Japan-US Workshop on
Fusion Power Plants and Related Advanced Technologies

Recent progress of the R&D and design for high temperature blanket and biomass hybrid concept

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Introduction

Background

Kyoto University pursues the Biomass Hybrid concept from various aspects.

Particular interest is on Socio-Economics and possible scenario for early introduction of Fusion, with minimal extrapolation of the current technology.

Safety, environment and the adoptation to the future energy system are our current concern.

Contents

- LiPb blanket and tritium recovery / SiC study
- zero-carbon electricity system with Micro DC grid.
- Tritium in the environment

Biomass Hybrid Concept

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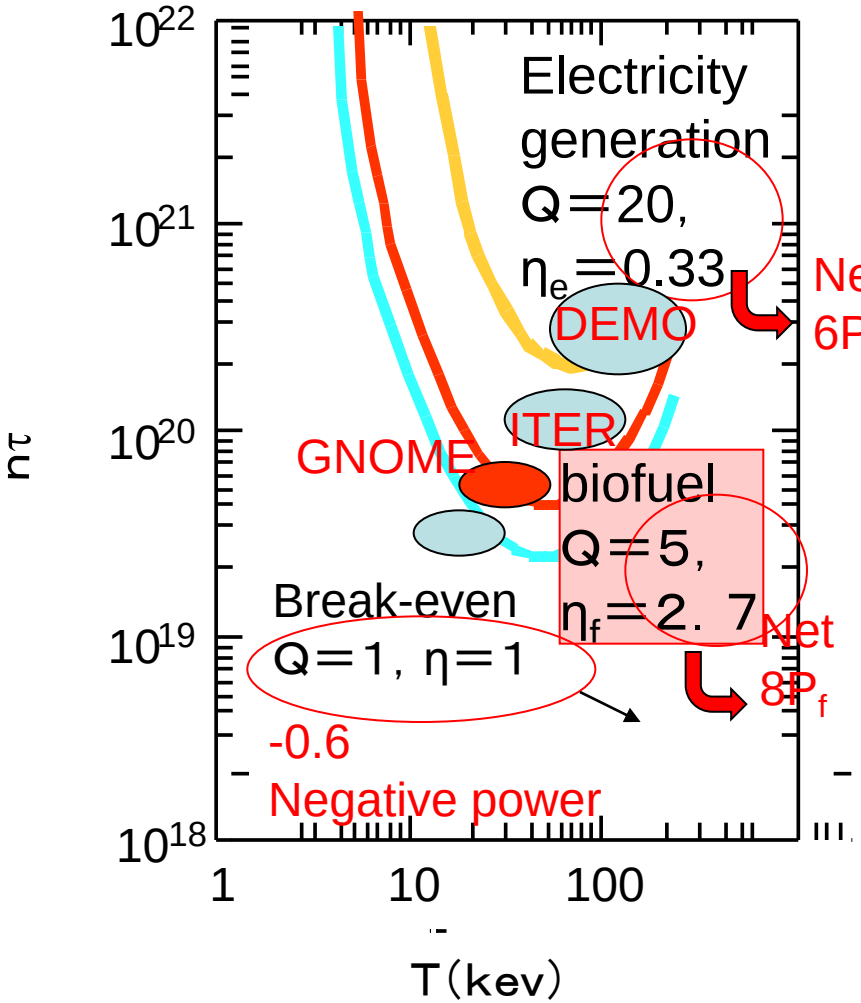


- High Plasma Q not required

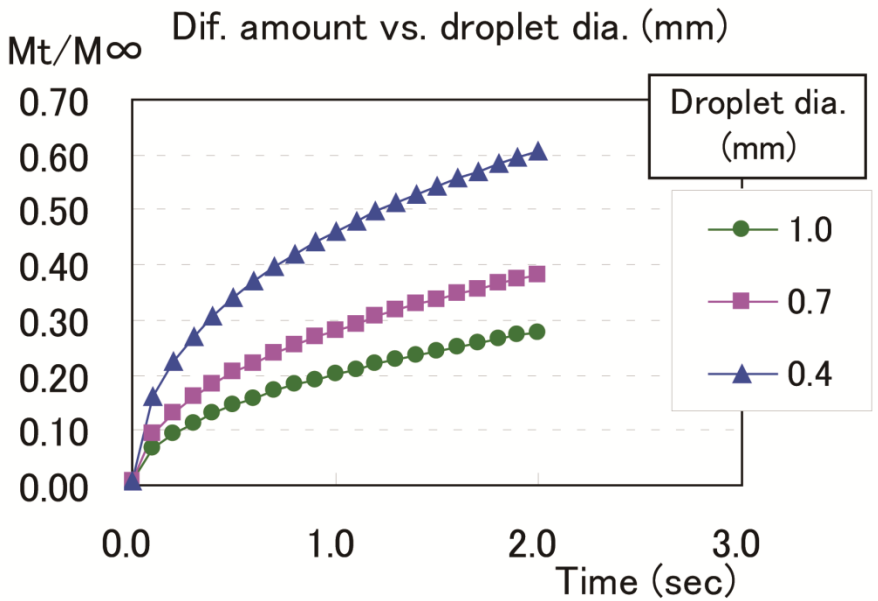
➡ **Driven and pulsed operation is acceptable**

- High output temperature is required for gasification efficiency is required

➡ High temperature blanket To be developed.

Droplet and Diffusion

$$\frac{M_t}{M_\infty} = 1 - \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-Dn^2\pi^2 t / \boldsymbol{a}^2\right)$$

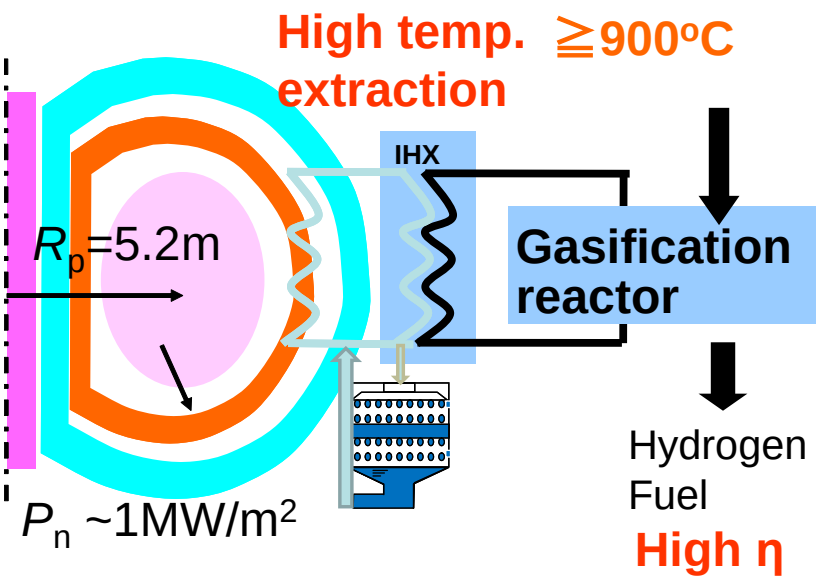


droplet diameter is a key factor for optimum design of the extraction system

Development of Vacuum Sieve Tray

A: Tritium balance study

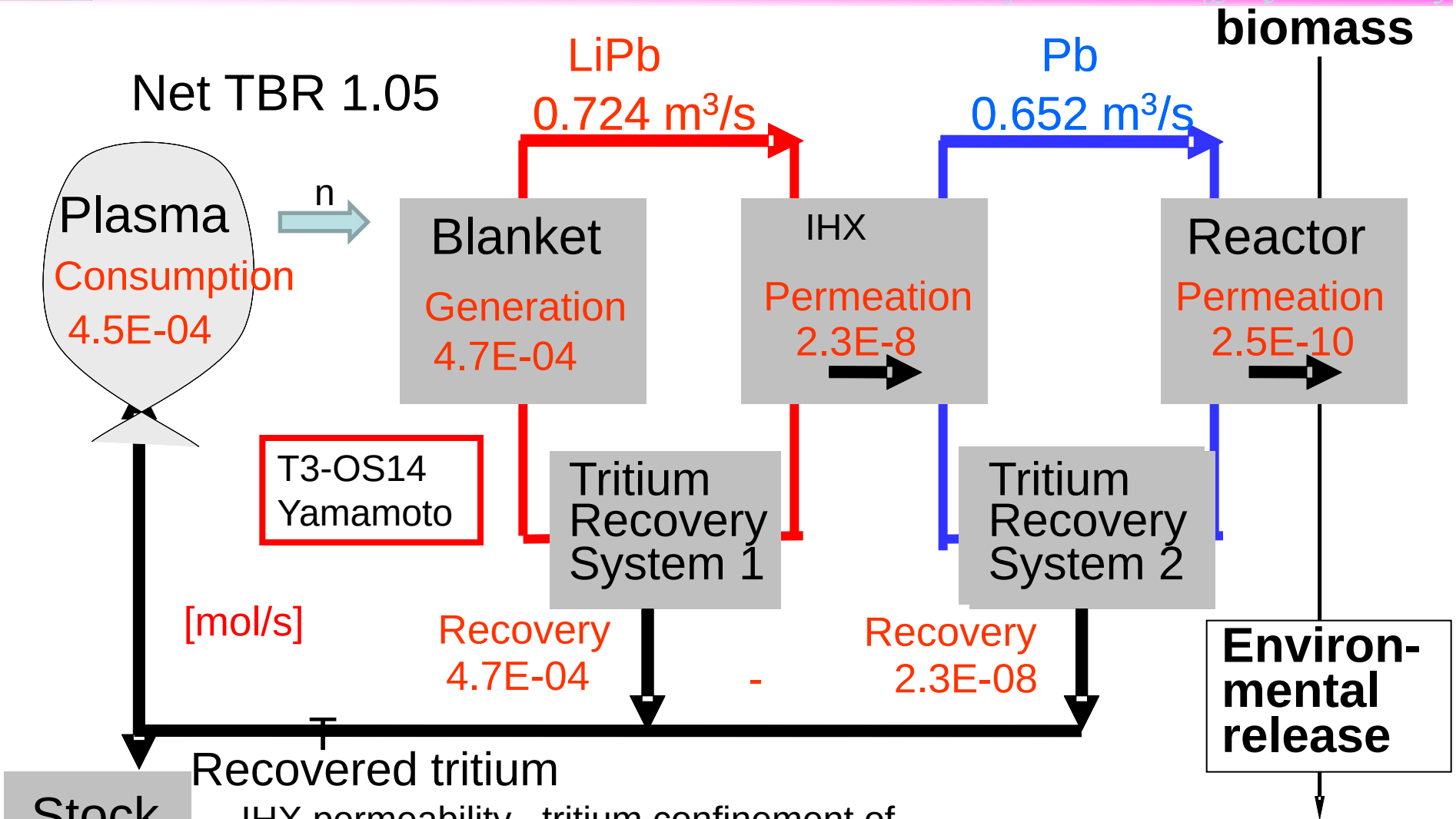
To explicate the recovery rate of Biomass Gasification fusion reactor GNOME



B: Tentative observation of droplet formation

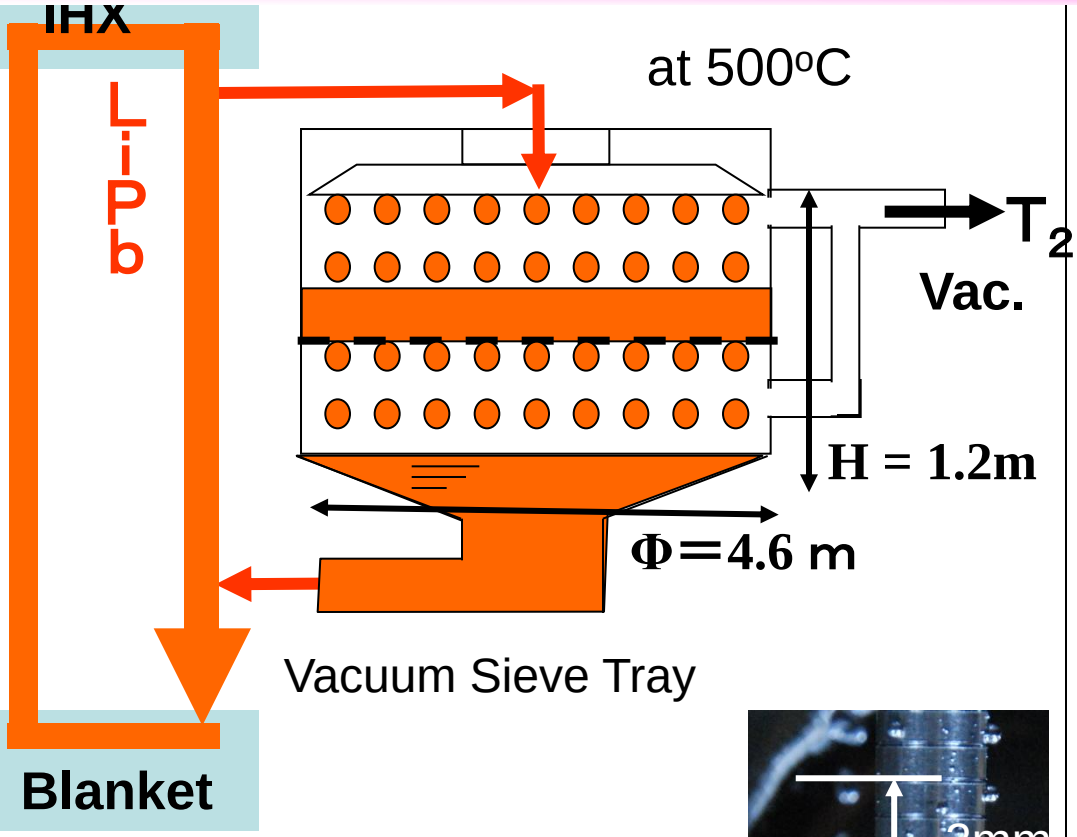
from 1mm dia. nozzle by an experimental setup (one point data)

Tritium Balance in plant



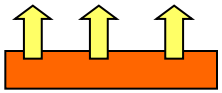
IHX permeability , tritium confinement of
Entire power plant needs maturity and
Demonstration for social understanding.

Tritium Recovery Process



Φ=4mm

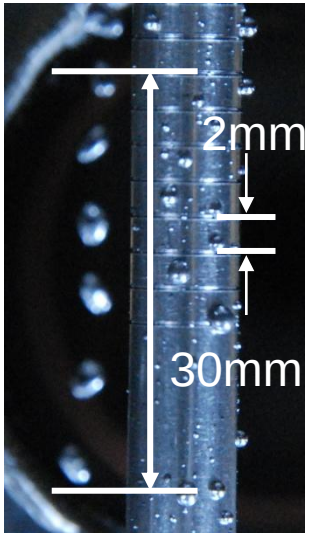
$$\frac{M_t}{M_\infty} = 1 - \sum_{n=1} \frac{6}{n^2 \pi^2} \exp\left[-\frac{n^2 \pi^2 D}{r^2} t\right]$$



depth=√D

$$\frac{M_t}{M_\infty} = 1 - \sum_{j=0}^{\infty} \frac{8}{(2j+1)^2 \pi^2} \exp\left[-\frac{(2j+1)^2 \pi^2 D}{4 l^2} t\right]$$

→ **Recovery ratio 45%**



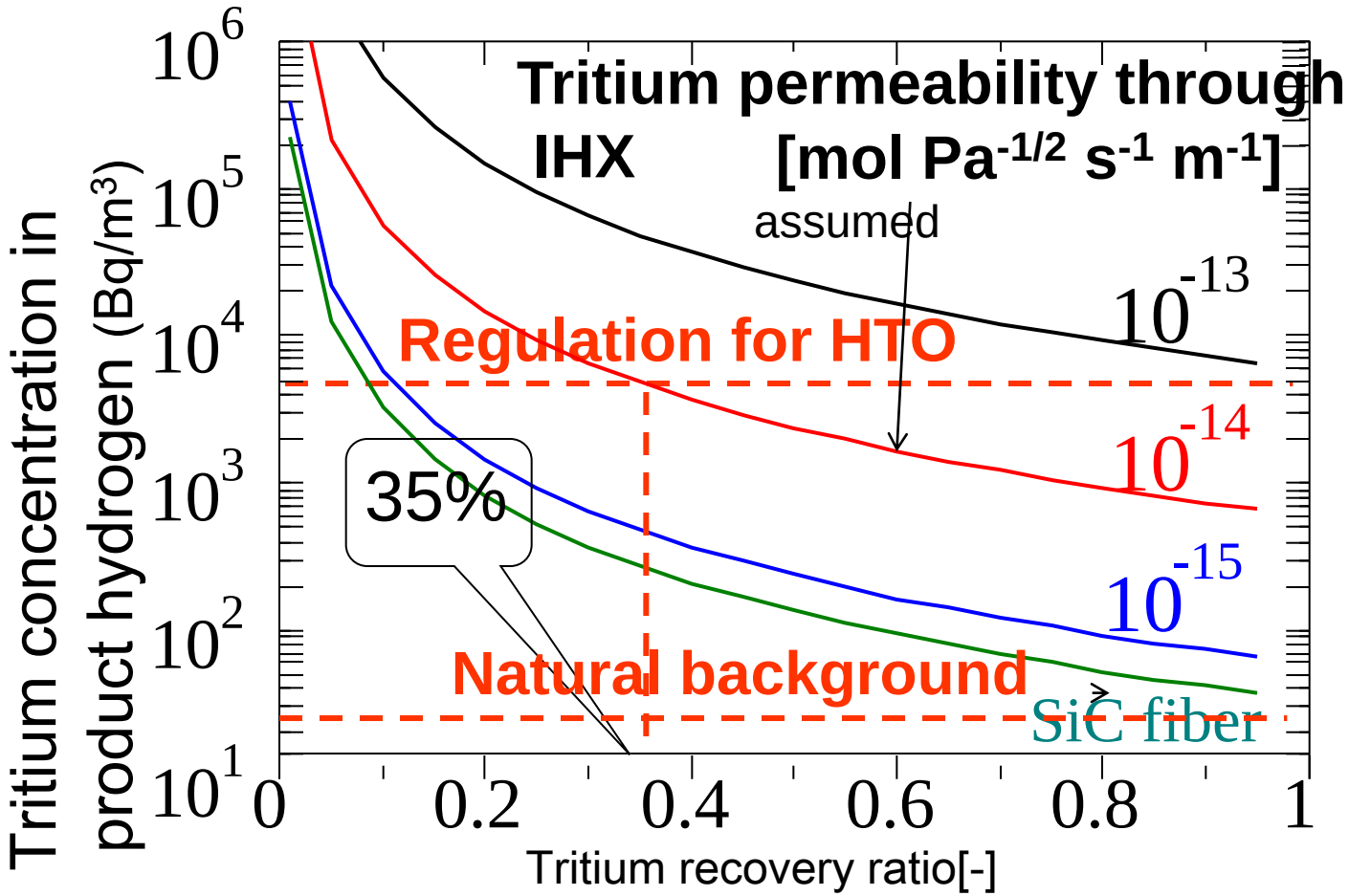
reruirement

- Inventory control
- Tritium in hydrogen product

$M(t)$ [mol] : gas release
M_∞ [mol] : dissolved tas

D [$m^2\ s^{-1}$] : diffusion coefficient
t [s] : time
r_0 [m] : radius of the droplet
l [m] : depth

Tritium Recovery Process



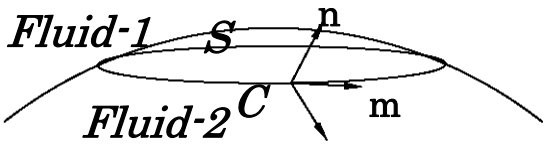
-Recovery ratio determined from the contamination of product.

-Requirement is a function of permeability through IHX

➡ Target recovery ratio >35% in the LiPb stream

Water (H_2O) vs. Liquid Pb-17Li

Boundary equilibrium equation



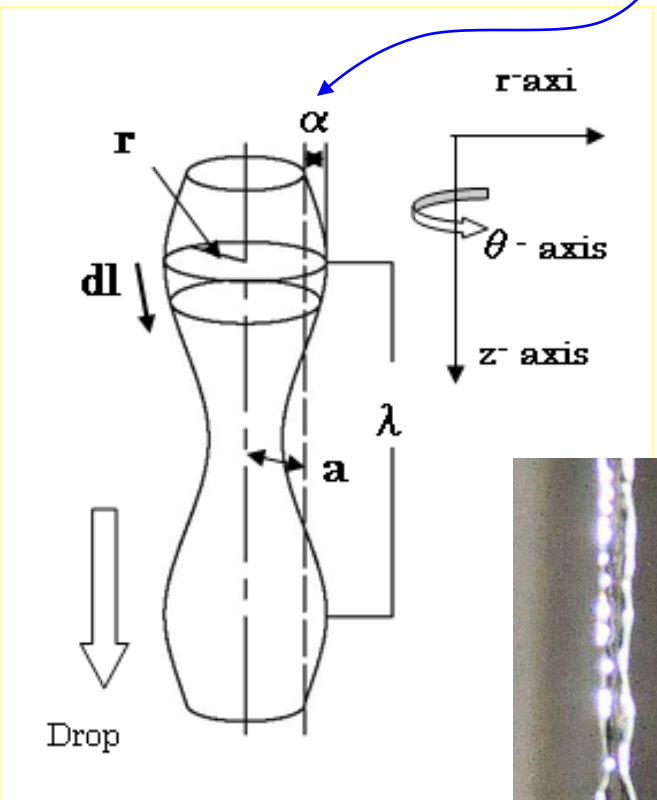
$$-p_d' + \frac{1}{Fr} z' + \frac{2}{Re} \mathbf{n} \cdot \mathbf{E}' \cdot \mathbf{n} = \frac{1}{We} \left(\nabla' \cdot \mathbf{n} \right)$$

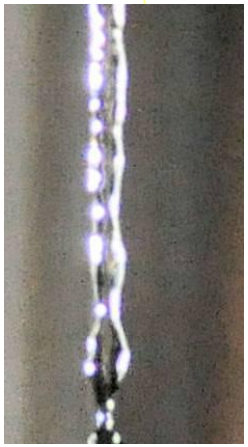
	Density	Visco-sity	Surface tension	Temperature	Velocity	Length	Reynolds number	Froude number	Weber number
	ρ [Kg/m^3]	μ [Pa·sec]	σ [N/m]	T(C)	V[m/sec]	L[m]	ρ UL/ μ	U^2/gL	ρ U^2 L/ σ
H2O	1.0E+3	1.0E-3	0.07	20	3	1.0E-3	3.0E+3	9.2E+2	1.3E+2
Pb-17Li	9.7E+3	1.5E-3	0.45	400	3	1.0E-3	1.9E+4	9.2E+2	2.0E+2
Pb-17Li	9.6E+3	1.2E-3	0.44	500	3	1.0E-3	2.5E+4	9.2E+2	2.0E+2

H_2O & Pb-17Li
Both *Surface tension regime* material

Deducing formula

$$r = a + \alpha \cos kz$$





Energy minimum by Euler-Lagrange-Equation

$$\frac{\partial L}{\partial q} - \frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}}\right) = 0$$

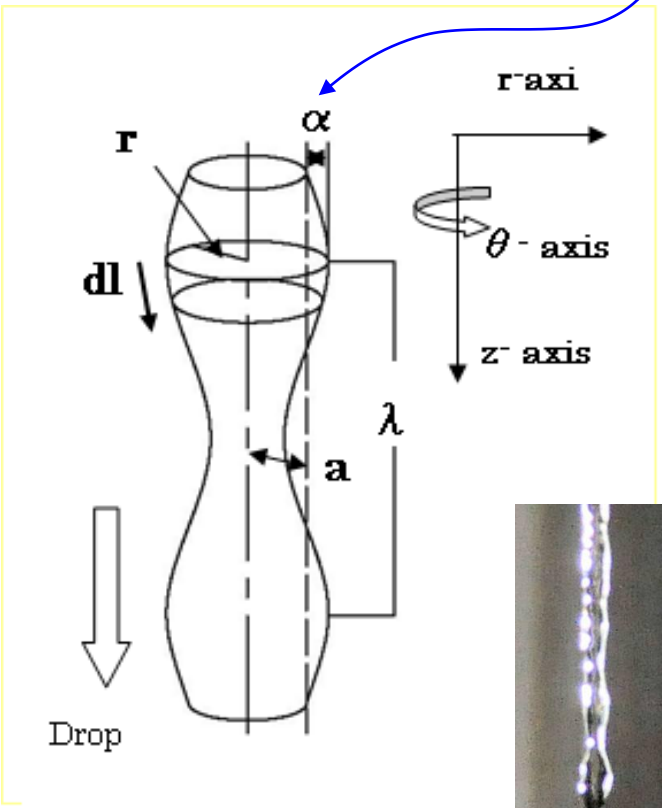
$$U = \sigma\left(s - s_0\right) = -\sigma \frac{\pi \alpha^2}{2a}\left(1 - a^2 k^2\right)$$

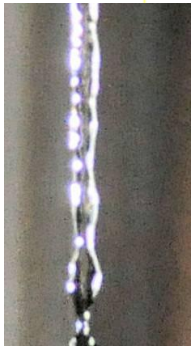
$$T = \tfrac{1}{2}\rho \int_V (\nabla\phi)\cdot(\nabla\phi)\,dV$$

$$= \tfrac{1}{2}\pi\rho a^2 \frac{I_0(ka)\dot{\alpha}^2}{kaI_1(ka)}$$

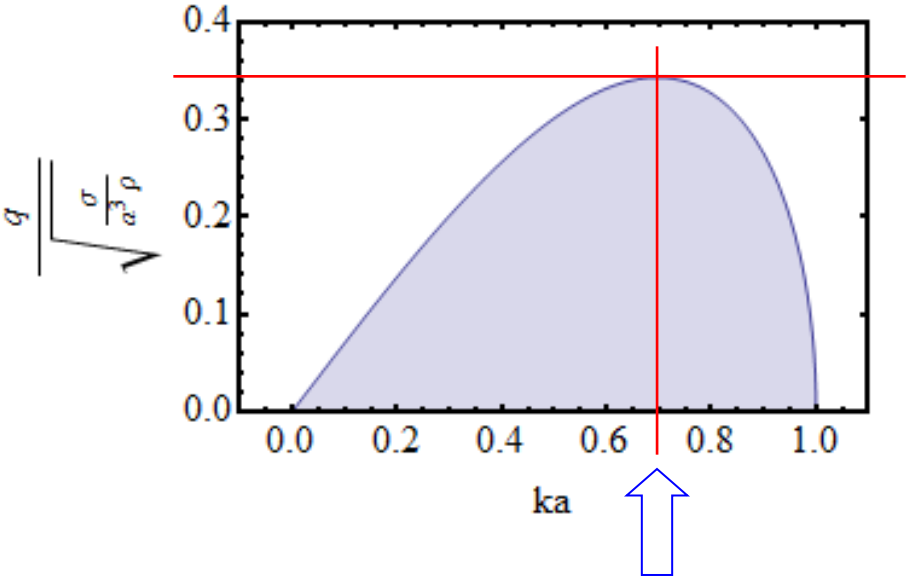
Deducing formula

$$\alpha = a_0 e^{qt}$$





$$\sqrt{\frac{ka\left(1-ka^2\right)I_1(ka)}{I_0(ka)}}$$

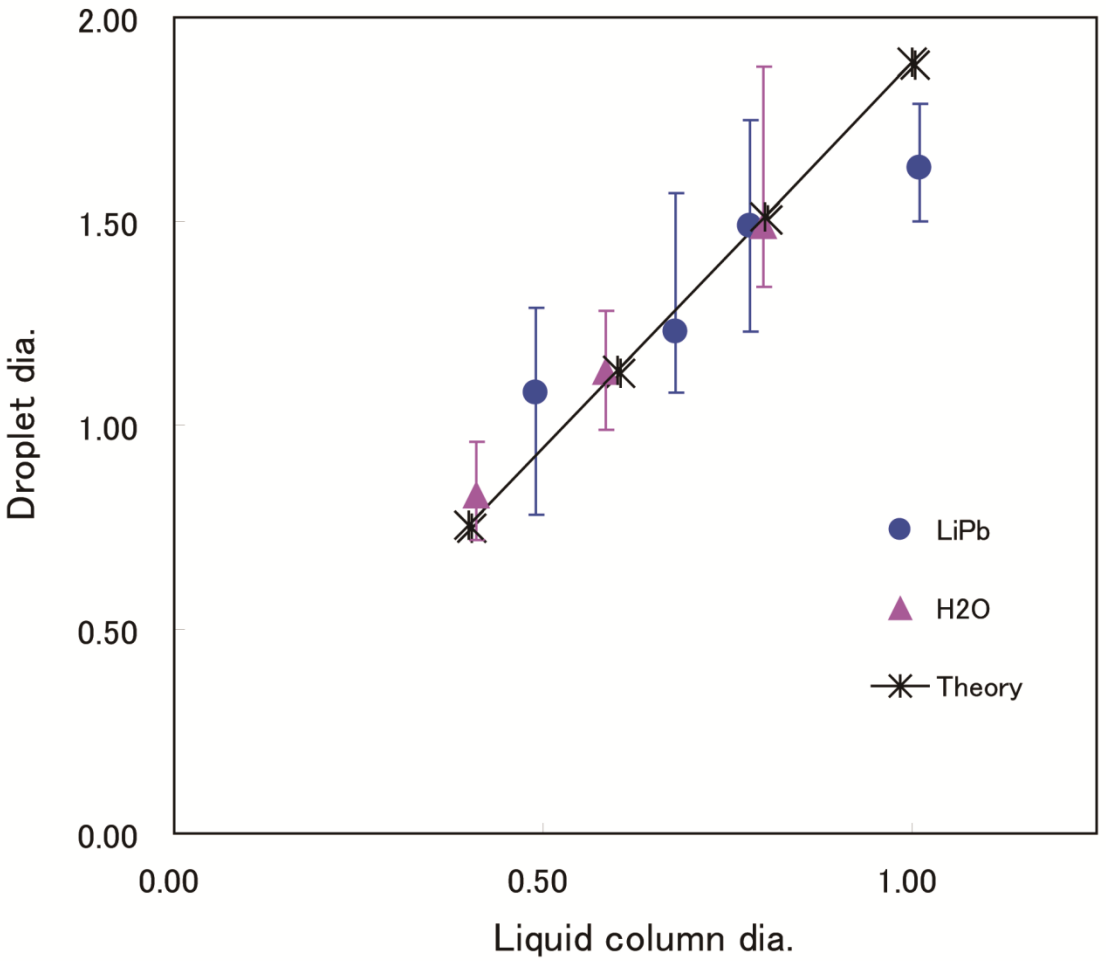


Fastest grow rate at ka=0.6970 overwhelm

$$d_{droplet} \simeq 1.89 D_0$$

Experimental Result

droplet dia. vs. nozzle



What is achieved in this study

Liquid metal Pb-17Li droplet

A: Theoretically deduced droplet size formula is

$$d_{droplet} \cong 1.89 D_0$$

B: Effective range is less than ϕ2.2mm

Both good accordance with the experimental results and well applicable for extraction system design engineering

SiC/SiC cooling panel

Blanket parameters	
Heat flux to the FW	0.2 MW/m^2
Neutron flux from the plasma	0.5 MW/m^2
Boundary temperature at the LiPb/SiC interface	1000 ^oC
He temperature at F82H channel	350 ^oC
He temperature at SiC channel	850 ^oC
Heat transfer coefficient of He coolant at F82H channel	10000 $W\ m^{-2}\ K^{-1}$
Heat transfer coefficient of He coolant at SiC channel	7000 $W\ m^{-2}\ K^{-1}$
Thermal conductivity of F82H	33.3 $W\ m^{-1}\ K^{-1}$
Thermal conductivity of SiC	20 $W\ m^{-1}\ K^{-1}$

SiC cooling panel

- Actively cooled SiC panel to control heat transfer
- isolate outer RAFM vessel structure
- obtain high temperature LiPb for heat

Fabrication R&D for SiC cooling panels

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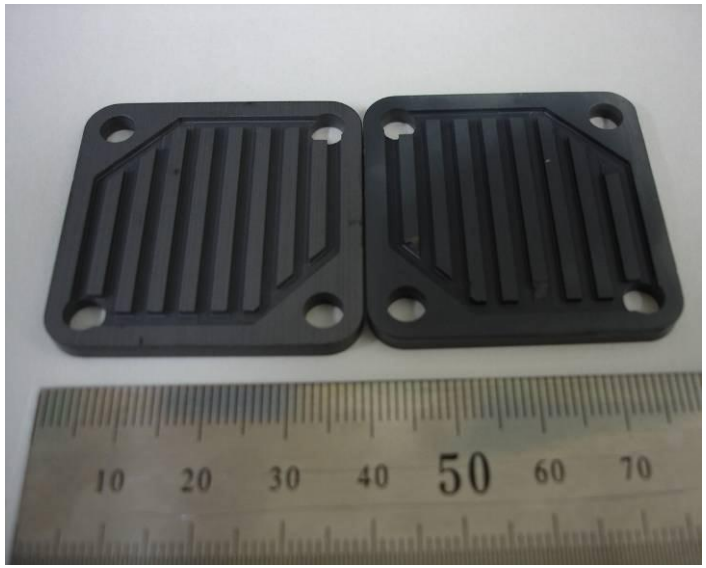

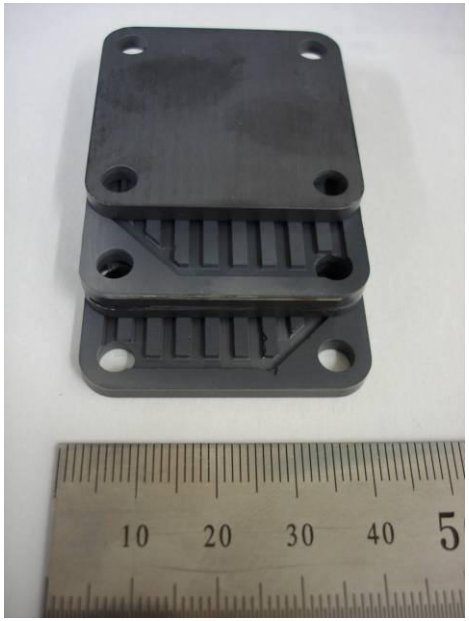

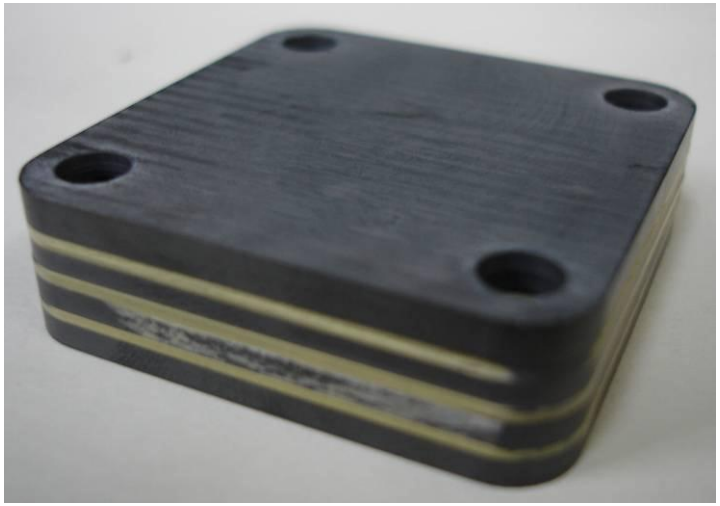

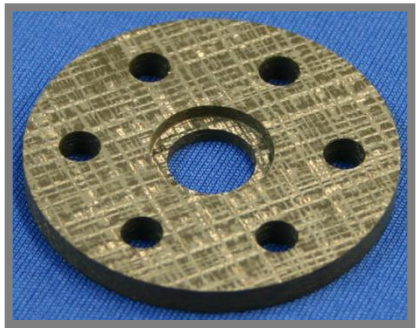

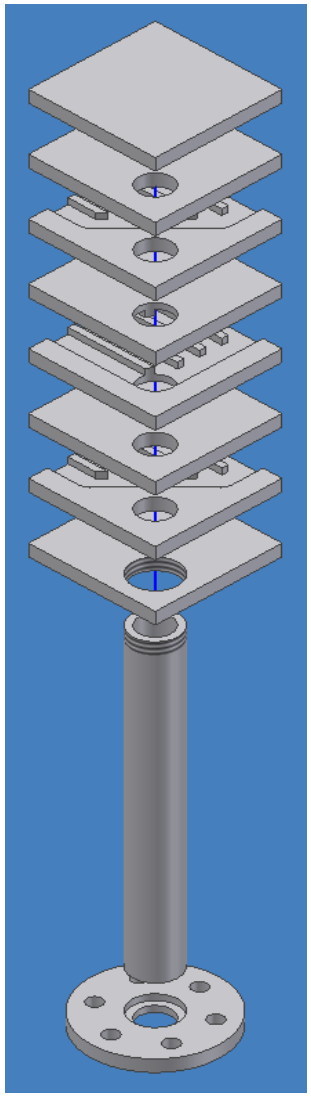

LiPb circulated >900°C

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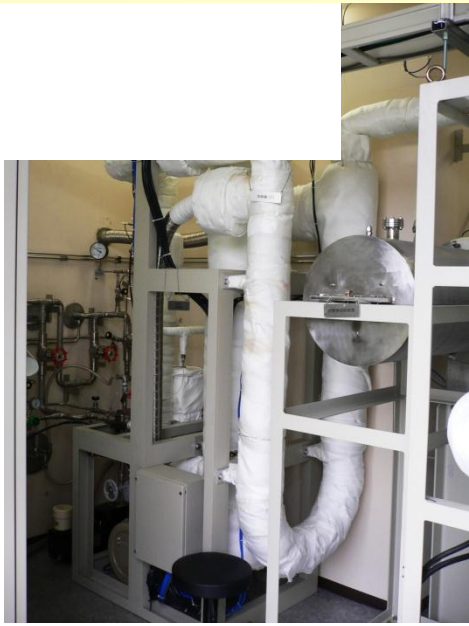
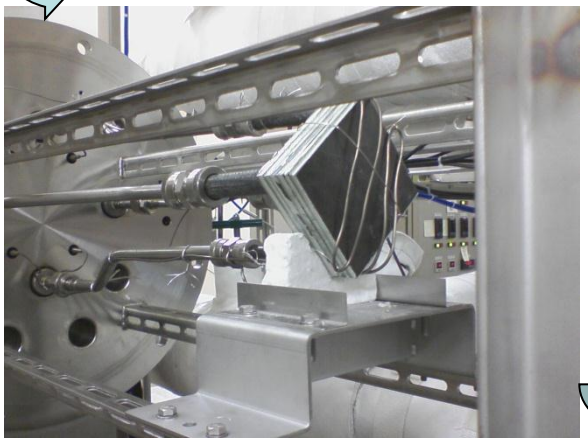
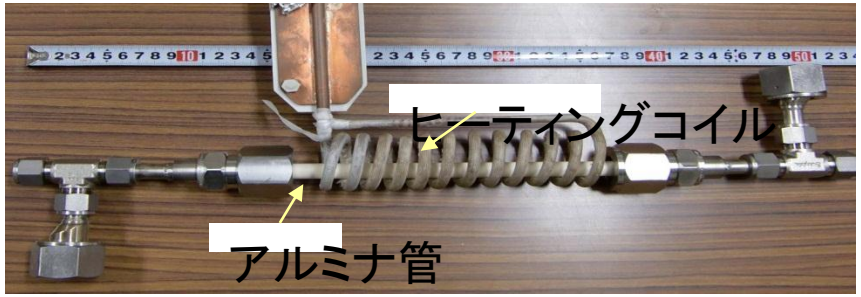
Loop operated >900 ° C
Only in the test vessel

SiC module







IHX heat transfer from LiPb to He

Installed in 900 ° C vessel

LiPb/He dual coolant loop

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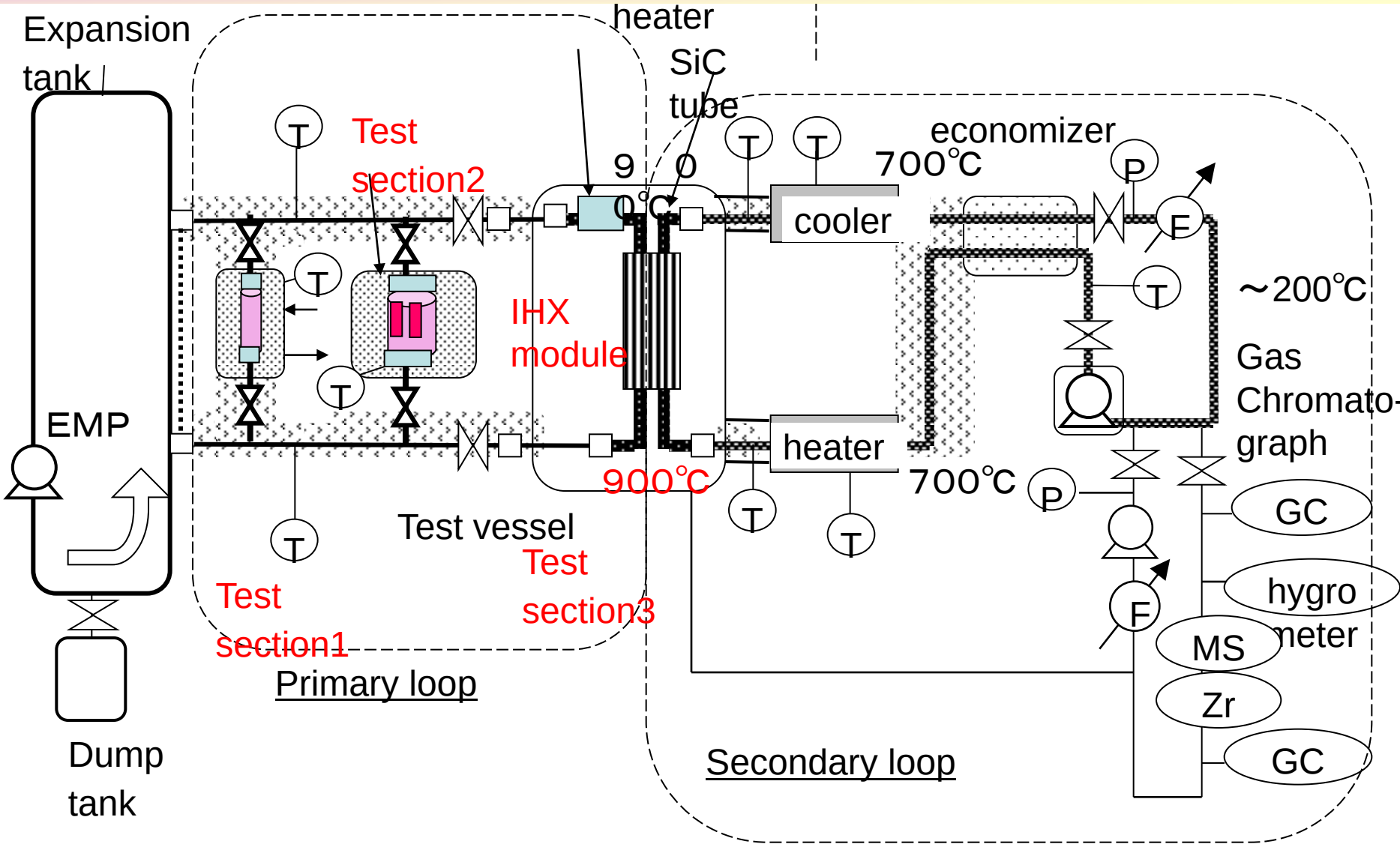
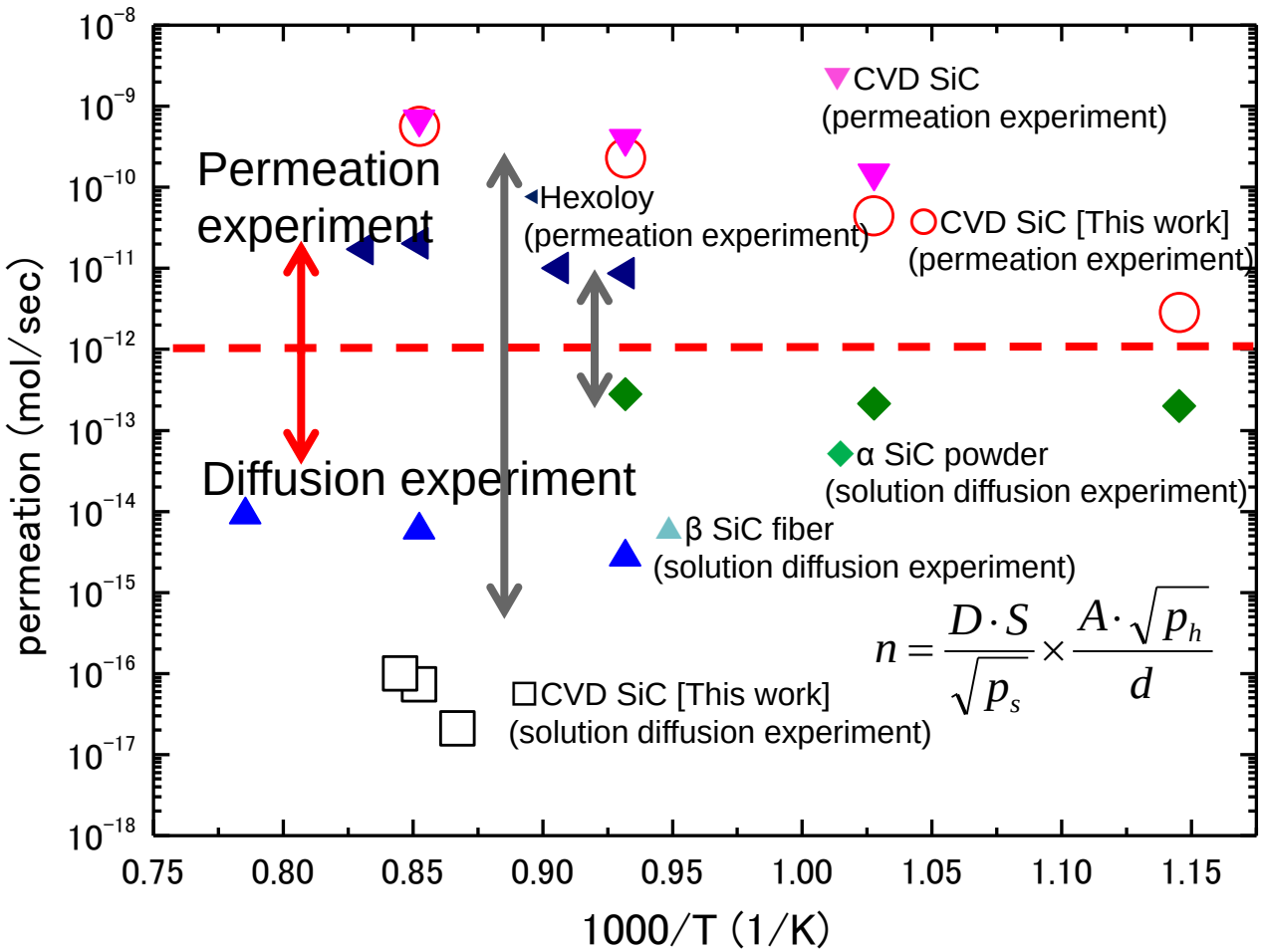
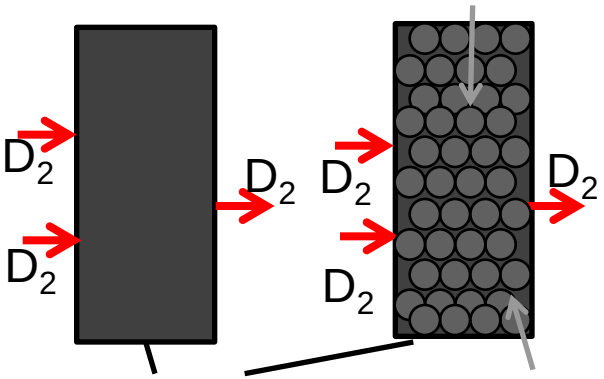


Hydrogen permeation through SiC



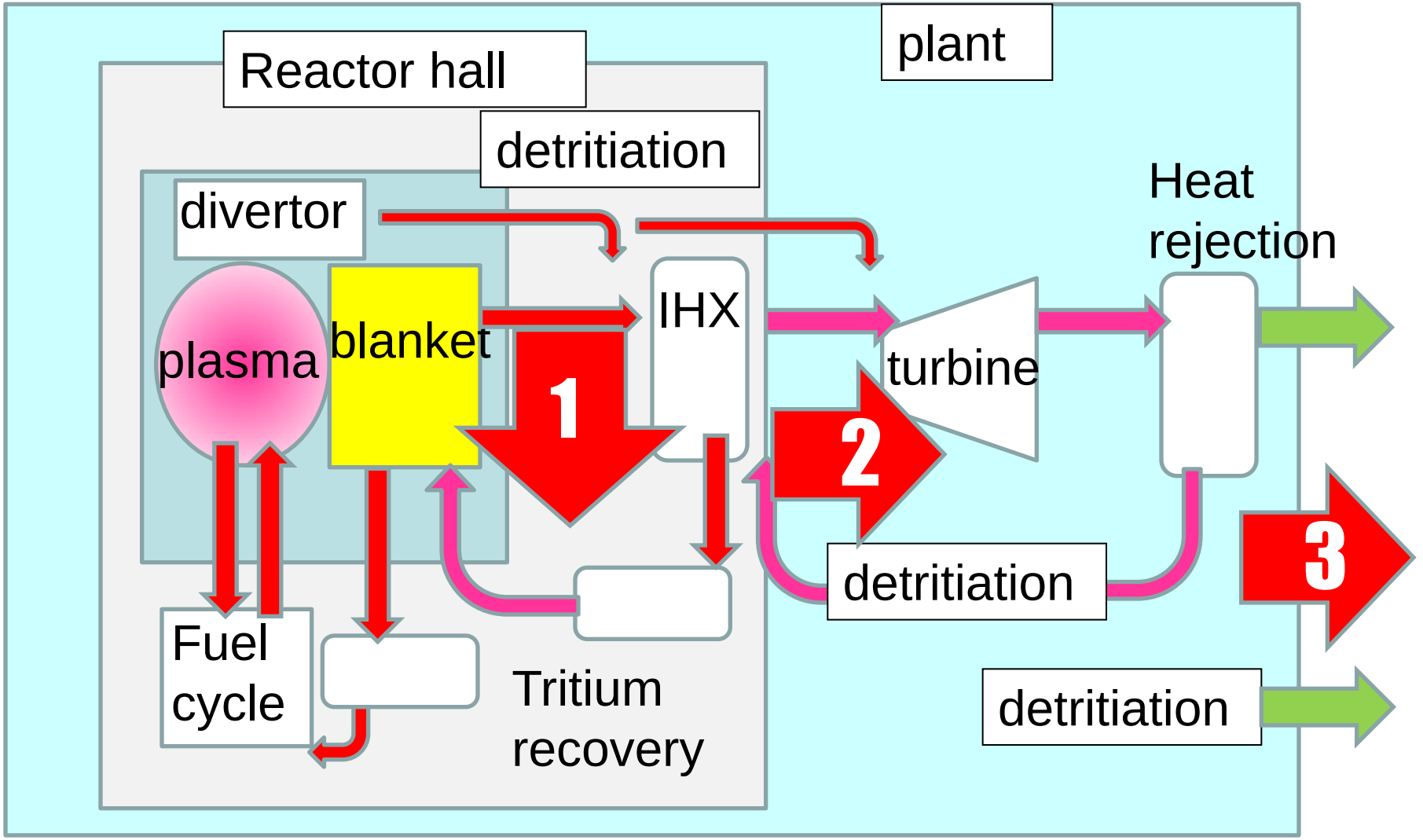


In Hexoloy(a), diffusion in bulk Is regarded as major path.

In CVD SiC, diffusion in grain boundary weems major path.

		Name	ITER	GNOME	Slim-CS	CREST	ARIES-RS	ARIES-AT	PPCS-A	PPCS-B	PPCS-C	PPCS-D
		Country		Japan	Japan	Japan	U.S.	U.S.	Euro	Euro	Euro	Euro
		Group		Kyoto	JAERI	CRIEPI	ARIES	ARIES				
		proposed year		2010	2007	2000	1998	2000	2005	2005	2005	2005
Major radius	Rp	m	6.2	5.2	5.5	5.4	5.52	5.2	9.55	8.6	7.5	6.1
Minor radius	a	m	2	1.7	2.1	1.6	1.38	1.3	3.2	2.9	2.5	2.0
Plasma current	Ip	MA	15	10.4	16	12	11.32	12.8	30.5	28	20.1	14.1
Toroidal field	Bt	T	5.3	4.4	6	5.6	7.98	5.86	7	6.9	6	5.6
Maximum field	Bmax	T		11	16	12.5	16	11.1	13.1	13.2	13.6	13.4
Safety factor	q_ψ			3.6	5.3	4.3						
Average temperature	<Te>	keV	8.9	13	17	15.4		18	22	20	16	12
Average density	$<n_e>$	10^{20} m^{-3}		0.61	1.1	2.1		2.15	1.1	1.2	1.2	1.4
Improvement factor	HHy2			1.4	1.3			1.37	1.2	1.2	1.3	1.2
Imporvement factor	H89P				2.59	3.2		2.65				
Normalized beta	βN			3.1	4.3	5.5	4.8	5.4	3.5	3.4	4	4.5
Bootstrap current fraction	fBS	%		45	66	83	88		45	43	63	76
Normalized density	f_{GW}			0.54	0.97	1.3		0.915	1.2	1.2	1.5	1.5
Fusion power	Pfus	MW	500 (700)	324	2877	2970	2170	1755	5000	3600	3410	2530
Conversion efficiency	η			2		0.41	0.38	0.59	0.31	0.37	0.43	0.60
Current drive power	P_{CD}		73 (100)	60.7	83	97	81	34.6	246	270	112	71
Neutron wall load	Pn		0.57 (0.8)	0.48	3.1	4.5	4	3.3	2.2	2	2.2	2.4
Energy multiplication	*Q*		10	5.3	35				20	13.5	30	35
Structure material							V & steel	ferrite	ferrite	ferrite	ferrite	SiCf/SiC
Support material								SiCf/SiC			SiCf/SiC	
breeder material					solid	Li2ZrO3	Lq. Li	LiPb	LiPb	Li ortho-silicate w/ Be	LiPb	LiPb
Coolant				LiPb	water	water	Lithium	LiPb	water (15 Mpa)	He (8 Mpa)	LiPb	LiPb
Coolant temp.		°C		> 900			610	1100	300	300-500		700-1100

DEMO power/tritium system



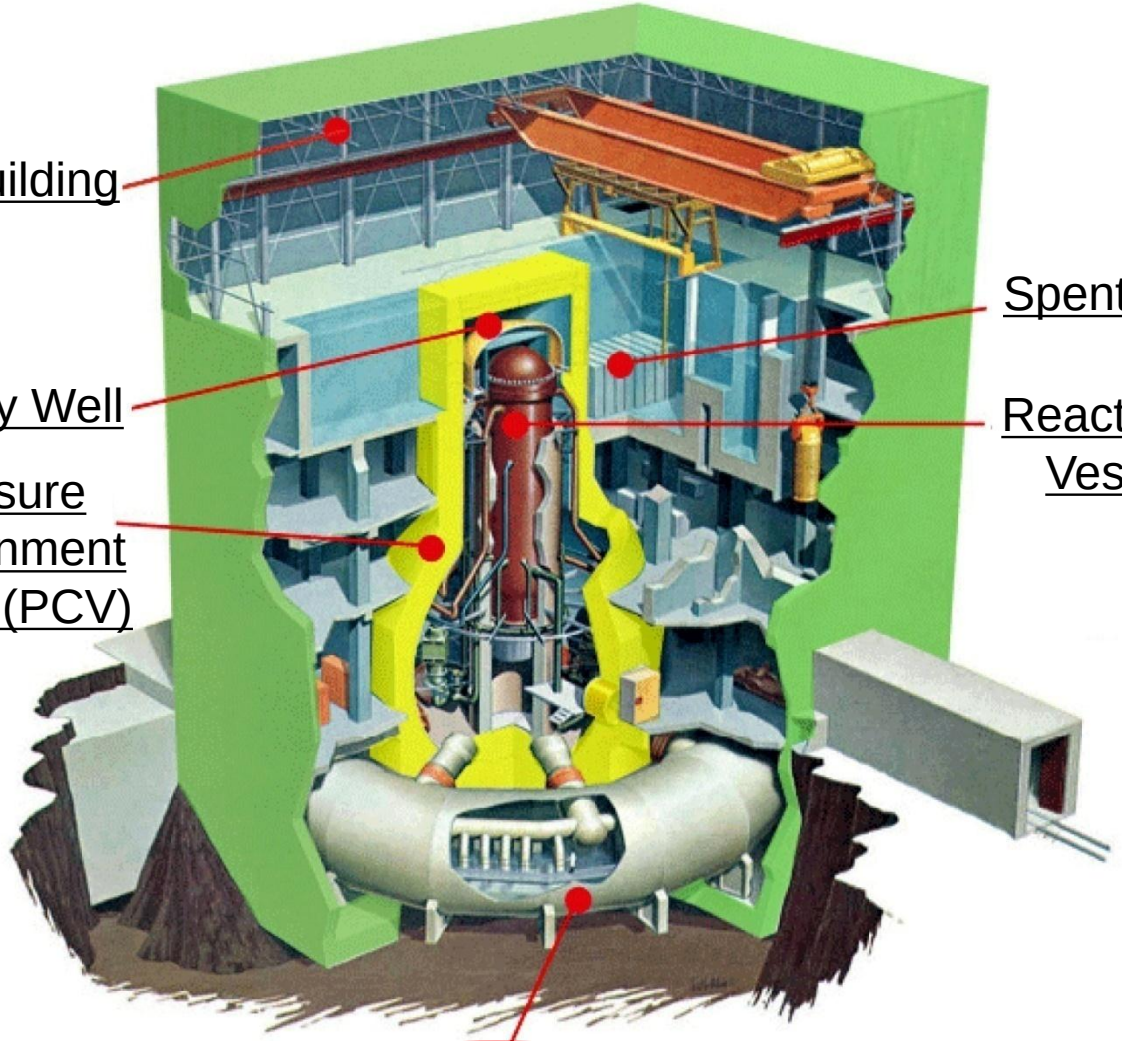
Tritium in power system is the major issue from TBM to DEMO.

Blanket and tritium flow

breeder	coolant	Tritium recovery	IHX	Genera-tion	Detri-tiation
solid	Water / He	Isotopic /chemical	Steam generator	Rankine	Isotope WDS
Solid	gas	chemical	Steam generator	Rankine	Isotope WDS
Liquid metal	metal	physical	Steam generator	Rankine	Isotope WDS
Liquid metal	gas	chemical	g-g IHX	Brayton	
	metal	physical		hybrid	

Primary coolant issue : accidental release

In the case of BWR..



Source: http://nei.cachefly.net/static/images/BWR_illastration.jpg

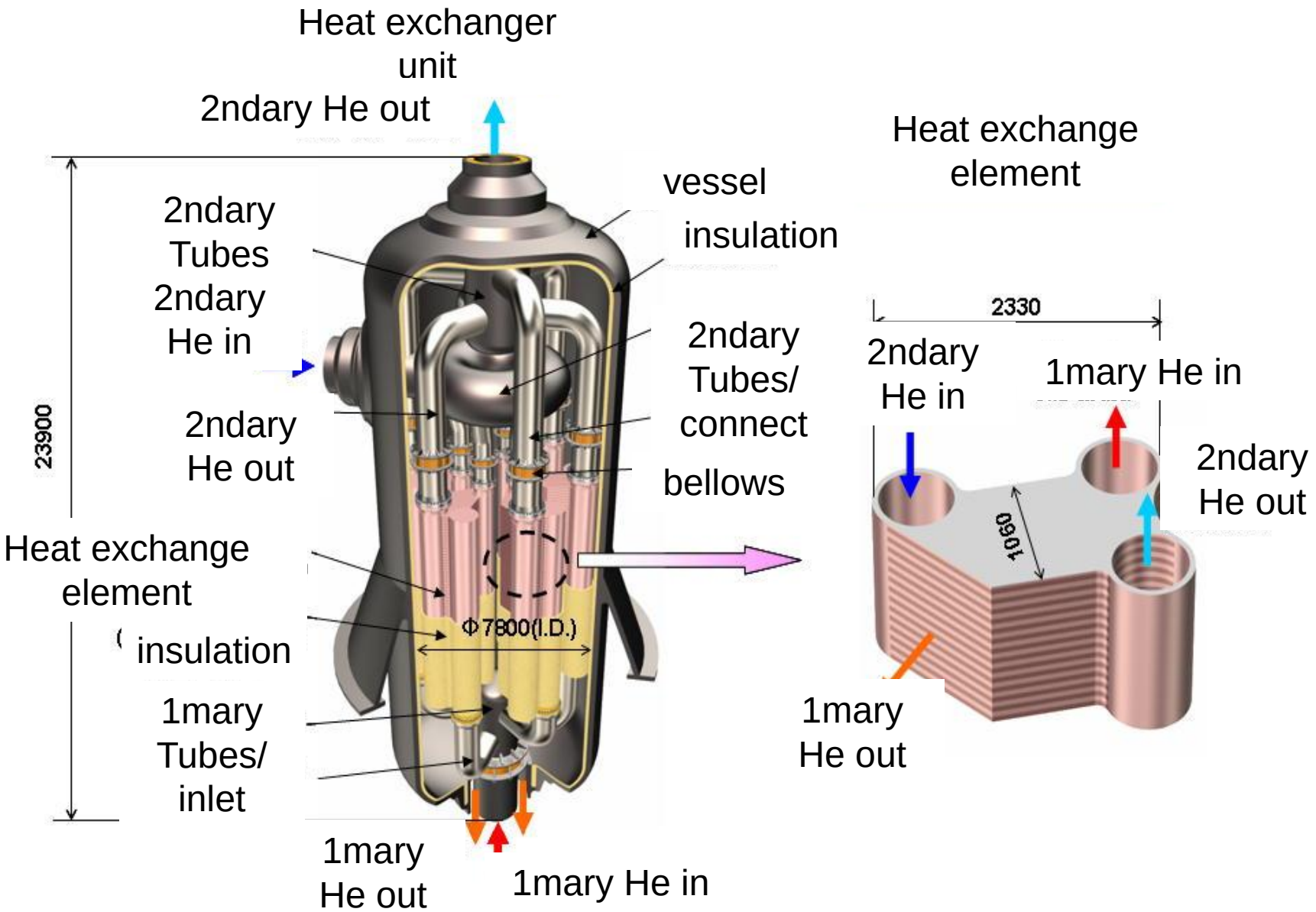
Source: The 2011 Pacific Coast of Tohoku Pacific Earthquake and the Seismic Damage of the NPPs, p9, Report to IAEA from NISA and JENES, 4th April, 2011

Blanket and tritium flow

breeder	coolant	Tritium recovery	IHX	Genera-tion	Detri-tiation
solid	Water / He	Isotopic /chemical	Steam generator	Rankine	Isotopic WDS
Solid	gas	chemical	Steam generator	Rankine	Isotopic WDS
Liquid metal	metal	physical	Steam generator	Rankine	Isotopic WDS
Liquid metal	gas	chemical	g-g IHX	Brayton	
	metal	physical	Metal-gas IHX	hybrid	

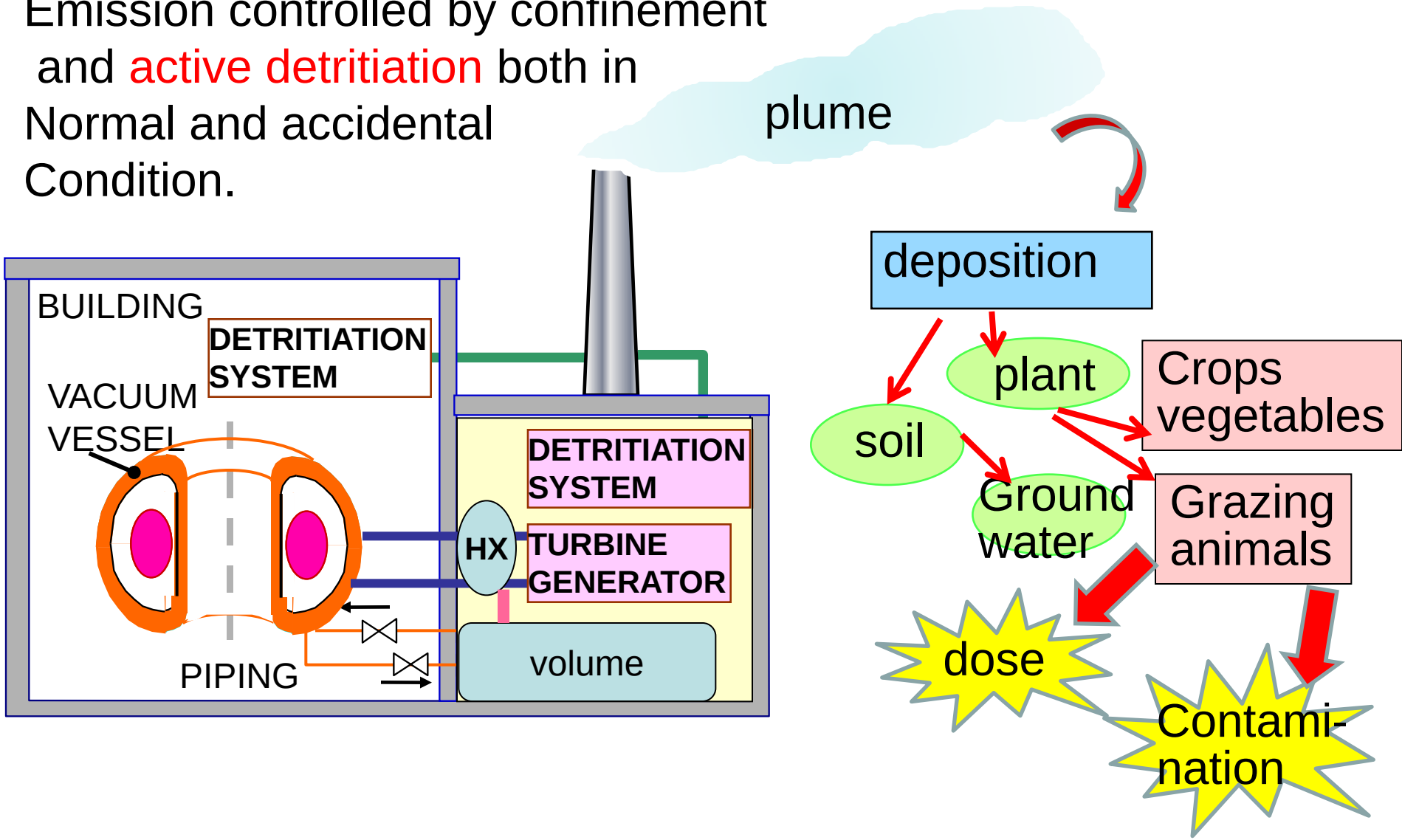
Secondary coolant issue : permeation in normal operation

SiC-He heat Exchanger



Tritium confinement

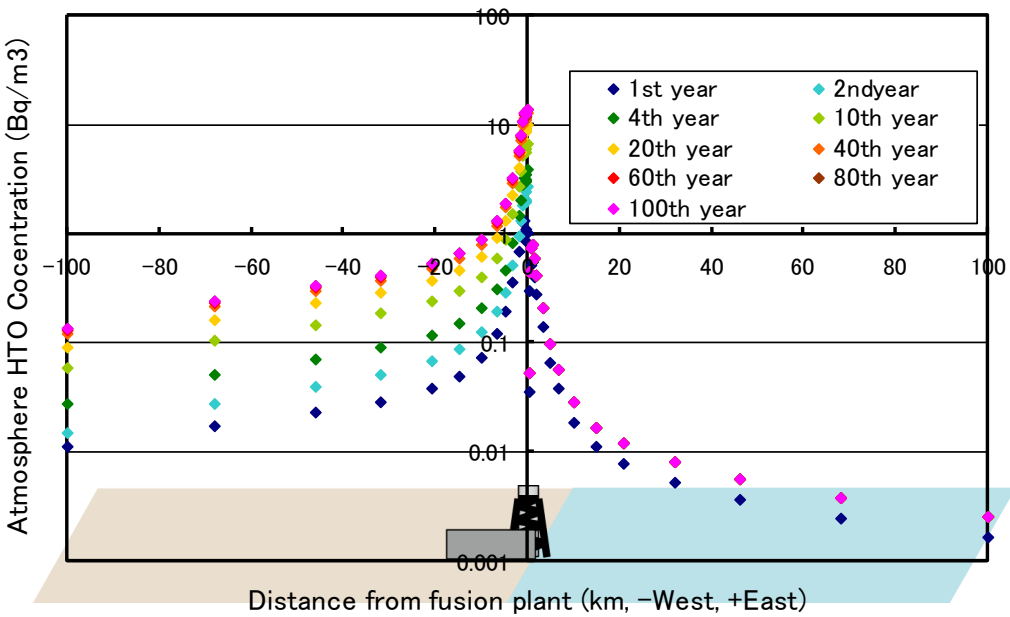
Emission controlled by confinement and active detritiation both in Normal and accidental Condition.



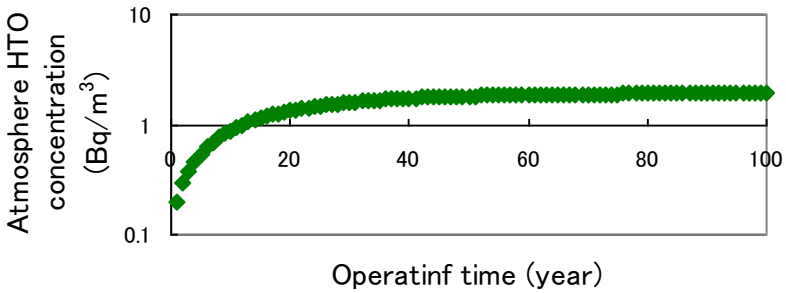
Yearly change of tritium concentration

Change on the tritium concentration in the atmosphere during prolonged operation is analyzed.

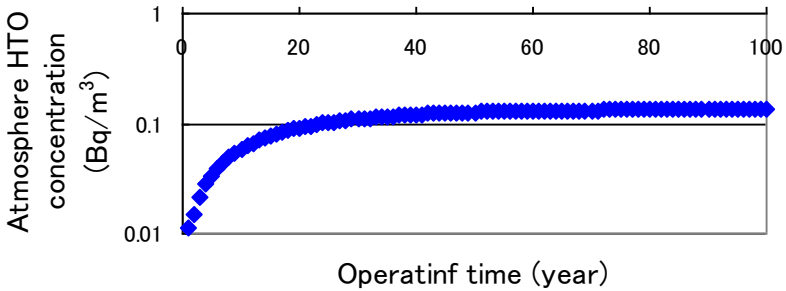
Emission rate: 1.35×10^{14} Bq/year



Atmosphere HTO concentration after 100 years operation.



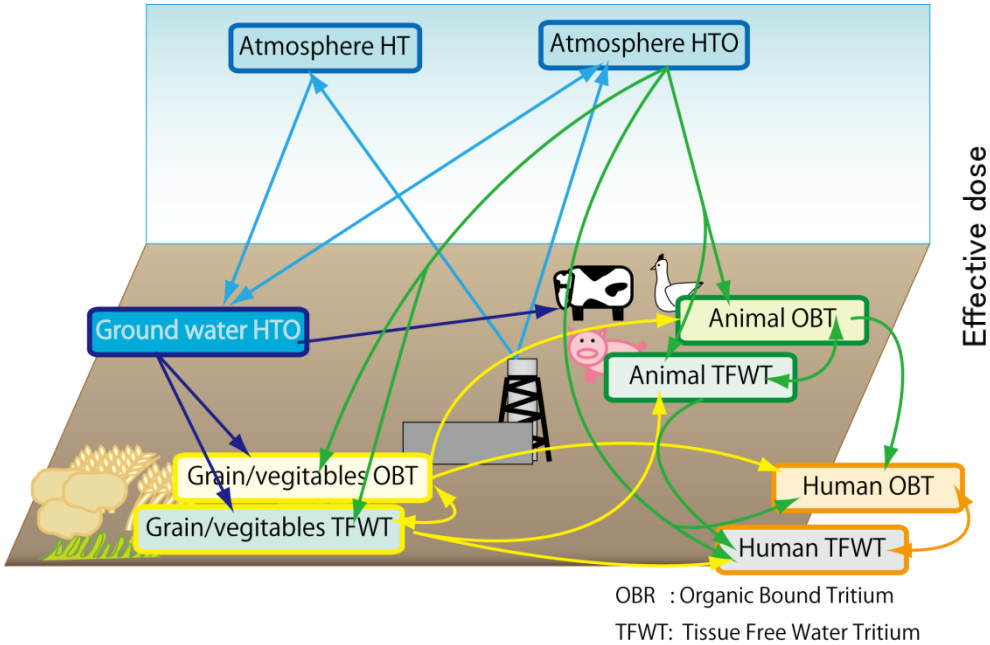
5.7 km west



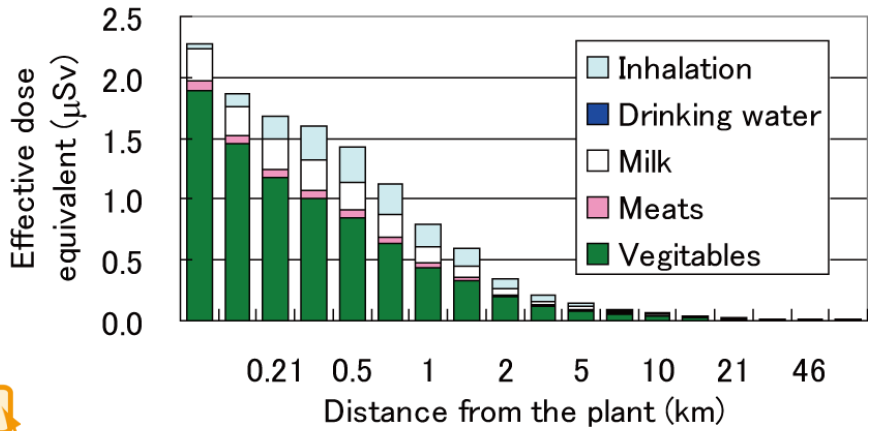
100 km west

- Tritium concentration increase for about 60 years on land.
- Tritium concentration on the sea surface is low and dose not show accumulation

Accumulation in the environment



Structure of NORMTRI model



Total tritium dose during 1 year operation calculated by NORMTRI.

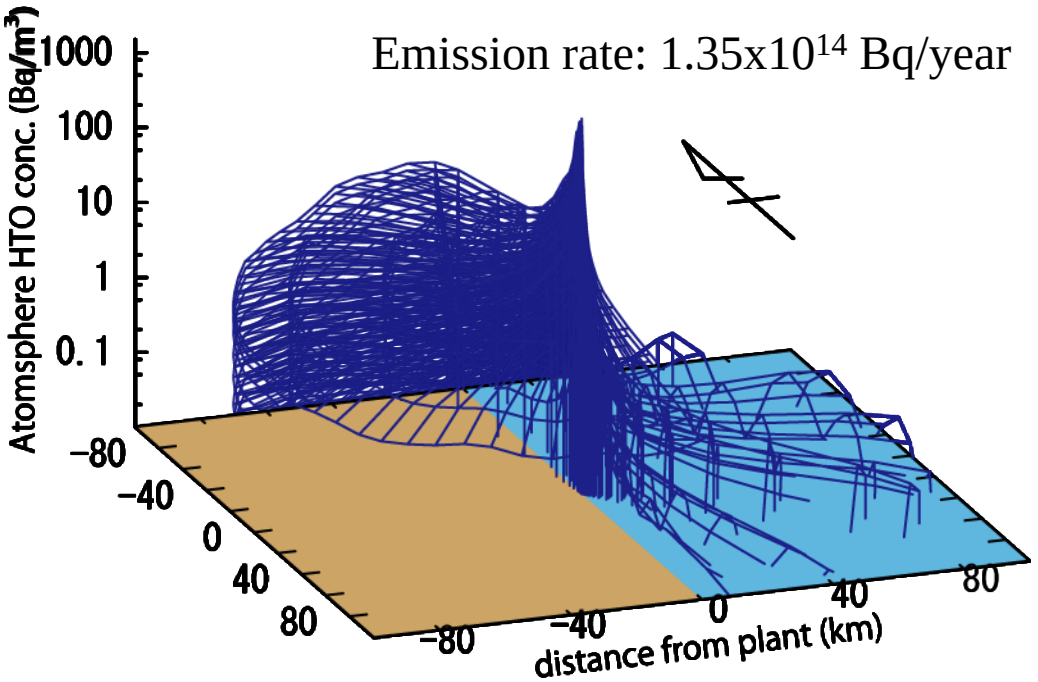
Acknowledge W. Raskov and D. Gale

- Environmental models converts emission to dose.
- Major dose from normal operation comes from ingestion
- μSv per person, per year per 1 gram emission.

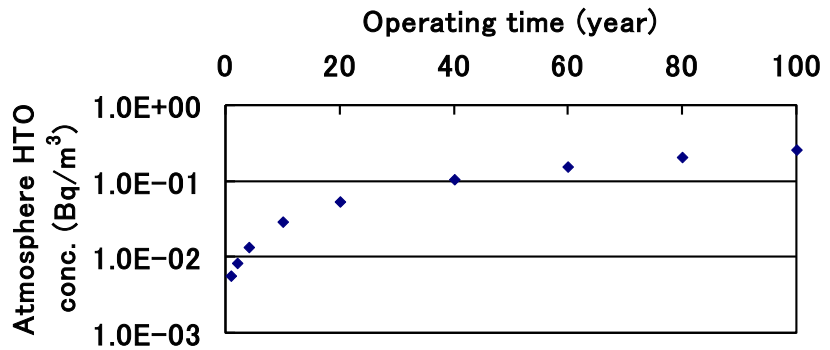
particular concern is a damage for sales of food products.

Accumulation in the environment

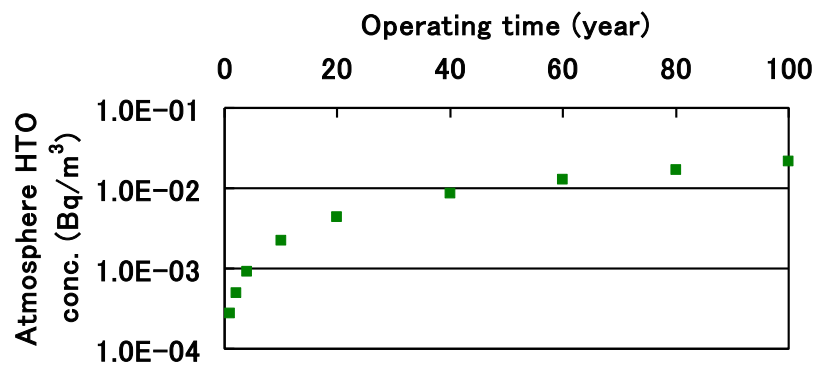
Annual emission accumulates in the environment



Operating time: 80 years



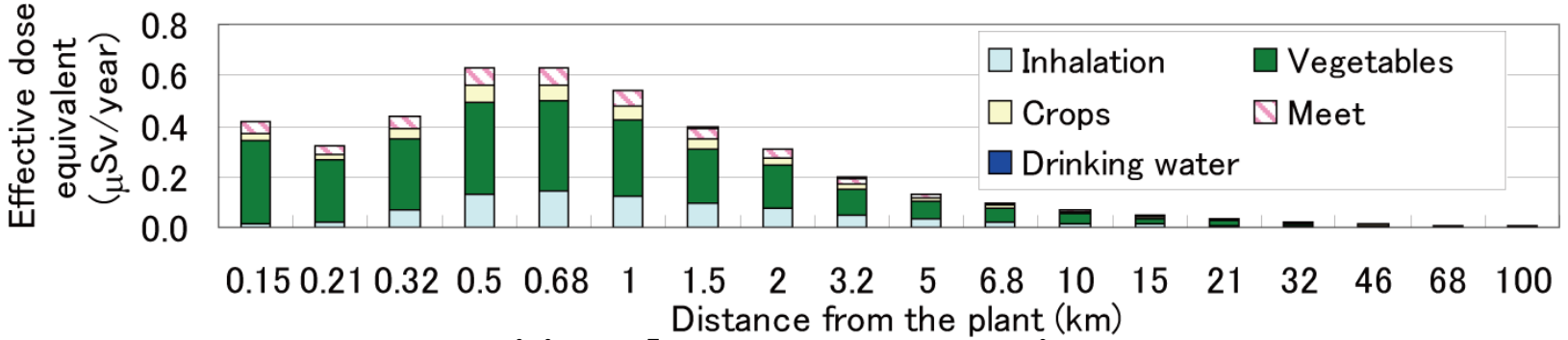
5.7 km west



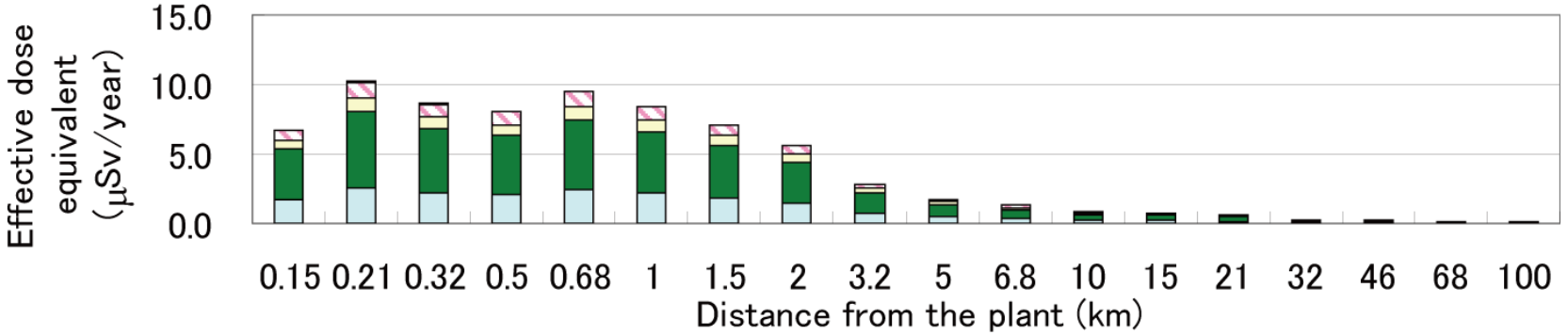
100 km west

- Considerably increases for 20 years
- Still negligible from dose, but easy to detect.
  - If 100 plants operated 100 years?

Effects on dose



Tritium dose: 1 year operation



Tritium dose: 100 years operation

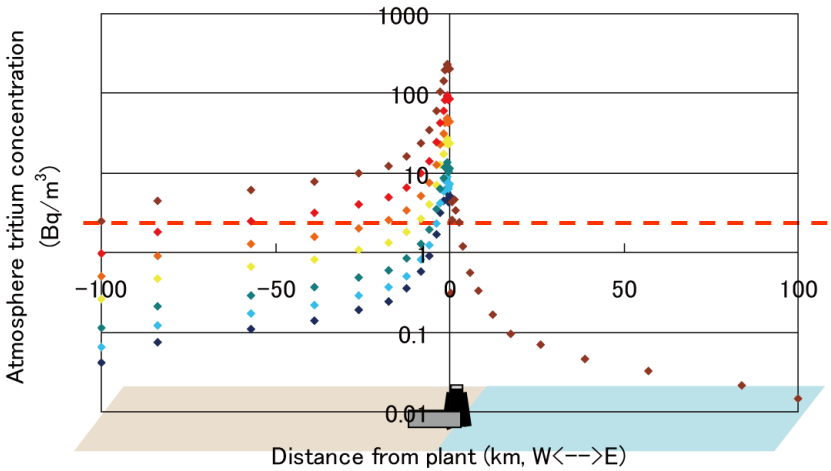
With accumulation, dose is still below 10 mSv/year

•However, 15 times larger than the first year.

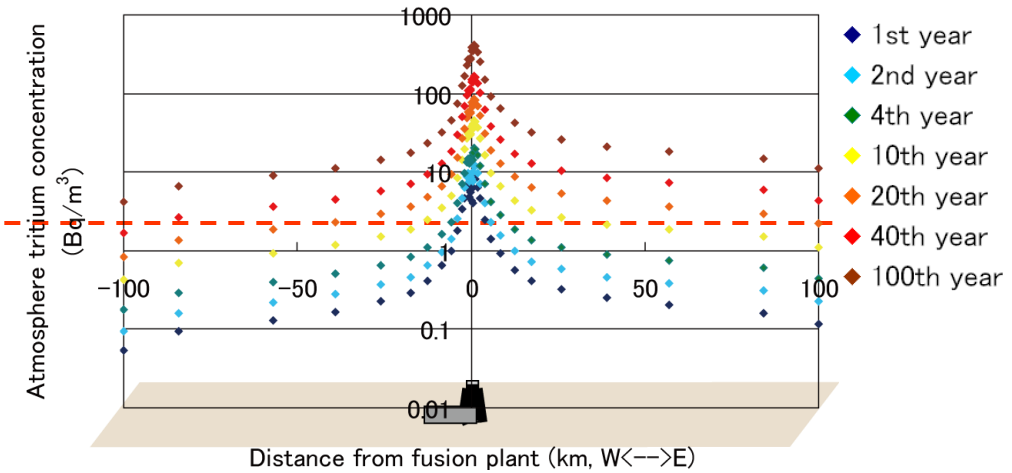
Effect of open water surface

Coastal siting absorbs tritium by isotopic dilution

Coastal model



Inland model

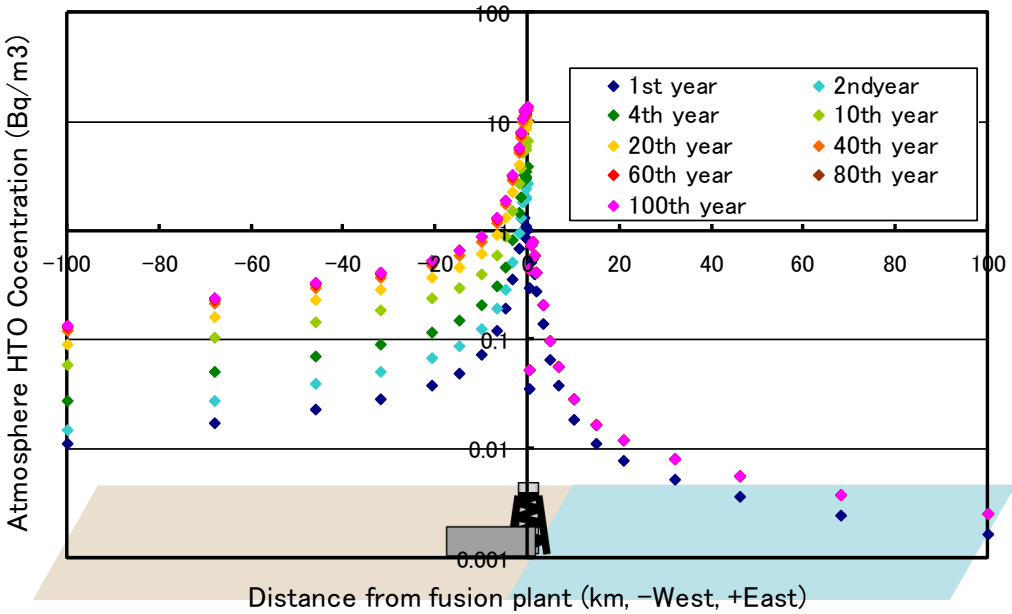


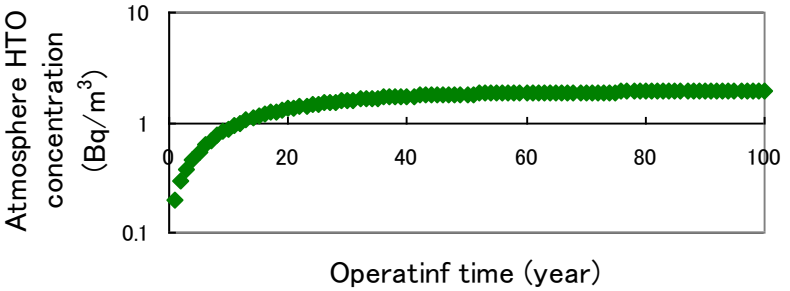
Tritium concentration distribution

- Inland tritium also decreases by the tritium migration
- Existence of sink prevents environmental accumulation.

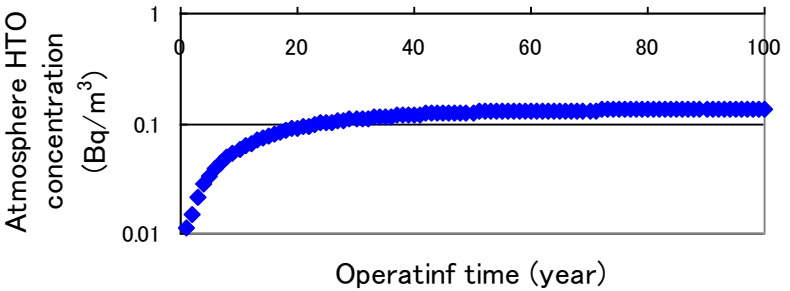
Stopped accumulation

Emission rate: 1.35×10^{14} Bq/year





5.7 km west



Atmosphere HTO concentration after 100 years operation.

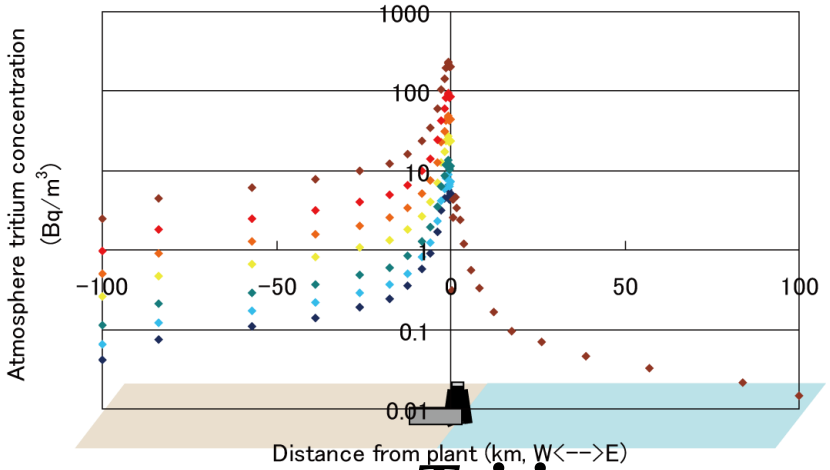
100 km west

- Inland tritium continue to accumulate until balance with decay.
- Little accumulation observed on the coast.

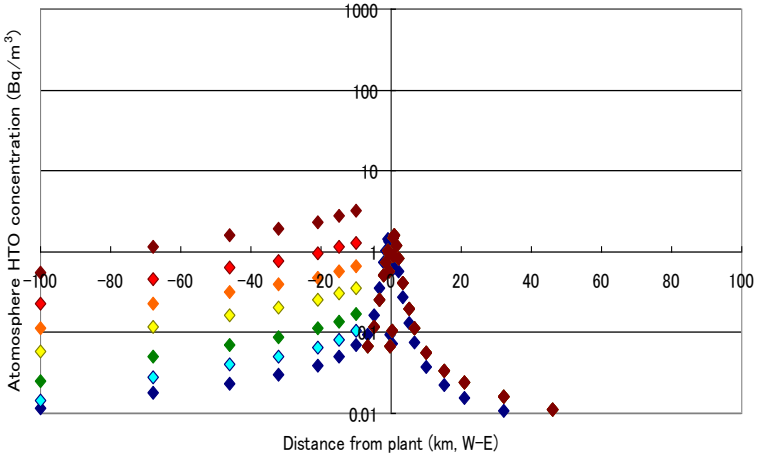
Off-shore location

Off shore siting is even more effective.

Coastal model



Off shore model



Tritium concentration distribution

Emission at 5 km from the coast decreases Atmospheric tritium to 1/10.

Tritium in the Environment

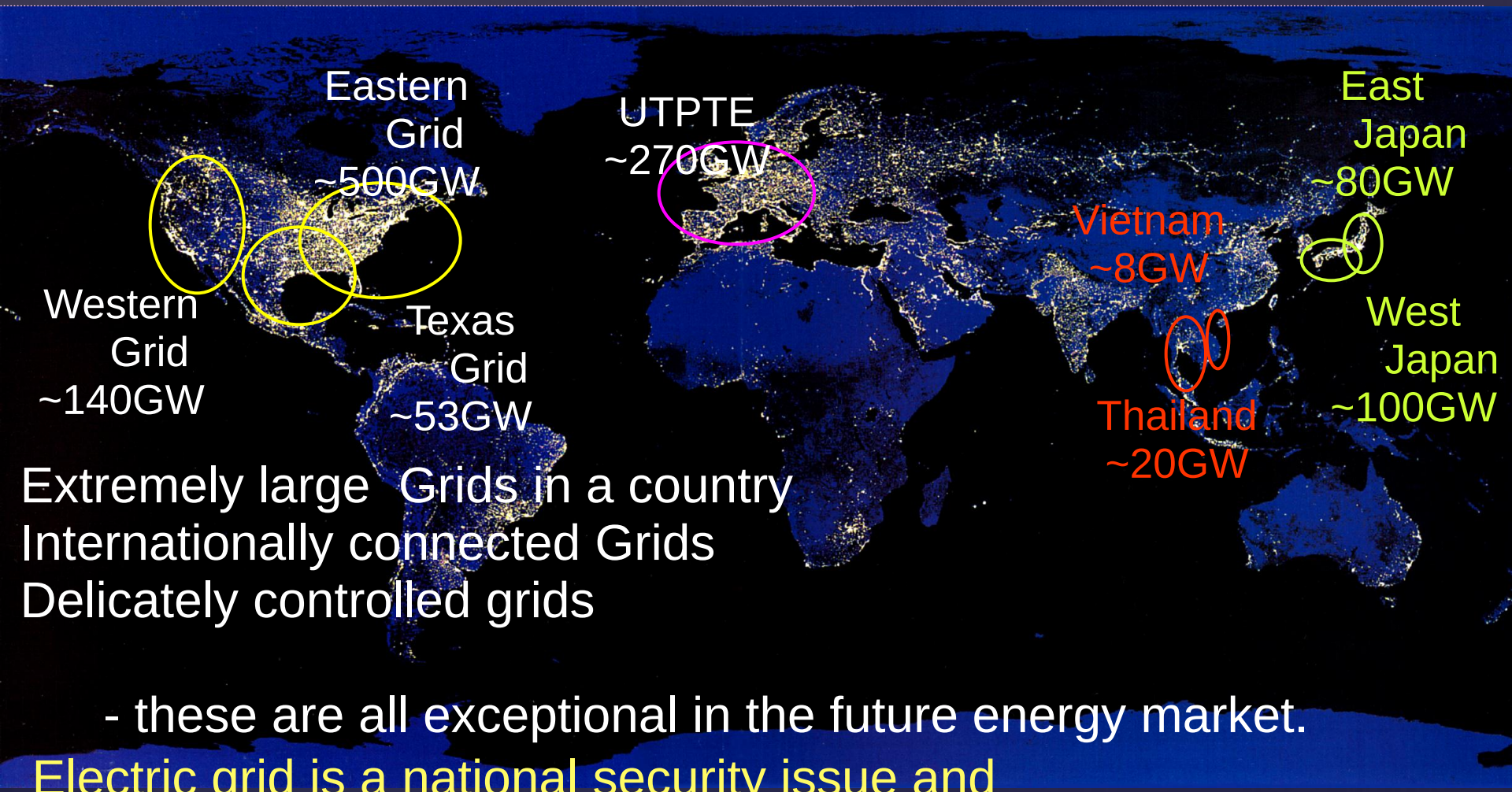
- Tritium can be well controlled but normally discharged at below legal limits.(annual, single plant.)
- Water detritiation requires further development and significant cost is anticipated.

- Tritium in the environment and foods can easily be detected.
- Annually controlled emission can be accumulated and spreads.
- Releases from multiple sources can be summed.

- Canadians report tritium control experience in normal operation of Heavy Water Reactors (expensive coolant with minimal loss with reasonable efforts) to be 1000Ci/y order /unit.

→Fusion should be as clean as fission with minimal cost.

Electric grid capacities



Extremely large Grids in a country
Internationally connected Grids
Delicately controlled grids

- these are all exceptional in the future energy market.

Electric grid is a national security issue and cannot be easily integrated.

Physics Today, vol.55, No.4 (2002)

Stability of the grid is region specific.

Fusion startup could be a problem

Zero-carbon energy Kyoto

All the generators on the grids are synchronized

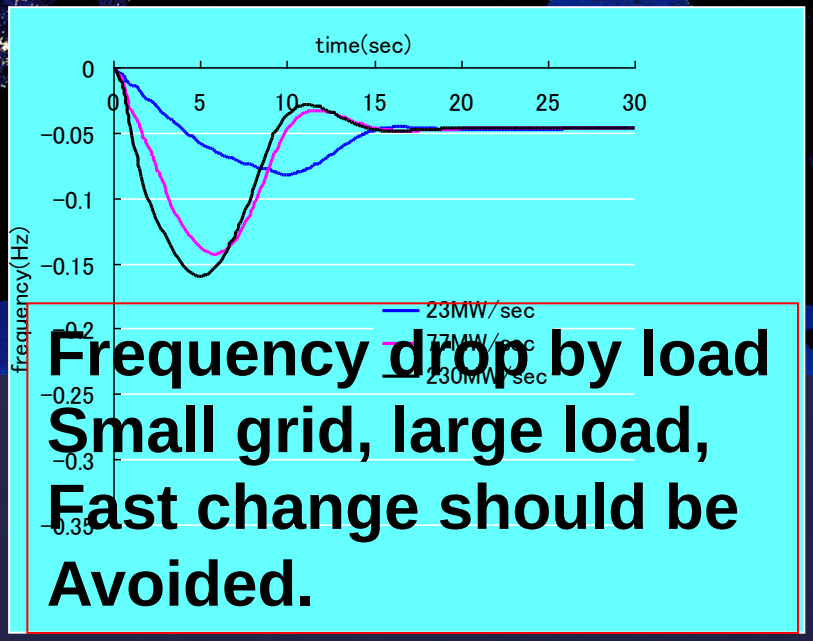
→ Exactly same amount generated as demanded.

Sudden increase of demand or unstable generator

- Demands exceed generation capacity
- Frequency drops (~0.1%)
- Load to the generators
- Generator disconnected

Chain reaction kills the grid.

→unstable renewables can initiate the blackout.

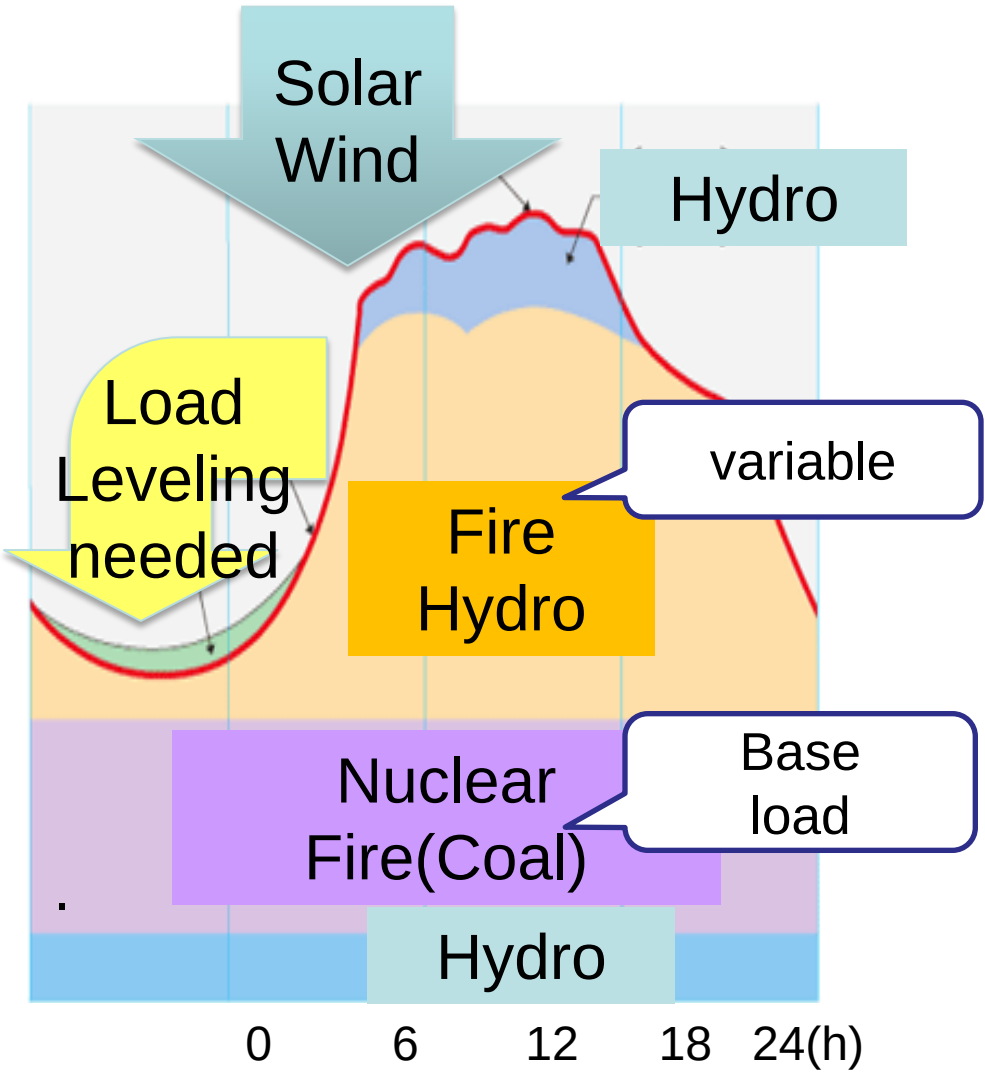


Frequency drop by load
Small grid, large load,
Fast change should be
Avoided.

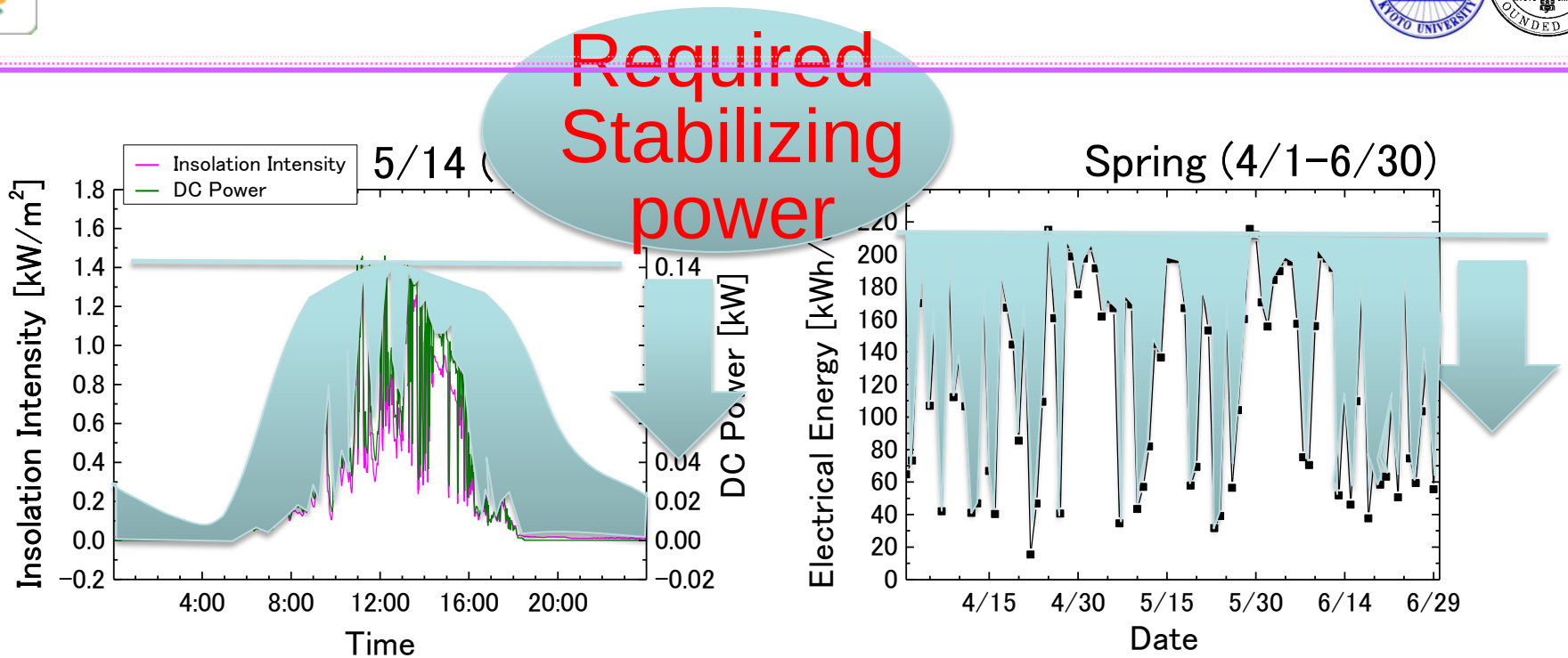
Daily Peaks

- For near term, leveling of the load is important.
- Local generators, co-generation and batteries preferred.
- Increased renewable jeopardizes grid
- For future, substitute of fire power needed.

→load leveling power is preferred. Can fusion be a base load?



Fluctuation of renewable

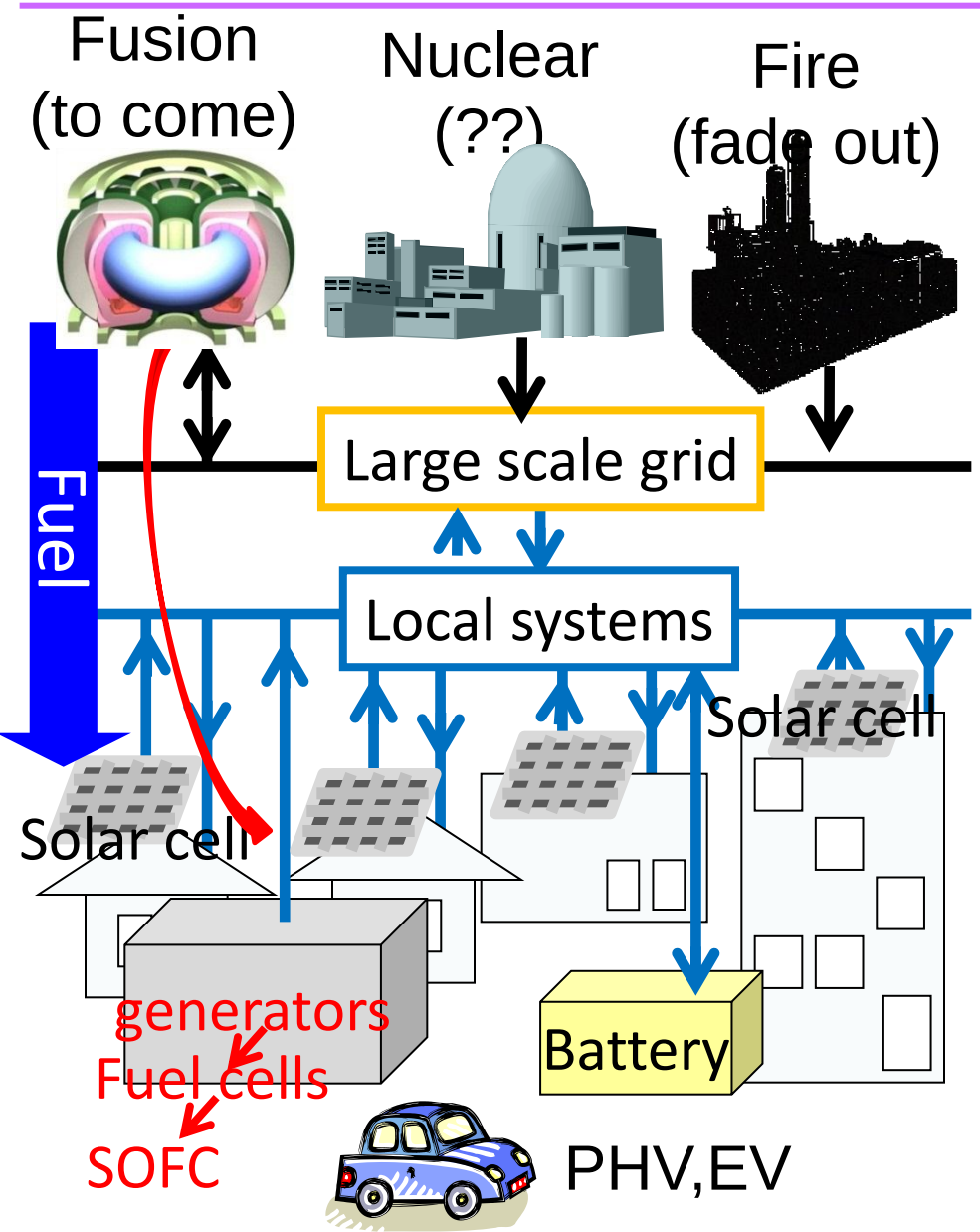


Change of solar in a day

Daily change of solar

- unpredictable change of generating power of renewable is large
- time constant of seconds
- controlled power to compensate this change needed
- connecting to grid decreases amplitude but not time constant
- fire power can provide only slow change (~5%/min)

Future low carbon Systems



Electricity must be powered by Carbon-free sources

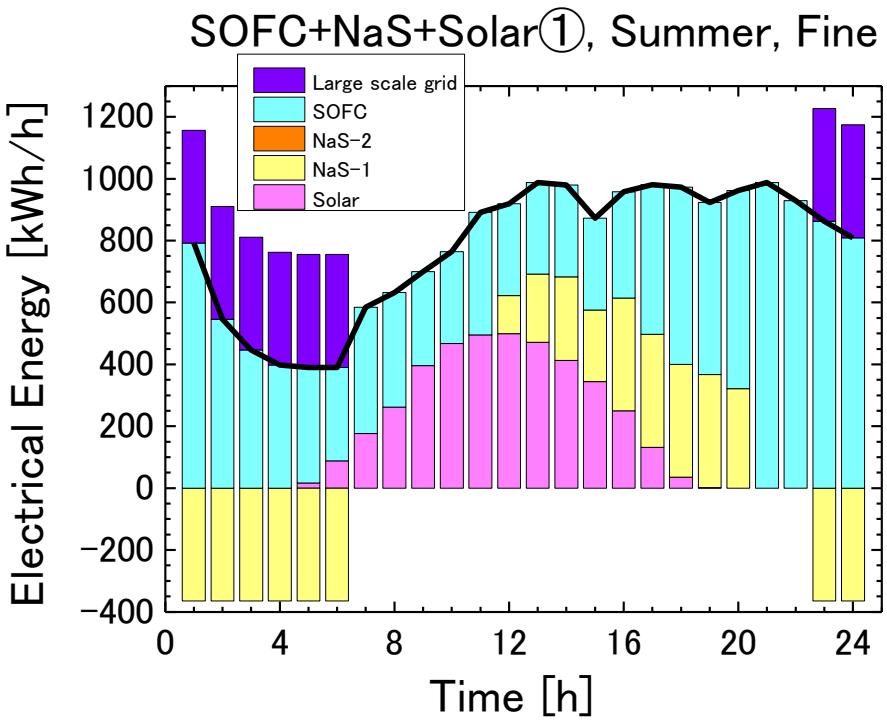
Both large grid and local systems are needed.

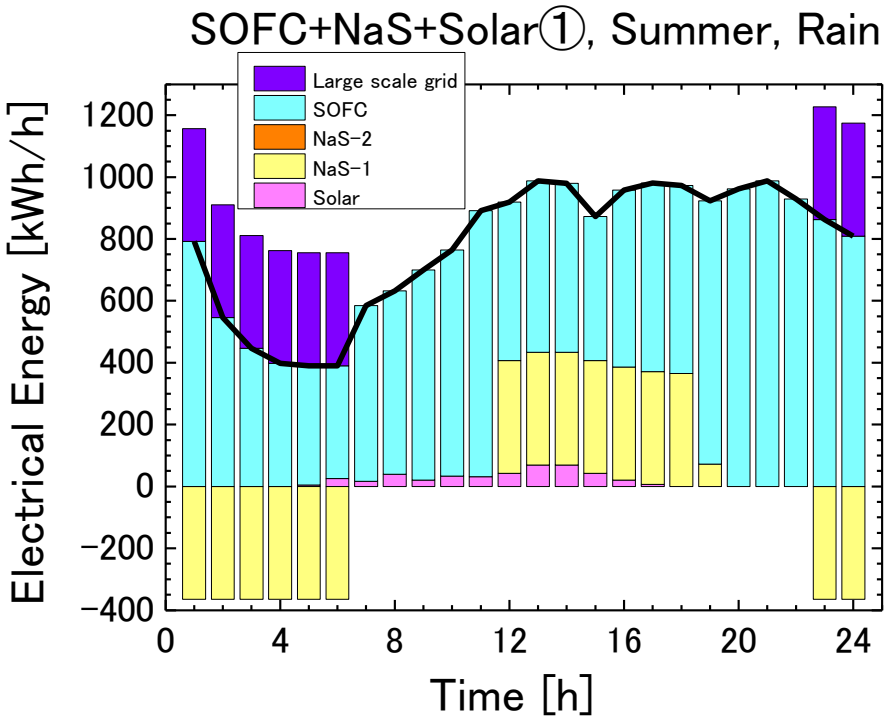
Battery, generators and fuel cells Stabilizes fluctuation by renewables.

Large scale supply of fuels for Fuel cells needed

Carbon-free elcecticty systems

	Power [kW]	Max.power[kW]	capacity[kWh]	units	area[m2]	Vol.[m3]
Solar	633	566.2	–	–	4740	–
battery	364.7	420	2625	7	–	16.7
Fuel cell	–	988	–	–	–	5.6
計	998	1974	2625	7	4740	22.2

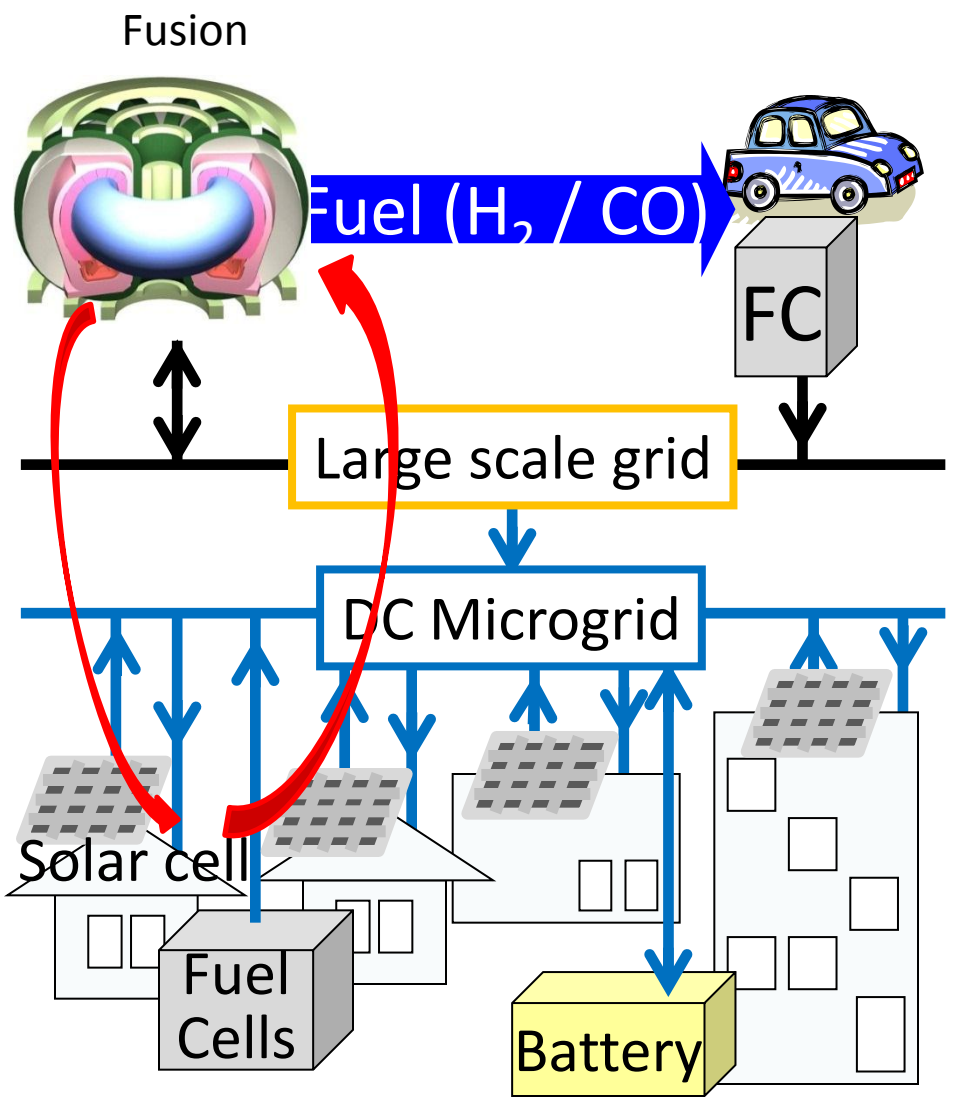


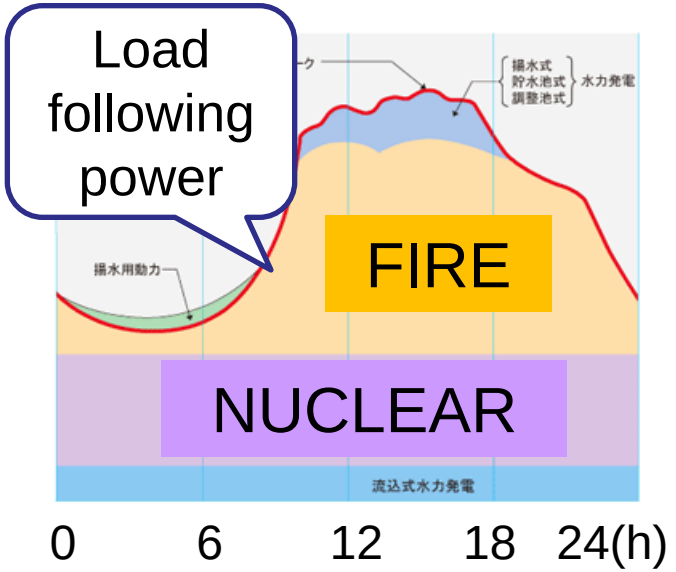


Future Energy Systems

Institute of Sustainable Science

Institute of Advanced Energy, Kyoto University



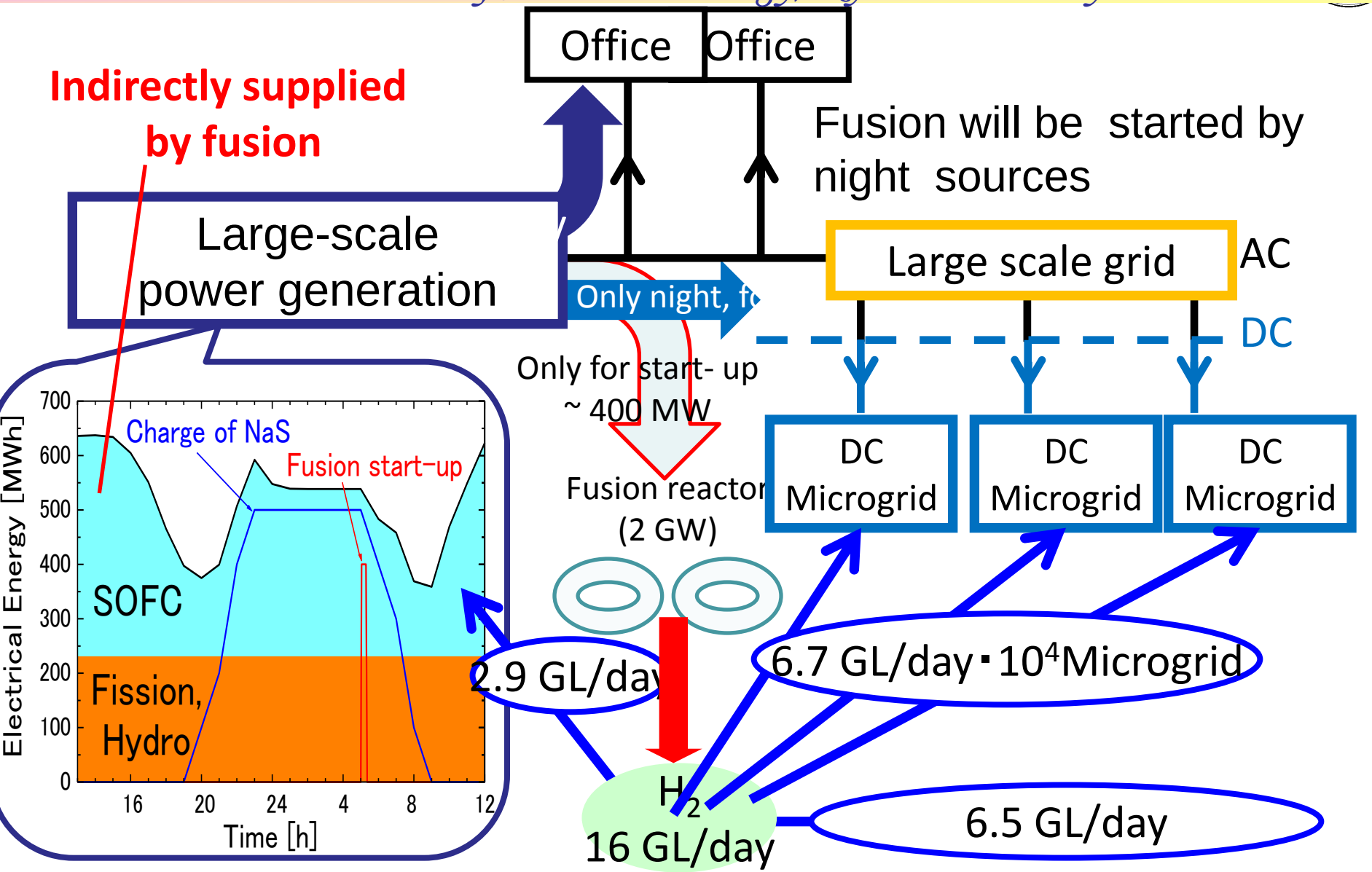


Electricity will be powered by Carbon-free sources

Day peak will be supplied by Battery and fuel cells.

Fusion and grid

Institute of Advanced Energy, Kyoto University

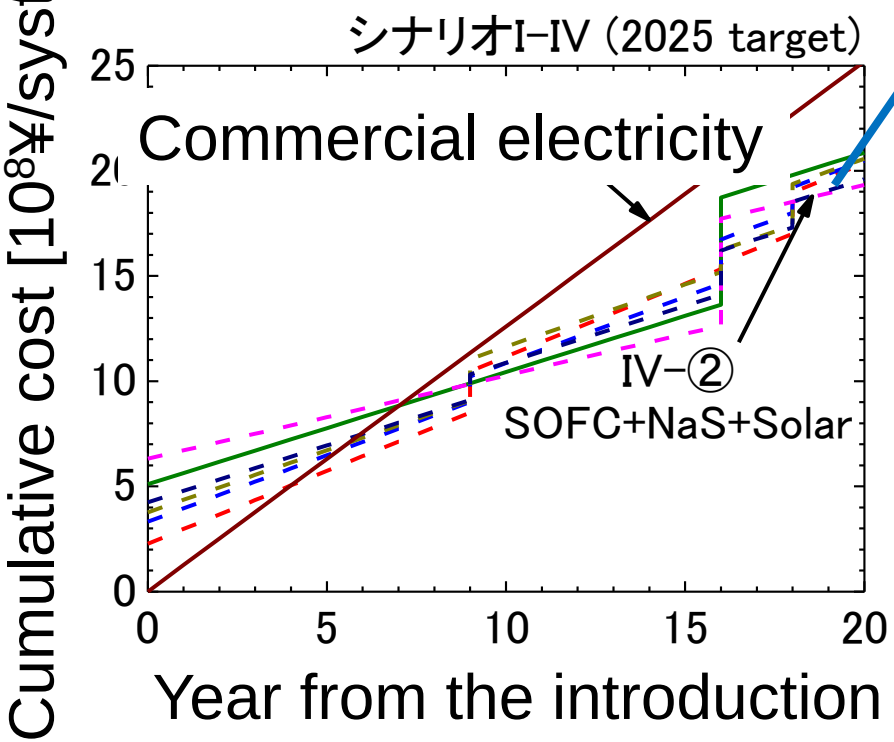


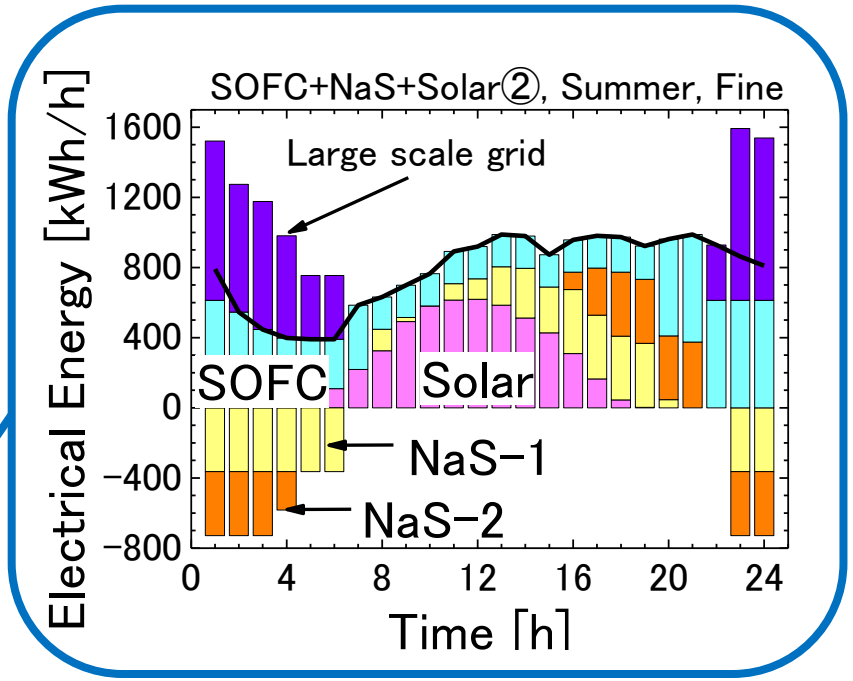
Cost of micro grid electricity

Institute of Advanced Energy, Kyoto University

2025cost(NEDO)

	generator [10^5¥/kW]
SOFC	20
Solar	12
NaS	29





- Micro Grid can be cheaper than large Grid for long runs.
- combination of generation technology is needed to stabilize the supply.
- Carbon-free system can be made before 2050

biomass hybrid from tritium aspect

Institute of Advanced Energy, Kyoto University

○Fusion –biomass hybrid may demonstrate fusion energy earlier than pure fusion electricity.

- small power generation has better market chance.
- cost requirements for the product (hydrogen, oil) may be easier (eventually. Depends on oil price and carbon tax)
- fusion-fuel cell combination may be a preferred option.

○High temperature blanket/divertor are realistic challenge

- SiC-LiPb blanket being developed.
- low pressure system is preferred from safety aspects

○ Tritium self sufficiency and environmental effect is concerned.

- tritium recovery from breeder needs demonstration (TBM)
- demonstrated safety will be important to launch DEMO
- environmental tritium contamination needs social understanding

Conclusion

- Fuel production from biomass continued to be studied.
- Fukushima accident required additional consideration for fusion safety.
- High temperature, low pressure LiPb blanket has preferred safety features.
- Public is aware of Existing radioactive contamination.
- Energy security with renewables will be a major concern in the future.
- Fusion needs an adequate position in the future energy system.