Flibe Assessment Summary

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Tritium Breeding

- The tritium breeding potential of flibe is marginal
- A parameter study of tritium breeding are being performed
- The parameters to be varied are:
  - Lithium enrichment
  - Flibe composition
  - Be content in the blanket
  - Structural fraction
- The tritium breeding results will be available before the next APEX meeting

Tritium Breeding in Flibe is Marginal

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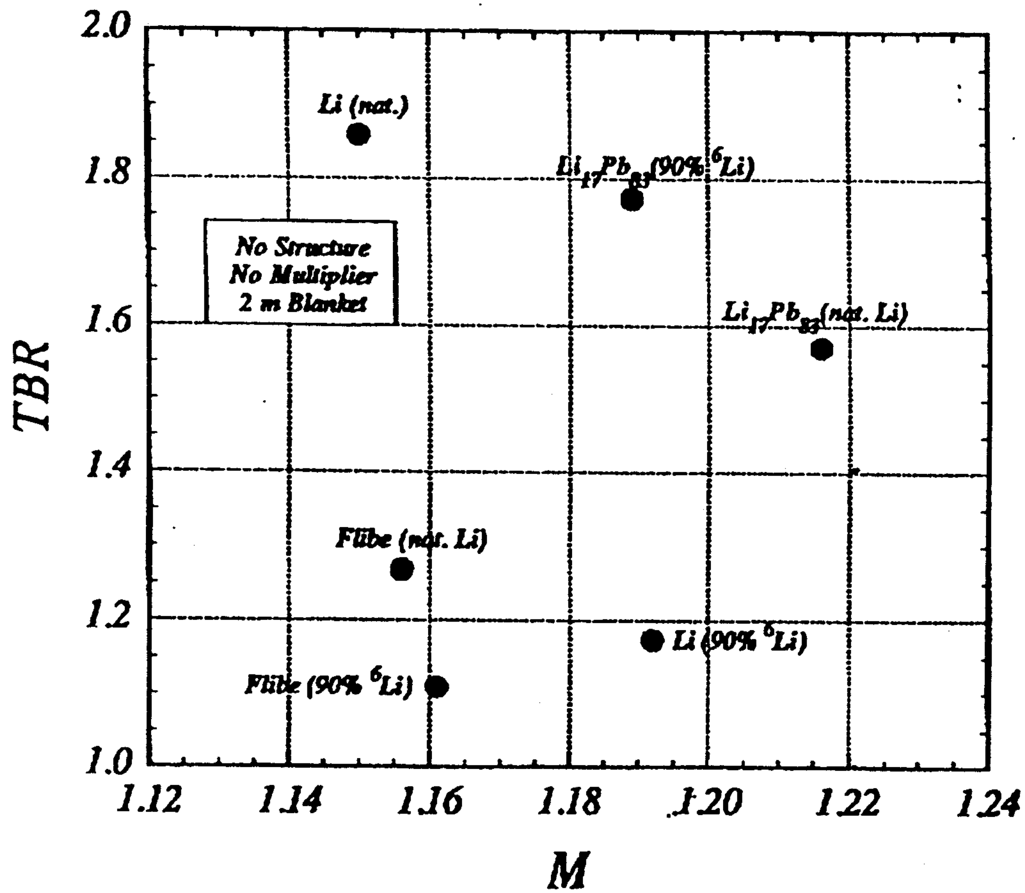

Varying Flibe Composition has Minimal Effect on Breeding

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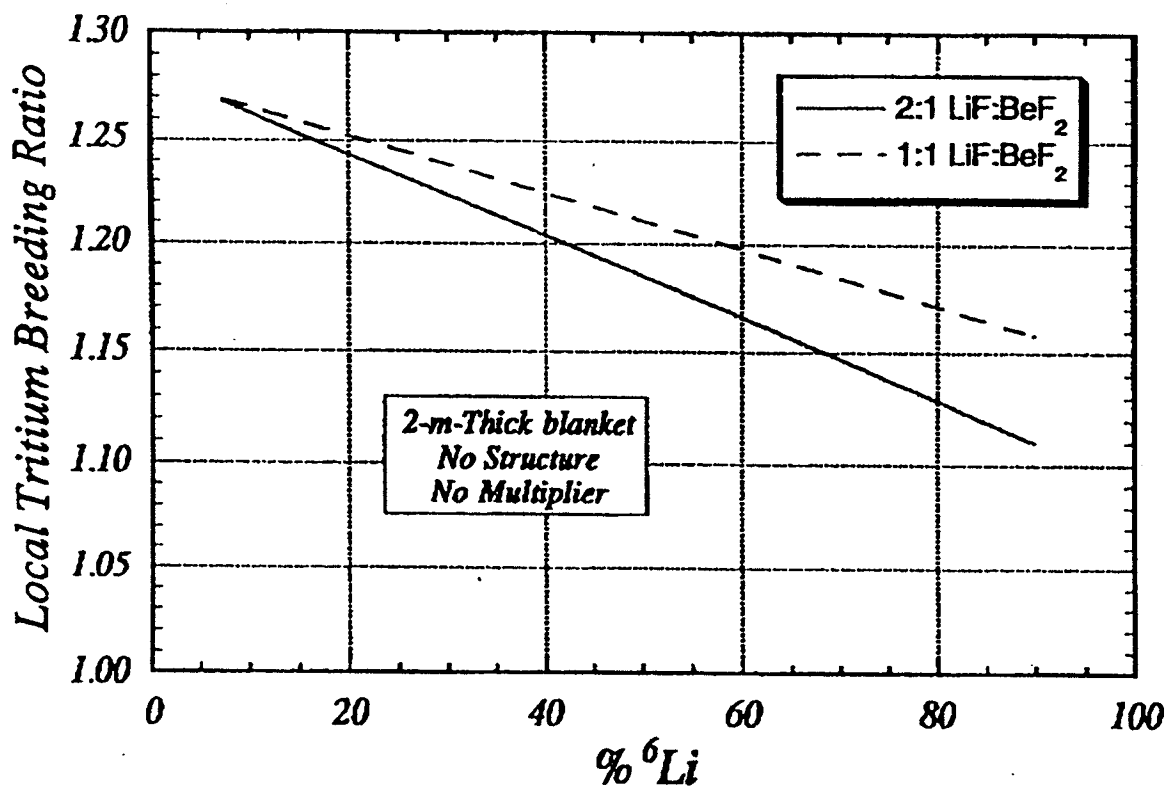

- Changing the mix ratio of $LiF:BeF_2$ to 1:1 has no effect on breeding at the optimum ^6Li content (nat. Li). Enhancement is only 4% for 90% ^6Li

Adding 5% V Structure Reduces TBR in a Flibe Blanket by ~2%

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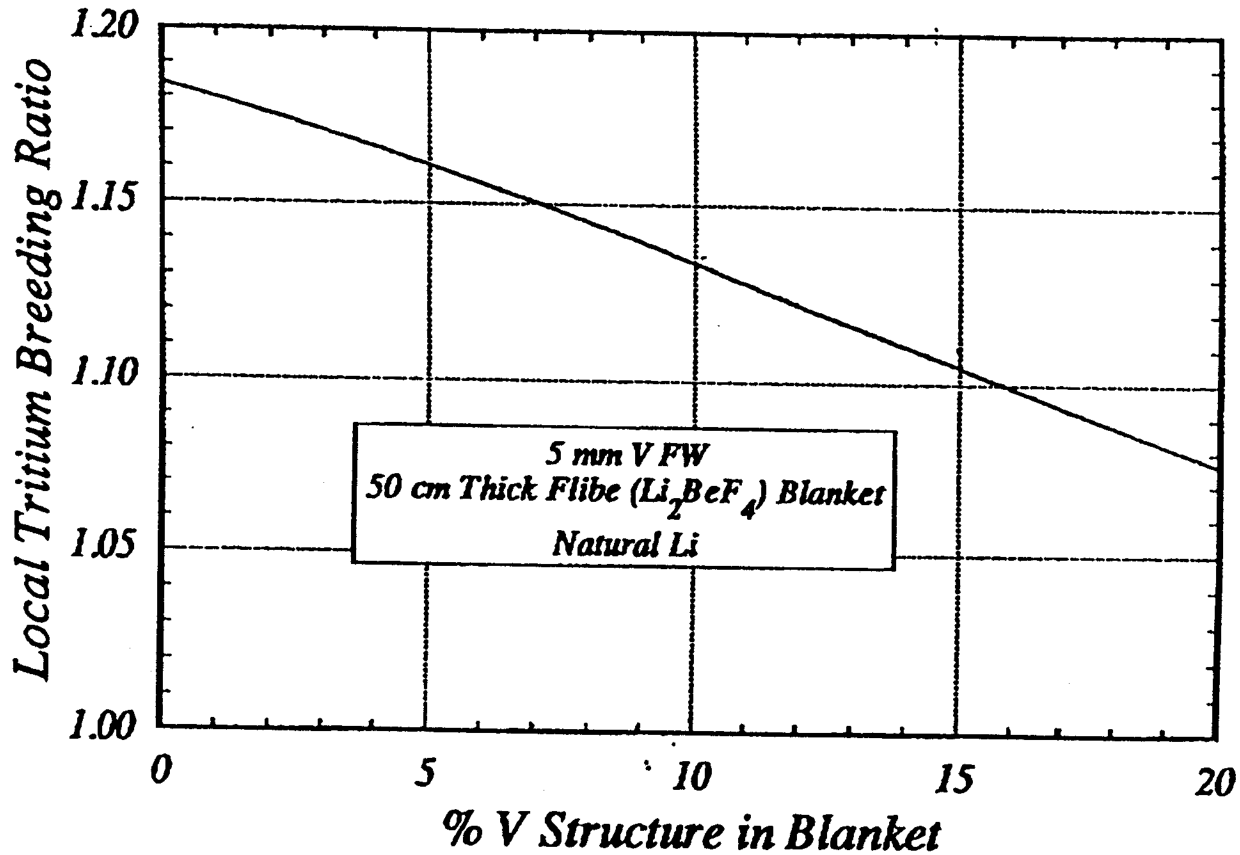

Adding Beryllium in the Front Zone of the Flibe Blanket Results in Significant Enhancement in TBR

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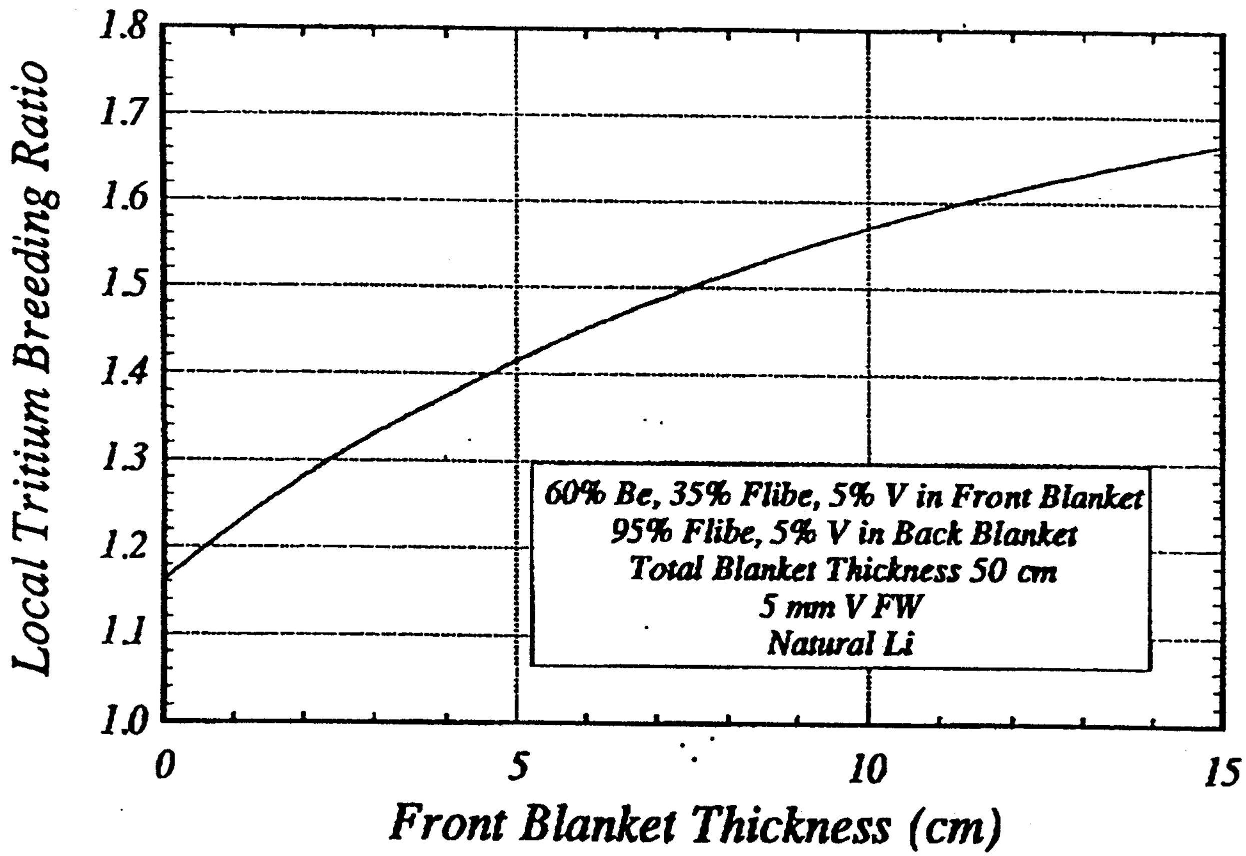

With Beryllium in the Front Zone of the Flibe Blanket TBR Maximizes at 30% ^{6}Li but Enhancement is only 2%

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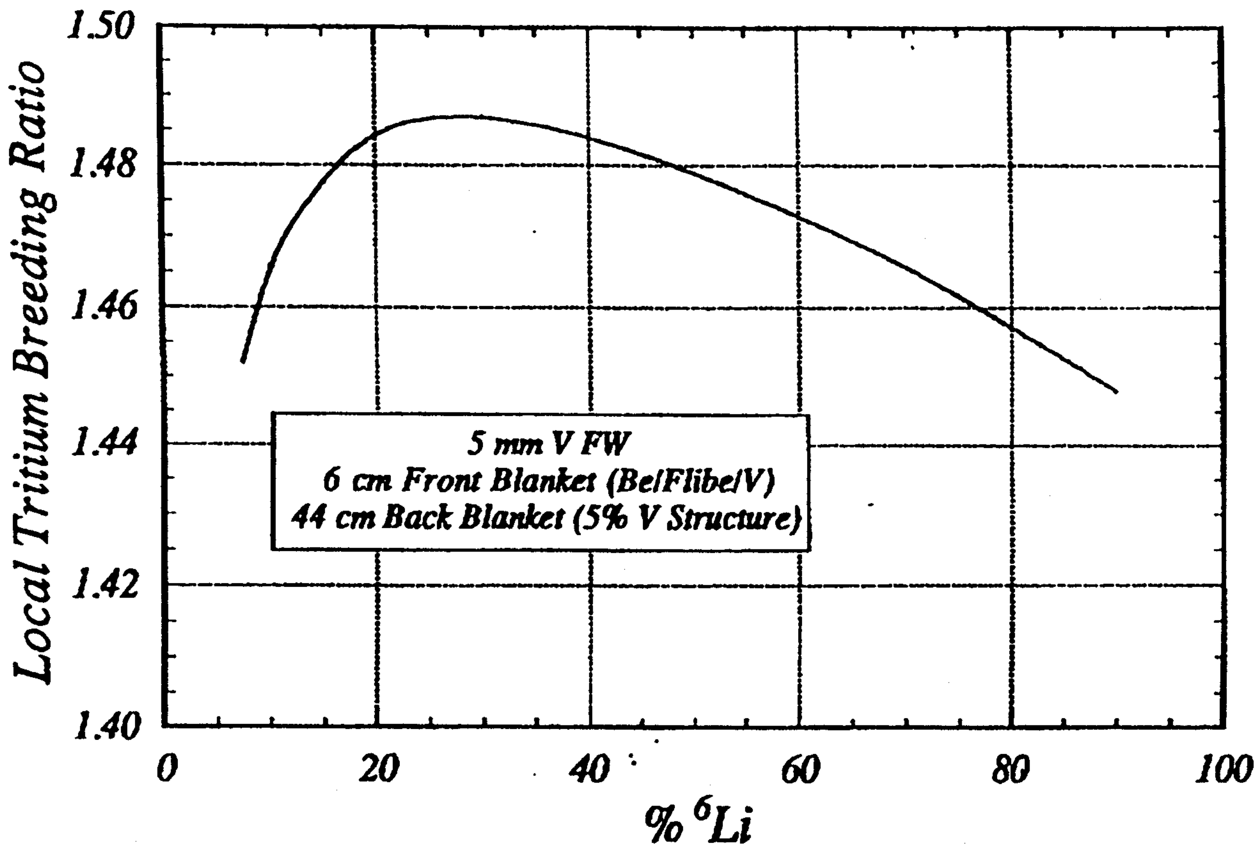

Conclusions

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- Tritium breeding in Flibe is marginal if a separate multiplier is not used
- Changing the mix ratio of $LiF:BeF_2$ from 2:1 to 1:1 is not recommended since it has no effect on breeding at the optimum ^6Li content (nat. Li)
- A small amount of structure (<5%) in the Flibe blanket reduces TBR by <2%
- Adding Be to the front of the blanket results in significant enhancement of TBR
- It is not recommended to enrich the Li in the Flibe even if Be is added

Flibe Chemistry Control

- Free fluorine will be released due to the transmutation of Be.
- Fluorine will attack any structural material, including Mo and W.
- Control of the F activity is the most critical issue of using flibe in a nuclear environment.
- A redox buffer process has to be established and demonstrated for flibe to be acceptable.

Possible Redox Buffer Reaction

- The key to a redox buffer reaction is for a material to react with F, before F can react with the structural material.
- For the MSBE, the UF3 <----> UF4 provide a natural redox buffer reaction.
- For fusion, a redox buffer system has to be established inside the molten salt.
- One possible reaction will be

  Ce3+ <-----> Ce4+
- Another possible reaction is

  V2+ <------> V3+, especially if V is used for structural material.

What Needs to be Done?

- How can we be sure that the reaction of

  Ce3+ + F ------> Ce4+ is much faster than

  M + F --------> MF?
- How do we reverse the first reaction to

  Ce4+ --------> Ce3+ + F ?
- Did MSRE ever measure the effectiveness of the redox buffer reaction?
- What kind of experimental set up did the MSRE have?

Goal of the Flibe Assessment

- To identify the feasibility issues of using flibe for fusion applications.
- To identify possible solutions to the feasibility issues.
- To make a recommendation to OFES if work on flibe needs proceed.
- To develop a R/D program for the US-Japan Monbusho collaboration.

Can we use Be?

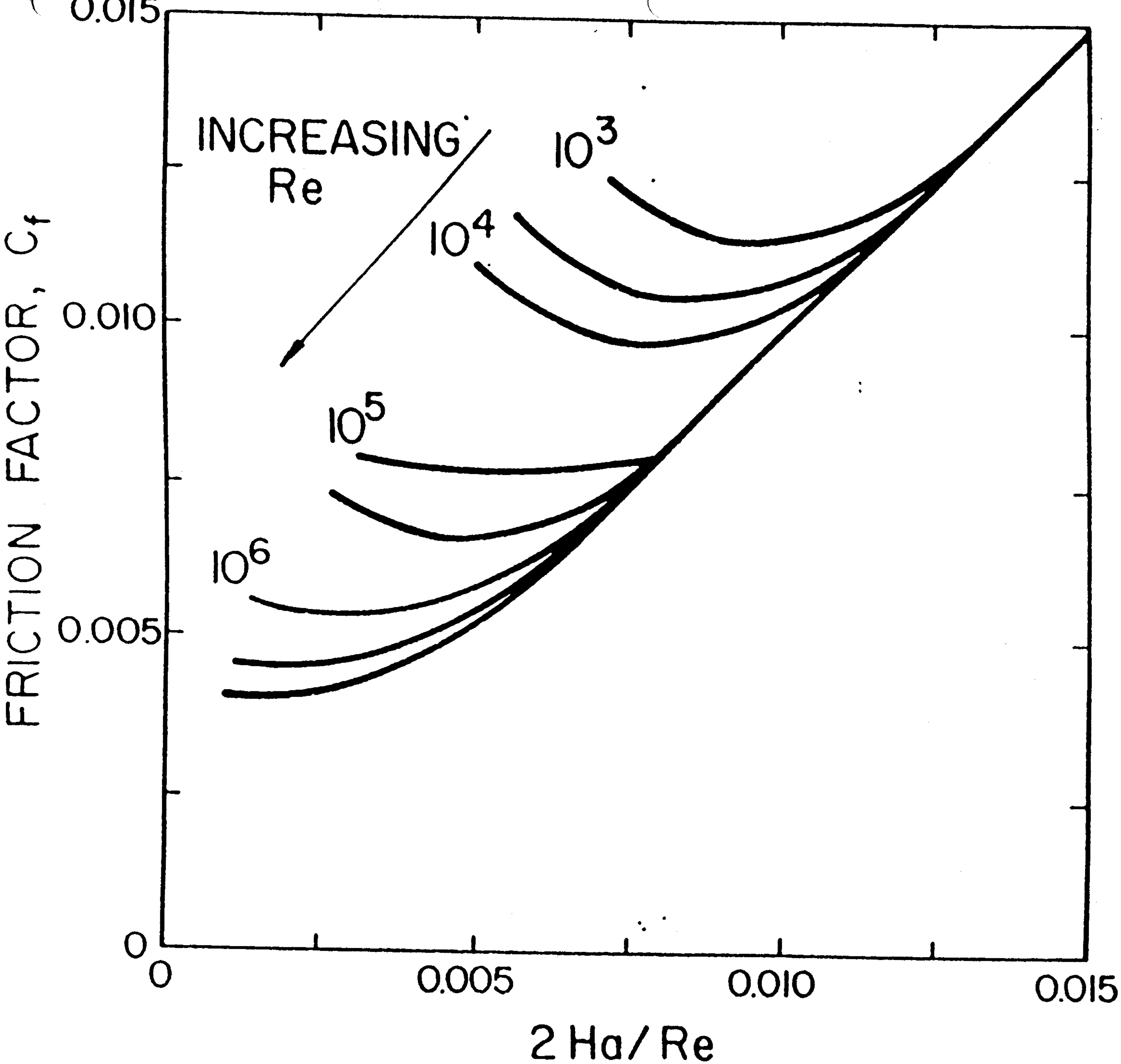
- Does Be have a finite solubility in flibe?
- Can we dissolve Be in flibe to react with F?
  2F + Be -----> BeF2?
- If Be is not dissolved in flibe, but has flibe in contact with Be, will the reaction of 2F + Be ------> BeF2 fast enough?
- If Be is keeping inside the blanket for neutron multiplier, do we have enough Be inside the blanket to react with F for years of blanket operation?

Heat Transfer

- MSRE operation has shown that conventional calculations can be used for predicting heat transfer.
- The ordinary fluid mechanics pressure drop can also be calculated by conventional correlations.
- Salt pumps and heat exchangers have also been developed.
- However, MHD effects on pressure drop and heat transfer are unique to fusion.

MHD Pressure Drop

- With a Hartman number of ~ 50, the MHD pressure drop is actually less than the ordinary pressure drop.
- Therefore, it is conservative to assume that the MHD has no effect on pressure drop.
- Since the volumetric heat capacity of flibe is rather large, the pumping power required for flibe circulation will be modest.



0.015
0.010
0.005
0
FRICTION FACTOR, C_f
INCREASING Re
10^3
10^4
10^5
10^6
0
0.005
0.010
0.015
2 Ha/ Re

Heat Transfer

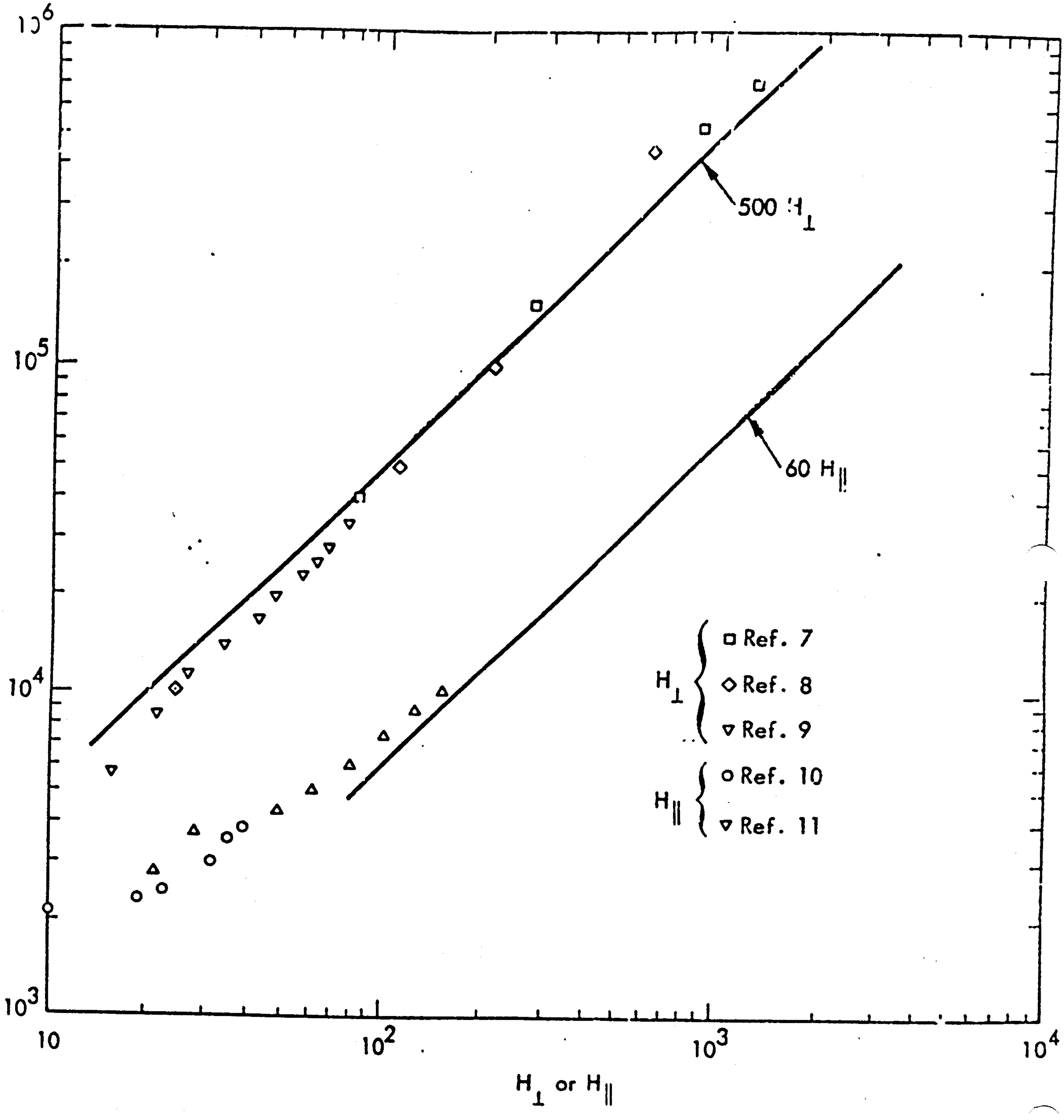
- There are some experimental results available on the MHD effects on heat transfer, with Hartman number of ~ 100.
- All the experiments have been done with a liquid metal, which has a very different Pr number from the flibe.
- It is difficult to use the heat transfer correlation developed for liquid metals, and apply that to molten salt.

Typical Re Number

Velocity	10 m/s
Diameter	0.1 m
Viscosity	0.015 kg/s-m
Density	2000 kg/m^3
Re Number	1.33 x 10^5

Typical Hartman Number

Magnetic Field	16 Tesla
Characteristic Dimension	0.05 m
Electrical Conductivity	155 ohm/m
Viscosity	0.015 kg/s-m
Ha Number	80



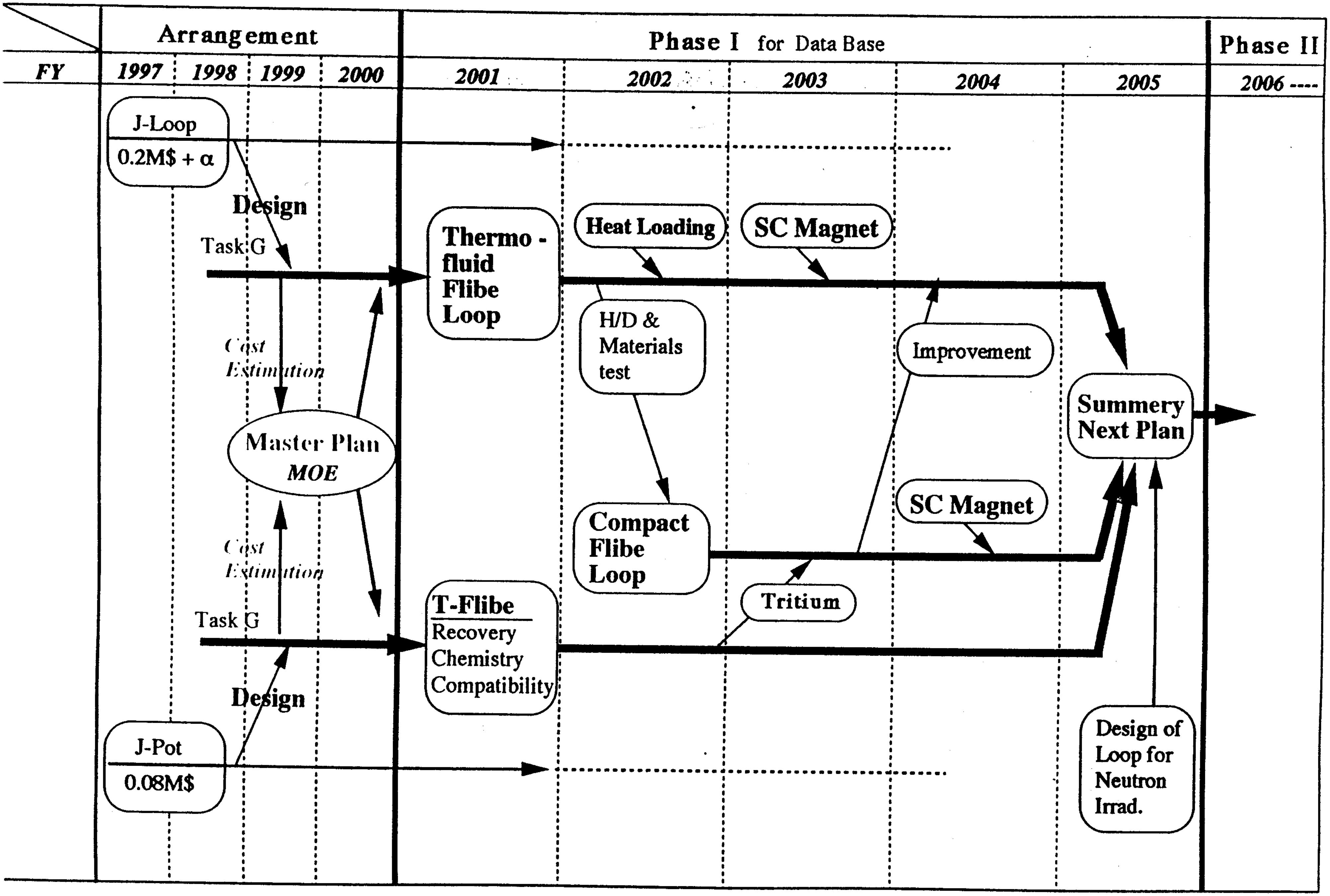
10^6
10^5
10^4
10^3
10
10^2
10^3
10^4
$500\ H_\perp$
$60\ H_\parallel$
$H_\perp$
Ref. 7
Ref. 8
Ref. 9
$H_\parallel$
Ref. 10
Ref. 11
$H_\perp$ or $H_\parallel$

Transient Re Number

- 500XHa is 40,000.
- The flow is just in the turbulence regime in a transverse magnetic field.
- 60XHa is 4,800.
- The transient Re is no much higher than the transient Re for ordinary flow mechanics.
- It is expected that there is a major reduction of heat transfer in a transverse magnetic field.
- The effect to heat transfer maybe moderate in a parallel field.

Heat Transfer Impact

- The only correlation to estimate impact on heat transfer by MHD is for liquid metals.
- The liquid metal has a very large Pr, number, and the correlation can not be applied to a salt.
- However,it is useful to use the correllations for the liquid metal, and to estimate the reduction of the convention heat transfer.


FY
Arrangement
1997
1998
1999
2000
Phase I for Data Base
2001
2002
2003
2004
2005
Phase II
2006 ----
J-Loop
0.2M$ + α
Design
Task G
Cost Estimation
Master Plan
MOE
Cost Estimation
Task G
Design
J-Pot
0.08M$
Thermo - fluid Flibe Loop
T-Flibe
Recovery
Chemistry
Compatibility
Heat Loading
SC Magnet
H/D & Materials test
Compact Flibe Loop
Tritium
Improvement
SC Magnet
Summery Next Plan
Design of Loop for Neutron Irrad.

1998.6.5 A. S

Effect of MHD to Heat Transfer

- For a flow in a transverse magnetic field, the heat transfer can be represented by,

$$\mathrm{Nu} = 10.0 + 0.025\left(\frac{\mathrm{Pe}}{1+\left(236\mathrm{Ha}^2/\mathrm{Re}\right)}\right)^{0.8}$$

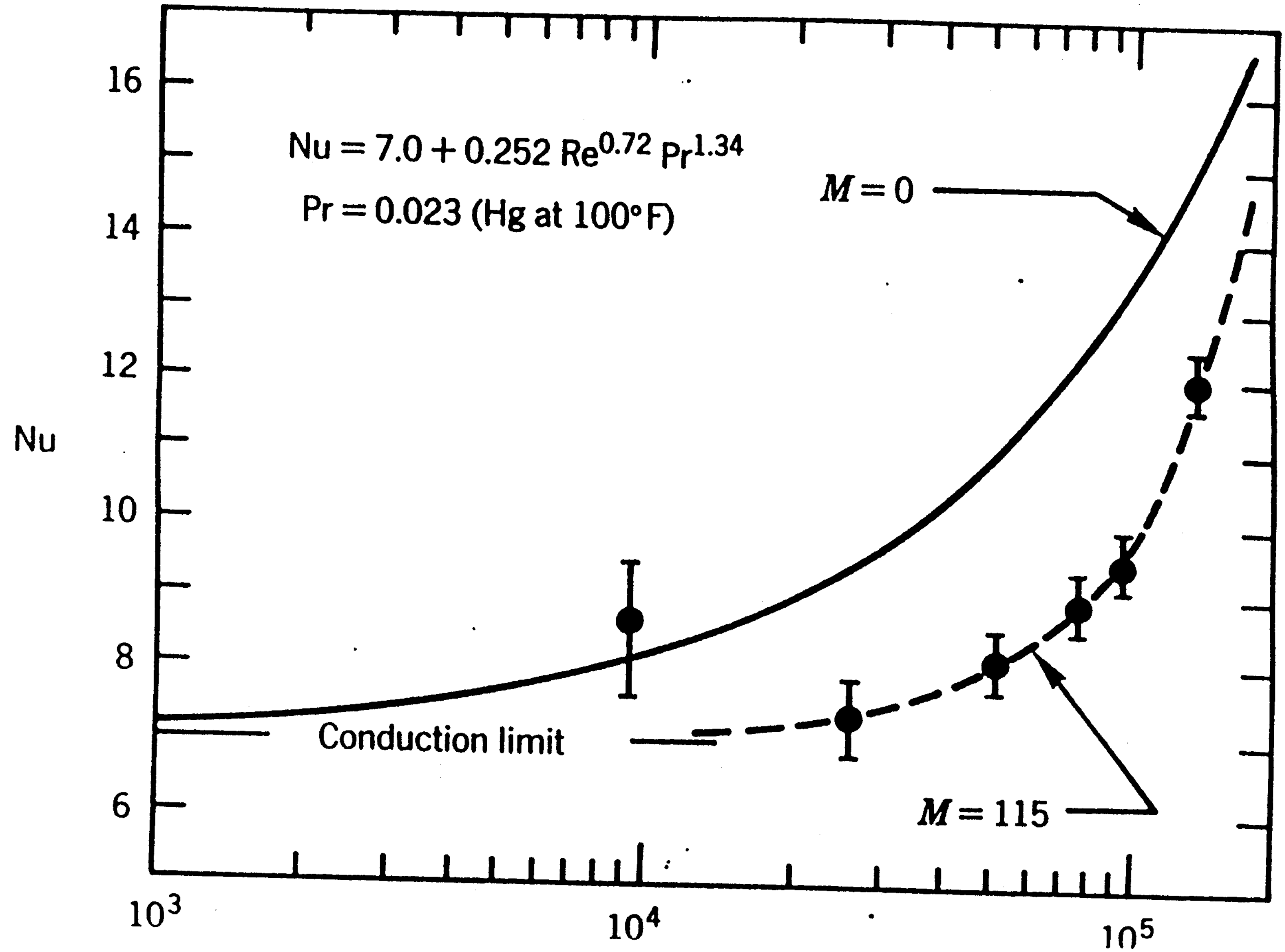
- The first term of this correlation is the conduction term, while the second term is the convention term.

- With Ha number of 80, and Re of 133,000,
  - 236Ha2/Re = 11.3
- Therefore, the heat transfer from turbulence is reduced by > 90%.

- If flow is parallel to the magnetic field, the correlation becomes,

$$Nu = 9.0 + \left(\frac{0.006\ Pe}{1 + \left(14.8M^2 / Re\right)} \right)$$

- 14.8Ha2/Re = 0.7
- The reduction of heta transfer becomes modest.


16
14
12
10
8
6
Nu
Nu = 7.0 + 0.252 Re^0.72 Pr^1.34
Pr = 0.023 (Hg at 100°F)
M = 0
M = 115
Conduction limit
10^3
10^4
10^5

Impact on Blanket Design

- For the IB blanket, the coolant has to be transported along the poloidal direction.
- For the first wall, the coolant has to flow along the toroidal direction for heat transfer.
- Therefore, the only possible coolant flow path is:

  Along poloitdal direction for coolant inlet.

  Turn toroidal direction for first wall cooling.

  Turn to poloidal direction again for coolant exit.
- It is difficult to see how this can be done for a free surface flow.

Preliminary Conclusion (1)

- Tritium breeding is marginal for flibe with no additional Be.
- Flibe composition and Li enrichment have minor impacts on the breeding.
- With additional Be in the blanket, sufficient breeding can be obtained.

Preliminary Conclusions (2)

- To assure tritium breeding, additional Be maybe necessary.
- The presence of free Be inside the blanket will have dominate effect on the flibe chemistry.
- The Be will certainly react with all TF, to reduce tritium into elementary form.
- Also, any fluorides introduced into the flibe for redox buffer control will also be reduced by the Be to form BeF2.

Preliminary Conclusions (3)

On the positive side:

- Be will reduce all the fluorides, beside LiF, to form BeF2.
- The flibe becomes pure, and much less corrosive, and most structural materials are expected to be compatible with flibe.
- The flibe chemistry becomes simple.
- The key question is whether Be, either in the metallic form, or dissolved in flibe, can control F activity fast enough.

Preliminary Conclusions (4)

- MHD has a small, and maybe positive effect on the MHD pressure drop.
- Ordinary fluid mechanics and heat transfer are well understood, and correlations are available to predict pressure drop and heat transfer coefficient.
- The only results on MHD effects on heat transfer is for liquid metals, which have a very different Pr number from flibe.

Critical Issues Identified by Preliminary Assessment

- Tritium breeding
- Flibe chemistry control
- MHD effects on heat transfer
- Tritium control
- Be resource and flibe cost
- Safety assessment
- Structural material selection

- Based on the results from the liquid metals, the following conclusion can be made for flibe:

  A.) Transvers MHD may reduce the heat transfer coefficient by about a factor of 10.

  B.) Parallel MHD may reduce the heat transfer coefficient maybe by 50%.

- Additional information will be required for the MHD effects on heat transfer.
- To facilitate the experiments, some other molten salt, such as HTS, can be used instead of flibe.

Information Required for Heat Transfer

- The effect of MHD on heat transfer can not be predicted at this time.
- It is important to find out the MHD effect on heat transfer for Ha < 100, and 1000 < Re < 50,000.
- Since heat transfer correlation's depend only on the parameters, the experiment does not have to be done with flibe.
- HTS (or maybe some other salts) can be used to develop heat transfer correlation's.

MHD Enhanced Decomposition

- VXB will generate voltage difference across the flibe flow.
- We know that 0.9 V voltage difference will decompose LiT.
- The free energy of formation of BeF_2 is about five times larger than that for LiT.
- It is expected that the decomposition voltage for BeF_2 is about 4.5 V.
- The Nernst equation can be used to get a similar decomposition voltage.

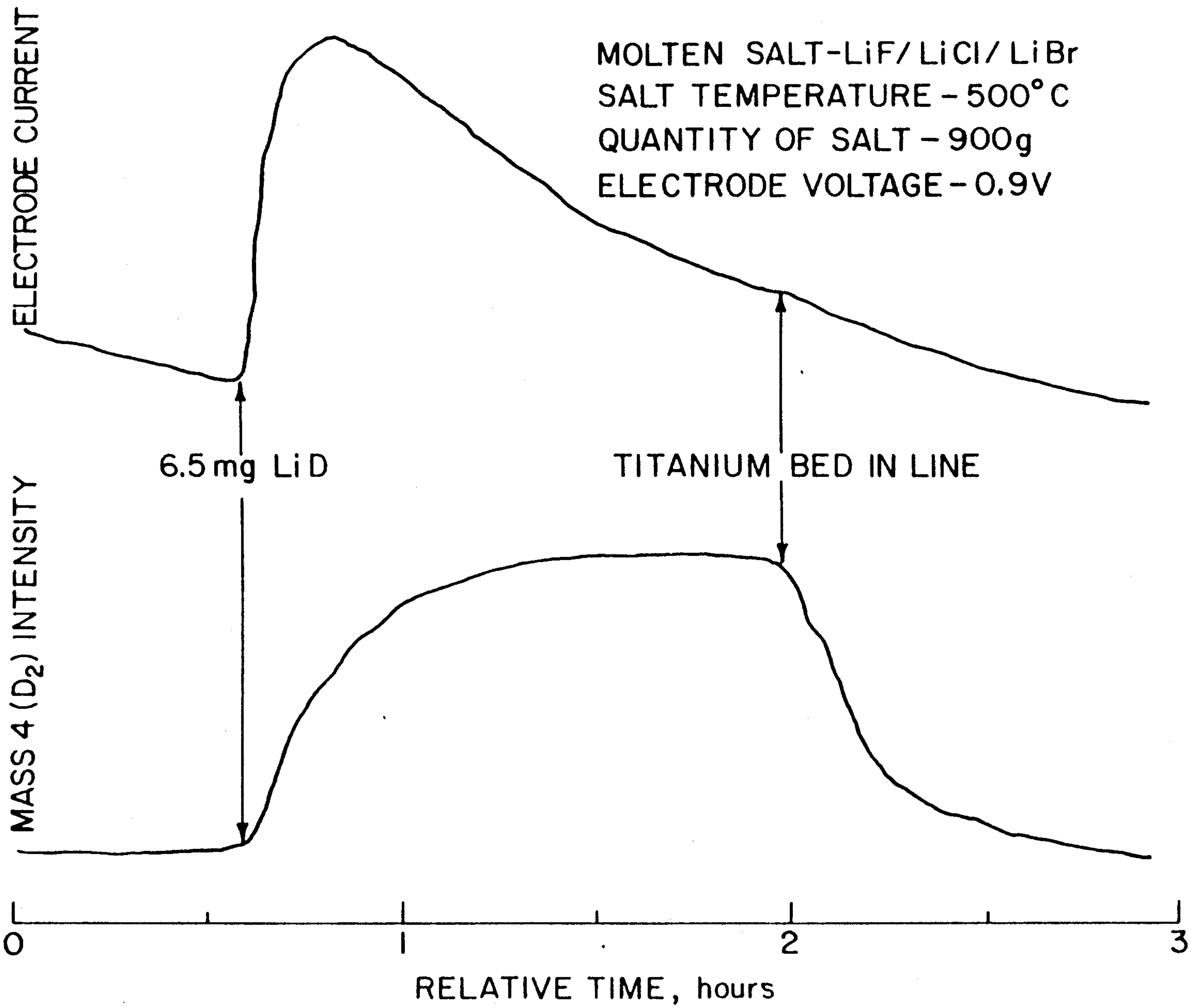


FIGURE 4. Results of a Typical Electrochemical Experiment to Evolve Deuterium using a Graphite Electrode

Reasons for use HTS

- Much lower cost.
- Much lower melting temperature.
- Much easier to handle.
- Require only 1/2 of the magnetic field to get the same Ha number.

- Concern: With the same Re number, the coolant velocity is much lower. Can we measure it?

Material Properties

	HTS	Flibe
Composition	$NaNO_2$ (49%) $NaNO_3$ (7%) KNO_3 (44%)	LiF (66%) BeF_2 (34%)
Melting temperature, C	140	460
Density, g/cm3	1.76	2.01
Thermal Decomp. Temp.	400 to 500°C	Very stable
Viscosity, cp	1.1	14.9
Thermal conductivity, w/cm-C	0.0057	0.008
Electrical Conductivity, mho/cm	0.59	1.55
$(EC/viscosity)^{0.5}$	0.73	0.32

Tritium Issue

- Tritium can exit in flibe either in the form of T2 or TF.
- The hydrogen solubility in flibe is very low, and obeys Henry's law.
- Therefore, the tritium partial pressure is very high, if the tritium produced is in the T2 form.
- If tritium is in the TF form, the structural material has to be carefully selected to be compatible to TF.

Key Issue on Chemistry Control

- The most important issue on chemistry control is to control the fluorine activity, because F will attack any structural material.
- The chemistry control process for F will determine what form tritium will be in.
- For instance, if Be can be dissolved in the flibe to control F, Be will reduce any tritium into elementary form.
- Therefore, some form of tritium control from permeation is necessary.

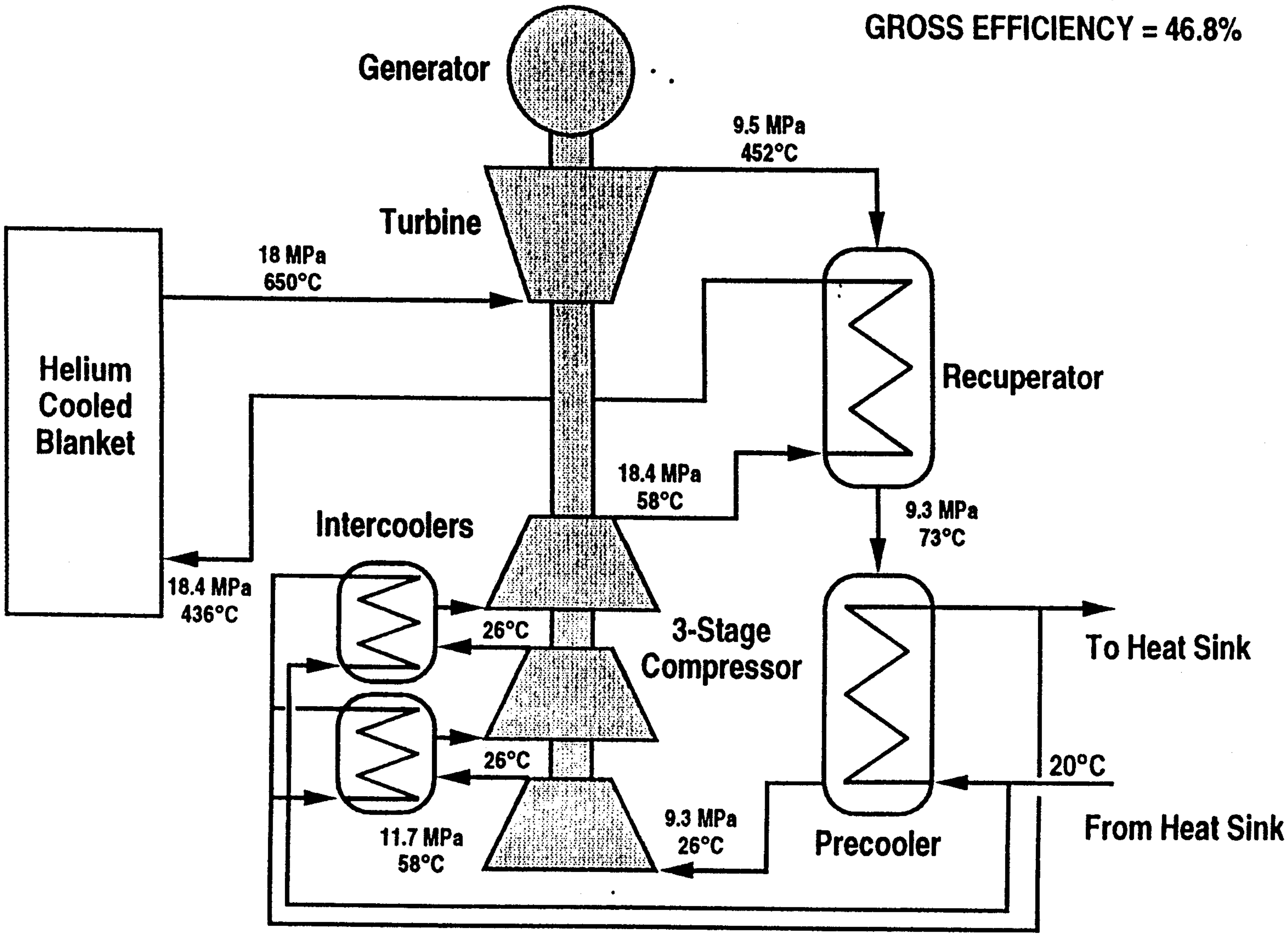
Tritium Control Possibility

- The easiest way for tritium to permeate to the environment is along the heat transfer system.
- The heat exchangers have very large heat transfer area and is at a high temperature.
- Tritium will permeate across the heat exchanger, and go down stream.
- Permeation barrier has limited effectiveness.
- MSRE developed an intermediate coolant for tritium control, and it can be used for our applications.
- Non-water power conversion system, such as close cycle He turbine, can be used to reduce the rate of tritium permeation

Comment on the Close-cycle Gas Turbine

- Close-cycle gas turbine has a very large recuperator heat exchanger, but it is He to He.
- The permeation of tritium across this heat exchanger does not go to ambient.
- The heat rejection heat exchanger will go to ambient.
- However, the temperature of the heat rejection HX is low (~100°C) and the surface area is small.
- Therefore, the He partial pressure can be large.
- Close cycle gas turbine can be very efficient if the coolant temperature is above 750°C.

FUSION DIRECT HELIUM BRAYTON CYCLE POWER COVERSION



GENERAL ATOMICS

Be Resource, in Metric Tons

	United States		World	
	Reserves	Resources	Reserves	Resources
US Bureau of mines	25,000	73,000	380,000	1,105,000
US Geological Survey	55,000	282,000	84,000	678,000

Be Requirement

- The flibe inventory in a 3000 MW fusion power plant is estimated to be 300m3.
- The Be required is 55 metric tons.
- If we use the average of the US resources, and assuming 50% is available for fusion, the available Be is 88,750 tons.
- 1600 fusion power plant can be build.
- Therefore, there is sufficient Be at least for the first generation of fusion power plant.,

Flibe Cost

- There is some uncertainties on the unit of flibe.
- If the flibe cost is 100 $/kg, the total cost of flibe is 60 M$.
- If the interest rate is 10%, the interest we have to pay for using the flibe is 6 m$/year.
- The cost of electricity due to the flibe is only 0.7 mils/kw-hr.
- The estimated flibe cost is from $45 a to $125 per Kg.
- Both cost is certainly affordable.