FLIBE
WHAT DO WE KNOW?

Dai-Kai- Sze

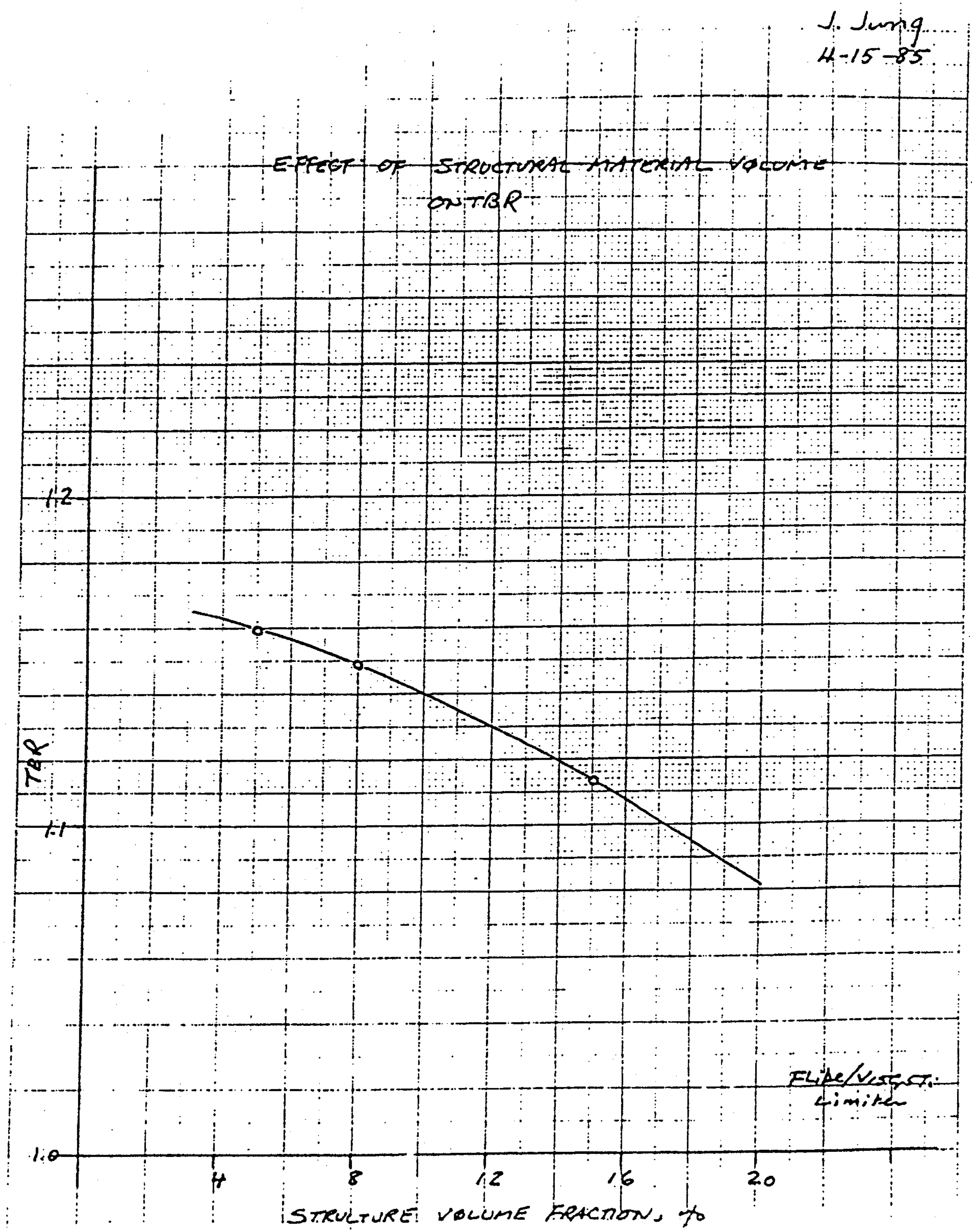
Zhanhe Wang

Argonne National Laboratory

Presented at the APEX/ALPS meeting.

Albuquerque, New Mexico

July 27-31, 1998


J. Jung
4-15-85
EFFECT OF STRUCTURAL MATERIAL VOLUME
ON TBR
1.2
TBR
1.1
1.0
4
8
12
16
20
Limit
STRULTURE VOLUME FRACTION, %

IMPLICATION

- Breeding will be a major concern of using flibe for D-T fusion.
- Sufficient breeding can not be assured even with the use of Be.
- Flibe is much more effective than Li or LiPb to protect radiation damage for the structure behind.
- Key work will be to assess the breeding with different Li enrichment, and with different structural material, flibe and Be composition.

TRITIUM

- H_2 is a "metallic like" element.
- Metal does not dissolve in salt.
- Salt (TF) will dissolve in salt.
- Solubility of T_2 in salt is very low, and obey's Henry's law.
- The solubility of TF in the salt is much higher.

IMPLICATION

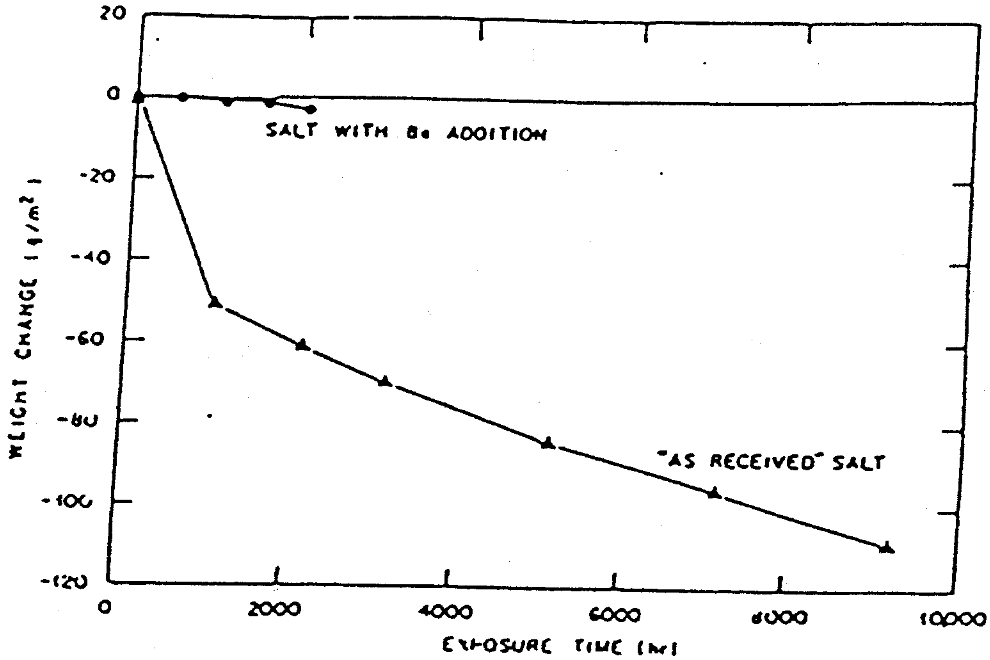
- **Tritium recovery to a low inventory is not issue for a flibe blanket.**
- **Tritium recovery to a low vapor pressure is key issue.**
- **Tritium containment was a severe problem for the MSBR, which had a very small amount of tritium.**
- **An intermediate coolant, and surface modification techniques, were developed for tritium containment.**
- **These methods may not be sufficient to resolve problem here because of the large throughput of the tritium.**

MATERIAL COMPATIBILITY

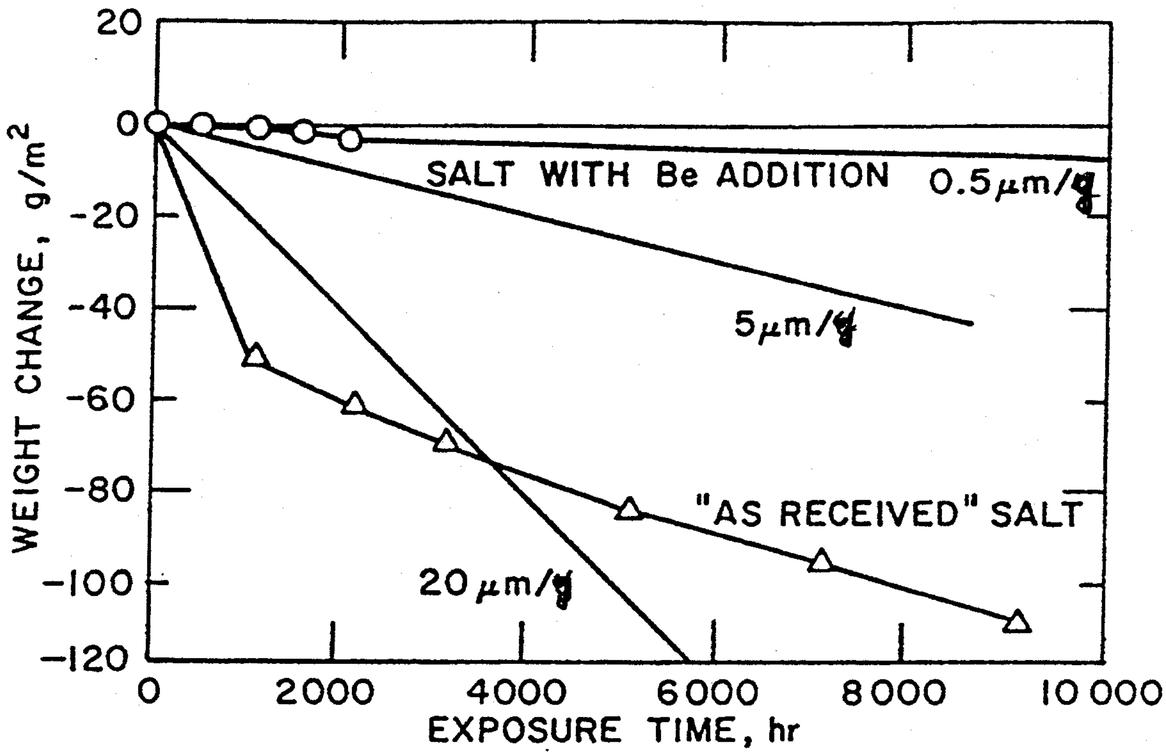
- **Metallic elements does not dissolve in salt.**
- **Metallic salt will dissolve in salt.**
- **For corrosion to occur, the reaction M + NF--> MF + N must occur first. (M is the structural material and NF is a component in the salt).**
- **LiF and BeF_2 are two of the most stable fluorides, and will not react with any structural material.**
- **TF can react with some structural material to form MF.**
- **i.e. corrosion is not caused by pure flibe, but by the impurities in the salt, including TF.**

FREE ENERGIES OF FORMATION OF FLUORIDES

	$\Delta G^f_{1000°K}$ (kcal/g-atom of fluorine
$MoF_6(g)$	-50.2
$WF_6(g)$	-56.8
$NiF_2(d)$	-55.3
$VF_5(g)$	-58
$VF_4(cr)$	-66
$HF(g)$	-66.2
$FeF_2(d)$	-66.5
$NbF_5(g)$	-72.5
$CrF_2(d)$	-75.2
$TaF_5(g)$	-82.2
$TiF_4(g)$	-85.4
$LiF(\ell)$	-125.2
$BeF_2(\ell)$	-106.9



WEIGHT CHANGE VERSUS EXPOSURE TIME FOR TYPE 316 STAINLESS STEEL IN $LiF-BeF_2$ SALT AT THE MAXIMUM LOOP TEMPERATURE OF 650°C.


WEIGHT CHANGE, g/m²
20
0
-20
-40
-60
-80
-100
-120
SALT WITH Be ADDITION
0.5 μm/y
5 μm/y
"AS RECEIVED" SALT
20 μm/y
0
2000
4000
6000
8000
10 000
EXPOSURE TIME, hr

RADIOLYSIS AND PYROLYSIS

- **No Radiolysis or pyrolysis have been observed in fission environment.**

ELECTROLYSIS

- The induced voltage of flowing flibe across a magnetic field is (velocity) (channel dimension) (magnetic field)

- Based on molten salt tritium recovery experiment, we know the LiF will be decomposed by electrolysis when the potential difference exceeds 2 volt.

- The design of the system has to keep maximum voltage difference below maybe 1.6 V.

WHAT IS FLIBE?

- **Flibe is the coolant salt used by the MSBR.**
- **It is an eutectic of LiF and BeF_2.**
- **The reason that MSBR selected flibe is the very high thermal and radiation stability.**
- **There are two mixtures of LiF and BeF_2 considered by MSBR.**
- **The one with higher melting point (460°C) was the one used by the MSBR because of its lower viscosity.**

FREE F FORMATION

- Transmutation of Be will release free F from BeF_2.
- The free F release rate is about 600g/ fpd for a 2250 MW fusion power plant.
- Free flourine will cause severe material compatibility problems for all structural materials.
- Redox buffer reaction is a possible way to control F activities.
- MoF_3 <--> MoF_6 is a possible redox buffer reaction. (Redox buffer reaction is to design a chemical reaction process which will remove free F faster than the F will react with the structural material.

IMPLICATIONS

- **Flibe can be controlled either in the reducing form, or in the oxidation form.**
- **The form of tritium is in the T_2 form if flibe is maintained in the reducing form.**
- **Due to the low tritium solubility, the tritium partial pressure will be very high, and tritium containment is an issue.**
- **The form of tritium is TF if flibe is maintained in the oxidation form.**
- **TF is very corrosive to some structural materials due to the high free energy of formation.**
- **To balance the containmination of T_2, and the compatibility issue of TF, is a key R/D issue.**

HEAT TRANSFER CHARACTERISTICS

- **The thermal conductivity of flibe is similar to that of water.**
- **At the same velocity, the heat transfer coefficient and the pressure drop of flibe are worse by about a factor of 2 comparing to water.**
- **However, the heat transfer DT of flibe can be much higher than that of water, because of the much higher boiling temperature.**
- **The flibe with low melting temperature is very viscose, and large pressure drop will develope for an acceptable heat transfer.**
- **Due to the low thermal conductivity, the salt needs to be in the turbulence regime for good heat transfer.**

COMPARISON OF HEAT TRANSFER CHARACTERISTICS BETWEEN FLIBE AND WATER

	LI_2BEF_4 (600°C)	H_2O (260°C)
Cp, J/G - °C	2.8	5.0
ρ, G/cm^3	1.92	0.79
μ, CP	7.5	0.11
K, W/cm - °C	0.01	0.006
ρCp, J/cm^3 - °C	5.4	4.0

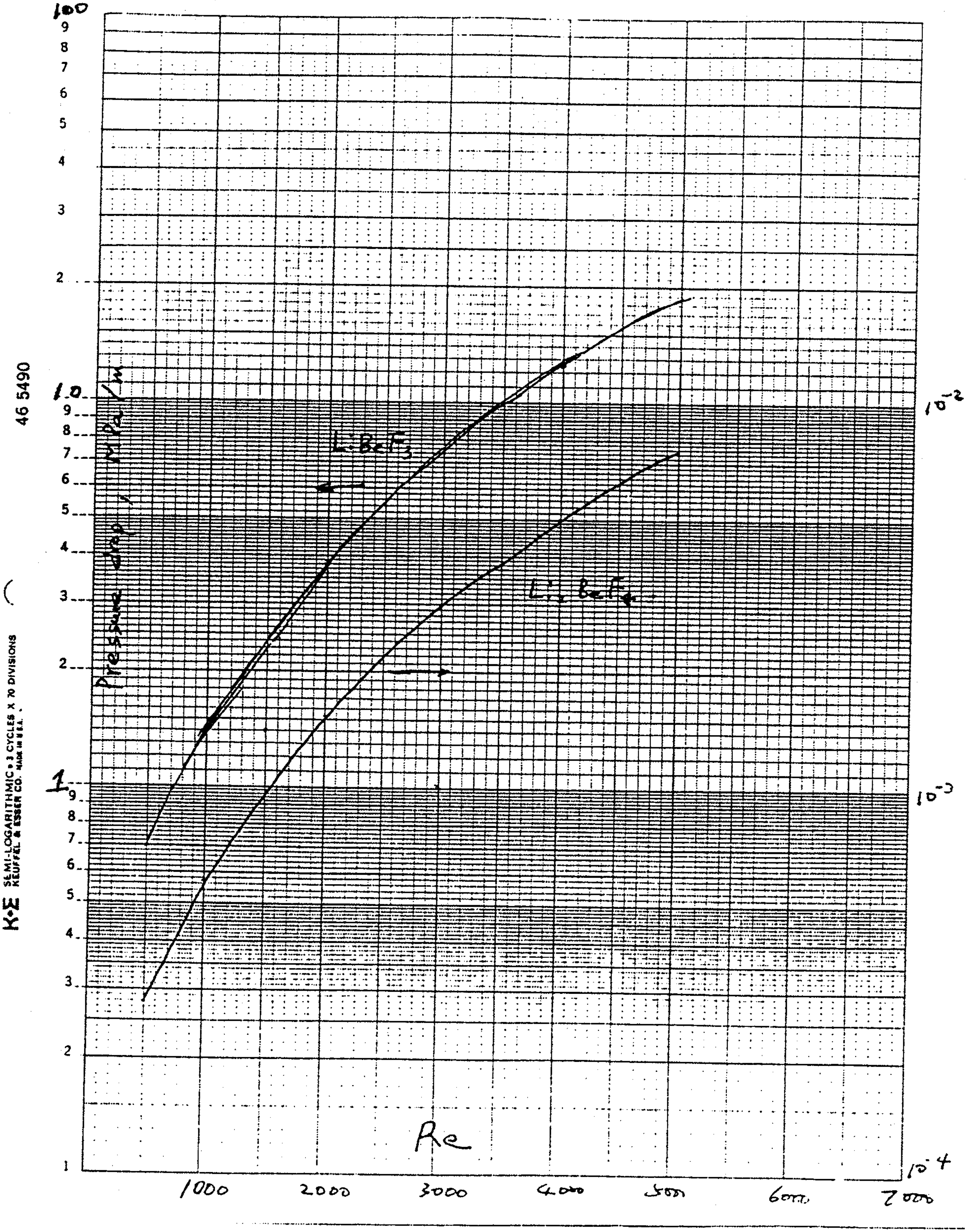
At same velocity $H\ H_2O = 2.5\ H_{salt}$

$\Delta P_{H_2O} = .5\ \Delta P_{salt}$

for V = 500 cm/sec, D = 1 cm

$H = 1.5\ watt/cm^2 - °C$

if $Q = 100\ W/cm^2$, $\Delta T = 67°C$



100
10
1.0
1
10^{-2}
10^{-3}
10^{-4}
Pressure drop, MPa/m
$LiBeF_3$
Li_2BeF_4
Re
1000
2000
3000
4000
5000
6000
7000
46 5490
K·E SEMI-LOGARITHMIC · 3 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.

MHD EFFECTS

- **Flibe has a very low electrical conductivity.**
- **The MHD pressure drop will be small comparing to the viscose pressure drop.**
- **Witha modest velocity, the flow will be in the turbulence regime.**
- **However, it is not certain what impact of MHD will have on the heat transfer.**

IMPLICATIONS

- The low melting temperature flibe is too viscose to be useful for a heat transfer coolant.
- The thermal conductivity of the flibe is too low to be an effective heat transfer medium in the laminar regime.
- If the high melting temperature flibe is used as the coolant, the blanket temperature will be around 600°C.
- Advanced structural material will be required.

ENVIRONMENT AND SAFETY

- **Flibe has no safety related chemical reactions with air, water, or concrete.**
- **Flibe has moderately low short term radioactivity, and very low long term radioactivity.**
- **Blanket tritium inventory is very low.**
- **Rated by ESECOM with inherent safety rating between 1 and 2.**

ENVIRONMENT AND SAFETY CONCERNS

- **Flibe has Be, and may require additional Be for tritium breeding.**
- **Be is chemically toxic.**
- **It is important to asses how to trade off between chemical toxicity and chemical reactivity.**
- **Tritium permeation is a major concern.**
- **It is also important to trade off between routine tritium release and accidental tritium release.**

Table 6.12-7

SUITABILITY OF MATERIALS FOR NEAR-SURFACE BURIAL

WDR<1 Class A(a)	1 < WDR < 5 Class C(b)	WDR > 5 Not suitable for near-surface Burial(c)
Be	V15Cr5Ti	HT9
Li_2O	ModHT9	PCA
Lithium	TENELON	$LiAlO_2$
FLIBE		17Li83Pb
		Nitrate Salt

(a) Requires only packaging to provide physical, mechanical and chemical stability for near-surface burial.

(b) Will be diluted to Class C by normal mixing with inert and less active materials from reactor during waste packaging. Requires packaging for physical, mechanical and chemical stability for near-surface burial.

(c) WDR and total quantities of material make reduction to Class C by dilution impractical. Processing is required to remove high activity nuclides to bring the remaining material to Class C for packaging for near-surface burial. The high activity nuclides require at least a "hot" waste facility or perhaps even deep geological burial.

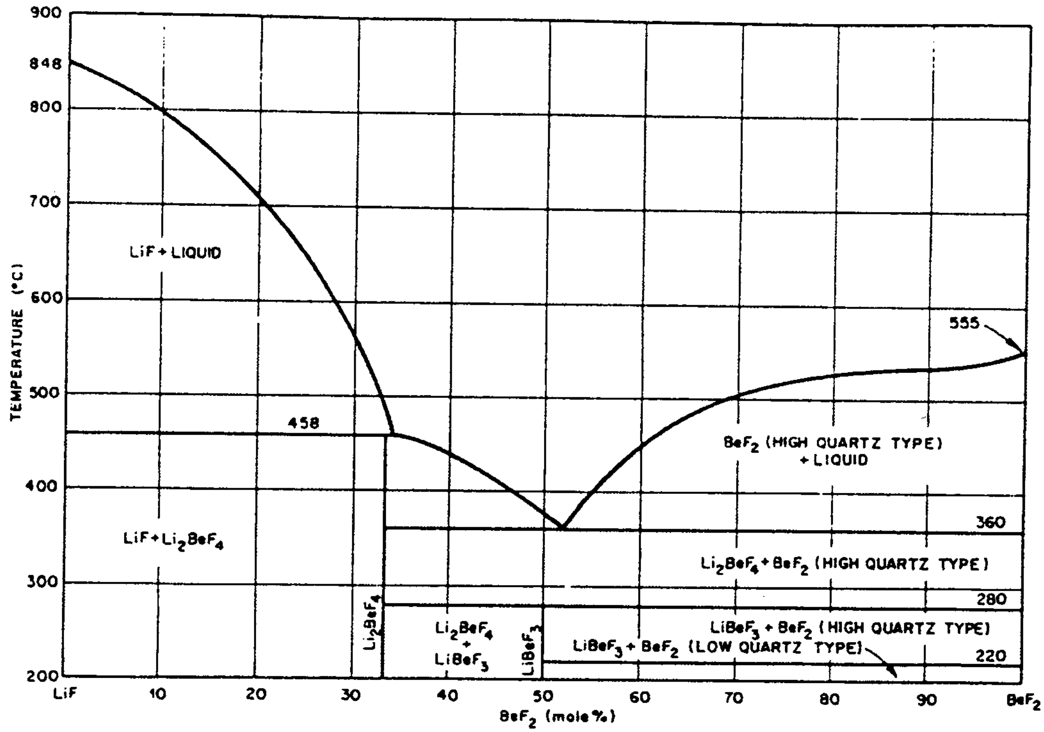


Fig. 1. The system $LiF-BeF_2$.

The binary diagrams $LiF-UF_4$[13] and $LiF-ThF_4$[14] $3LiF{\cdot}ThF_4$ can incorporate Be^{2+} ions in both

Table 6.12-6

WASTE DISPOSAL RATING AT 10 YEARS AFTER SHUTDOWN

	WDR (dimensionless ratio)											
Material Nuclide	HT9	PCA	$LiAlO_2$	Nitrate Salt	LiPb	VCrTi	TENELON	Mod HT9	Be	Li_2O	FLIBE	Li
C14	1.0	0.21	0.38	70.9	0.03	0.16	0.10	0.02	0.15	0.33	0.14	0.01
Ni59	0.08	2.4										
Ni63	0.40	6.6			0.01		0.01	0.01	0.01			
Nb94	477	176	0.02	0.10	0.10	1.32	0.46	0.46	0.01			
Tc99	5.38	11.0	0.01		0.02							
Sub Total	484	196	0.41	71	0.16	1.48	0.57	0.49	0.17	0.33	0.14	0.01
Al26	0.11	0.33	147		0.07	0.17	0.09	0.09	0.23	0.01		
Ag108m	0.85	0.86	2.8		10.6		0.77	0.76				
Bi207					0.02							
Bi208	0.25	0.26	0.08		13.6		0.05	0.05				
Sub Total	1.2	1.45	150		24.3	0.17	0.91	0.90	0.23	0.01		
Total	485	198	150	71	24.5	1.65	1.5	1.4	0.40	0.34	0.14	0.01

Table 6.12-2

RELATIVE RANKINGS OF MATERIALS BY RMR

Time After Shutdown							
1 Hour		1 Day		10 Years		100 Years	
Material	RMR(mrem/hr)	Material	RMR(mrem/hr)	Material	RMR(mrem/hr)	Material	RMR(mrem/hr)
TENELON	9.14E+10	$LiAlO_2$	2.83E+10	PCA	2.30E+08	$LiAlO_2$	2.09E+04
$LiAlO_2$	8.17E+10	VCrTi	1.36E+10	Nitrate salt	4.61E+07	HT9	2.07E+04
PCA	3.69E+10	TENELON	1.33E+10	HT9	4.41E+07	PCA	9.44E+03
ModHT9	2.93E+10	PCA	1.16E+10	TENELON	1.39E+07	LiPb	9.24E+03
HT9	2.89E+10	ModHT9	4.24E+09	ModHT9	1.11E+07	ModHT9	4.26E+02
VCrTi	1.93E+10	HT9	4.17E+09	$LiAlO_2$	5.36E+06	TENELON	4.22E+02
Nitrate Salt	8.55E+09	Nitrate salt	3.25E+09	LiPb	4.16E+06	VCrTi	1.83E+02
Be	4.92E+08	Be	1.67E+08	Be	1.26E+06	Be	4.99E+01
LiPb	1.42E+08	LiPb	8.85E+07	Lithium	9.13E+04	Nitrate salt	2.33E+01
Li_2O	2.17E+07	Lithium	5.86E+06	Li_2O	4.44E+04	Li_2O	1.72E+00
Lithium	1.48E+07	Li_2O	5.53E+06	FLIBE	2.79E+04	FLIBE	2.02E-01
FLIBE	6.06E+06	FLIBE	1.73E+06	VCrTi	6.53E+03	Lithium	1.87E-02

Key Problems

- Can flibe breed?
- Is flibe safe?
- Can a chemical state be defined and verified to satisfy both tritium containment and material compatibility issuse?
- Will MHD significantly reduce the heat transfer?
- What will be the structural material for the blanket? The primary loop? and the HX?
- Can we design a system, and can operate reliabliy, with a tritium recovery effciency of 4 to 6 9's?
- Canwe afford flibe?
- Do we have enough Be?

CONCLUSIONS

- **The reasons for evaluate flibe for APEX/ALPS are**

  - Flibe is chemically inert.

  - Flibe may have acceptable neutronics properties.

  - Pure flibe has excellnt compatibility with most structural materials.

  - Flibe offers potantial for a highly compact and efficient power conversion system.

  - Flibe has accetpable heat transfer characteristics.

  - Flibe blanket has a very low pressure.

  - For ALPS/APEX applications, Fe-based and Ni-based alloys may be possible.

VIEW OF PREVIOUS FLIBE CONCERNS

- T Breeding
  - FLIBE was considered sub-marginal on tritium breeding before blanket comparison and selection study (BCSS).
  - Shown to be adequate for vanadium alloys and ferritic steel
- Be Resource
  - Adequate for hundreds of reactors
  - No recycling necessary, Be burn up is only 18 kg/y
- Molten Salt Breeder Reactor Issues
  - Fissile fuel reprocessing
  - Corrosion due to fission products
  - Marginal fissile fuel breeding

  Not relevant for fusion applications.

NONE OF THESE CONCERNS REMAINS AS A CRITICAL ISSUE.

TOPICS TO BE DISSCUSSED

- Neutronics
- Tritium Issues
- Material Compatibility
- Heat Transfer Characteristics
- Environment and Safety

NEUTRONICS

- **Flibe is a marginal breeding material without Be.**
- **For a blanket with 8% V structure, 30 cm flibe thickness is required to achieve a breeding ratio of 1.0, based on 2-D calculation.**
- **Flibe is good moderating and shielding material.**
- **Radiation damage reduces by a factor of 10 for each 24 cm thick flibe layer.**

Ref. Design

FW : 3mm : 100% V15Cr5Ti

BLK : 60 cm : 8% V15Cr5Ti + 92% Flibe

SLD : 30 cm : 80% Fe1422 + 20% H_2O

	No Limiter	Flibe/V Limiter	H_2O/Cu-2Be Limiter	Self-Pumped Limiter	
T_6	1.05	1.02	1.04	1.05	
T_7	0.14	0.13	0.12	0.12	
$T_6 + T_7$	1.19 (±1.3%)	1.15	1.16	1.17	

No Strong Adverse Effects on TBR

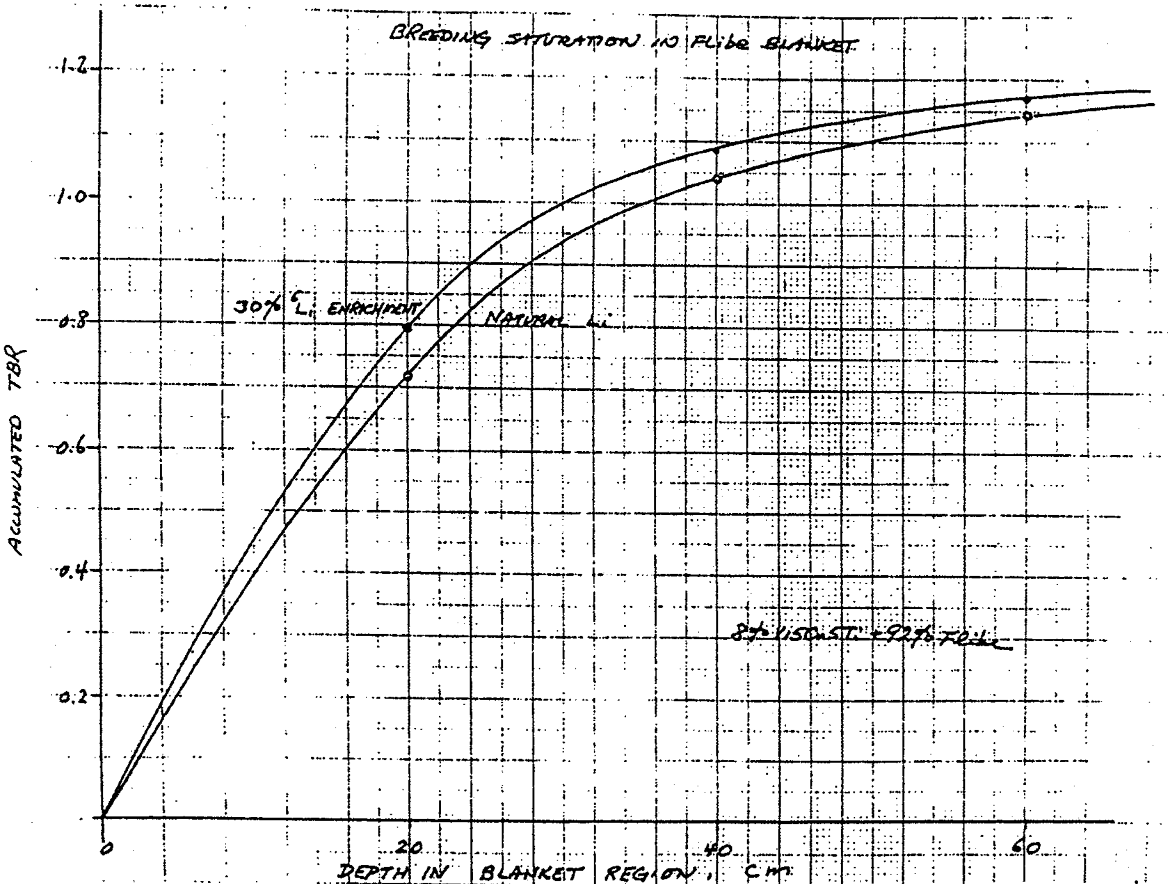
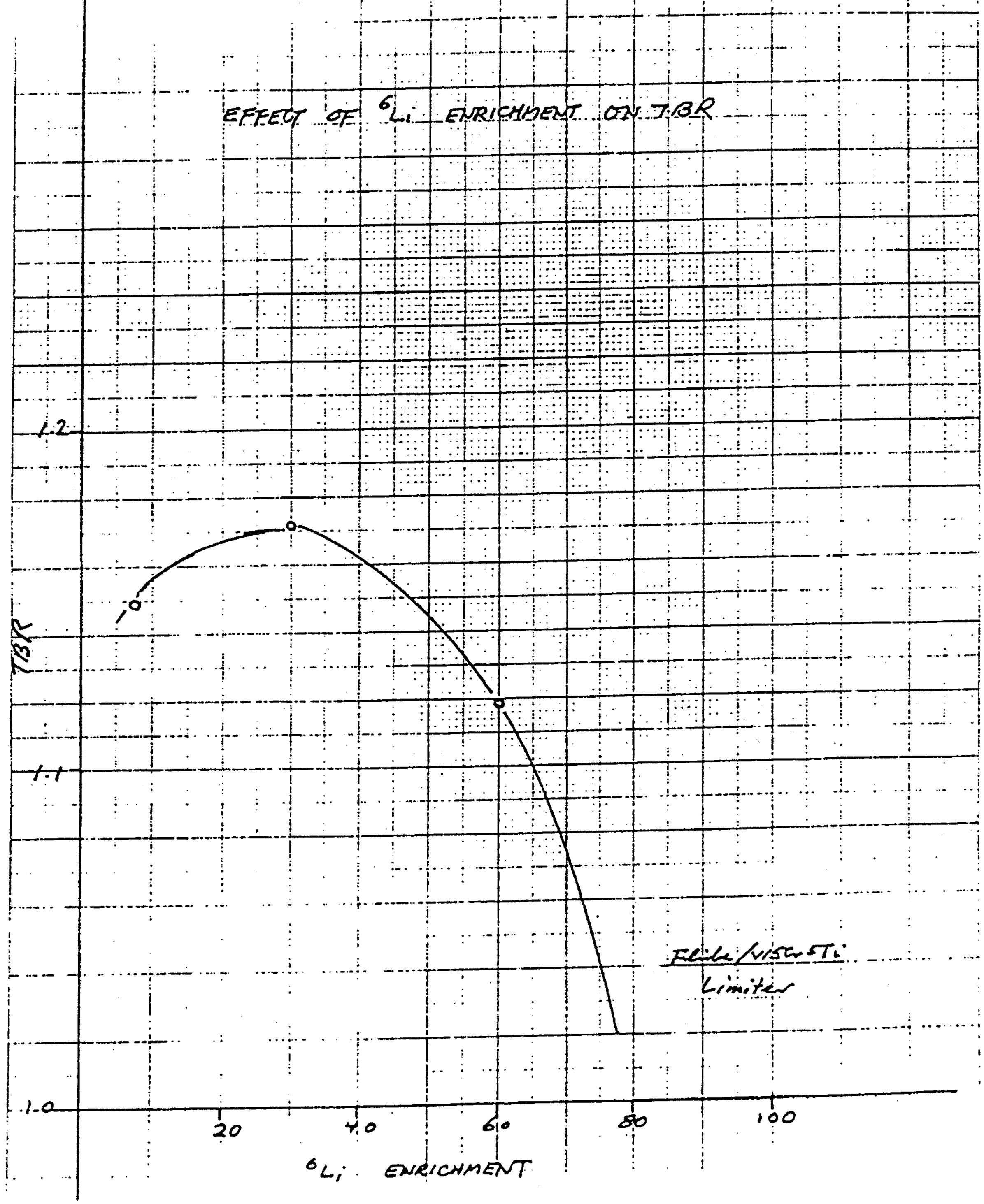

BREEDING SATURATION IN FLiBe BLANKET
ACCUMULATED TBR
1.2
1.0
0.8
0.6
0.4
0.2
0
20
40
60
DEPTH IN BLANKET REGION, CM
30% 6Li ENRICHMENT
NATURAL Li
8% VISCAST + 92% FLiBe

FIG. H-12

J. Jung
4-15-85


EFFECT OF 6Li ENRICHMENT ON TBR
1.2
1.1
1.0
TBR
20
40
60
80
100
6Li ENRICHMENT
Flibe/V15Cr5Ti
Limiter