Innovative Liquid Blanket Design Activities in Japan

Akio Sagara[1],

Teruya Tanaka[1], Takeo Muroga[1], Hidetoshi Hashizume[2], Tomoaki Kunugi[3], Satoshi Fukada[4], Akihiko Shimizu[4]

[1]National Institute for Fusion Science, Japan

[2]Tohoku University,

[3]Kyoto University,

[4]Kyushu University,

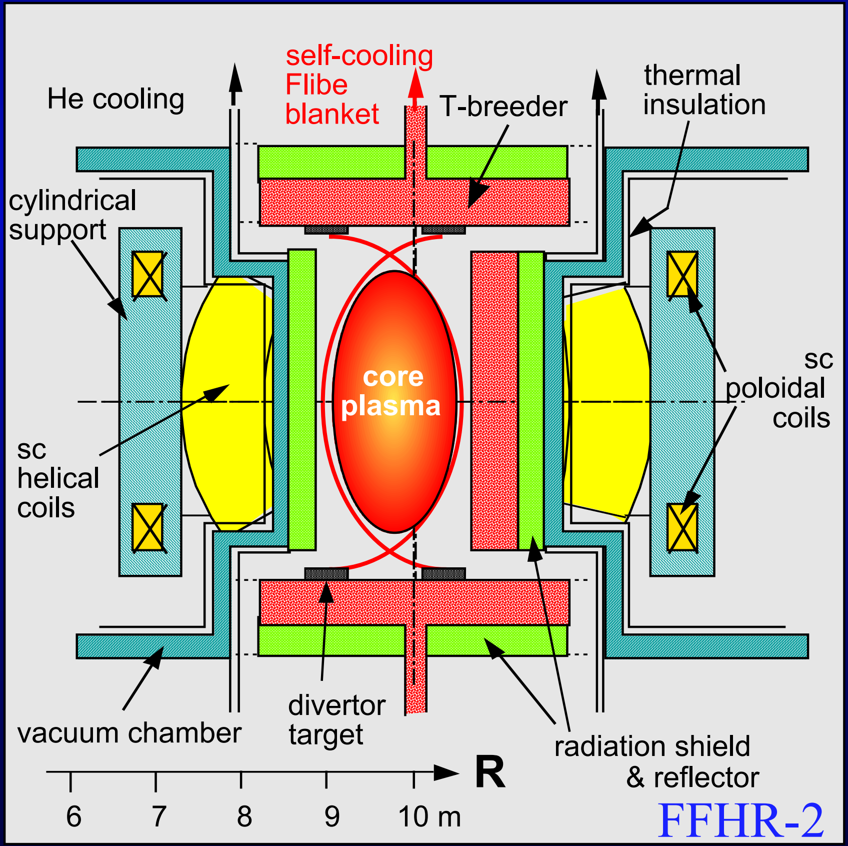
16th ANS Topical Meeting on the Technology of Fusion Energy

September 14-16, 2004

Madison, Wisconsin

After selecting and proposing the molten-salt Flibe blanket in the LHD-type helical reactor FFHR in 1995, intensive design studies on Flibe blanket have been continued and expanded into wide R&D areas

- in the NIFS collaborations
- under the Fusion Research Network in Japan Universities.
- And then, expanded into international research programs□JUPITER-II (2001-2006)



Reactor design collaborations in NIFS

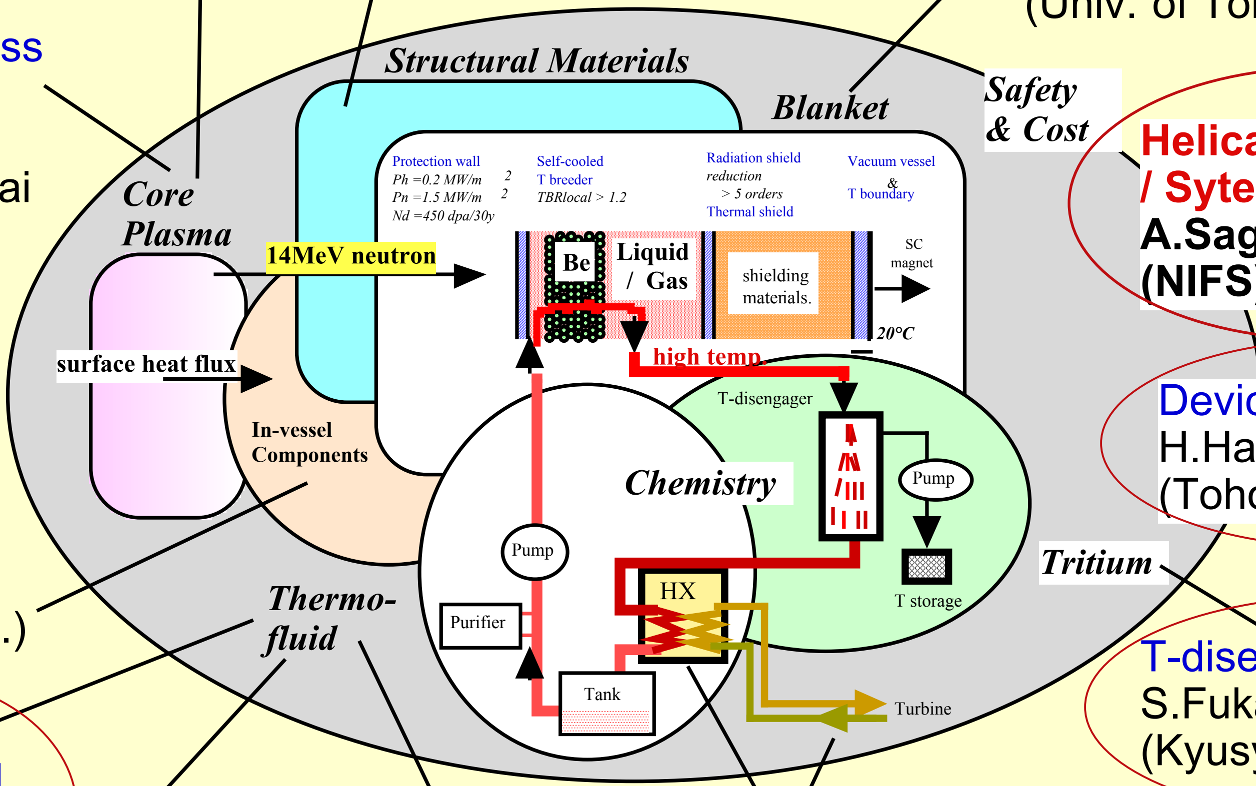
1993

Helical core plasma
K.Yamazaki
(NIFS)

Thermo-mechanical analysis
H.Matsui
(Tohoku Univ.)

Blanket system
S,Tanaka
(Univ. of Tokyo)

Ignition access
& heat flux
O.Mitarai
(Kyusyu Tokai
Univ.)



Helical reactor design / Sytem Integration
A.Sagara
(NIFS)

FFHR

Device system code
H.Hashizume
(Tohoku Univ.)

Advanced
first wall
T.Norimatsu
(Osaka Univ.)

T-disengager system
S.Fukada, M.Nishikawa
(Kyusyu Univ.)

Advanced
thermofluid
T.Kunugi
(Kyoto Univ.)

Thermofluid
MHD
S.Satake
(Tokyo Univ. Sci.)

Thermofluid
system
K.Yuki
(Tohoku Univ.)

Heat exchanger & gas turbine system
A.Shimizu
(Kyusyu Univ.)

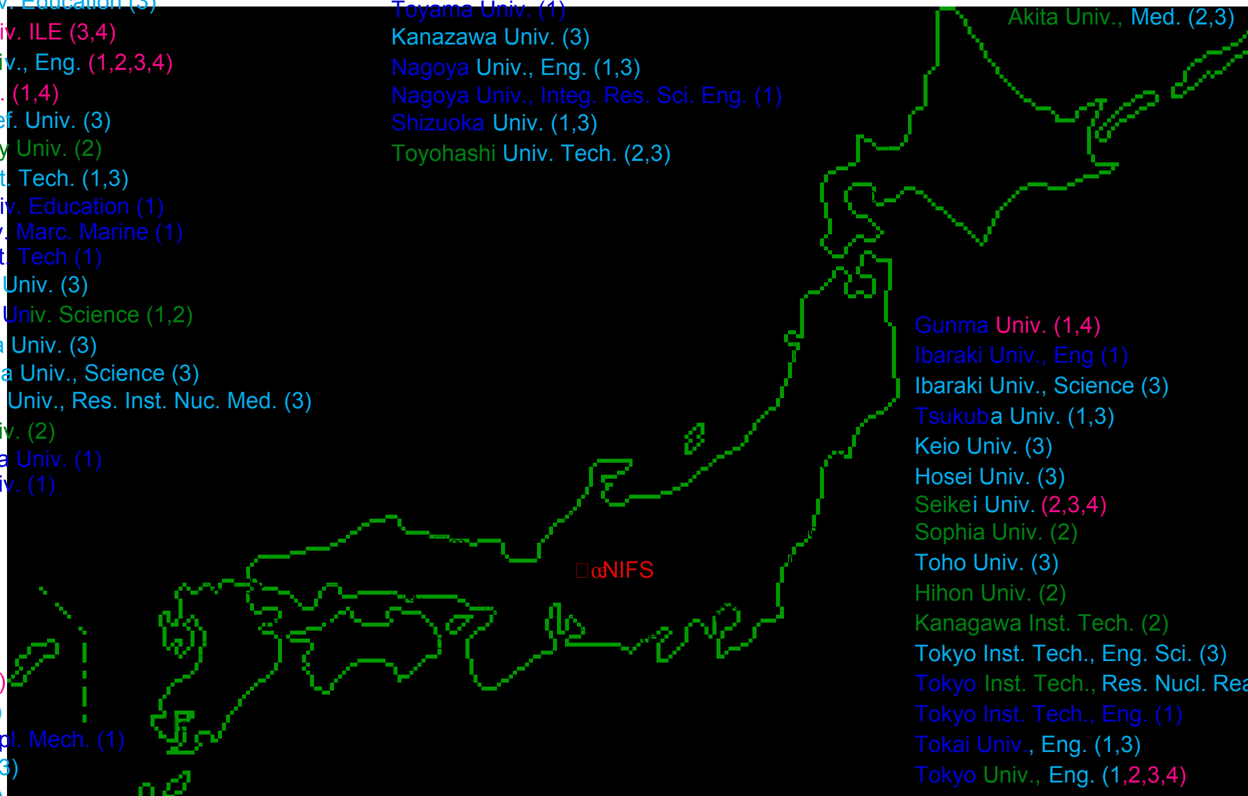
June 6. 2003, A.Sagara

Fusion Engineering Network

Kyoto Univ., Eng., (1,2,3,4)
Kyoto Univ., Res. Reactor Inst. (1,3)
Kyoto Univ., Inst. Adv. Energy (1,3)
Kyoto Univ., Energy Science (1,3)
Kyoto Univ. Education (3)
Osaka Univ. ILE (3,4)
Osaka Univ., Eng. (1,2,3,4)
Kinki Univ. (1,4)
Osaka Pref. Univ. (3)
Osaka City Univ. (2)
Osaka Inst. Tech. (1,3)
Hyogo Univ. Education (1)
Kobe Univ. Marc. Marine (1)
Himeji Inst. Tech (1)
Okayama Univ. (3)
Okayama Univ. Science (1,2)
Fukuyama Univ. (3)
Hiroshinma Univ., Science (3)
Hiroshima Univ., Res. Inst. Nuc. Med. (3)
Tottori Univ. (2)
Tokushima Univ. (1)
Ehime Univ. (1)

Niigta Univ. (1,3)
Nagaoka Univ. Tech. (4)
Toyama Univ. (1)
Kanazawa Univ. (3)
Nagoya Univ., Eng. (1,3)
Nagoya Univ., Integ. Res. Sci. Eng. (1)
Shizuoka Univ. (1,3)
Toyohashi Univ. Tech. (2,3)

Hokkaido Univ., Eng. (1,2,4)
Hokkaido Univ., CARET (1,3)
Muroran Inst. Tech (1,4)
Tohoku Univ., Eng. (1,2,3)
Tohoku Univ., Science (1)
Tohoku Univ., Med. (3)
Tohoku Univ., IMR (1)
Tohoku Univ., IMR-Oarai (1)
Tohoku Univ., Inst. Fluid Sci. (2)
Iwate Univ. (2)
Akita Univ., Med. (2,3)



Gunma Univ. (1,4)
Ibaraki Univ., Eng (1)
Ibaraki Univ., Science (3)
Tsukuba Univ. (1,3)
Keio Univ. (3)
Hosei Univ. (3)
Seikei Univ. (2,3,4)
Sophia Univ. (2)
Toho Univ. (3)
Hihon Univ. (2)
Kanagawa Inst. Tech. (2)
Tokyo Inst. Tech., Eng. Sci. (3)
Tokyo Inst. Tech., Res. Nucl. Reac. (1,2,3)
Tokyo Inst. Tech., Eng. (1)
Tokai Univ., Eng. (1,3)
Tokyo Univ., Eng. (1,2,3,4)
Tokyo Univ., Nucl. Eng. Res. Lab. (1,2,3)
Tokyo Univ., Res. Artifact (1)
Tokyo Univ., Science (2)
Tokyo Univ., Isotope (1,3)

Kyushu Univ., Eng. (1,2,3,4)
Kyushu Univ., Science (1,3)
Kyushu Univ., Res. Inst. Appl. Mech. (1)
Kyushu Univ., Eng. Sci. (1,3)
Kyushu Inst. Tech., Eng. (3)
Kyushu Inst. Tech., Comp. System (2)
Oita Univ. (2)
Kagoshima Univ. (2)
Kyushu Tokai Univ. (3)

(1) Materials and Fuels
(2) Magnet, Electromagnetics
(3) Reactor System, Safety
(4) ICF Technology

Flibe/RAF blanket, Li/V blanket, SB-He/SiC Blanket R&D in Japan-US joint project JUPITER-II(FY'01~'06)

INEEL

1-1-A: FLiBe Handling/Tritium.Chemistry

Japan

1-1-B: FLiBe Thermofluid Flow Simulation
2-2 : SiC System Thermomechanics

UCLA

3-1: Design-based Integration Modeling
3-2: Materials Systems Modeling

ORNL

1-2-B: V Alloy Capsule Irradiation
2-1 : SiC Fundamental Issues, Fabrication, and Materials Supply
2-3 : SiC Capsule Irradiation

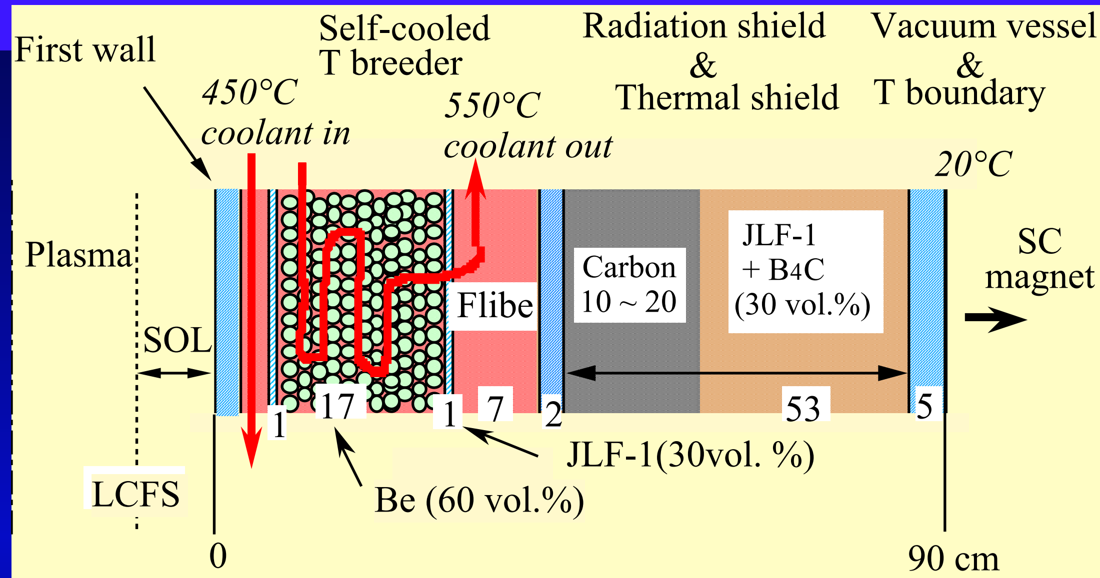
ANL
(2001)

1-2-A: Coatings for MHD Reduction

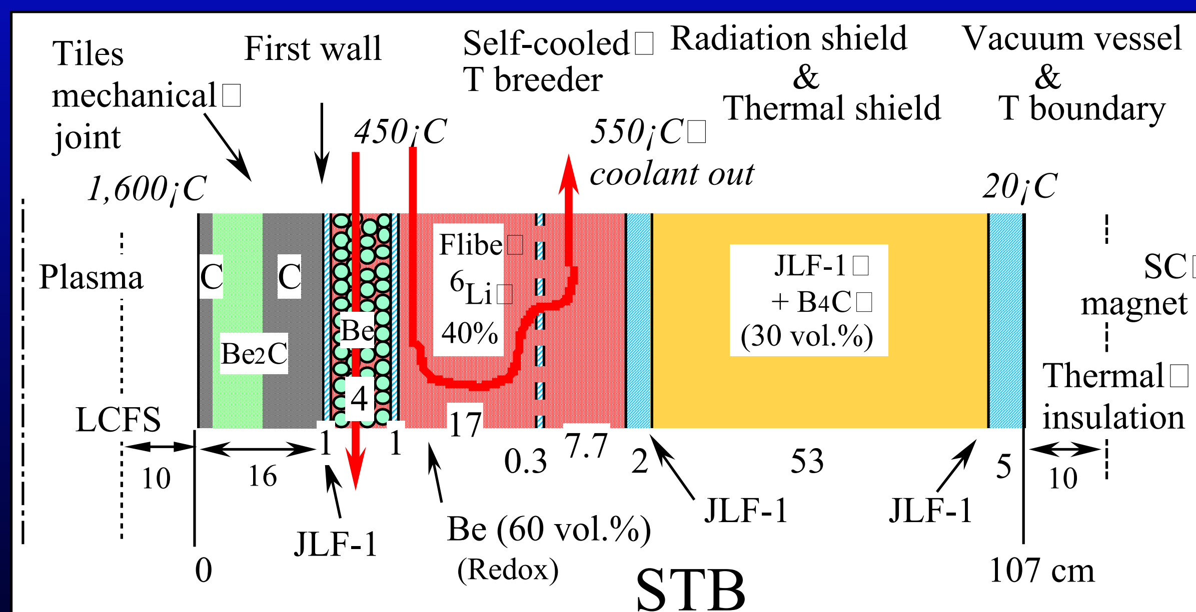
http://jupiter2.iae.kyoto-u.ac.jp/index-j.html

New proposal of Spectral shifter and Tritium breeder Blanket (STB)

- Carbon as energy shifter (ISSEC,'75)
- Optimization of Be use (new development)
- Mechanical bonding ($h \sim 6kW/m^2/s$)



Be2C in C

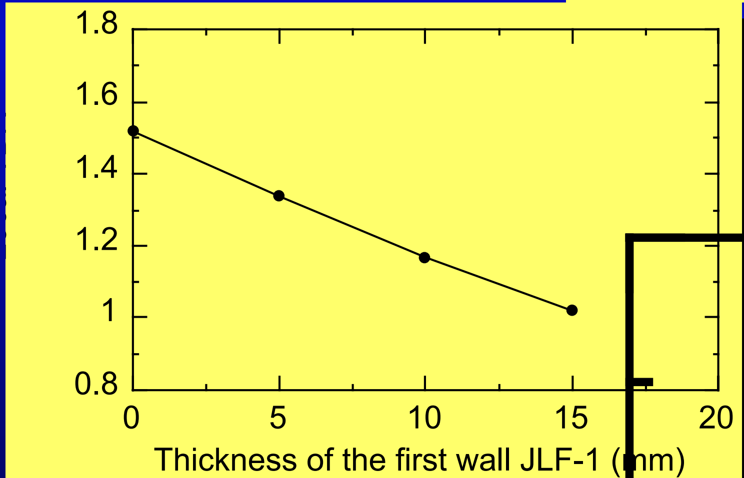


STB

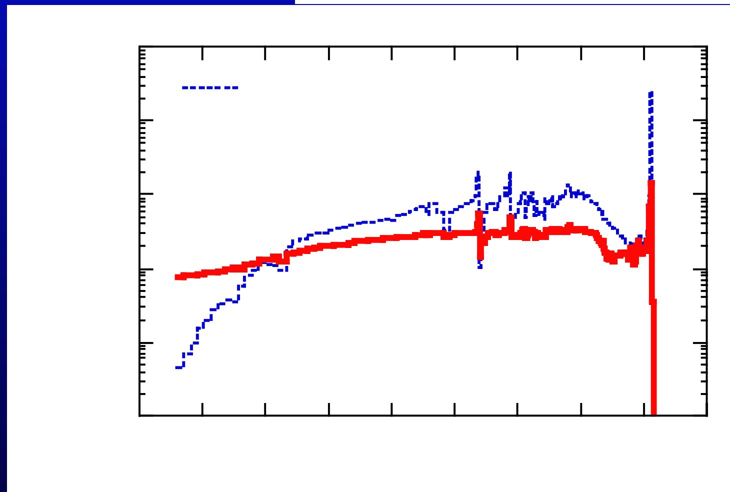
					Neutron flux(n/m2/s) for 1.5MW/m2	
	First Layer	Second Layer	Reflector	TBR	JLF-1 > 0.1MeV	SCM > 0.1MeV
Original 90 cm	JLF-1 + Flibe	[Flibe]+[Be60%+Flibe40%]+[Flibe]	carbon	1.37	4.2E+18	6.5E+14
STB 107 cm	Carbon+Be2C +Carbon	[Be60%+Flibe40 %]+[Flibe] <Li-6 40% enriched>	JLF-1+B4C	1.17	1.3E+18	5.3E+13

Ts ~ 1,600°C

TBR >1.2



Wall load reduced to 1/3

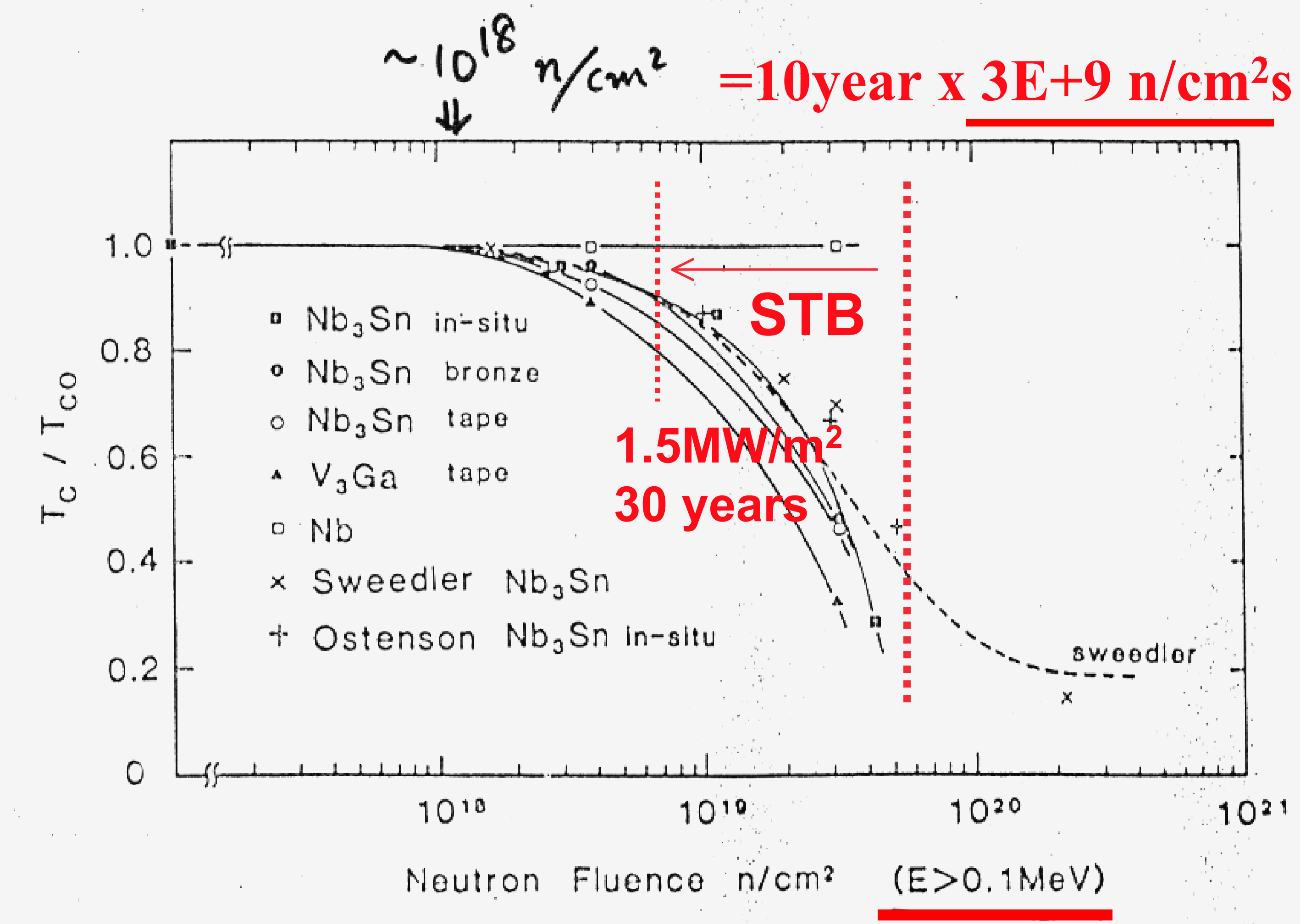


1 order reduced for SC shielding

Radiation damage of C

***k* > 100W/m/K, Volume change**

Dose effects of fast neutrons on SC magnets



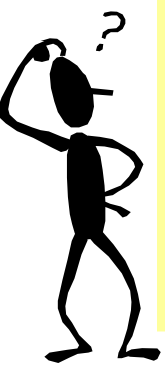
Kodama et al., JNM(1985) 819.

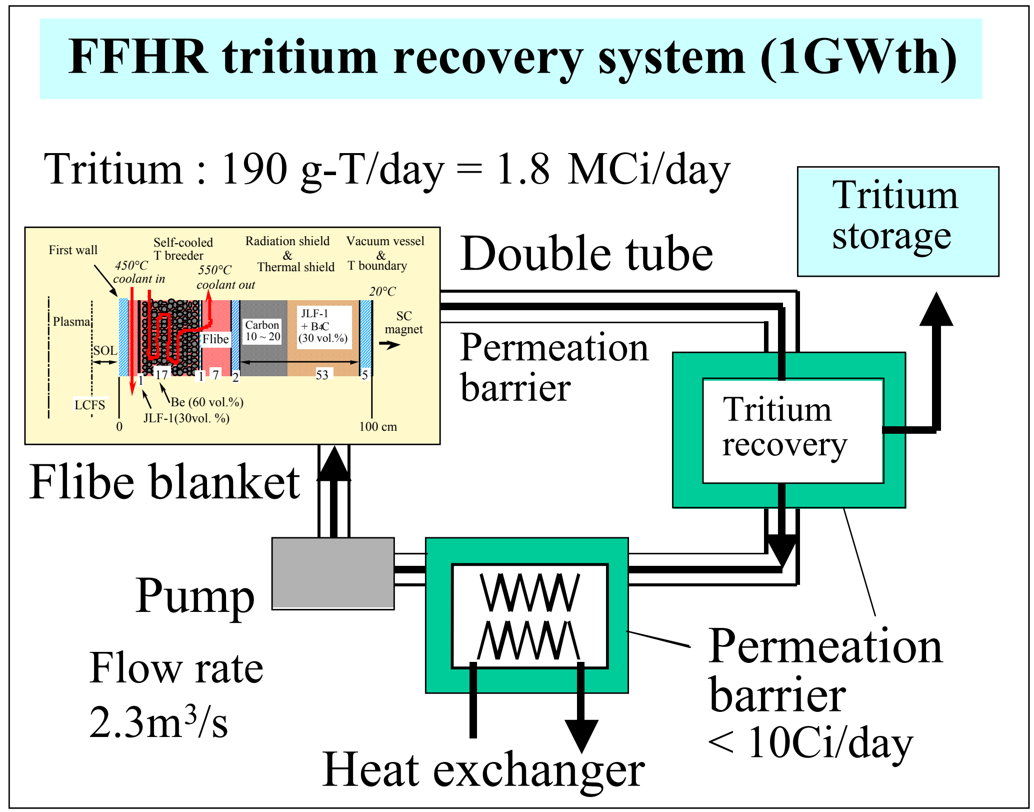
Tritium recovery systems

Kyushyu Univ.: S.Fukada

Permeation leak through the recovery system
is a crucial problem

- **Small amount of Flibe or He gas flow in the double tube are good as permeation barrier to reduce < 10Ci/day.**
- **The most serious problem is permeation leak of ~34 kCi/day through the heat exchanger to the He loop**





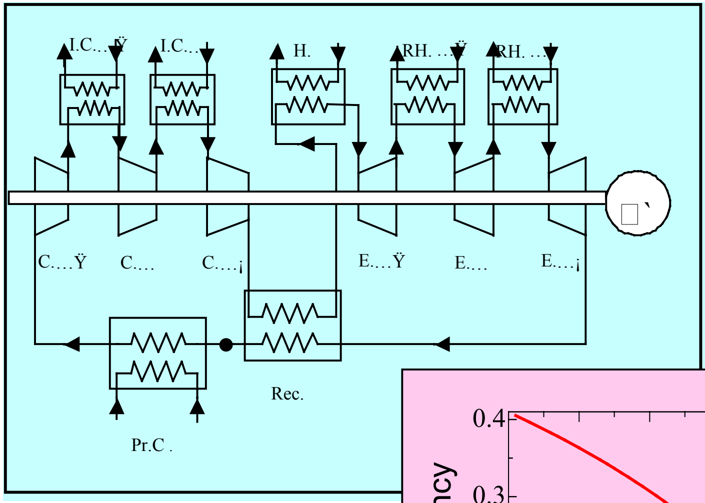
Energy conversion systems

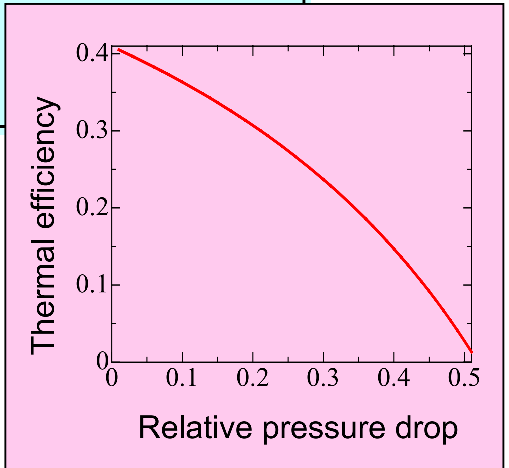
for Flibe in/out temperature of 450˚C and 550˚C

Kyushyu Univ.: A.Shimizu

Three-stage compression-expansion He-GT system was newly proposed

- η_{max} ~ 37% for compression ratio of 1.5,
- However, η_{max} decreases rapidly with the increase of pressure drop.
- Therefore the layout of energy conversion system is a key design issue.



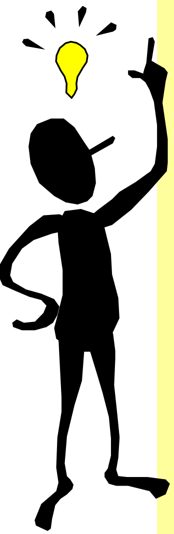


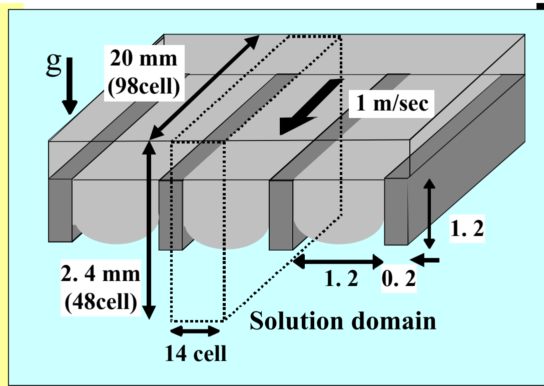
innovative free surface wall* design

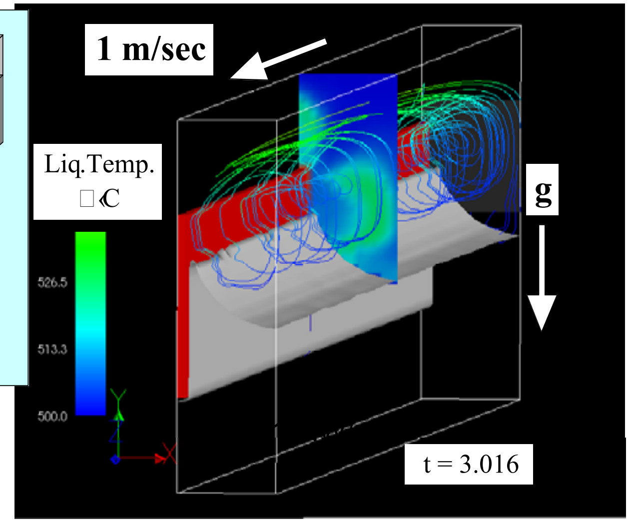
Kyoto Univ.: T.Kunugi

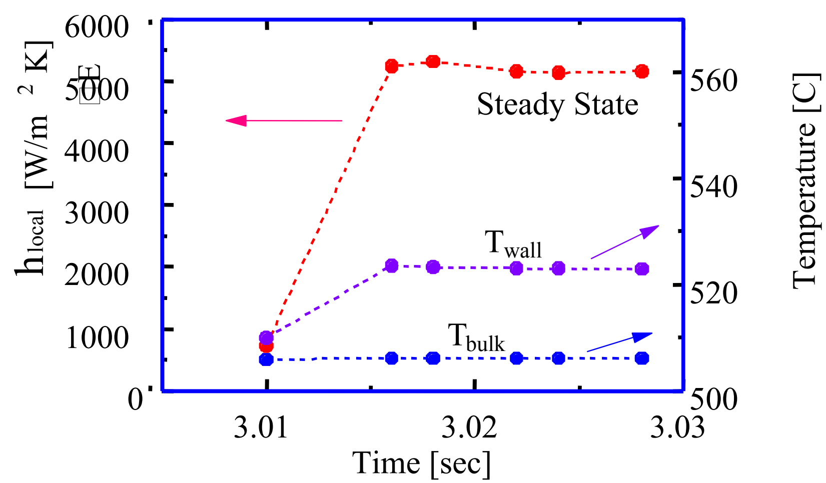
*KSF wall (Kunugi-Sagara type Free surface wall)

- **Micro grooves are made on the first wall to use capillary force to withstand the gravity force**
- **Numerical simulation has explored the formation of a pair of symmetrical spiral flow,**
- **which enhances heat transfer efficiency about one order.**









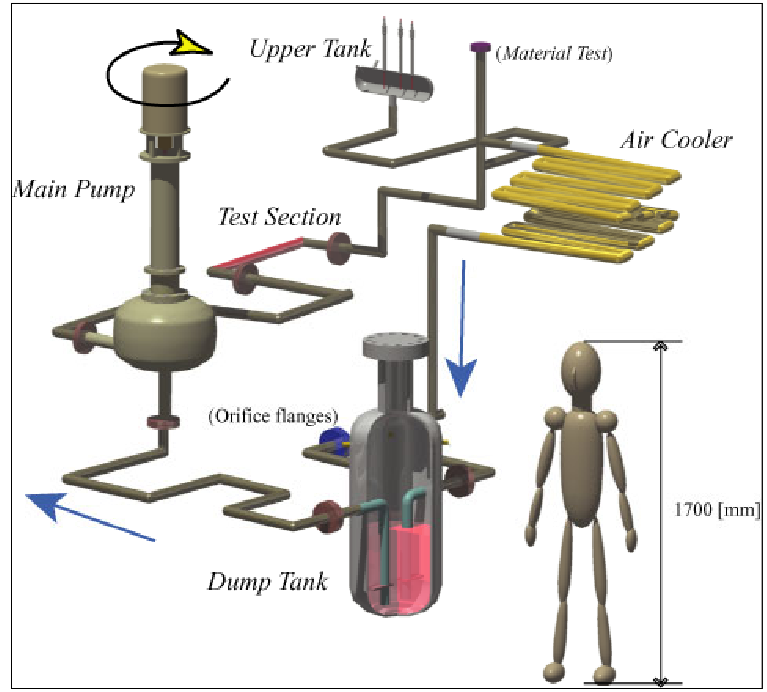
Thermofluid R&D activities

Tohoku Univ.: H.Hashizume

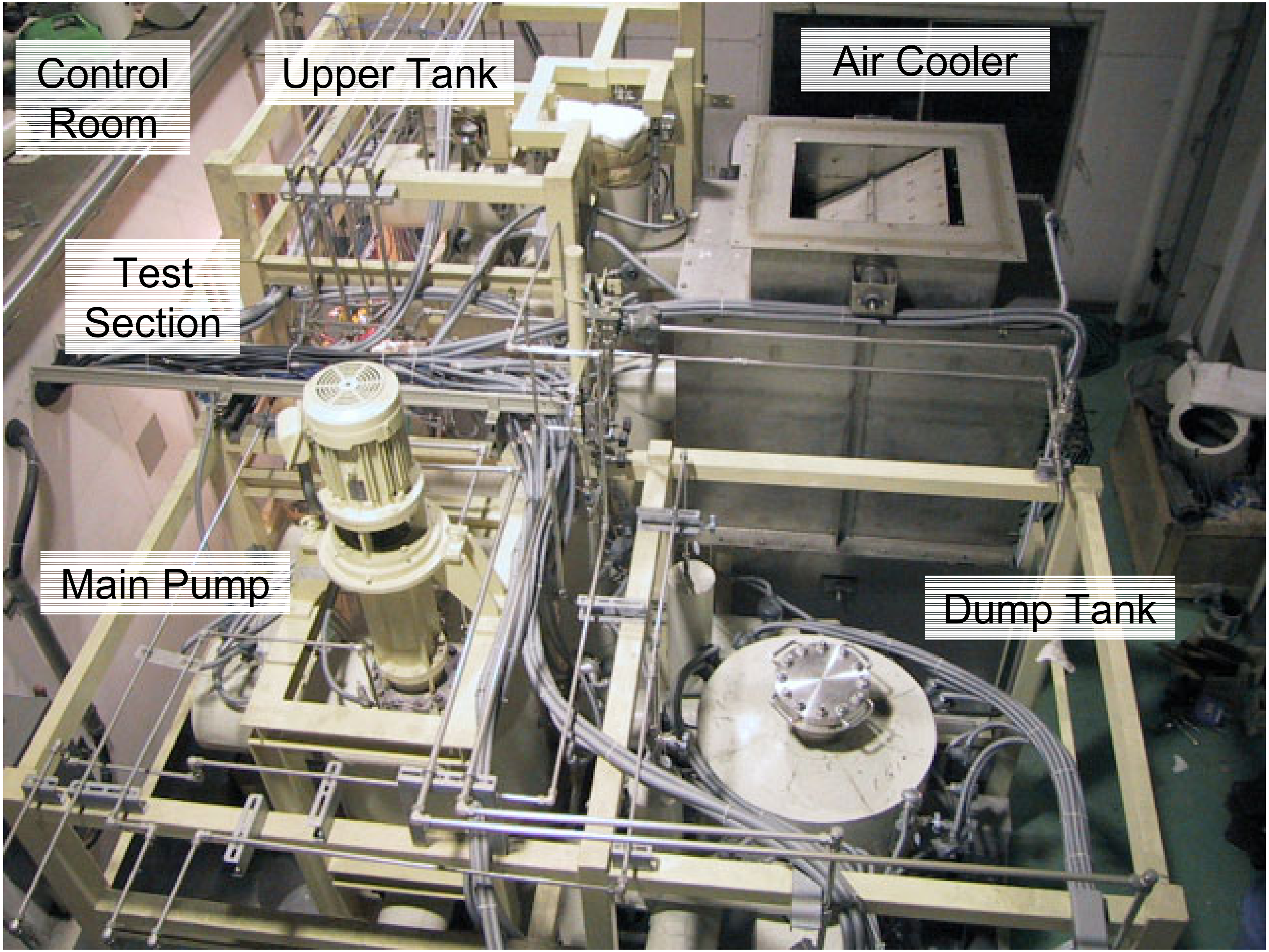
for enhancing heat-transfer in such high Prandtl-number fluid as Flibe

- "TNT loop" (Tohoku-NIFS Thermofluid loop) has been operated using HTS
  (Heat Transfer Salt, T_m= 142°C)
- Results are converted into Flibe case at the same Pr=28.5
  (Tin=200°C for HTS and 536°C for Flibe)
- Same performance as turbulent flow is obtained at one order lower flow rate.
- This is a big advantage for MHD effects and the pumping power.

TNT loop ~ 0.1m^3, < 600°C



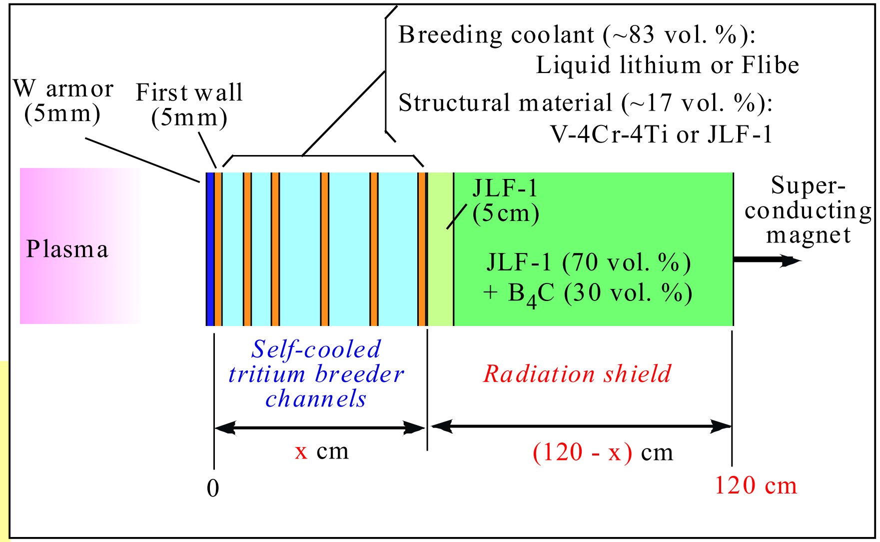
Bird's eye view of TNT loop



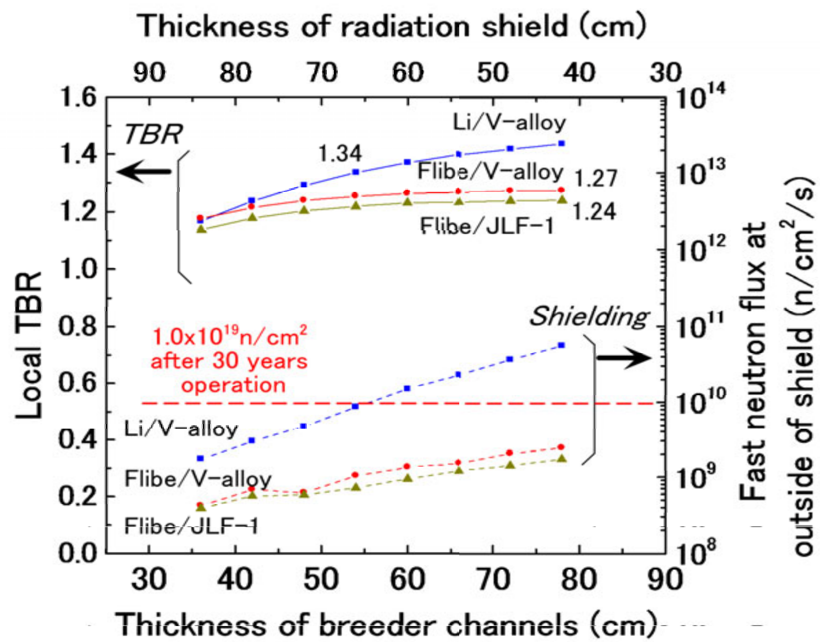
Self-cooled Be-free Li/V blanket

NIFS : T.Tanaka, T.Muroga

based on R&D progress on in-situ MHD coatings and high purity V fabrication



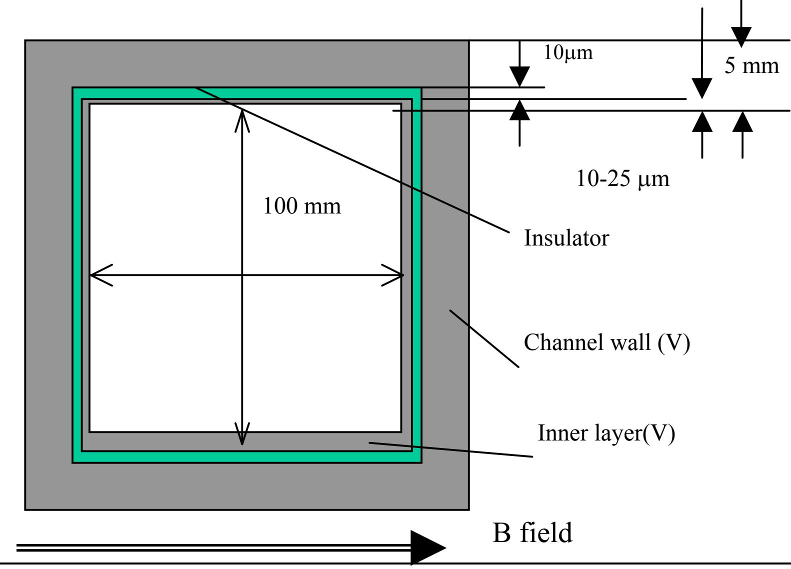
- **Simple models are evaluated as alternatives for FFHR2 blanket..**
- **Balance of TBR and the shielding performance is examined, because shielding is poor w/o Be.**
- **TBR of Li/V is higher than 1.3 at about 50 cm with an acceptable shielding efficiency for super-conducting magnets.**



Regarding to Li-V Blanket,

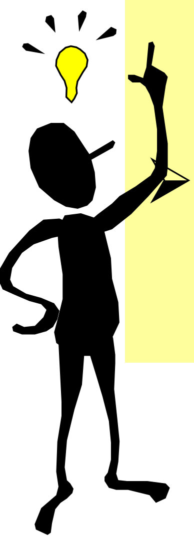
Modeling to Evaluate MHD pressure drop is established for self-cooled lithium blanket.

Tohoku Univ. : H.Hashizume



- Three-layered wall is proposed, where the inner thin metal layer protects permeation of lithium into the crack of coated layer
- Extremely good agreement between FEM and theory has been obtained
- The performance required to the insulator is evaluated to be

$$\frac{\sigma_{insulator}}{\sigma_V} \approx 10^{-8} - 10^{-9}$$



Acompaning papers

P-I-21	Muroga	Neutronics Investigation into Lithium/Vanadium Test Blanket Modules
P-I-24	Tanaka	Tritium Self-Sufficiency and Neutron Shielding Performance of Liquid Li Self-Cooled Helical Reactor
P-I-39	Nagasaka	Tungsten Coating on Low Activation Vanadium Alloy by Plasma Spray Process
P-I-48	Hashizume	Jointing Performance in HTc SC Tape for remountable magnet system
P-II-46	Chiba	Experimental Research on Heat Transfer Enhancement for High Prandtl-Number Fluid
P-II-48	Okumura	Evaluation of flow structure in packed-bed tube by visualization experiment
P-II-49	Togashi	Heat Transfer Enhancement Technique with Copper Fiber Porous Media

CONCLUSION

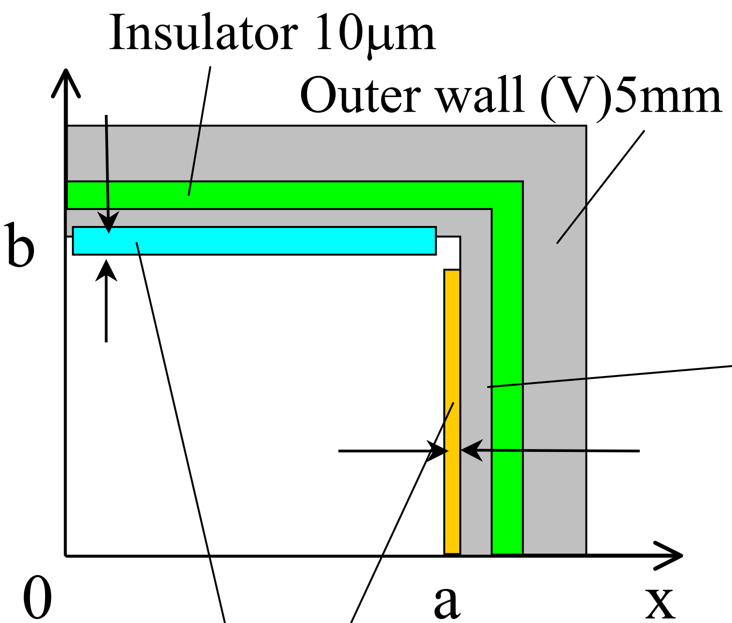
- Liquid blanket researches in Japan have been widely expanded into key elemental activities, and much progress has been made in those ten years.
- Furthermore the network research activities have been grown up including international collaborations.
- Based on those activities, the next steps will be :
  (1) System integration modeling,
  (2) Liquid loop experiments for each key issues,
  (3) Irradiation loop experiments in a hot cell,
  (4) Blanket system fabrication and operation tests in such as ITER

MHD pressure drop in coated channel

Tohoku University : H. Hashizume

1. Derivation of theoretical equation to evaluate Δp for multi layer wall

- Conventional circuit theory + effect of Hartmann and M-shape layer

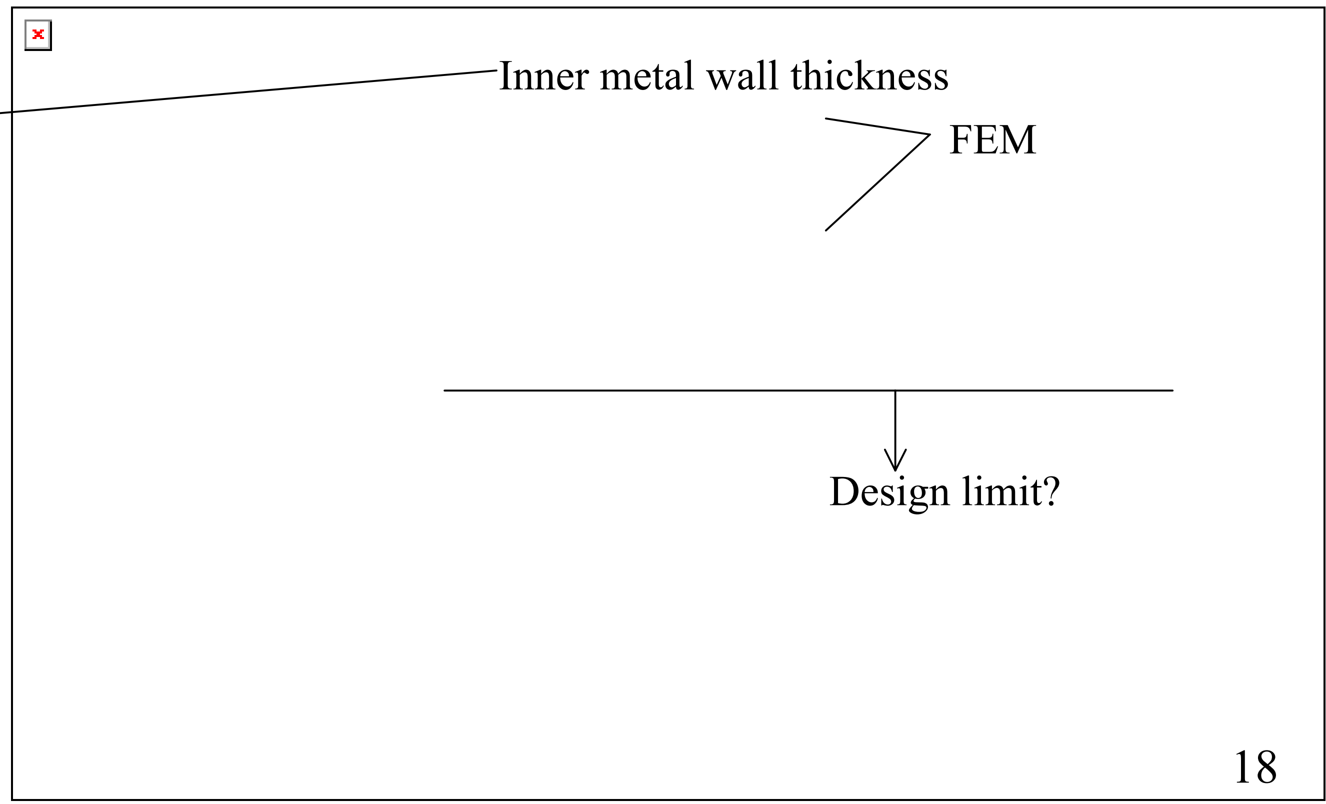


$$M - shape\ layer = \frac{b}{\sqrt{H_a}}$$

$$Hartmann\ layer = \frac{a}{H_a}$$

$$a = b = 5cm, \quad B = 5T, \quad v = 0.5m/sec, \quad Ha = 48000$$

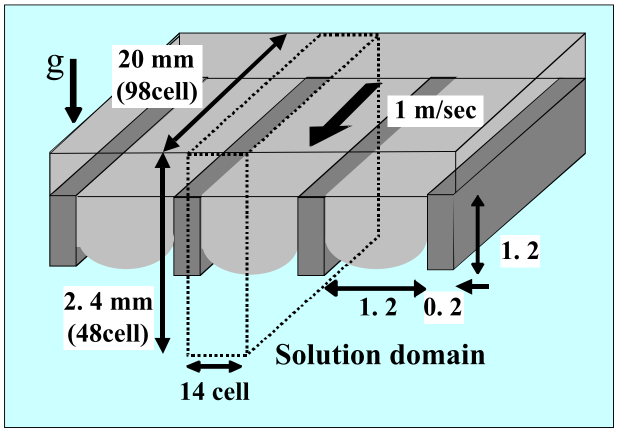
$$\frac{dp}{dz} \propto t_{inner\ wall} \times velocity \times B^{\alpha} \ (\alpha = 1.75 - 1.88 < 2)$$



Advanced Free Surface Concept for FFHR in Kyoto University

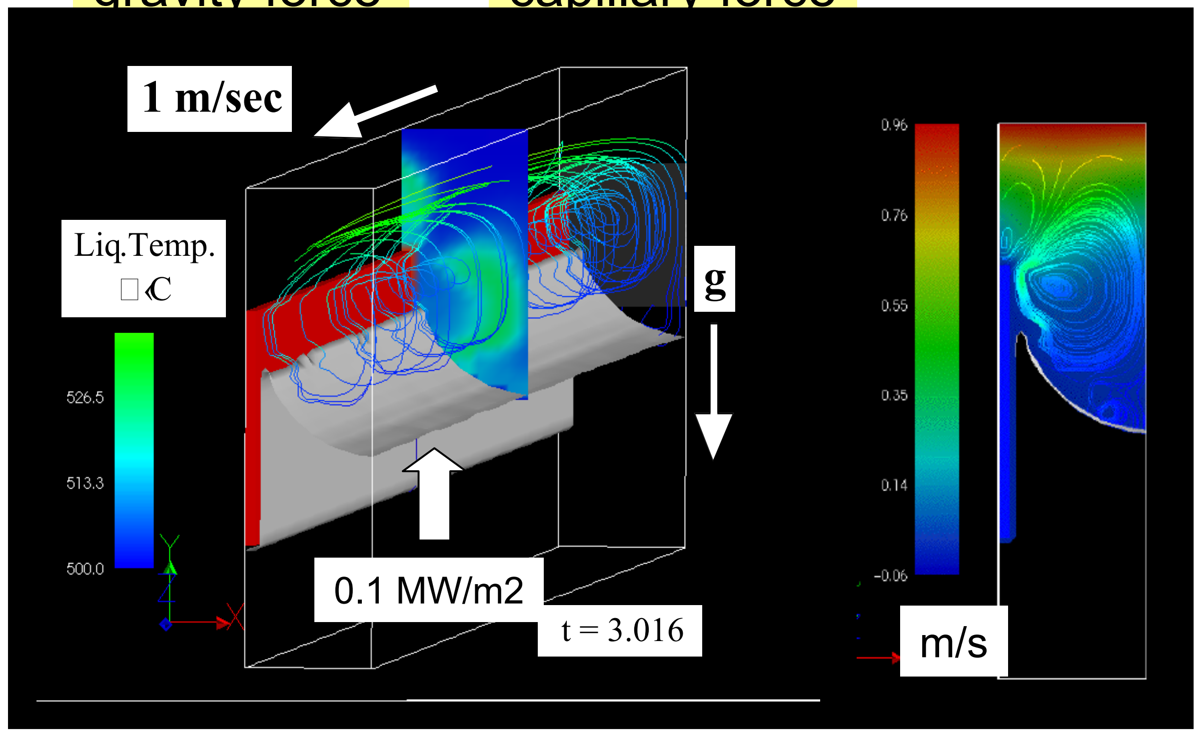
many micro grooves on the first wall, $\rho g h = 2\gamma \cos\theta / r$

gravity force capillary force



For LiF-BeF$_2$(66-34 mole %) at ~ 500°C,

- ρ = 2,036 kg/m^3,
- γ = 0.196 N/m,
- θ ~ 135 deg (on Au),
- λ ~ 0.10W/mK.



By T. Kunugi et al.

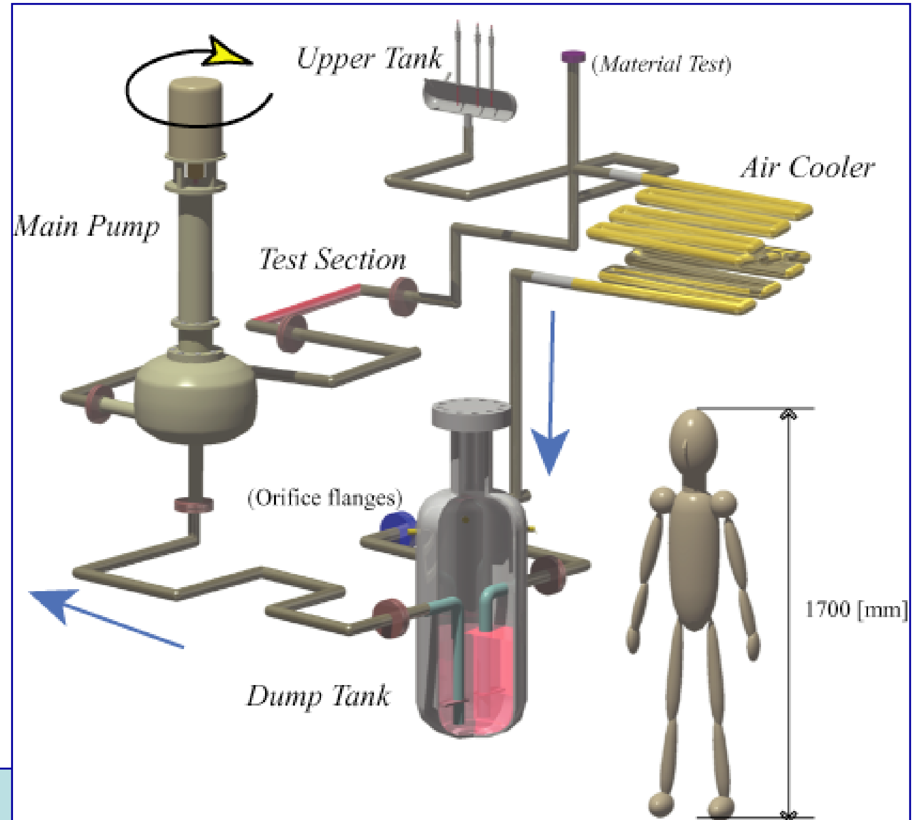
A.Sagara et al., Fusion Technol.,39 (2001) 753.

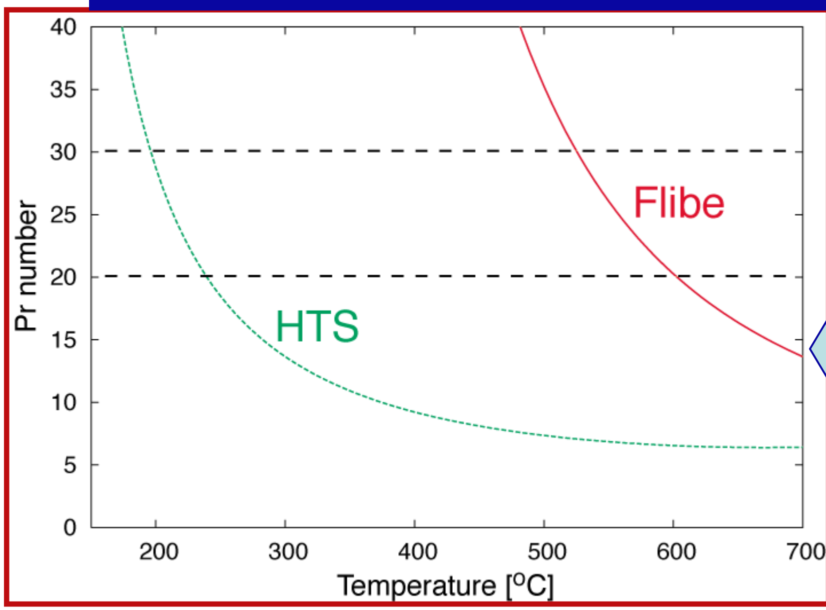
large size spiral flow is formed due to combination of buoyancy driven natural convection and forced convection, and enhances heat transfer efficiency

Tohoku-NIFS Thermofluid Loop for molten salt (1997~) has accumulated high Temperature Device Technology

TNT loop .

- u = 8 ~ 20 L/min
- T < 600 °C
- V ~ 0.1m³
- P < 0.7 MPa.
- operation ~ 30 kW
- air cooler < 80 kW
- material = ss316





Now HTS (heat transfer salt) is used as a simulant for Flibe

HTS

53% KNO_3
40% $NaNO_2$
7% $NaNO_3$
T_m =142°C

Overview of the Flinak-H_2 (D_2) permeation experimental apparatus in Kyushyu University

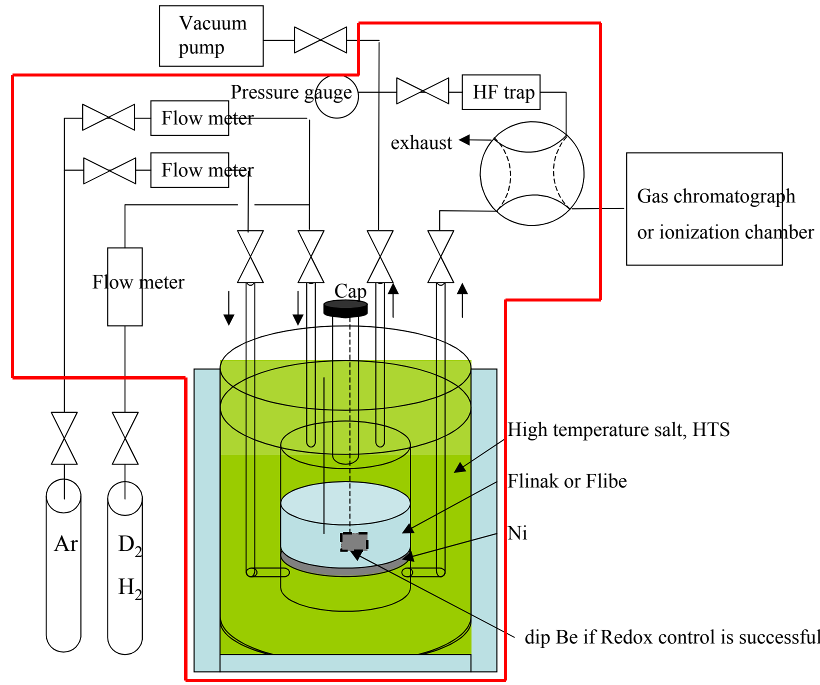
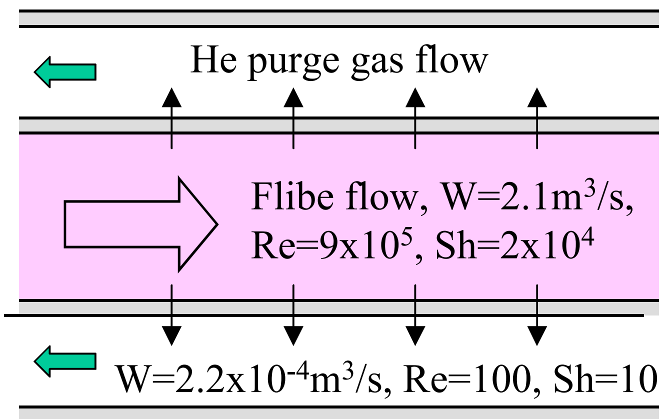
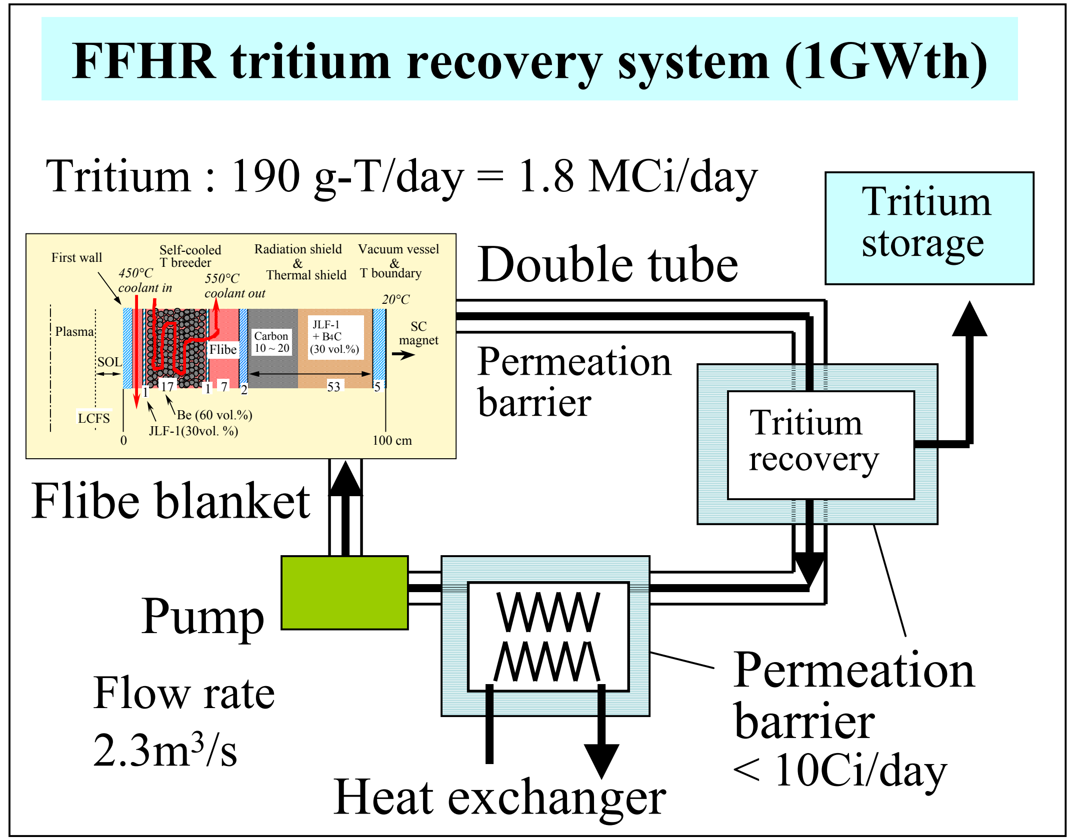


Fig. 1 Assemble of Flinak(Flibe)/H_2 (T_2) permeation pot system

With barrier of He sweep gas (W=220cc/s) and/or Flibe stagnant (t=0.5m) in double wall (100m^2), the leak level is 1.6Ci/day < 10Ci/day.





	(1) α = 1 (no by-pass)	(2) α = 1 (Flibe barrier)	(3) α = 0.1
T generation rate in blanket	1,800kCi/day	1,800kCi/day	1,800kCi/day
T concentration in Flibe	5x10^{-4}wppm (1kPa)	5x10^{-4}wppm (1kPa)	5x10^{-3}wppm (10kPa)
In T recovery system	1,765kCi/day	1,766kCi/day	1,441kCi/day
T leak through line from blanket to TRS	**1kCi/day**	1Ci /day	**10kCi/day**
T leak through secondary flow	**34kCi/day**	**34kCi/day**	**340kCi/day**
T Leak from heat exchanger	10Ci /day	10Ci /day	**9kCi/day**
T leak through line from HX to blanket	10Ci /day	10Ci /day	**30Ci/day**
T inventory in sus 316	8kCi /ton	8kCi /ton	30kCi /ton

Research on Self-Cooled Li/V Blanket in NIFS

Blanket design

Tritium self-sufficiency for Li/V blanket with acceptable shielding was demonstrated by neutronics calculation in Tokamak and Helical systems (Poster PI-21,24)

Development of vanadium alloys

Fabrication technology of V-4Cr-4Ti was highly enhanced by recent researches

T recovery

Feasibility of gettering T by Y was demonstrated, which can be applied to IFMIF and Li/V blanket (Fukada, IFMIF-KEP)

MHD insulator coating

(1) PVD coating of Er_2O_3, Y_2O_3

(2) Two layer coating with Er_2O_3 and V-alloy

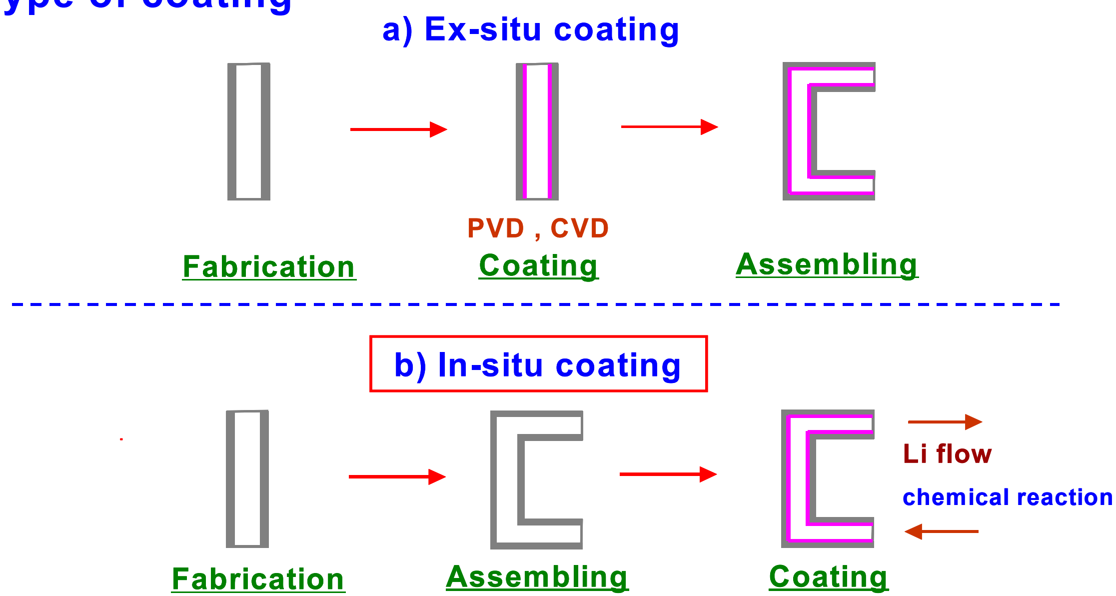
(3) in-situ Er_2O_3 coating

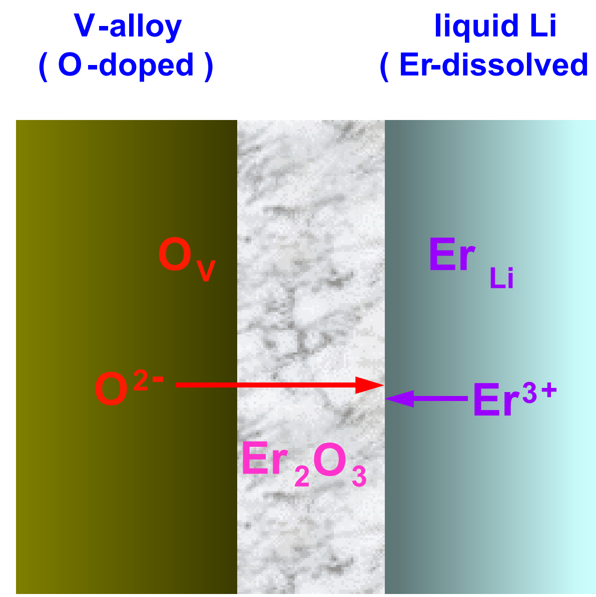
are under development

In-situ MHD coating with Er_2O_3 on V alloys

- Er_2O_3 was identified as promising candidate MHD insulator coating material (JUPITER-II)
- In addition to PVD coating, in-situ Er_2O_3 coating method has been developed in Japan
- Advantages of in-situ coating
  - Coating on complex component
  - Healing without disassembling coating

Type of coating



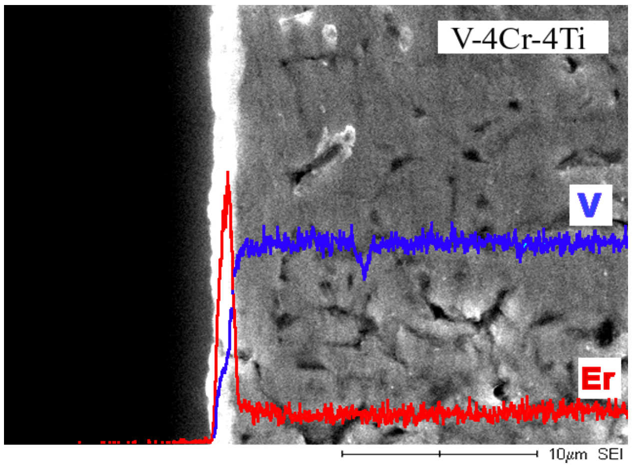


Generic model of in-situ method

In-situ Formation of Er_2O_3 Layer

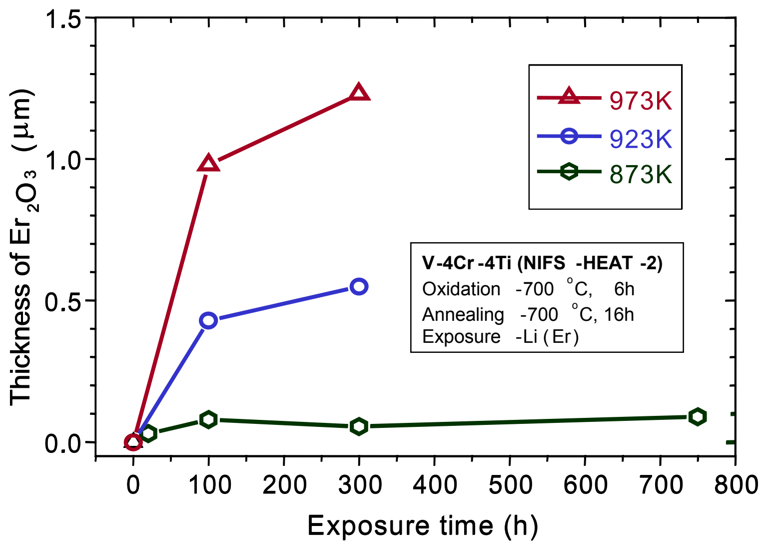
Er_2O_3 coating formed successfully on V-4Cr-4Ti

SEM and EDS of cross section



oxidized	700°C,	6h
annealed	700°C,	16h
exposed in Li (Er)	600°C,	300h

XPS and XRD confirmed the Er_2O_3 phase



Er_2O_3 layer grow and saturate

Stable to 750h at 600C
300h at 700C

Neutronics Investigation of Self-Cooled Liquid Blanket System for FFHR2

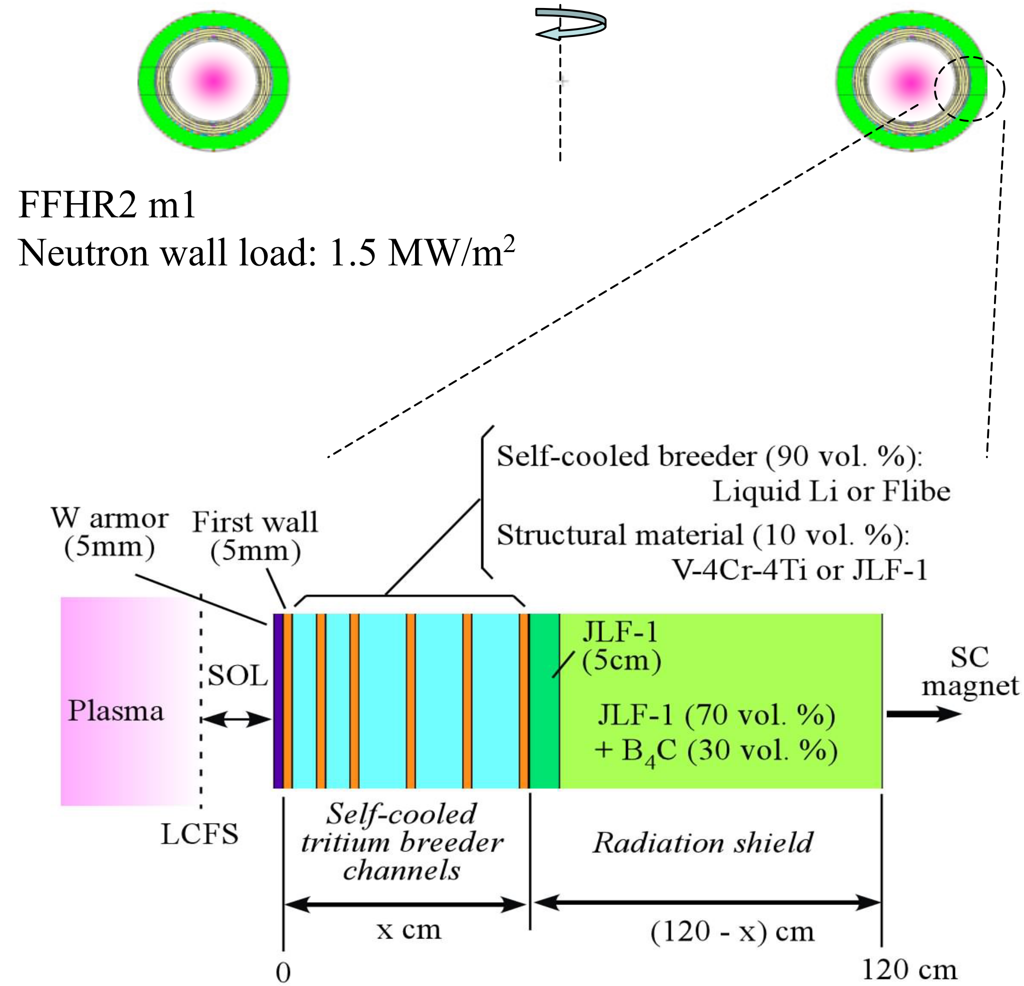
- Expansion of blanket space in recent design study
  (Original FFHR2: 90 cm,
  FFHR2 m1 design: 120 cm)

  ↓

  Possibility of self-cooled liquid blanket system without solid neutron multiplier

- Compatibility investigation between tritium self-sufficiency and neutron shielding performance for
  (1) Li / V-4Cr-4Ti
  (2) Flibe / V-4Cr-4Ti
  (3) Flibe / JLF-1(RAS)
  blanket systems

- Monte Carlo calculation using MCNP-4C code and JENDL3.2 nuclear data

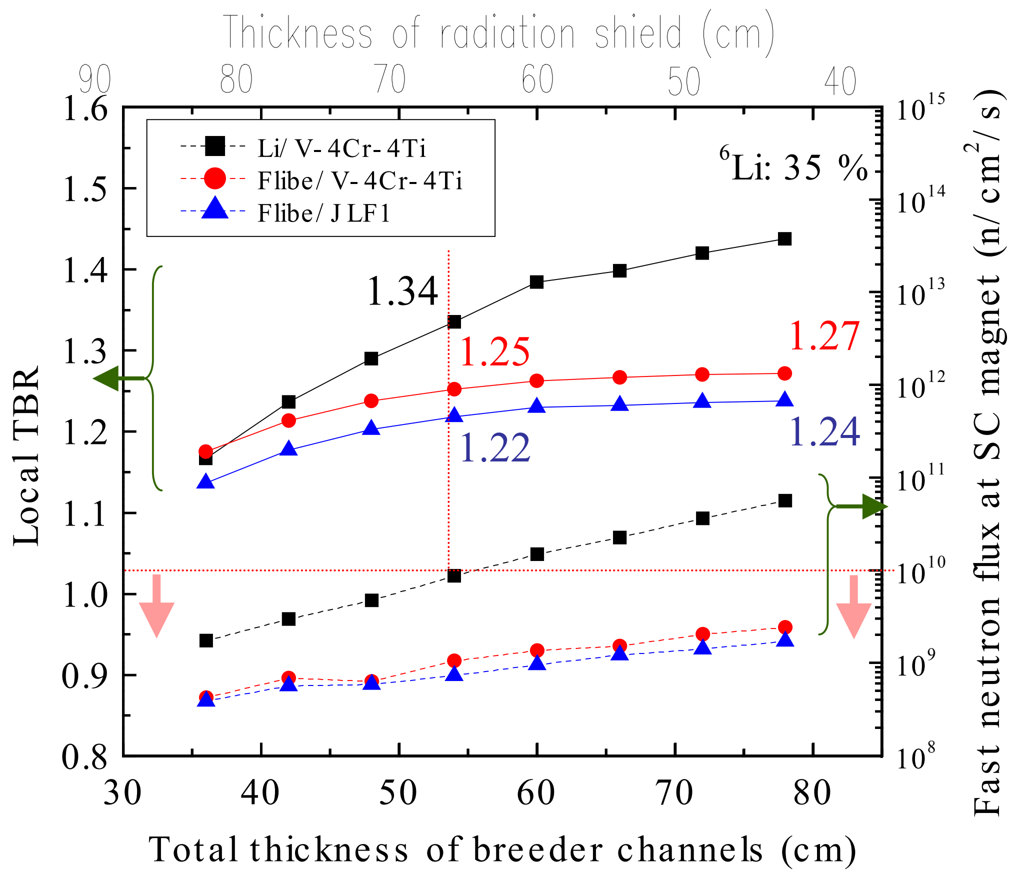


Geometry Model of Self-Cooled Liquid Blanket System for Nuclear Calculation*

(*T.Tanaka *et al.*, present conference, P-I-24.)

Neutronics Investigation of Self-Cooled Liquid Blanket System for FFHR2

- **Targets:**
  - Local TBR: ~ 1.37 (Original FFHR2)
  - Fast neutron flux (>0.1 MeV) at SC magnet : <1.0 x 10^{10} n/cm²/s
- **Li / V-4Cr-4Ti**
  - Local TBR: 1.34 (^{6}Li: 35 %)
  - Fast neutron flux: 8.7 x 10^9 n/cm²/s
- **Flibe / V-4Cr-4Ti, JLF-1**
  - Local TBR: ~1.25 (^{6}Li: 35 %)
  - Fast neutron flux: << 1.0 x 10^{10} n/cm²/s
- Li/V-4Cr-4Ti blanket can achieve the targets.
- For Flibe/V-4Cr-4Ti and Flibe/JLF-1 blankets, optimization of neutron reflectors are required to increase TBR.



Relations of Local TBR and Neutron Shielding Performance to Thickness of Breeder Channels*

(*T.Tanaka *et al.*, present conference, P-I-24.)

Activities on LiPb blanket study in Kyoto University

LiPb blanket is studied as both for

- **near term candidate for ITER test blanket module under TBWG, WSG2, and**
- **long term advanced blanket concept.**

Research program in Japanese universities covers

- **development of SiC insert for dual coolant concept, and**
- **reactor design study.**

Dynamic compatibility study of of LiPb with newly developed SiC component will be tested.

Present R & D activities on Flibe blanket in Japan

Presented by A.Sagara(NIFS) , Feb.'04