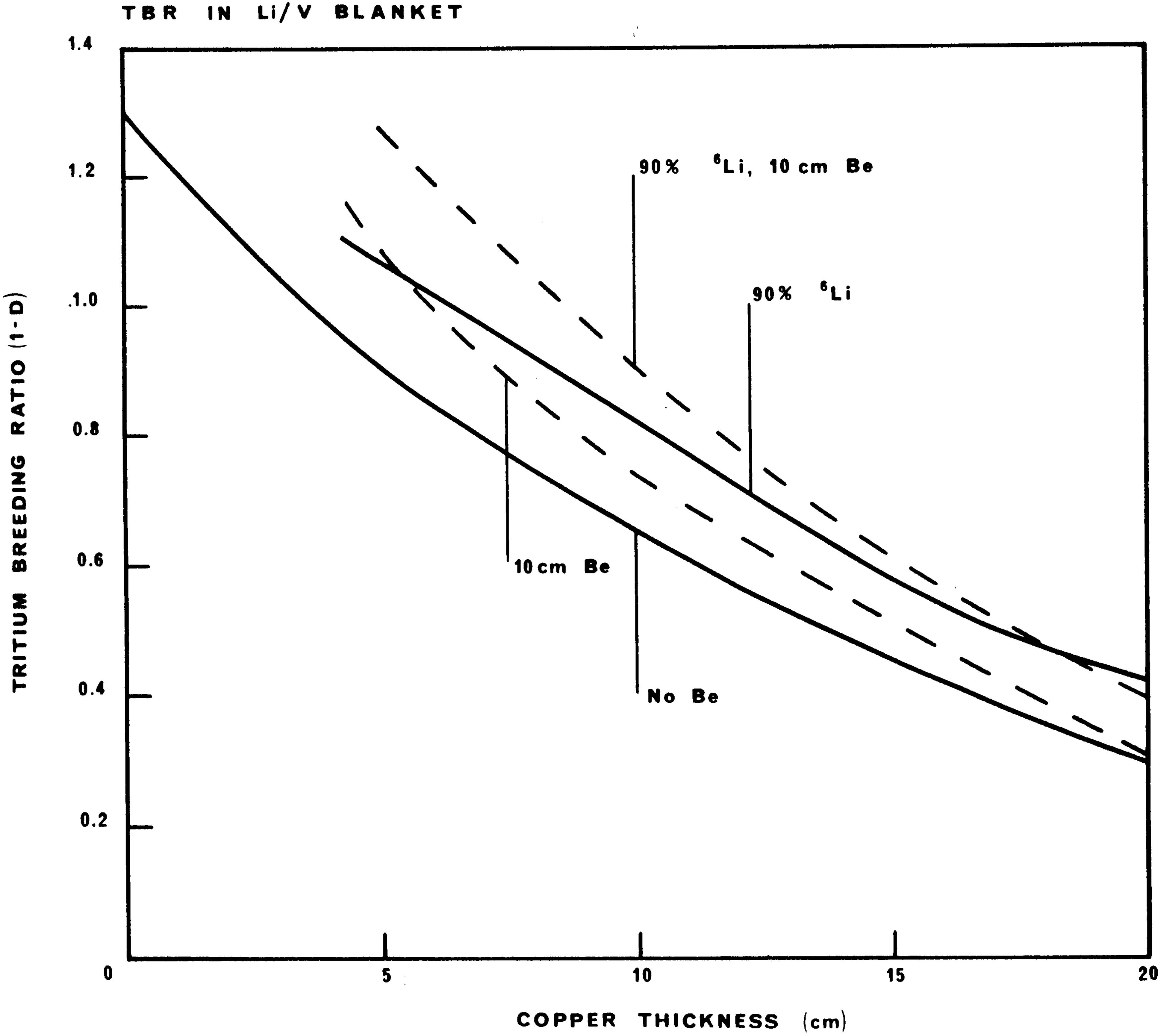
SHIELD

- LARGEST VOLUME AND MASS

- CAN REDUCE THICKNESS BY USE OF VERY HEAVY MATERIALS (TUNGSTEN, DEPLETED URANIUM?)

- REDUCING MASS OF SHIELD IS UNLIKELY EXCEPT BY REDUCING THE SURFACE AREA (NEUTRONICS/PHOTONICS CHARACTERISTICS)

- REDUCING SHIELD THICKNESS MAY PERMIT REDUCING MASS OF OTHER COMPONENTS (MAGNETS, HEAT TRANSPORT PIPING, ETC.)


TBR IN Li/V BLANKET
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
5
10
15
20
TRITIUM BREEDING RATIO (1-D)
COPPER THICKNESS (cm)
90% ^{6}Li, 10 cm Be
90% ^{6}Li
10 cm Be
No Be

CONCLUSIONS

- PREVIOUS "CONVENTIONAL" DESIGN STUDIES HAVE FOCUSED ON NEUTRON WALL LOADS (P_{NW}) OF < 5 MW/M^2

- DESIGN OF VIABLE AND ATTRACTIVE BLANKET/FIRST WALL IS DIFFICULT FOR TOKAMAKS AT $P_{NW} = 5$ MW/M^2
(LESS DIFFICULT FOR MIRRORS BECAUSE OF LOWER SURFACE HEAT FLUX, LOWER WALL EROSION)

- PRIMARY ISSUES/CONSTRAINTS: SOLID BREEDERS

  - TRITIUM BREEDING AND INVENTORY
    MINIMUM AND MAXIMUM BREEDER TEMPERATURES

  - STRUCTURE/COOLANT
    COMPATIBILITY OF COOLANT/STRUCTURE (E.G., HE/V)
    MAXIMUM STRUCTURE TEMPERATURE

  - BREEDER/CLAD MECHANICAL INTERACTION

  - OTHERS

THE COMPLEXITY OF THESE ISSUES WILL INCREASE WITH HIGH POWER DENSITY. SUCCESS DOES NOT SEEM LIKELY.

CONCLUSIONS
(CONTD.)

- **PRIMARY ISSUES/CONSTRAINTS: LIQUID METALS**
  - MHD PRESSURE DROP ($\ell^2 B^2$)
  - COMPATABILITY CORROSION (LIQUID METAL/STRUCTURE INTERFACE T)
  - STRUCTURE TEMPERATURE, ALLOWABLE STRESS
  - TRITIUM BREEDING (IN SOME CASES)
  - OTHERS

- SOME OF THESE ISSUES WILL BE ADVERSELY AFFECTED BY HIGH POWER DENSITY
- OTHERS MAY BENEFIT DEPENDING ON SYSTEM PARAMETERS

CONCLUSIONS
(CONTD.)

- NEUTRON WALL LOADS IN THE RANGE OF 5-10 MW/M^2 MAY BE POSSIBLE BY A COMBINATION OF IMPROVED REACTOR SYSTEM FEATURES AND AGGRESSIVE BLANKET ENGINEERING R&D

- PROMISING DIRECTIONS FOR ACHIEVING VIABLE SYSTEMS AT P_{NW} 5-10 MW/M^2:

  - EMPHASIZE LIQUID METALS
  - REDUCE SURFACE HEAT LOAD AND EROSION AT FIRST WALL TO MINIMUM
  - FIND SOLUTIONS TO IMPURITY CONTROL:
    VERY LOW PLASMA EDGE TEMPERATURE
    THROW AWAY HEAT
    DIRECT ENERGY CONVERSION (IMPROVES η)
  - CONSIDER A SEPARATE FIRST WALL, FIND A SUITABLE COOLANT
  - KEEP MAGNECTIC FIELD LOW
  - SYSTEM GEOMETRY SHOULD ALLOW SHORT PATH LENGTH FOR LIQUID METAL FLOW
  - EXAMINE THE POSSIBILITY OF ELECTRIC INSULATORS IN THE BLANKET

- NEUTRON WALL LOADS > 10 MW/M^2 ARE BEYOND THE CREDIBLE EXTRAPOLATION RANGE

CONCLUSIONS
(CONTD.)

- THERE ARE IDEAS FOR IMPROVING MASS UTILIZATION FOR BLANKET/SHIELD OTHER THAN INCREASING NEUTRON WALL LOADS. SUCH IDEAS DESERVE EXPLORATION.

- ATTAINING DT FUEL SELF SUFFICIENCY WITH BLANKET EXTERNAL TO COIL:

COIL THICKNESS > 10 CM	IMPOSSIBLE
COIL THICKNESS ~ 5-8 CM	UNLIKELY