2nd IAEA DEMO Programme Workshop
17-20 December 2013, IAEA Headquarters, Vienna, Austria

Assessment on safety and security(reassurance) for fusion plant

The University of Tokyo
Y. Ogawa

Contents

1. Report on Fusion Energy Assessment published at JSPF*
   @ Decay Heat Problem
   @ Safety issue related with tritium
2. Recent progress on safety research in Broader Approach (BA) activity

* JSPF (The Japan Society of Plasma Science and Nuclear Fusion Research)

Acknowledgements : K. Tobita, M. Namakura (JAEA)

Task Force Committee on Fusion Energy Assessment
at JSPF (The Japan Society of Plasma Science and Nuclear Fusion Research)

(1) Purpose

The accident of nuclear power plant at Fukushima Diichi has brought terrible damages, and a lot of public people has been evacuated. **Since a fusion reactor is a plant to harness nuclear fusion energy, we should carefully pay attention to safety issues related to nuclear accidents, as well.** It is worthwhile to reconsider the safety issues related with fusion reactor. In addition, since the accident of nuclear power plant has drawn attention to energy policy in Japan, we should explain the role of fusion energy to the public.

From these viewpoints the JSPF has organized the task force committee, in which these issues (i.e., safety problem in the fusion reactor and the role of the fusion energy) should be discussed so as to summarize an assessment to the development of fusion energy.

(2) Members

@ **Executive board members**

- Y. Ogawa (Univ. of Tokyo: Chair), S. Nishimura (NIFS), H. Ninomiya (JAEA), A. Komori (NIFS), H. Azechi (Osaka Univ.), H. Horiike (Osaka Univ.), M. Sasamo (Tohoku Univ.), K. Shimizu (MHI)

@ **Experts**

- JAEA: K. Tobita, I. Hayashi, Y. Sakamoto, N. Tanigawa, R. Someya
- NIFS: A. Sagara, T. Muroga, T. Nagasaka, T. Tanaka
- Universities: T. Yokomine, T. Sugiyama, R. Kasada
- Industries: K. Okano, T. Kai

@ **Observers**: H. Yamada (NIFS), S. Kado(Univ. of Tokyo)

Contents of Report (December 2012)

1. Role of fusion energy in 21st Century
   - 1.1 Energy problem and energy policy
   - 1.2 Characteristics of fusion energy and introduction scenario
2. Evaluation on safety issues for fusion plant
   - 2.1 Safety issue on ITER
   - 2.2 Safety issue on fusion plant
3. Radioactivity on a fusion reactor
   - 3.1 Decay heat problem of a fusion reactor
   - 3.2 Radioactive waste
4. Safety analysis for a fusion reactor
   - 4.1 Safety analysis codes and V&V experiments
   - 4.2 Safety issues for solid breeder blankets
   - 4.3 Safety issues for liquid breeder blankets
5. Safety aspect on tritium
   - 5.1 Environmental behavior of tritium
   - 5.2 Biological effect of tritium
   - 5.3 Measurement of environmental tritium
   - 5.4 Safety analysis of tritium
6. Summary





Basic Principle for Safety Securement at Nuclear Plant

- Basic principles for safety securement at fission reactors
  - **Stop** a chain reaction
  - **Cool down** a fissile fuel
  - **Confine** radioactive isotopes

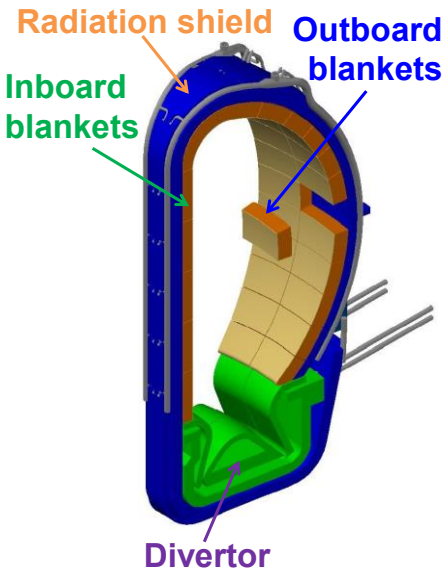
Accident at Fukushima Daiichi Nuclear Power Plants

- Chain reaction has stopped ＜＝ 「**Stop**」
- Cooling of fuel rod due to decay heat was insufficient ＜＝ 「**Cool down**」
  Decay Heat of Blanket
- Radioactive isotopes was released in the environment ＜＝ 「**Confine**」
  Tritium

Decay Heat Problems In Fusion Reactors

Decay heat for fusion DEMO reactor (3 GW)

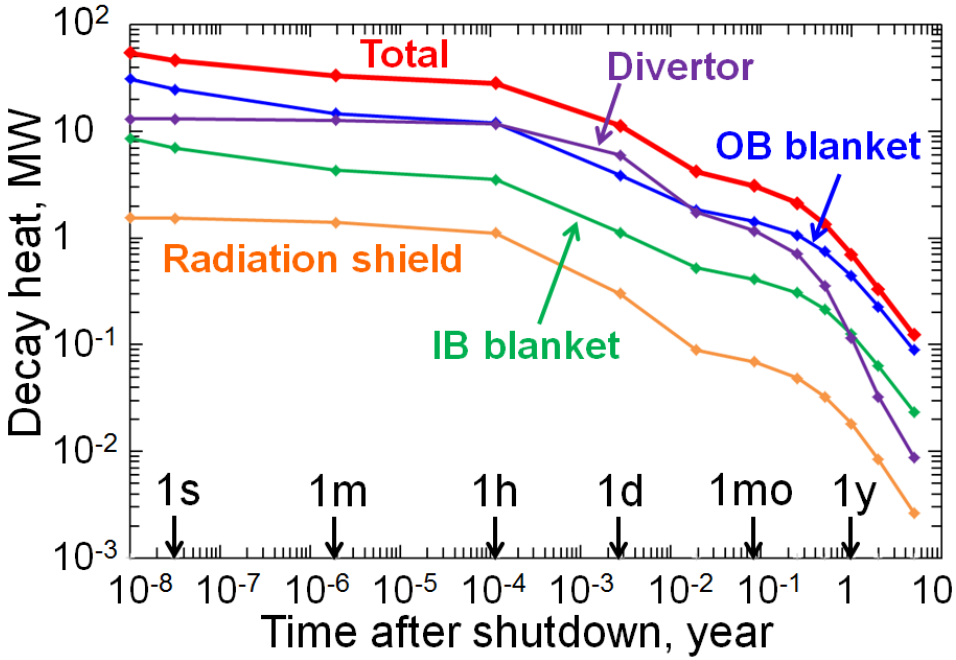
By Y. Someya (JAEA)



Fusion power	3.0 GW		
Time	Stop	1 day	1month
OB blanket	30.87	3.88	1.42
IB blanket	8.58	1.13	0.41
Divertor	13.1	5.97	1.16
Radiation shield	1.79	0.34	0.08
Total decay heat	54.1	11.3	3.1

MW

$P_{D.H.}/P_F$	1.8 %	0.4%	0.1%

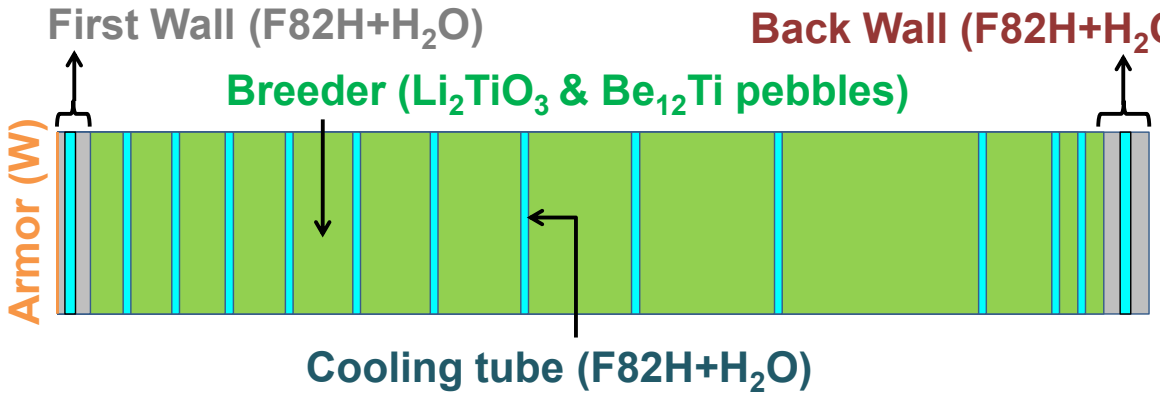


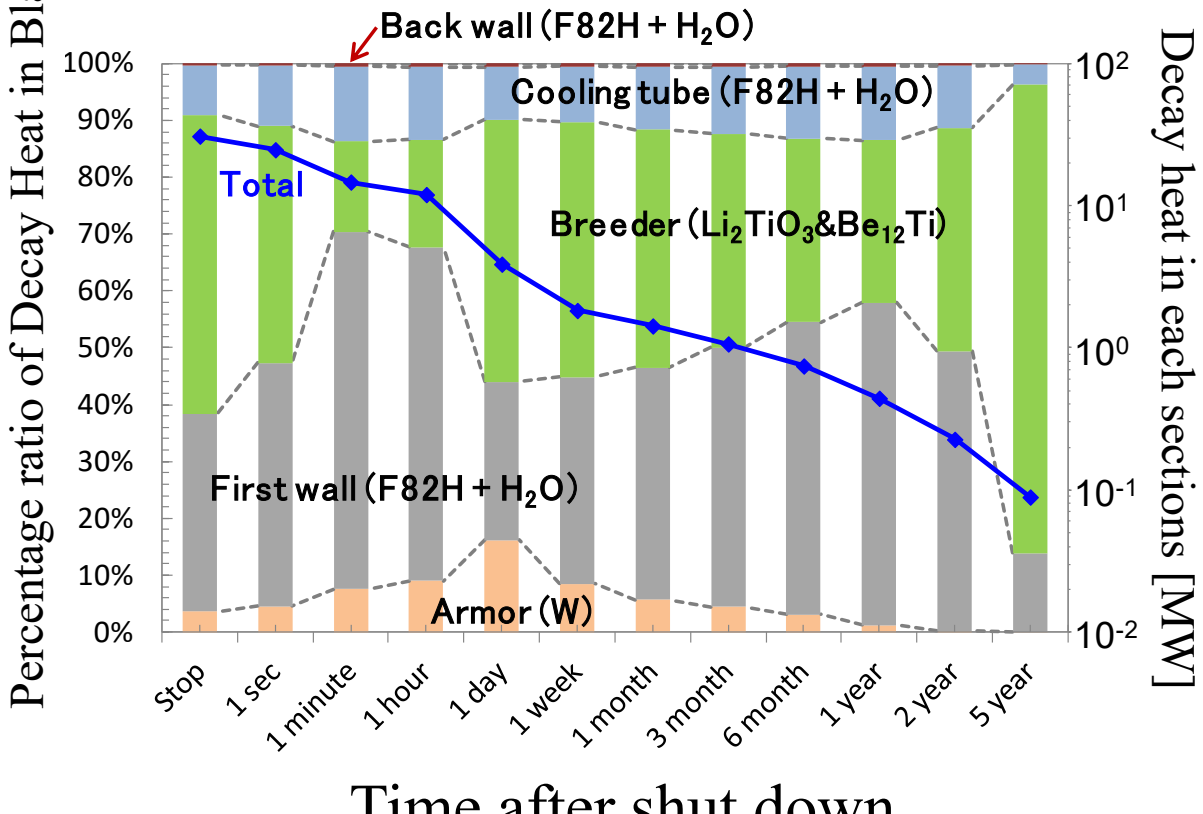
＞Divertor produces the largest portion of decay heat at 1 day.

- **Blanket：First wall（F82H）**
  ⇒ dominant：^{56}Mn (2.58 h)
- Divertor：Tungsten（W）
  ⇒ dominant：^{187}W (1 day)

Decay Heat of Breeding Blanket

By Y. Someya (JAEA)



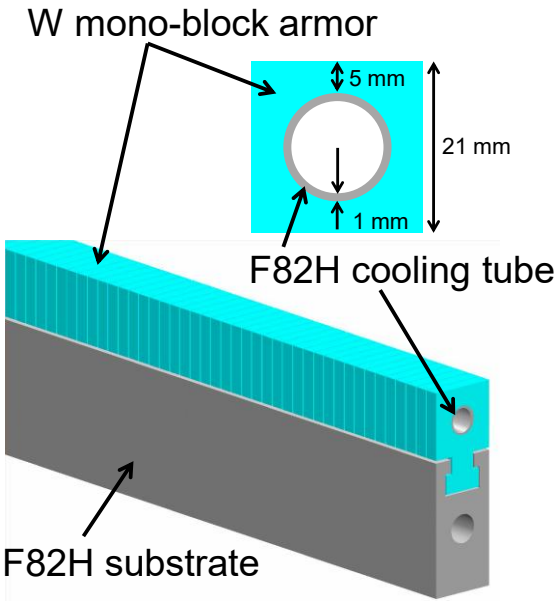


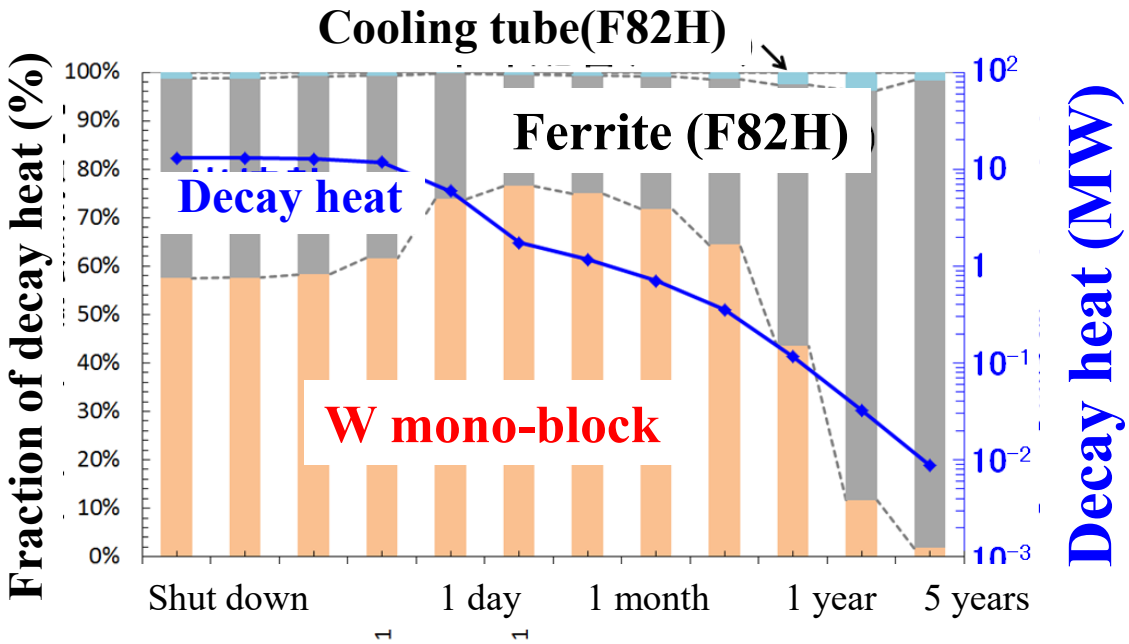
- **Decay heat of Tungsten**

- ✓ **Thickness of W is 0.2mm.**
- ✓ **The contribution of W decay heat to the total amount of the decay heat is not so large, because the volume of W itself is not so large.**

Decay Heat in Divertor

By Y. Someya (JAEA)





Safety Analysis in Europe

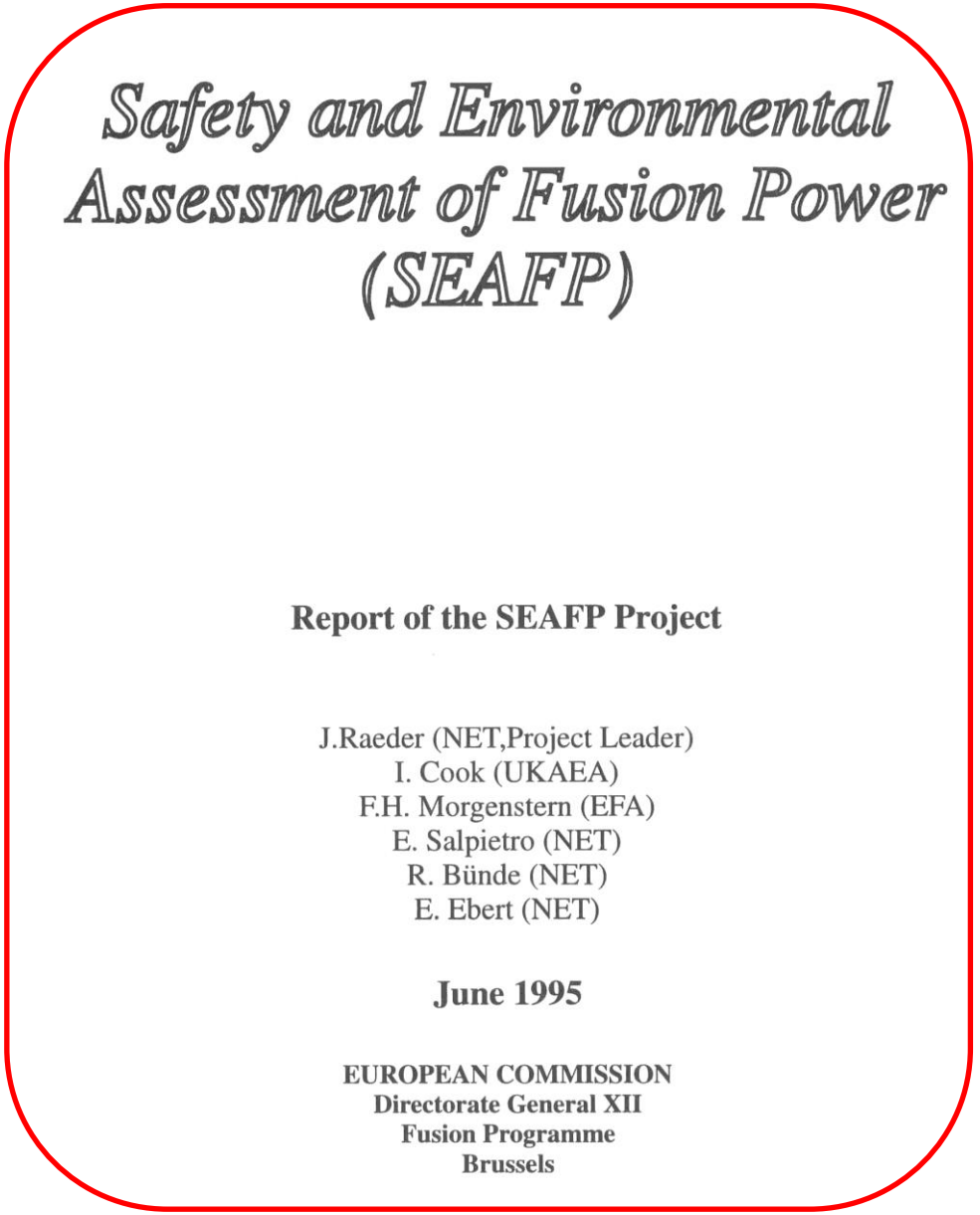
1990 ~

SEAFP (Safety and Environmental Assessments of Fusion Power)

SEAL (Safety and Environmental Assessment of Fusion Power-Long Term)

2000 ~

PPCS (Power Plant Conceptual Study)



Safety and Environmental Assessment of Fusion Power (SEAFP)

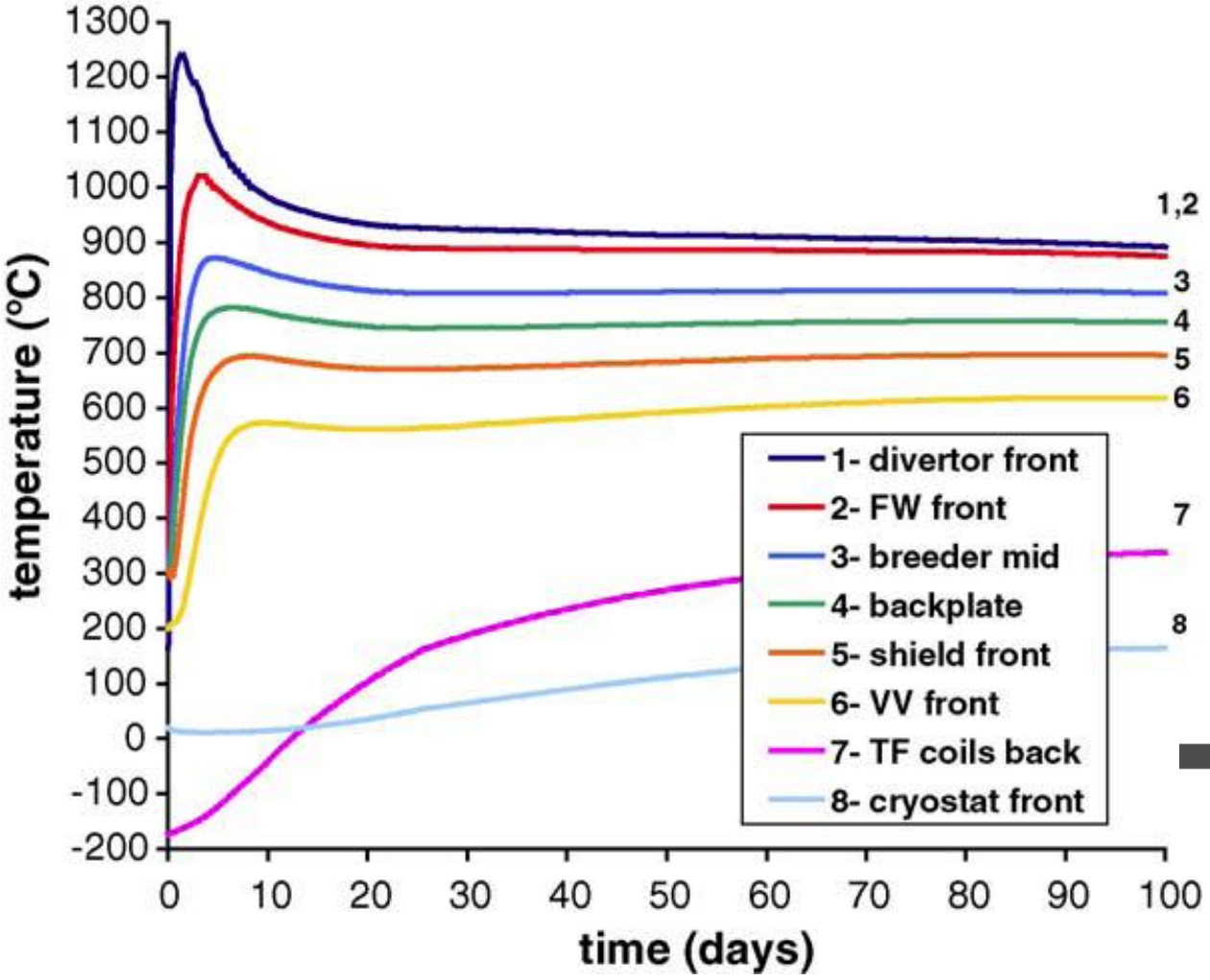
Report of the SEAFP Project

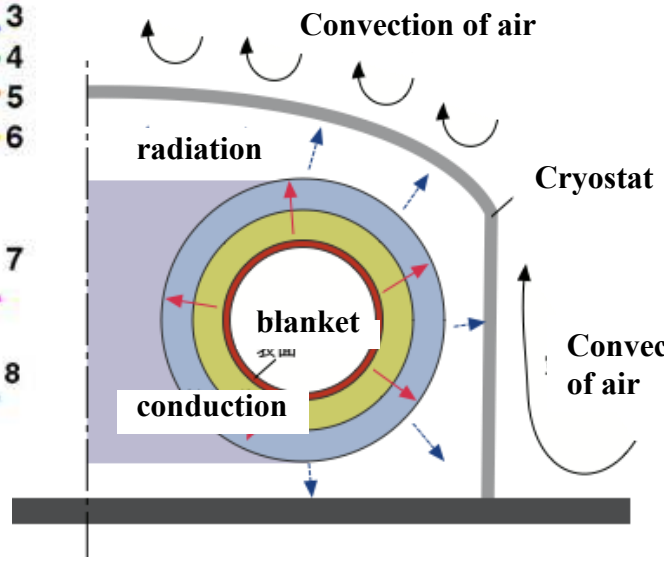
J.Raeder (NET,Project Leader)
I. Cook (UKAEA)
F.H. Morgenstern (EFA)
E. Salpietro (NET)
R. Bünde (NET)
E. Ebert (NET)

June 1995

EUROPEAN COMMISSION
Directorate General XII
Fusion Programme
Brussels

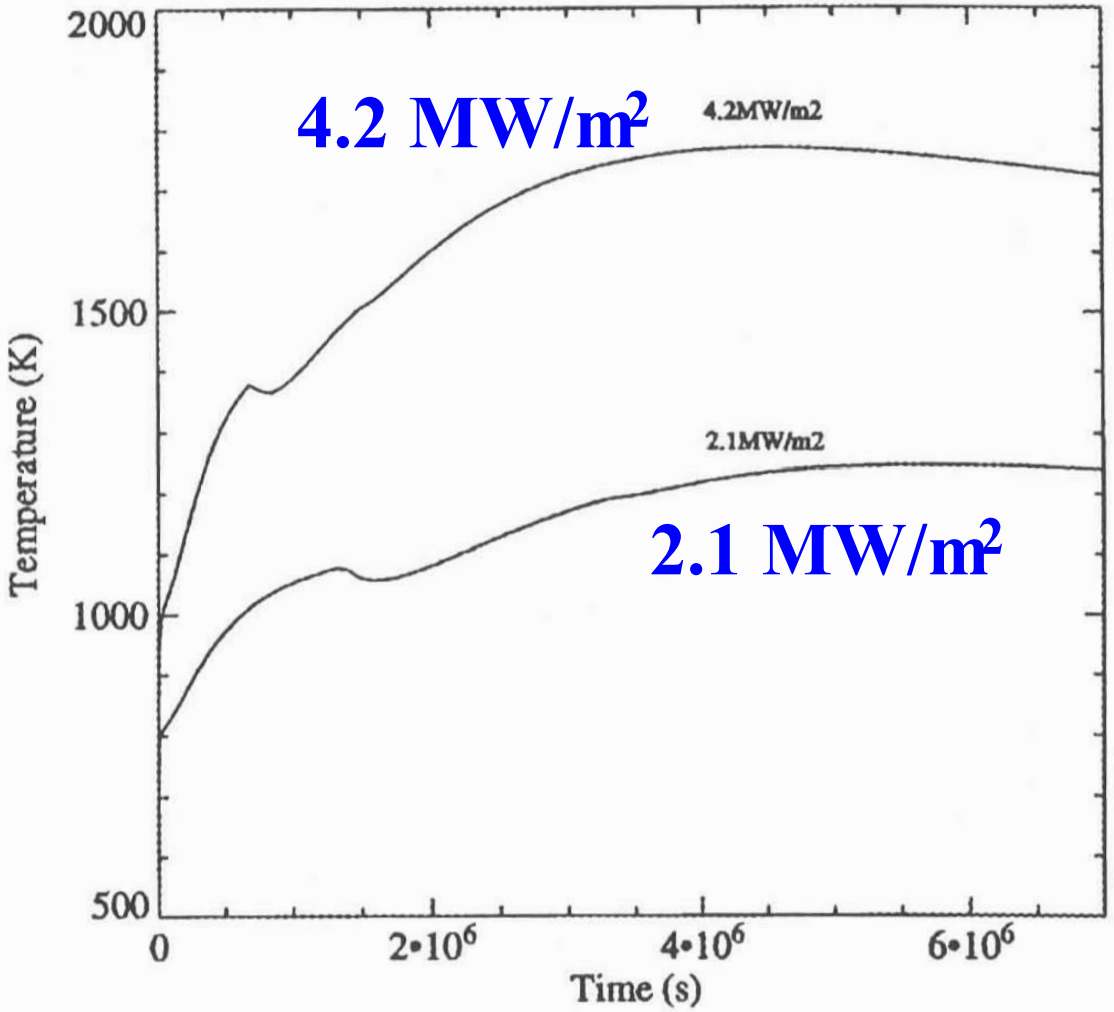
Analysis of LOCA in PPCS





← Neutron wall loading is ~ 2 MW/m^2.

Dependence of the maximum temperature on the neutron wall loading



I. Cook, et al, "Synergies and Conflicts between Safety and Economic Objectives for Fusion; Implications for Fusion Development Strategies"

- **The decay heat density** just after the shut down is proportional to **neutron flux** (not to neutron fluence).

Decay heat density

$P(MW/m3) \sim \phi n(MW/m2)$

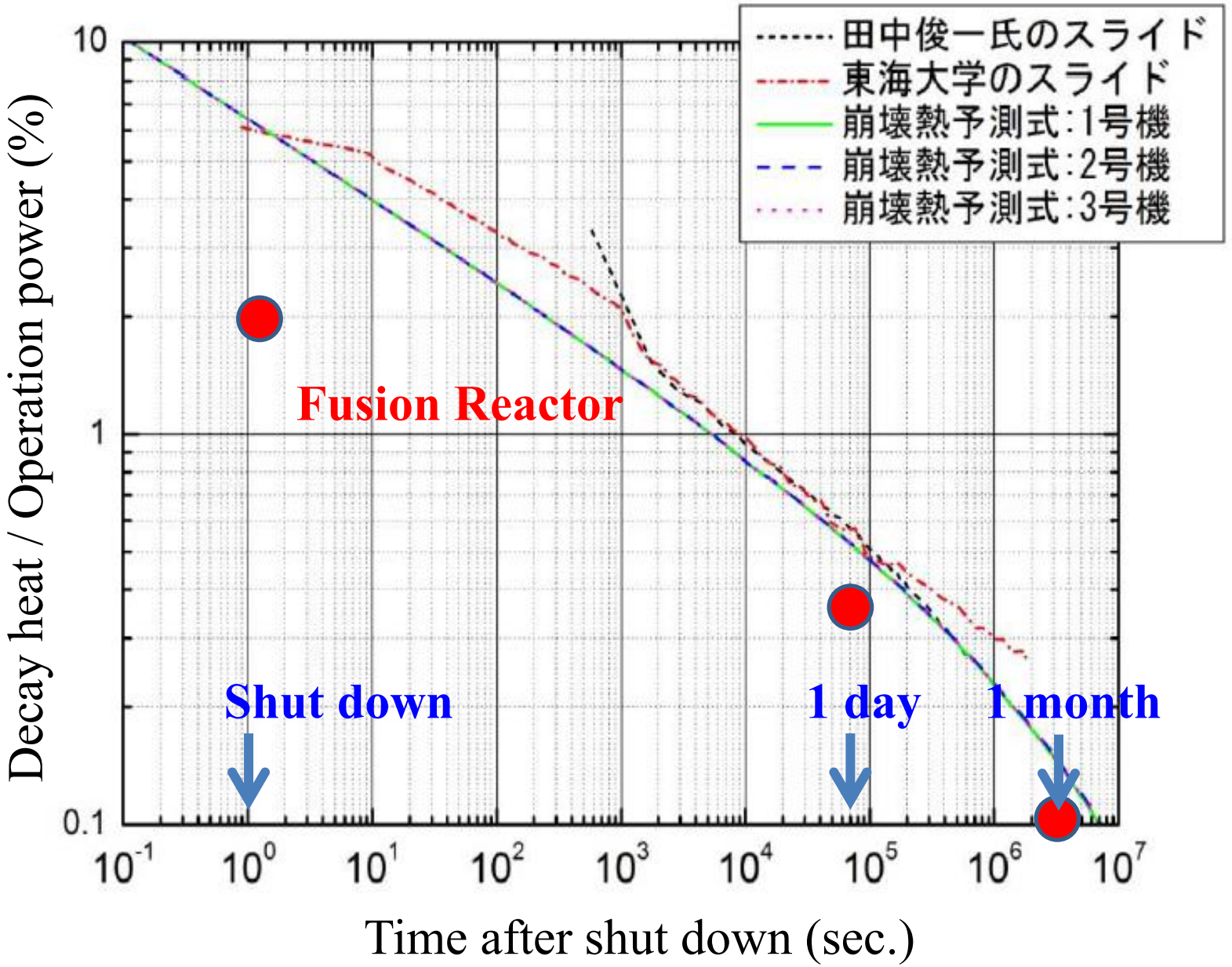
➔ Wall Temperature

- **The total decay heat** is, roughly speaking, proportional to the **total fusion power** (not to the neutron flux).

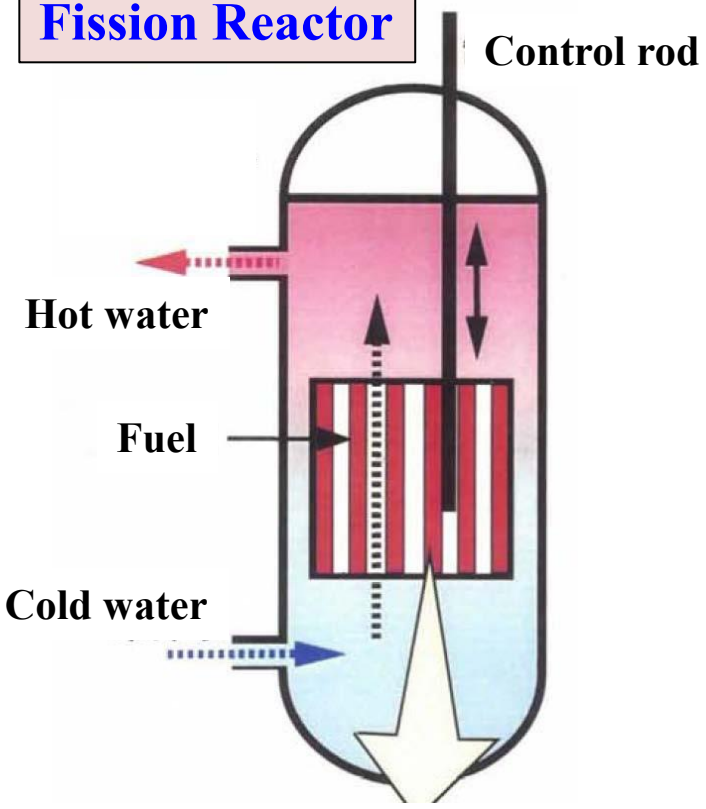
Total decay heat

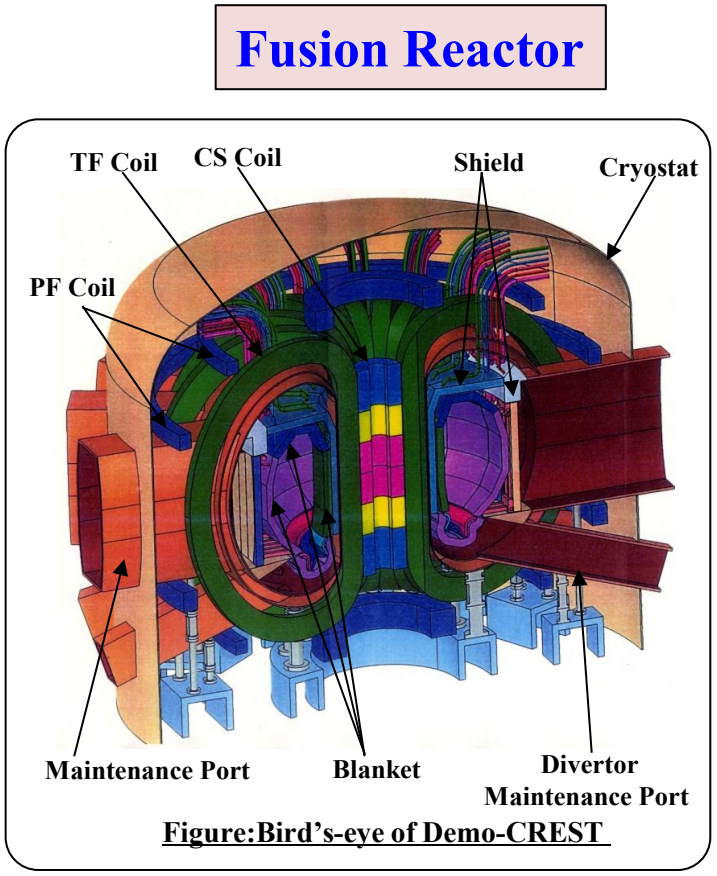
$P(MW) \sim P_{Fusion}(GW)$

Comparison of decay heat to Fukushima Daiichi Nuclear Plant



Difference between fission and fusion reactors





- The total amount of decay heat of the fusion reactor is comparable with or slightly smaller than that of fission reactor.
- The differences between fission and fusion reactors are
  - @ Volume of heat source
  - @ Heat pass to the heat sink
  - @ Heat capacity of the surrounding components

Safety issues on Tritium

A sense of security (reassurance)

From the viewpoint of a sense of security or reassurance, a hazard potential of the plant should be taken into account.

	Fusion plant Tritium (1 kg)	**LWR I-131**
Amount of Radioactive isotope (A)	0.38×10^{18} Bq	5.4×10^{18} Bq
Kind of Radioactivity	18.6 keV : β ray	610 keV: β ray
Maximum permissible density in the air (B)	5000 (Bq/m^3)	10 (Bq/m^3)
Hazard potential(=A/B)	7.8×10^{13} m^3	5.4×10^{17} m^3
Comparison of hazard potential	**1/6800**	**1**
INES	**1/680**	**1**

International Nuclear and Radiological Event Scale : IAEA and OECD/NEA

=> **~1/10**

=> **~1/500**

I-131 equivalence
For workers (B)
~1/500
For public(B)
~1/50

1 GW fusion reactor ~ 1 MW fission research reactor

I-131 equivalence for public

1/50

nuclide	External exposure[1] D_grad e(50) Sv/(Bq m^{-2})	External exposure[1] D_grad x Vg Sv/(Bq s m^{-3})	Internal exposure[2] D_inh Sv/Bq	Internal exposure[2] D_inh x B.R. Sv/(Bq s m^{-3})	Total dose Sv/(Bq s m^{-3})	I-131 equivalence
H-3	0	0	2.60E-10	8.58E-14	8.58E-14	**0.02**
I-131	2.70e-10	2.70E-12	7.40E-09	2.44E-12	5.14E-12	1
Cs-137	1.30E-07	1.95E-10	3.90E-08	1.29E-11	2.08E-10	40

Vg：adsorption rate（I-131:1.0E-02 m/s，others:1.5E-03 m/s），Breathing rate：3.3E-04 m^3/s[ICRP 71], standard adult（179 cm，73 kg）[ICRP 23]

Effective dose rate due to internal exposure by inhalation（D_inh）[2]

Migration speed		Fast		Medium		Slow		Maximum of adult
nuclide	type	Infant	Adult	Infant	Adult	Infant	Adult	
H-3	M	2.60E-11	6.20E-12	3.40E-10	4.50E-11	1.20E-09	2.60E-10	2.60E-10
I-131	F	7.20E-08	7.40E-09	2.20E-08	2.40E-09	8.80E-09	1.60E-09	7.40E-09
Cs-137	S	8.80E-09	4.60E-09	3.60E-08	9.70E-09	1.10E-07	3.90E-08	3.90E-08

[1] IAEA, “Generic procedures for assessment and response during a radiological emergency”, [IAEA-TECDOC-1162], Section E Table 15(2000).
[2] "Age-dependent Doses to Members of the Public from Intake of Radionuclides: Part 4 Inhalation Dose Coefficients, " (1995)

INES（International Nuclear and Radiological Event Scale）

[131-I equivalence Bq]

Level 7 :	**> several x 10^{16} Bq**	**Chernobyl, Fukushima**
Level 6 :	**several x 10^{15} ~ 10^{16} Bq**	
Level 5 :	**< several x 10^{15} Bq**	**Three mile island**
Level 4 :		**JCO critical accident**
Level 3 :		**no evacuation**

Tritium 1 kg, = > 3.6 x 10^{17} Bq

131-I equivalence

1/500	**~ 7x10^{14} Bq**	**=> Level 4-5**
1/50	**~ 7x10^{15} Bq**	**=> Level 5-6**

Plan and current status of the BA safety research

By M. Nakamura and K. Tobita (JAEA)

Kicking-off the DEMO safety research in Japan

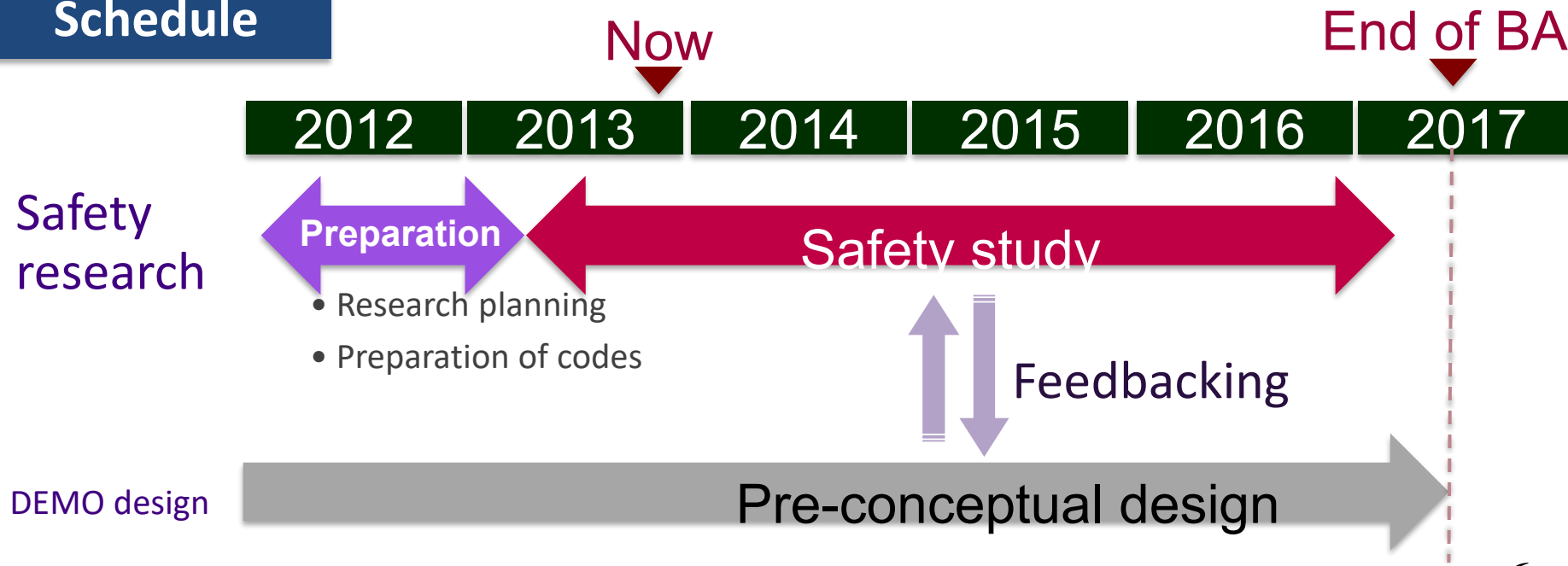
Background

- The fusion safety research in Japan got less vigorous after the activity of the ITER site invitation
- Necessity of demonstrating the DEMO safety

Purposes

- To clarify safety characteristics of fusion DEMO
- To propose safety projections for DEMO
- To foster human resources of the next generation

Schedule



Research items in 2013

S0	Revisiting the source term assessment
S1	Design of DEMO safety systems
S2	Analysis of steam condensation in suppresion pool
S3	Analysis of DEMO bounding sequences
S4	Detailed analysis of residual heat removal at LOCA
S5	Analysis of dynamic load after in-blanket LOCA
S6	Mitigation of severe accidents
S7	Analysis of tritium release and dose rate
S8	Management strategy for waste produced in maintenance
S9	Benchmarking the plasma transient analysis codes

Preparation of computer codes

	Code (developer)	Status (A= available)	Functions
Neutronics	**THIDA-3** (JAEA)	A	• Versatile neutronics calculation code. • n, γ transport, dpa, W/cm^3, Bq/cm^3, TBR, etc. • Multiple reaction included.
	MCNP (LANL)	A	• n, γ transport, mainly for 3D cal.
Thermo-hydrolics	**MELCOR-FUS** (INL/SNL)	A	• Severe accident code based on compartment model. • Capable of dealing with chemical reactions
	TRAC (LANL)	In progress	• Thermo-hydrodynamics • Best estimate code based on precise 3Dmodel Now, TRACE (TRAC/RELAP advanced computational engine)
Plasma operation	**SAFALY** (JAEA)	A	• Transient events in tokamak
	AINA (U. Catalunya)	A	• Engineering parts of SAFALY, upgraded
Tritium / Dust	**TMAP-4** (INL)	A	• Tritium transport in materials
	ACUTRI/ ACUTAP (JAEA)	In progress	• Dose due to T/dust release to the environment (plume model)
	UFOTRI (KIT)	A	• Dose due to dust release to the environment
Heat trans.	**ANSYS**	A	• Residual heat analysis using the output of neutronics codes
	PHOENICS	A	• Heat and CFD analysis

Source term assessment

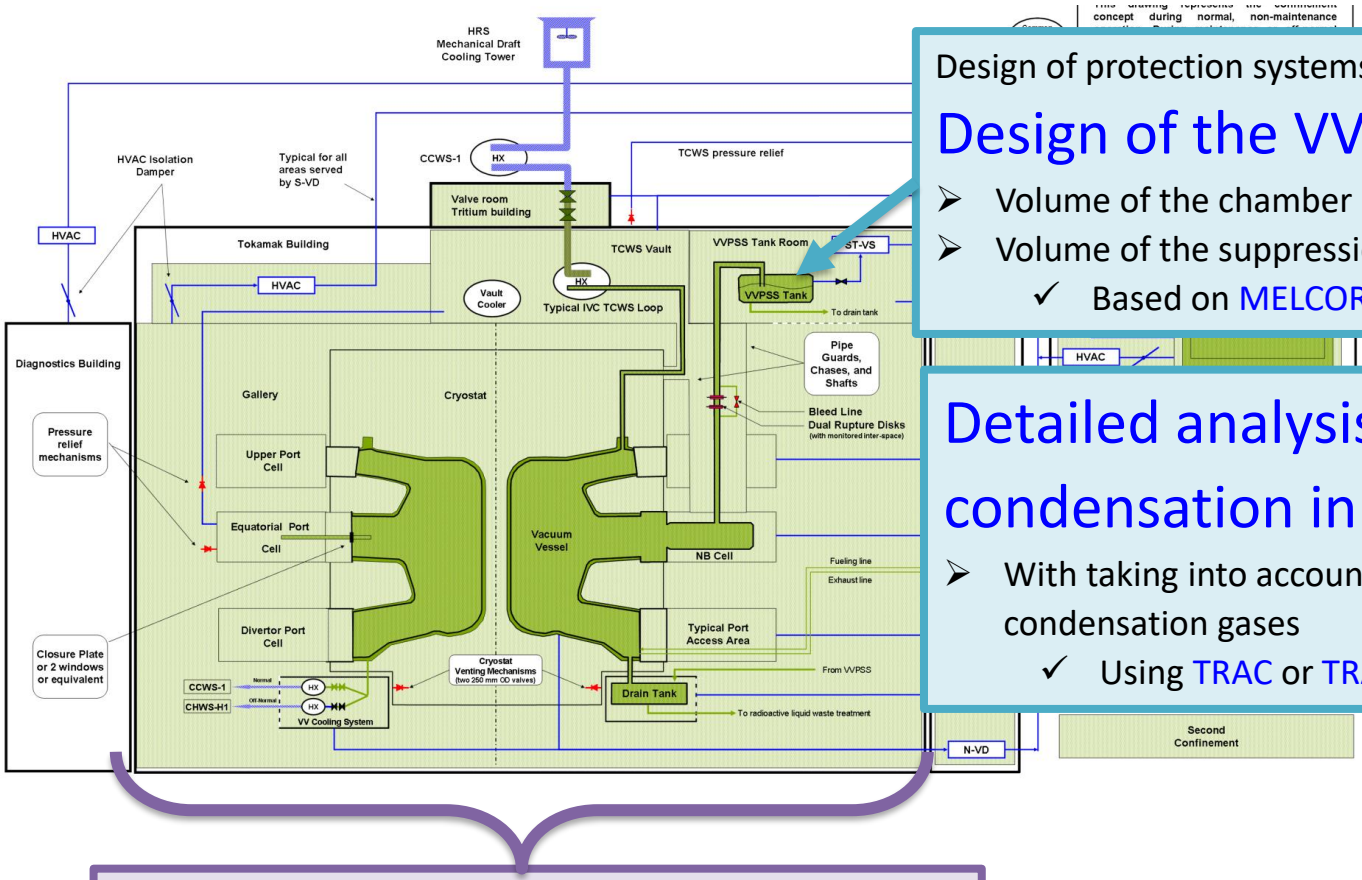
Energies that can mobilize radioactive source terms

Parameter		ITER	DEMO	DEMO/ITER
Plasma	Fusion power (MW)	500	1,350	2.7
	Thermal energy (MJ)	350	870	2.5
	Mag. energy (MJ)	400	450	2.4
Magnet	Mag. energy (GJ)	50	120	2.4
Coolant	Enthalpy in the FW/BLK cool. ch. (GJ)	260	1,300	5.0
	Enthalpy in the DIV cool. ch. (GJ)	90	230	2.5

The energies involved in the DEMO are larger than those in ITER.

- The enthalpy in the first wall/blanket (FW/BLK) cooling loops is larger than other energies in DEMO.
  - ✓ Because
    the coolant temp. (~320° C) is larger than in ITER (~180° C), and
    the coolant volume (240 m^3/loop) is larger than in ITER (140 m^3/loop).

S1: Design of DEMO safety systems



Design of protection systems

Design of the VVPSS

- Volume of the chamber
- Volume of the suppression water
  - ✓ Based on MELCOR simulations

Detailed analysis of steam condensation in the VVPSS

- With taking into account effects of non-condensation gases
  - ✓ Using TRAC or TRACE

Design of mitigation systems

Design of the tokamak building

- Volume of the building
- Threshold pressure to open the blowout panel to the stack
  - ✓ Based on MELCOR simulations

Accident scenario analysis

Analysis method

The Master Logic Diagram (MLD) and
the Functional Failure Modes and Effects Analysis (FFMEA)



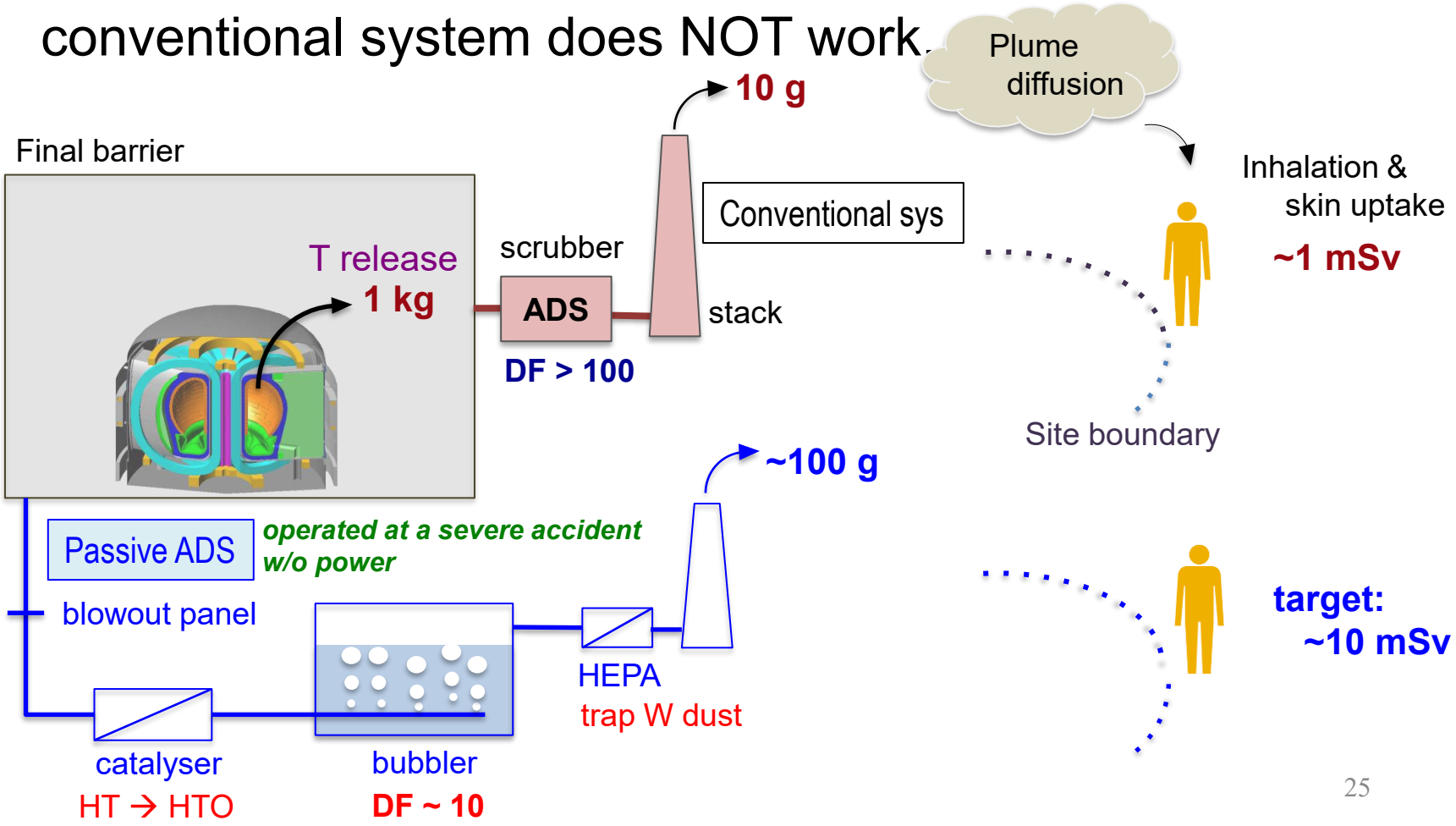
22 reference event sequences have been identified.
Of these sequences, we have selected **events of particular concern**.

Events selected	Why selected ?
LOFA of the FW cooling channels	Involved in many of the event seqs. The FW coolant enthalpy is released in the VV
In-VV LOCA of FW cooling channels	Same as above
Ex-VV LOCA of the FW cooling channels	Same as above
LOVA	The event directly breaks the 1st barrier
In-BLK LOCA	DEMO-specific event

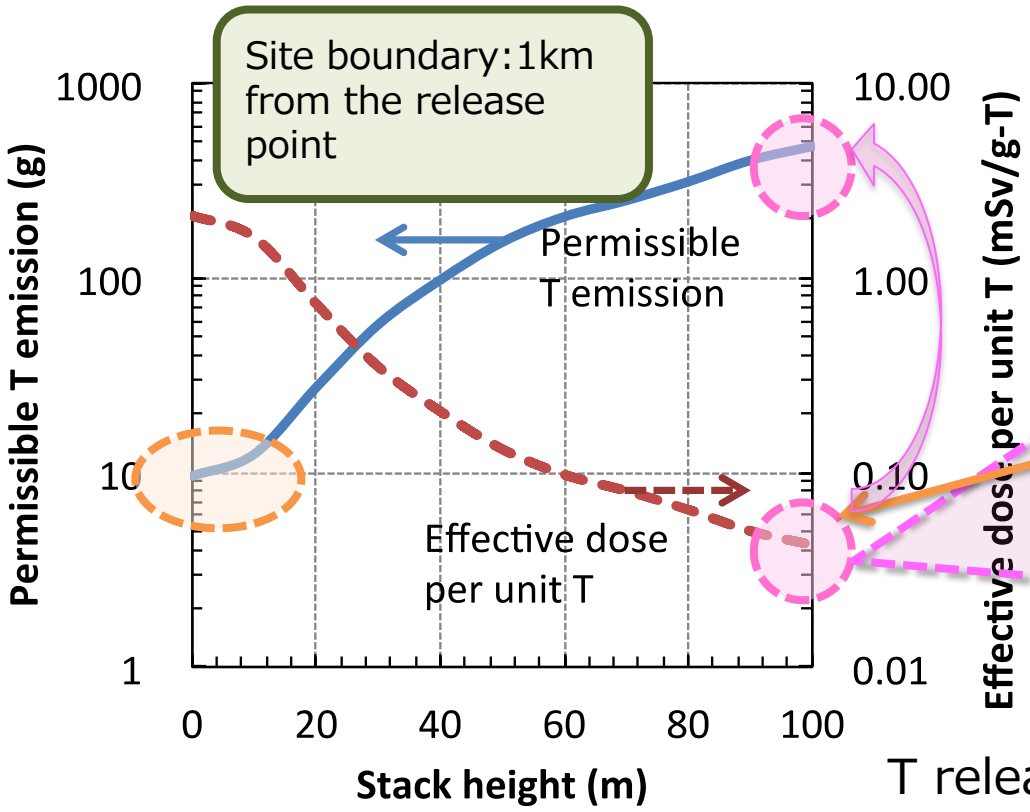
S6: Mitigation of severe accidents

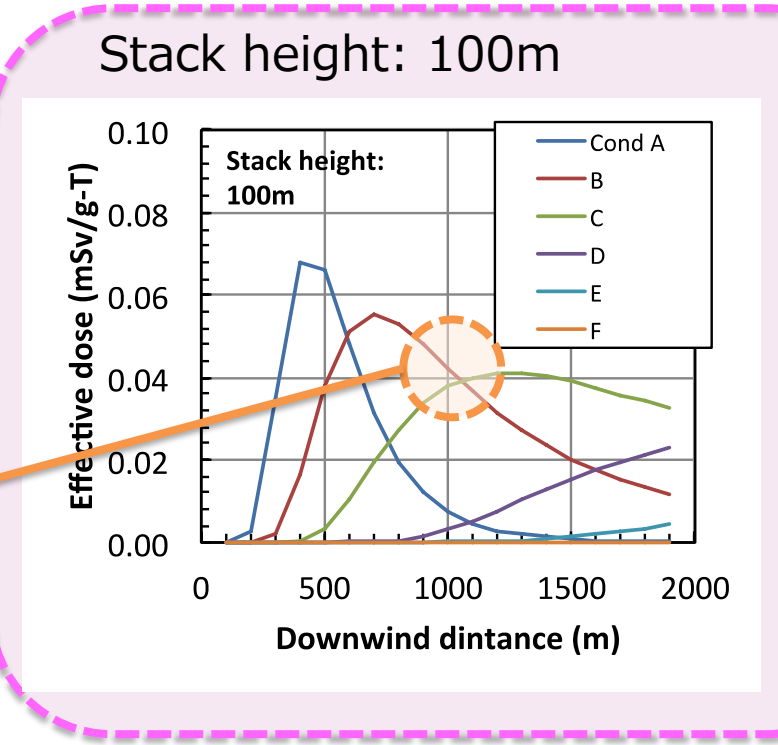
Passive ADS (atmospheric detriation sys) is under study to mitigate upper bounding sequences assuming no power supply

- In case of "LOVA + total LOCA + total loss of power", the conventional system does NOT work.



Calculation results of the T dose





T release amaout corresponding to the evaluation guideline 20mSv/7d

❖ The stack lower, the allowable T release amount smaller.

Stack height (m)	Release (g-T)
100	470
0 (ground level release)	10

Summary

@ Task force committee organized at JSPF has reviewed the safety/security issues of a fusion reactor, paying much attention to decay heat problem and tritium safety.

=> Removal of decay heat should be carefully taken into account, because a total amount of the decay heat in a fusion reactor is comparable with or slightly lower than that of fission reactors.

=> Much attention should be paid to confinement of tritium in a fusion plant, and research on an environmental behavior of tritium should be endorsed.

@ Safety research has been launched in Japan as a BA Demo Design Activity, putting emphasis on pursuing safety improvement by iterating safety analysis and its projection to a DEMO design.

@ From the viewpoint of public acceptance, we have to pay much attention to the safety issues in a fusion reactor. By considering safety issues as one of highest priority, reactor design should be optimized.

SEAFP report

Loss of Site Power (LOSP)

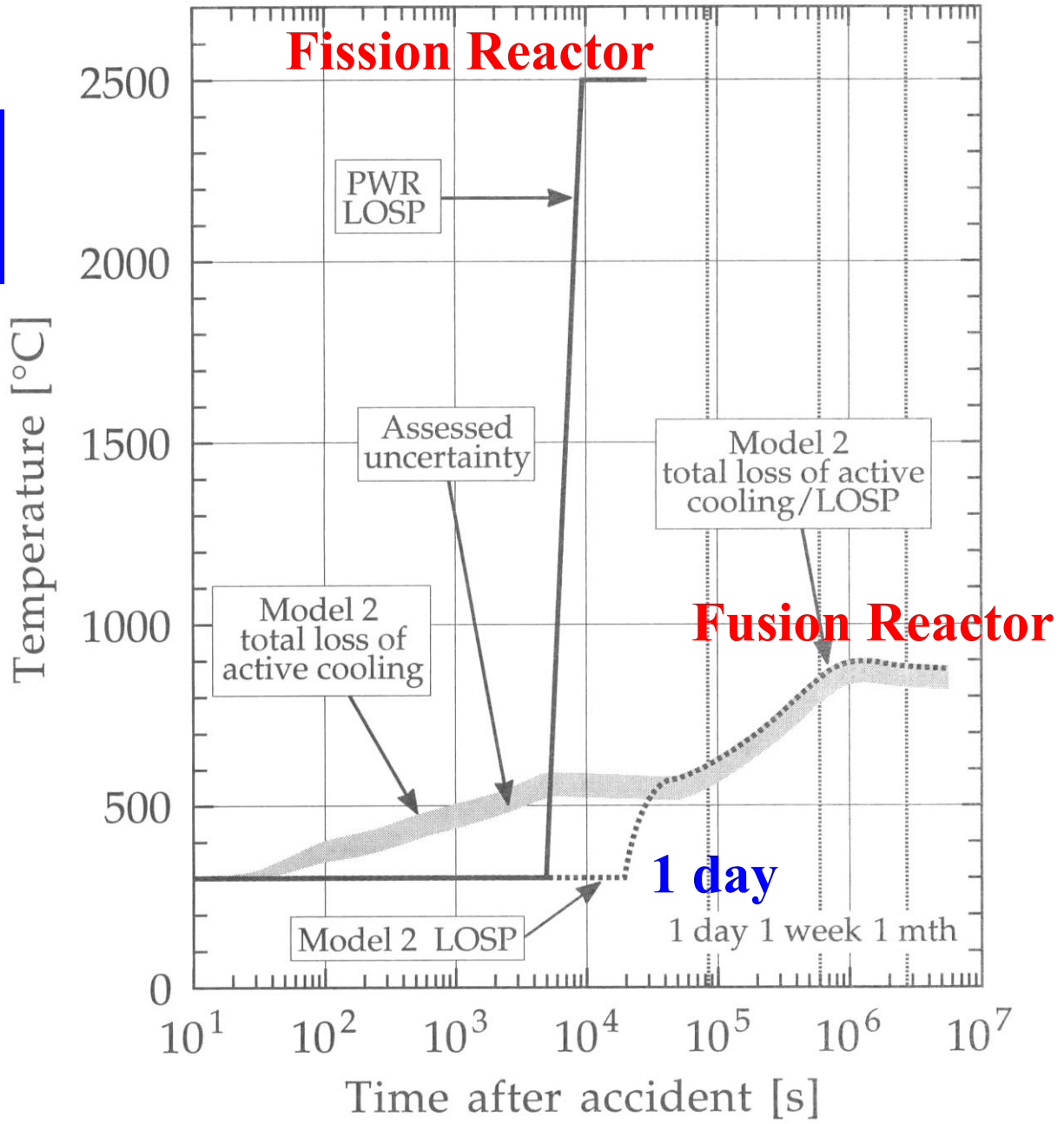


Fig. 5-15:

Environmental behavior of tritium (air and water)

(a) Tritium in the rain

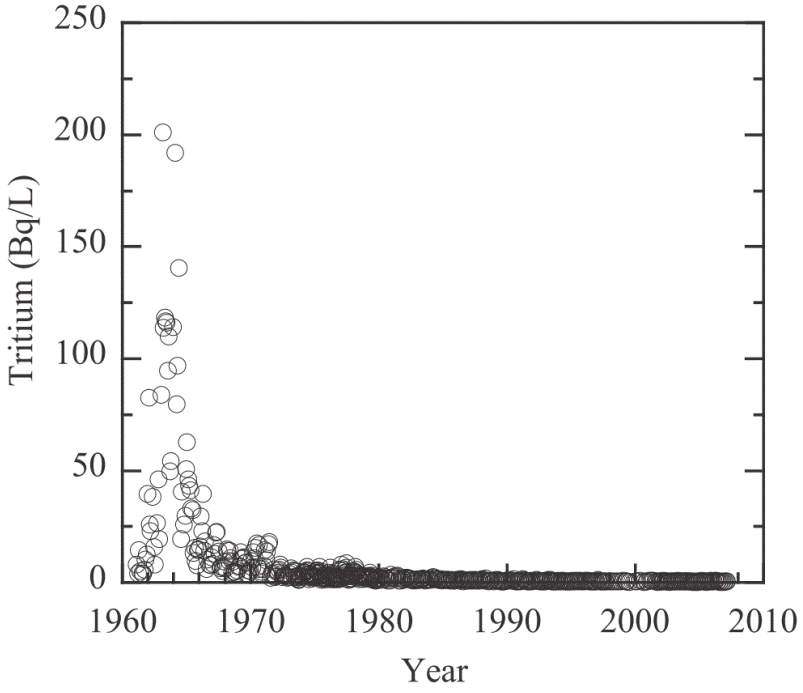


図１　雨のトリチウム濃度の経時変化（東京と千葉）[9].

(b) Tritium in the air

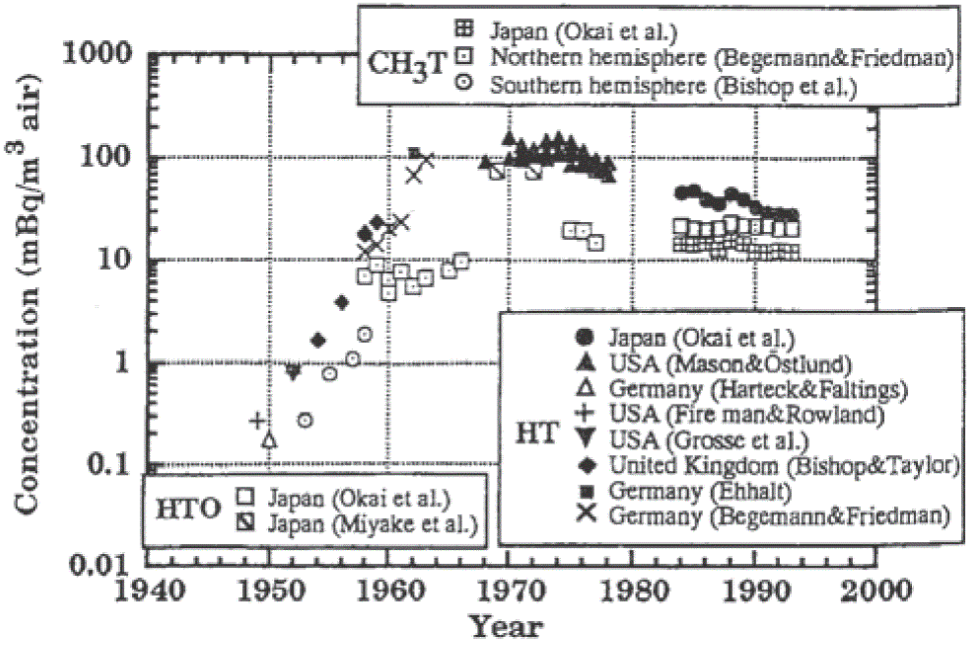
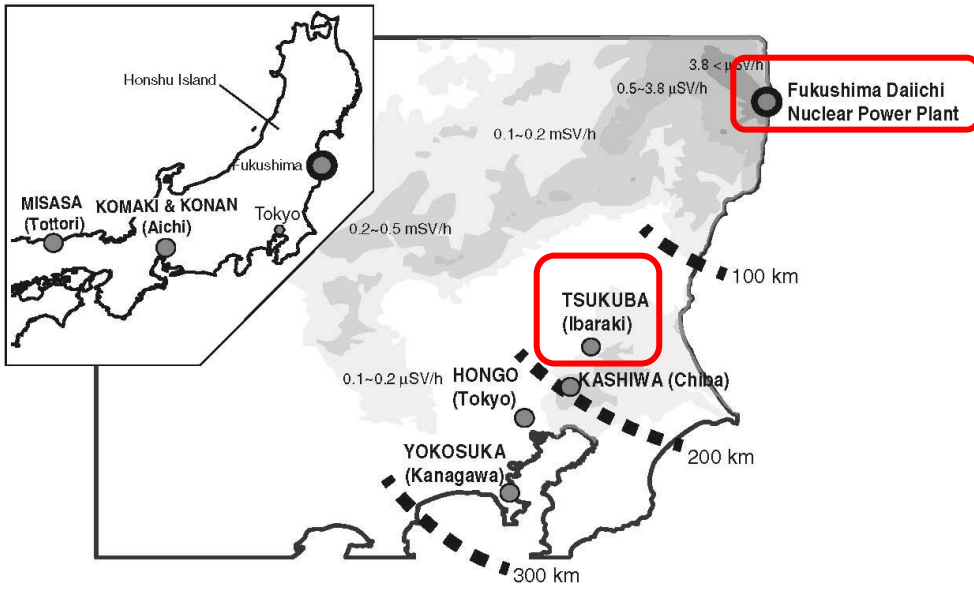
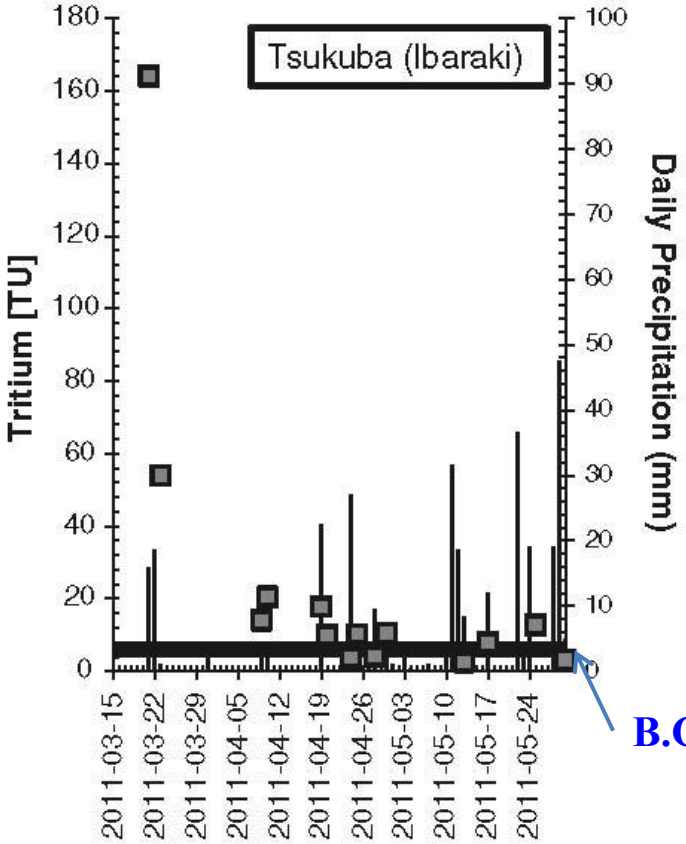


図１　化学形態別に示した大気中トリチウム濃度の変遷[8].

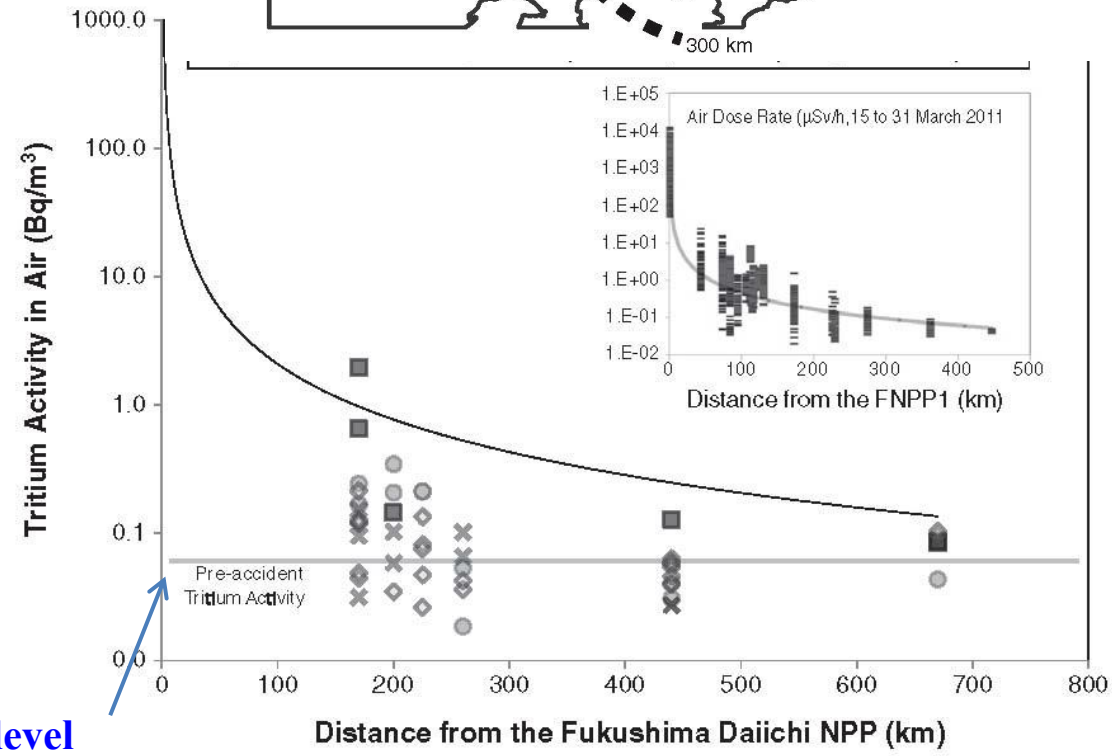
Tritium concentration in Fukushima Daiichi Nuclear Plant Accident

T. Matsumoto, et al., "Tritium in Japanese precipitation following the March 2011 Fukushima Daiichi Nuclear Plant Accident", Science of the Total Environment, 445-446 (2013) 365-370





B.G. level



=> 10^{15} Bq in total (6×10^{14} Bq/year in LWR)

Calculation model of the T dose

Wind speed *U*

Convection & diffusion by the wind

Solar radiation effect on the diffusion

Relative intensity of the radioactive cloud

$$\chi/Q \propto \frac{1}{U\sigma_y\sigma_z}\exp\left(-\frac{H^2}{2\sigma_z^2}\right)$$

- The parameters σ_y and σ_z are dependent on the solar radiation and wind speed.

T inventory released Q_T

Stack emission

T release

Stack height *H*

Inhalation
Skin absorption ***M***

Conversion to dose equivalence ***F***
(Bq → mSv)

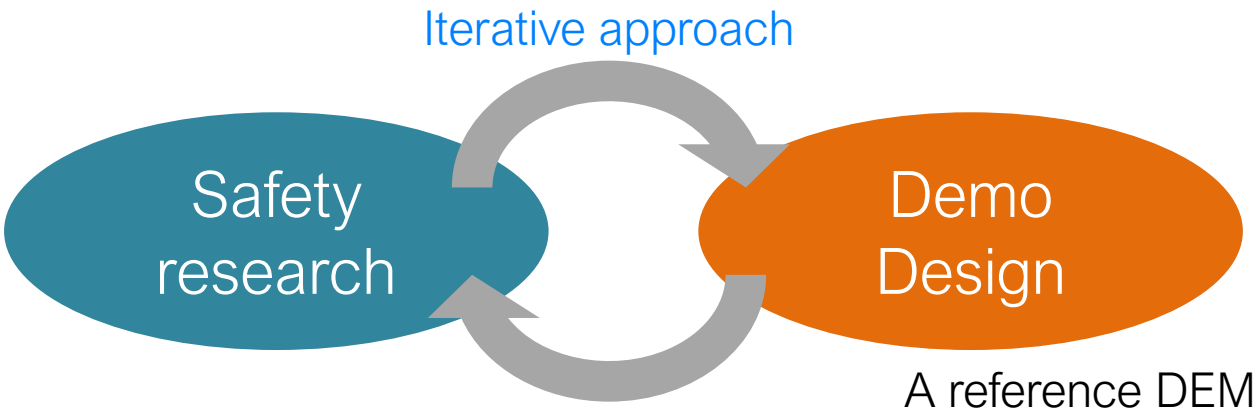
Site boundary

Tritium dose rate

$$H_T = Q_T(\chi/Q)MF$$

Approach for the BA-DDA safety research

- The safety research starts as early as in the pre-conceptual design phase being conducted under the BA-DDA where neither key design parameters nor plant configuration is determined.
- We put emphasis on pursuing safety improvement by iterating safety analysis and its projection to a DEMO design. Such a DEMO design will be a 're-input' parameter to revised safety analysis.



A reference DEMO design as an initial condition is necessary.

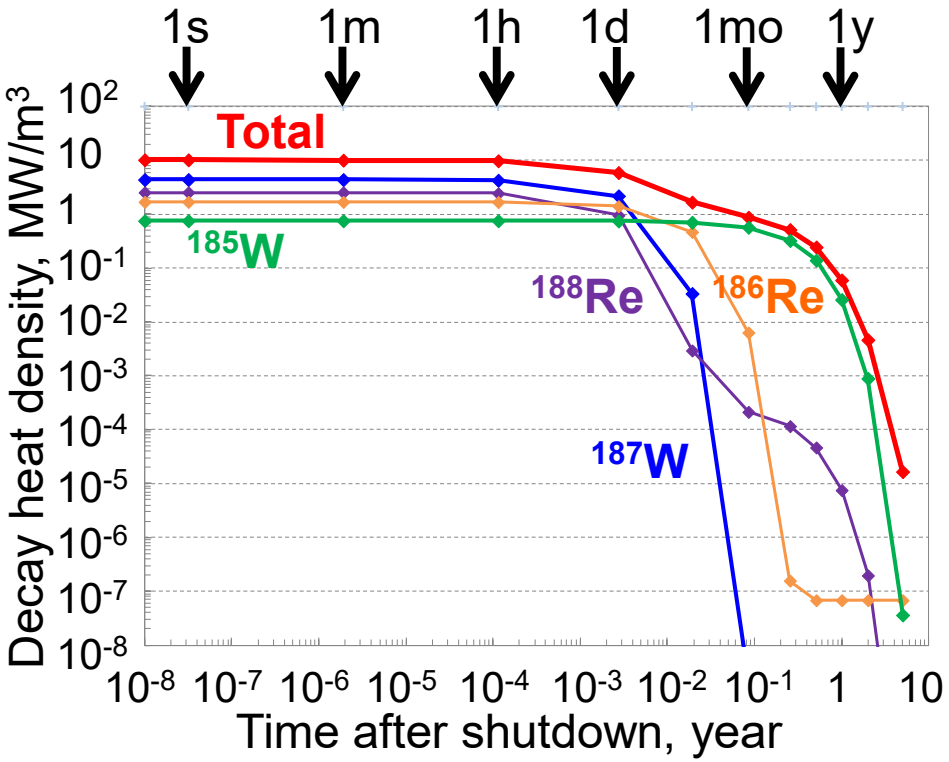
I-131 equivalence for workers [ICRP 68]

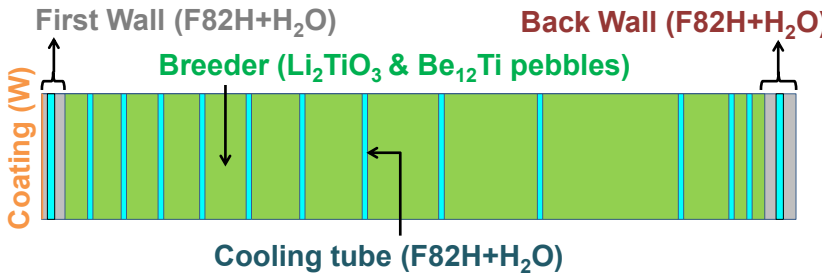
1/500

RI	Type	Inhalation **Adult** (1μm)	**Adult** (5μm)	Ingestion **Adult** (ing)	Inhalation SR-1,2 gas		INES	1 digit
H-3 gas	SR-1				**1.8E-15**	1.80E-15	1.64E-07	2.E-07
HTO	SR-2			1.8E-11	**1.8E-11**	1.80E-11	1.64E-03	**0.002**
OBT	SR-2			4.2E-11	**4.1E-11**	4.10E-11	3.73E-03	0.004
I-131 vapor	F				2.0E-08	2.00E-08	1.82E+00	2
I-131	F	7.60E-09	**1.10E-08**	2.2E-08		1.10E-08	1.00E+00	**1**
Cs-137	F	4.80E-09	**6.70E-09**	1.3E-08		6.70E-09	6.09E-01	0.6

Decay heat density for W

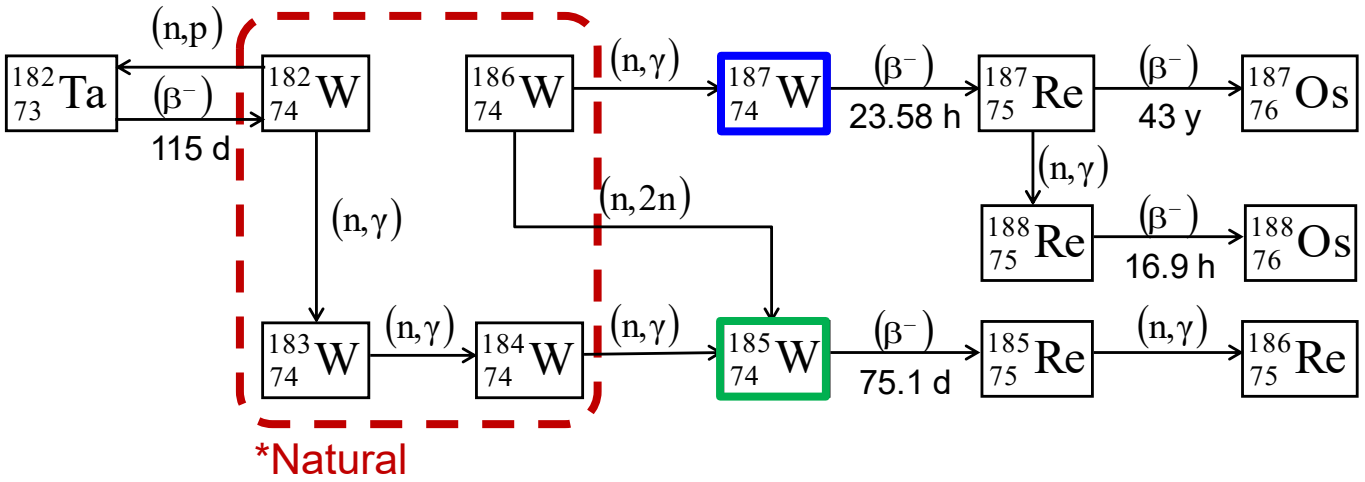
By Y. Someya (JAEA)





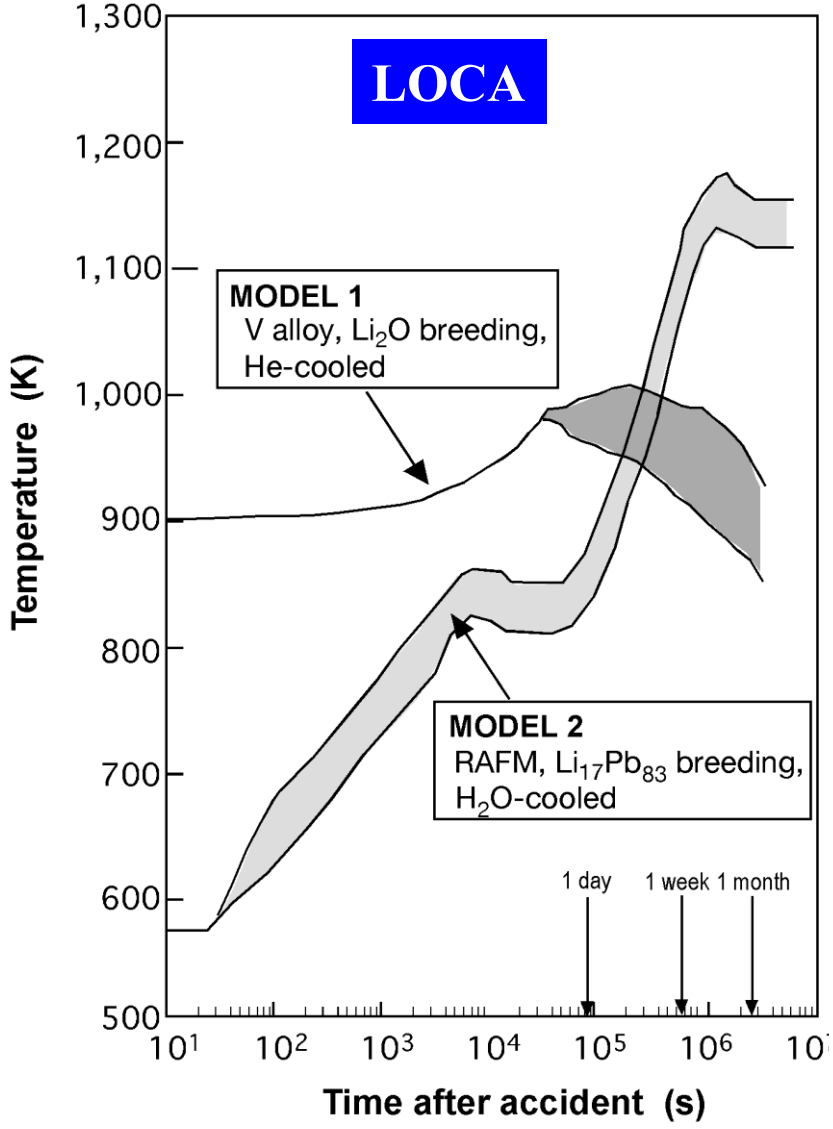
«Dominant nuclides»

- ✓ $^{187}_{74}\mathrm{W}:(\mathrm{n},\gamma)$ reaction
  (time < 1 day)
- ✓ $^{185}_{74}\mathrm{W}:(\mathrm{n},\gamma)$ reaction
  $:(\mathrm{n},2\mathrm{n})$ reaction
  (1day < time < 1 year)



SEAFP report

LOCA



LOSP event

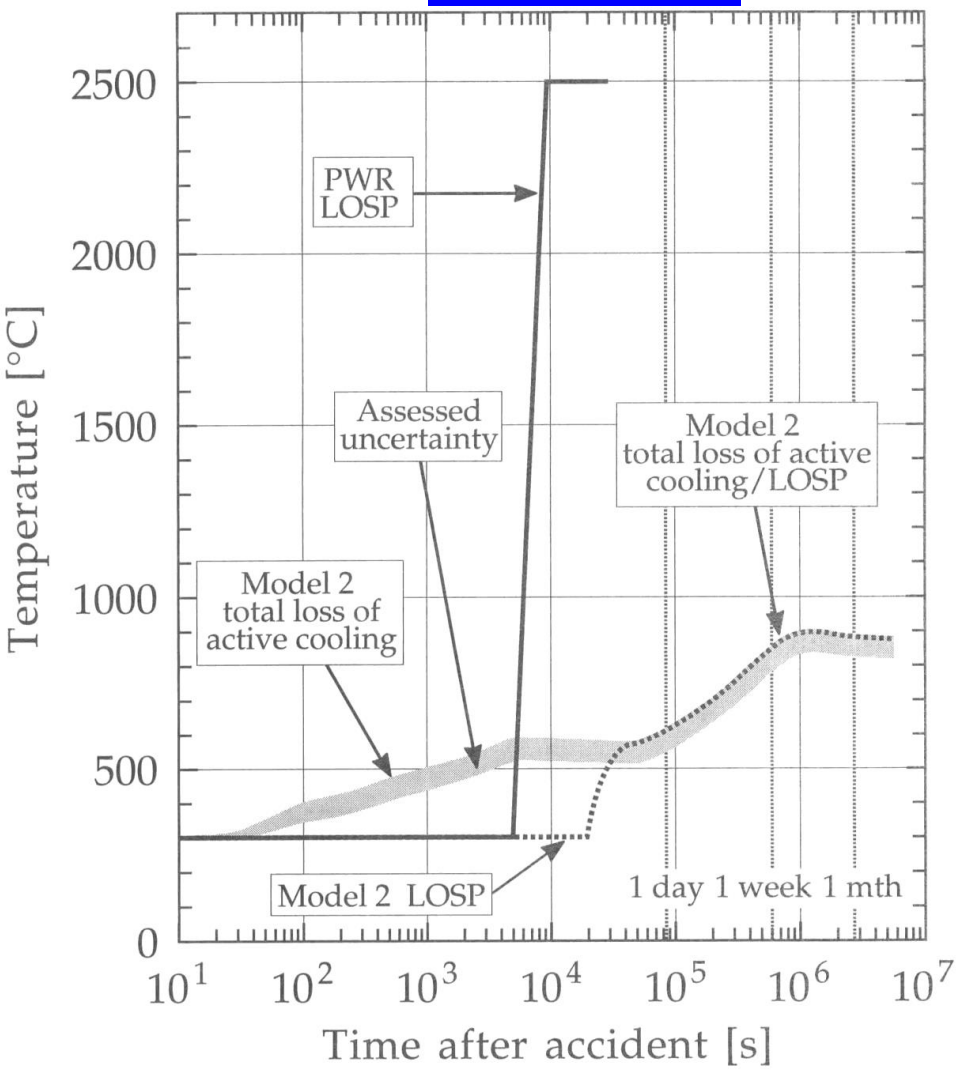
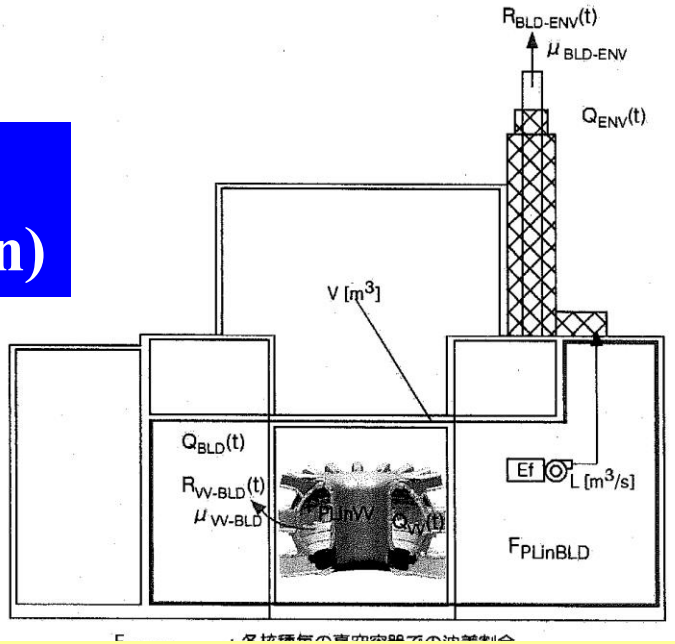


Fig. 5-15:
Temperature transients, PWR core and SEAFP model 2 (reduced activation martensitic steel, water cooling). LOSP = Loss Of Site Power.

Safety analysis in ITER (case study for inviting ITER to Japan)



@ Total inventory of tritium : 1.2 kg
@ All of tritium is assumed to be released inside the building.
@ The efficiency of tritium capture by the ventilation system of the building is assumed to be 99 %.
@ This results in the 1 % tritium release (12g HTO) through a stack (100 m in height).
@ Several climate conditions have been considered, and most severe condition is employed.

=> **This yields 0.9 mSv at 400 m from the site, resulting in no evacuation.**

ARIES-AT
in-vessel LOCA

	inventory	release
tritium	**205 g**	**7.6 g**
W dust	10 kg	207 g

➡ Site boundary < 10 mSv