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Molten-Salt Reactor FUJI and Related Thorium Cycles

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International Thorium Molten-Salt Forum

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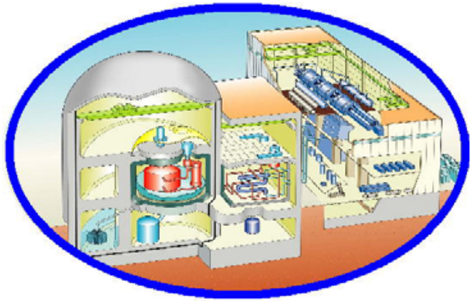
Ritsuo Yoshioka
1970-2004: Nuclear engineer for 30 years on BWR design and licensing, and 15 years for MSR design
2005- :President of Japan Functional Safety Laboratory
2008-:Vice-president of International Thorium Molten-Salt Forum

(1)

Molten-Salt Reactor "FUJI"



"Self-sustaining Core Design for 200 MWe Molten-Salt Reactor with Thorium-Uranium Fuel :FUJI-U3", K. Mitachi, R. Yoshioka et.al.TU2007, Beijing, China

Previous works at ORNL

1.0GWe large plant

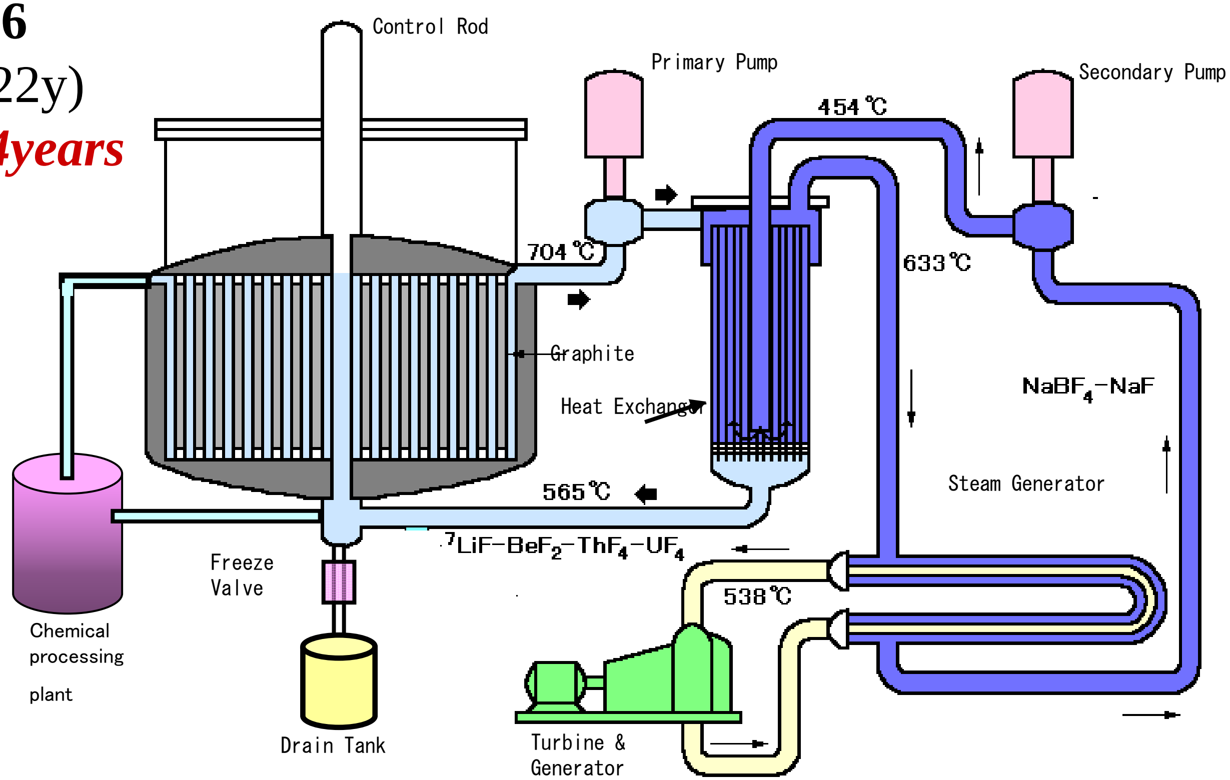
Reactor vessel: 6.8m in diameter
6.1m in height

Continuous chemical processing

Conversion ratio: **1.06**
(Fuel doubling time=22y)

Replace Graphite at every 4years

MSBR (1970)



Previous works in Japan

Target: (1) Small plant to deploy widely in the world.

(2) Remove Continuous chemical processing to simplify.

(3) Increase graphite replacement interval.

FUJI-II (1990)
Output power : 150MWe (350MWt)
Batch chemical processing
at every 7.5years
Replace graphite at every 15years

FUJI-12 (1999)
Output power : 150MWe (350MWt)
Batch chemical processing
at every 7.5years
Conversion ratio is **0.92**
Replace graphite at every 15years

Not enough for the above targets.

FUJI-U3 design targets

Design targets

1. Output power: 200MWe, Load factor: 0.75
2. Reactor is operated without graphite replacement for 30years of reactor life
3. Reactor is operated with batch chemical processing at every 7.5years (=2000 Effective Full Power Days).
4. Self sustaining, if possible (Conversion ratio=1.0)

Irradiation limits

Graphite(>52keV) : $\phi_G < 4.2\times10^{13}$ [1/(cm^{2}s)]

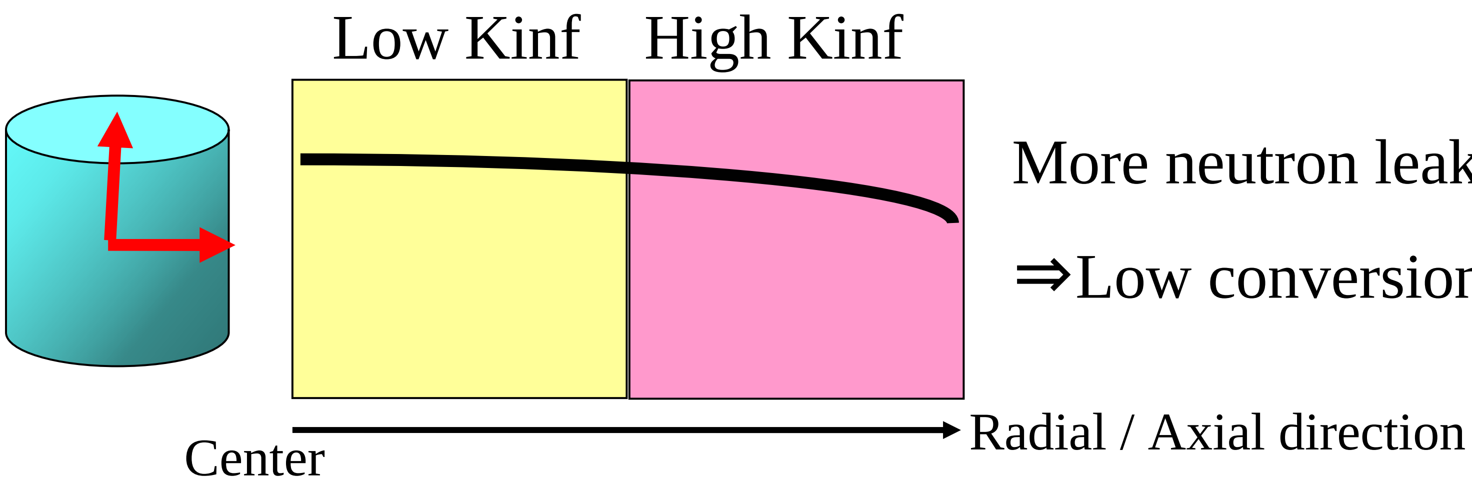
Vessel(>0.8MeV) : $\phi_F < 1.4\times10^{11}$ 〃

(<0.18eV) : $\phi_{th} < 7.1\times10^{12}$ 〃

⇒ Flux flattening is necessary
to reduce irradiation at core graphite..

FUJI-U3 concept

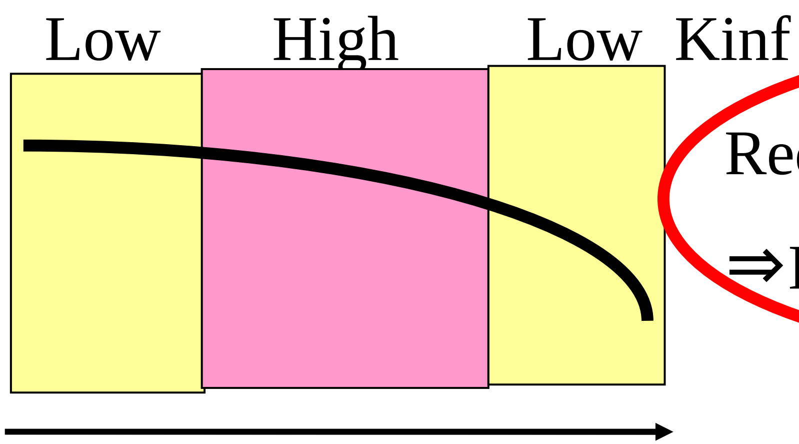
Flux flattening for 2-region core.



More neutron leakage,

⇒Low conversion ratio.

Flux flattening for 3-region core.

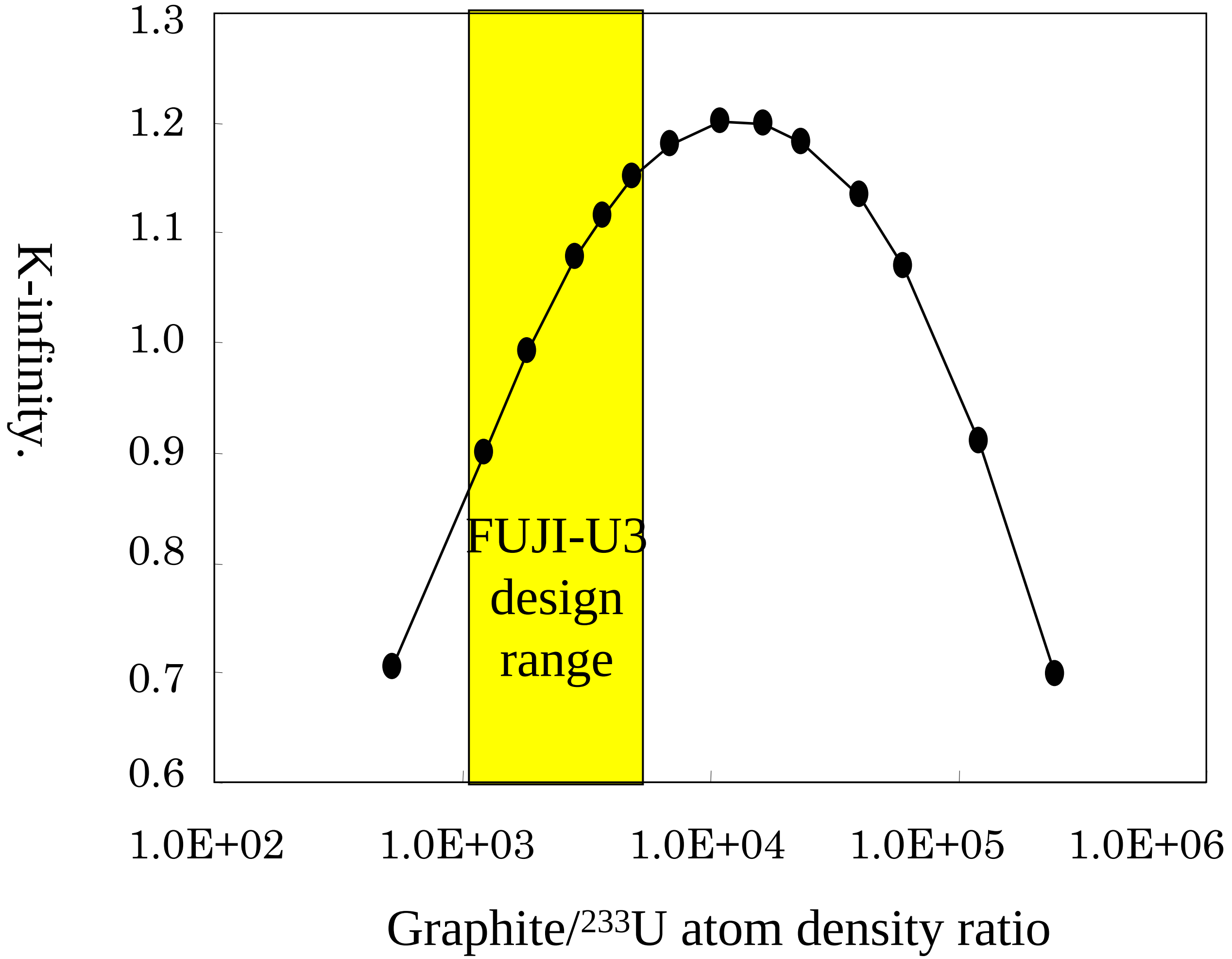


Reduced neutron leakage,

⇒High conversion ratio.

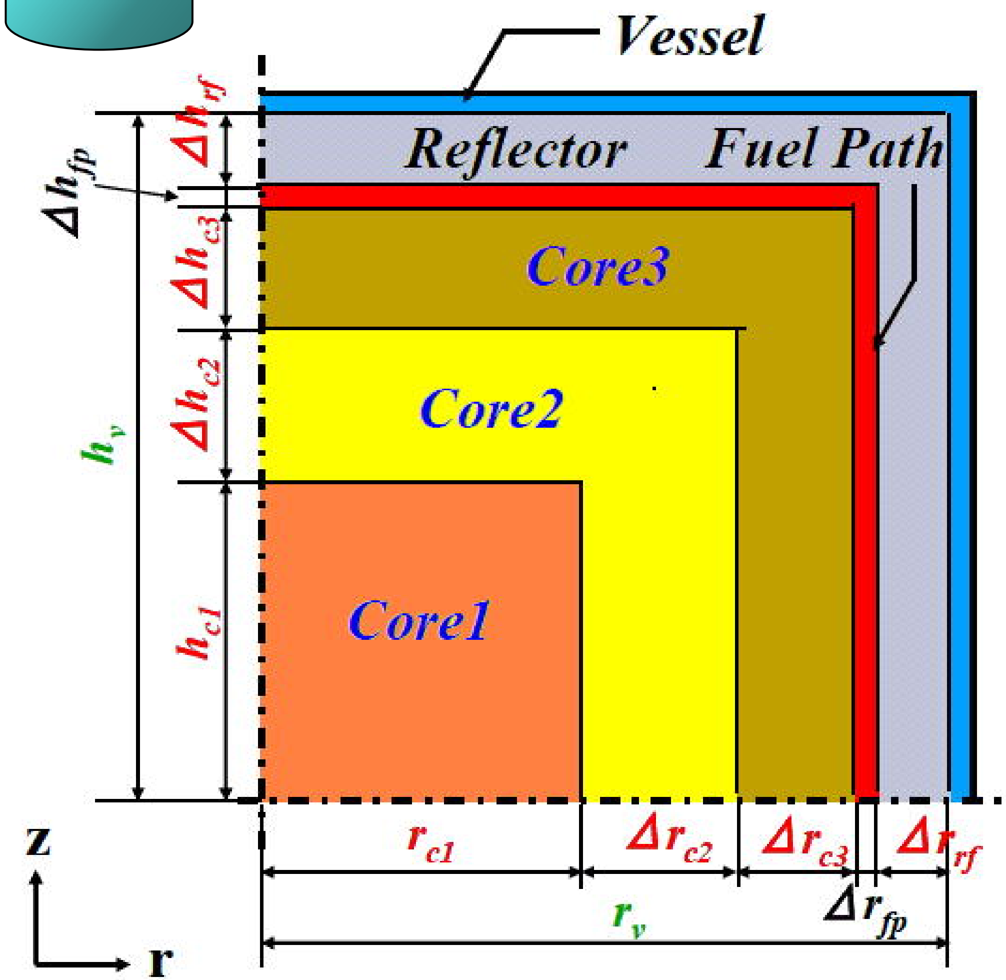
FUJI-U3 design

K-inf. vs. G/U ratio



K-inf can be changed by changing G/U ratio.

FUJI-U3 dimension



	Core 1	Core 2	Core 3
r or Δ r (m)	1.16	0.80	0.40
h or Δ h (m)	1.23	0.70	0.40
Graphite volume fraction	0.61	0.73	0.55

Reflector thickness= 0.30 m

FUJI-U3 design results (1/2)

Electric output Thermal output Thermal efficiency	200 MWe 450 MW(th) 44.4%
Conversion ratio (av.)	1.01
Temperature coefficient (av)	-2.7×10^{-5} 1/K
Maximum neutron flux Graphite (>52 keV) Vessel (>0.8 MeV) (<1.0 eV)	 4.1×10^{13} 1/(cm^2·s) 1.4×10^{11} 1/(cm^2·s) 2.5×10^{12} 1/(cm^2·s)

Self-sustaining is achieved.

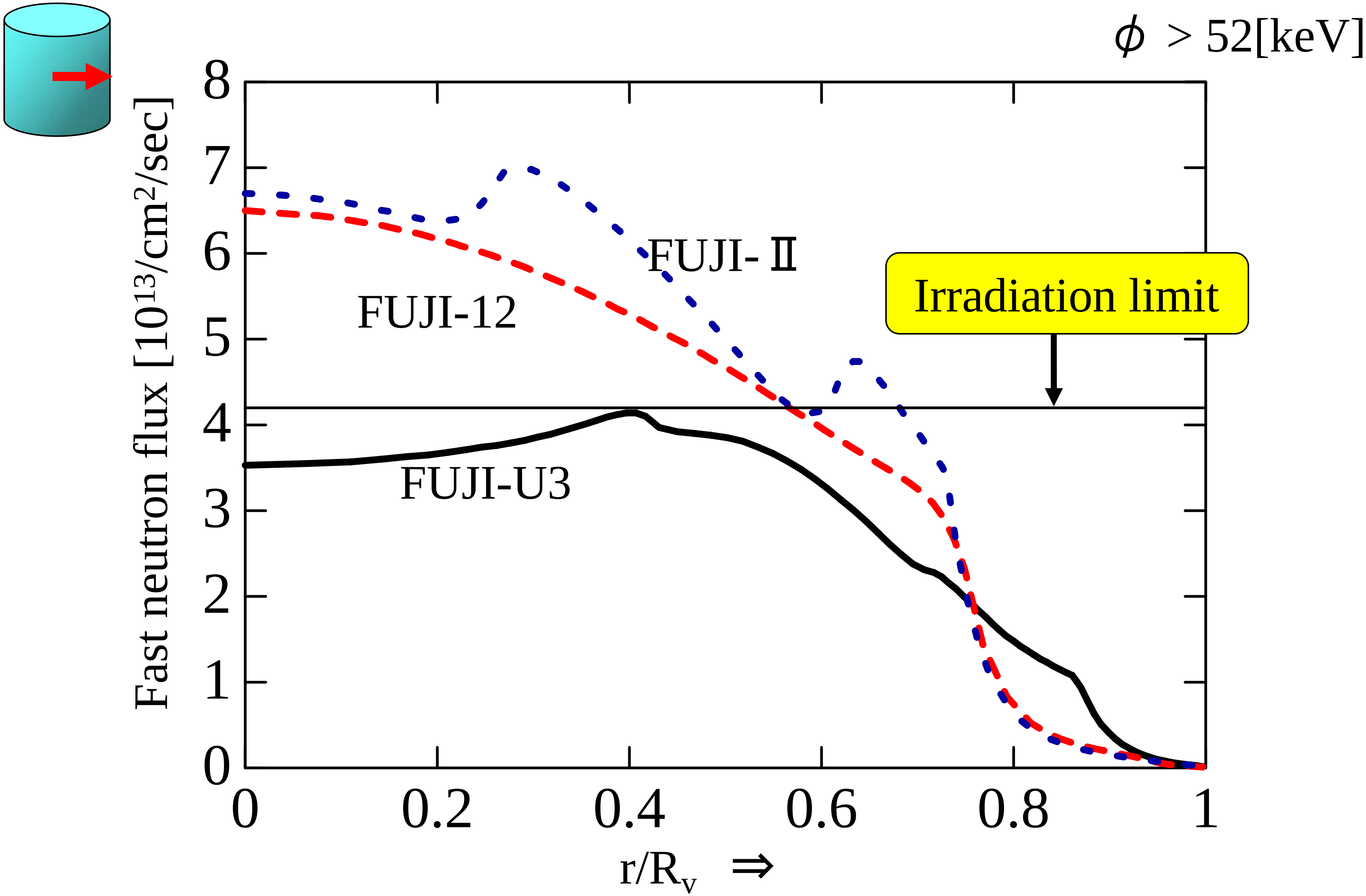
Irradiation limits are satisfied.

FUJI-U3 design results (2/2)

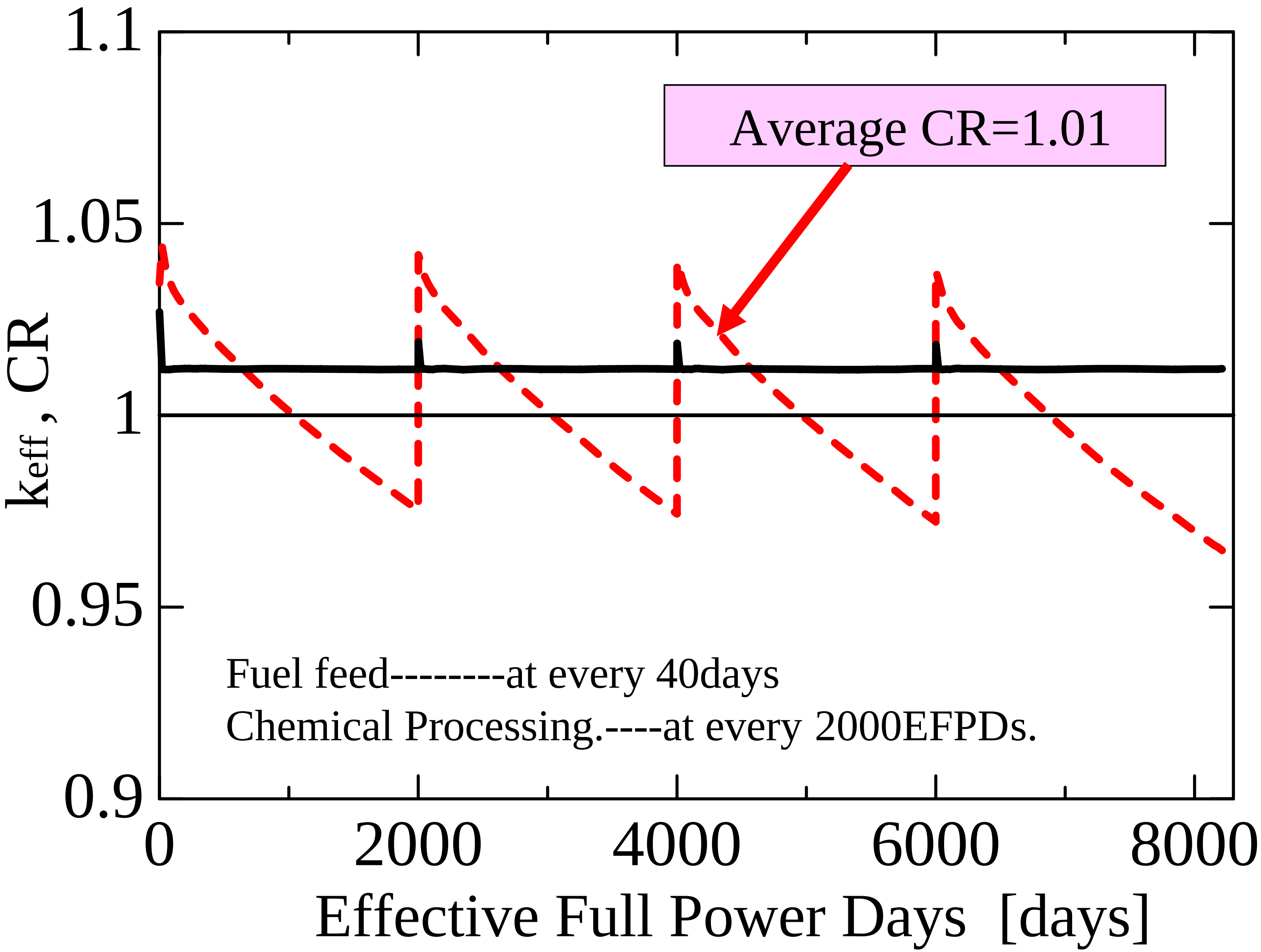
Fuel salt	
Composition	$LiF-BeF_2-ThF_4-UF_4$
mol%	71.76-16.0-12.0-0.24*
Inventory in primary loop	
^{233}U	1.133 ton*
Th	56.4 ton*
Graphite	163.1 ton

*: Initial condition

Fast neutron flux distributions (Radial)



Keff and Conversion Ratio



Material balance (200MWe FUJI)

	Th(t)	U-fissile(t)	Pu(kg)	MA(kg)
(1) Initial iventory	56.4	1.133	--	--
(2) Net feed	5.2	0.426	--	--
(3) Total demand =(1+2)	61.6	1.559	--	--
(4) Final remaining amount	57.5	1.584	0.70	4.55(*)
(5) Net production =(4-3)	-4.1	0.025	0.70	4.55(*)

(*) MA:Minor Actinides:

Np=3.16kg, Pa(except ^{233}Pa) =1.39kg, Am=0.2g, Cm=0.02g

Material balance (scaled to 1 GWe plant)

	FUJI-U3	BWR
Output power (Gwe)	1.0	1.0
Reactor operation time (year)	30.0	25.9
Load factor	0.75	0.87
(1) Initial inventory of U-fissile (t)	5.7	3.9
(2) Net feed of U-fissile (t)	2.1	20.7
(3) U-fissile total demand (t) =(1+2)	**7.8**	24.6
(4) Final remaining U-fissile (t)	7.9	(6.9)
(5) Net production in reactor life =(4-3)		
U-fissile (t)	**0.1**	-17.7
Pu-total (kg)	**3.5**	5080
Minor Actinides (kg)	**23**	543

FUJI-U3 Conclusion (1/2)

1	30 years operation (with load factor 75%) is possible, **without replacing graphite moderator**, for FUJI-U3 of 200 MWe and 44.4% thermal efficiency.
2	Average Conversion Ratio is as high as **1.01**, and it is almost **self-sustaining**. Also, the residual fissile at the end of the reactor life can be used to the next FUJI.

FUJI-U3 Conclusion (2/2)

(Scaled to 1-GWe, to compare with 1-GWe BWR)

3	The ^{233}U requirement for FUJI-U3 is 7.8 t (= **32% of BWR)**. Also, the residual fissile, which is 7.9 t at the end of the reactor life, can be used to the next FUJI.
4	Pu production for FUJI-U3 is only 3.5 kg (=**0.1% of BWR**).
5	Minor Actinides production is only 23 kg (=**4% of BWR**).

(2)

1GWe MSR "superFUJI"

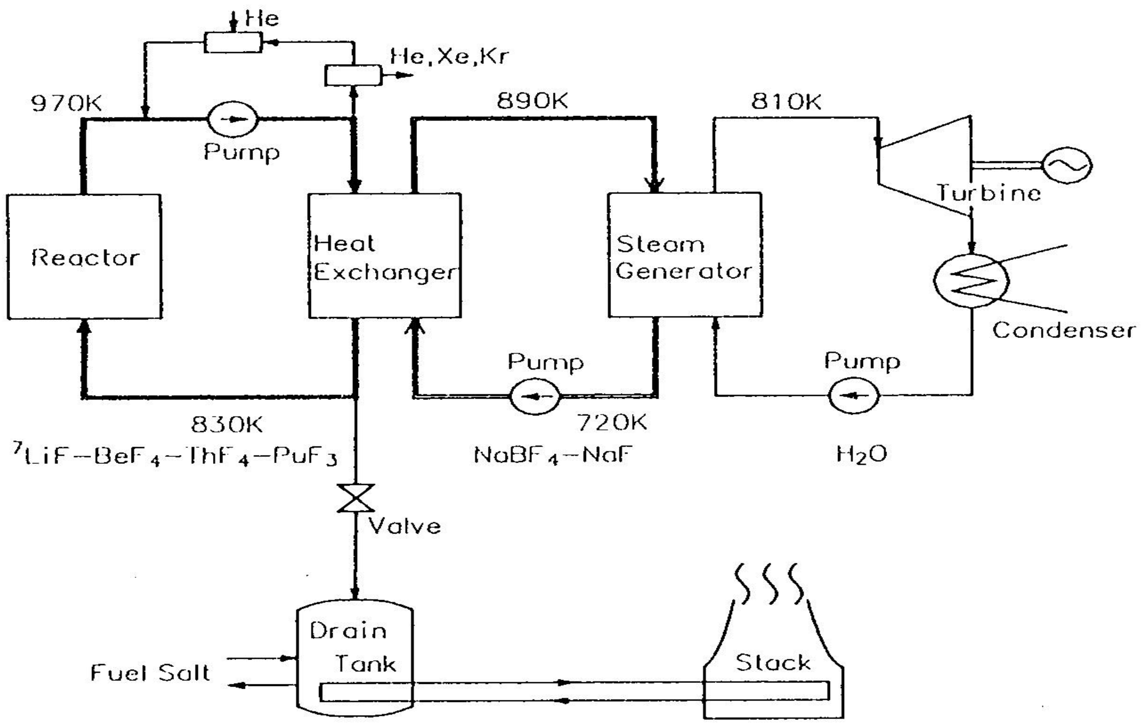
"A Conceptual Design of 1GWe Molten Salt Reactor"

K. Mitachi, R. Yoshioka et.al. 4th Power Energy Symposium, 1994

(in Japanese)

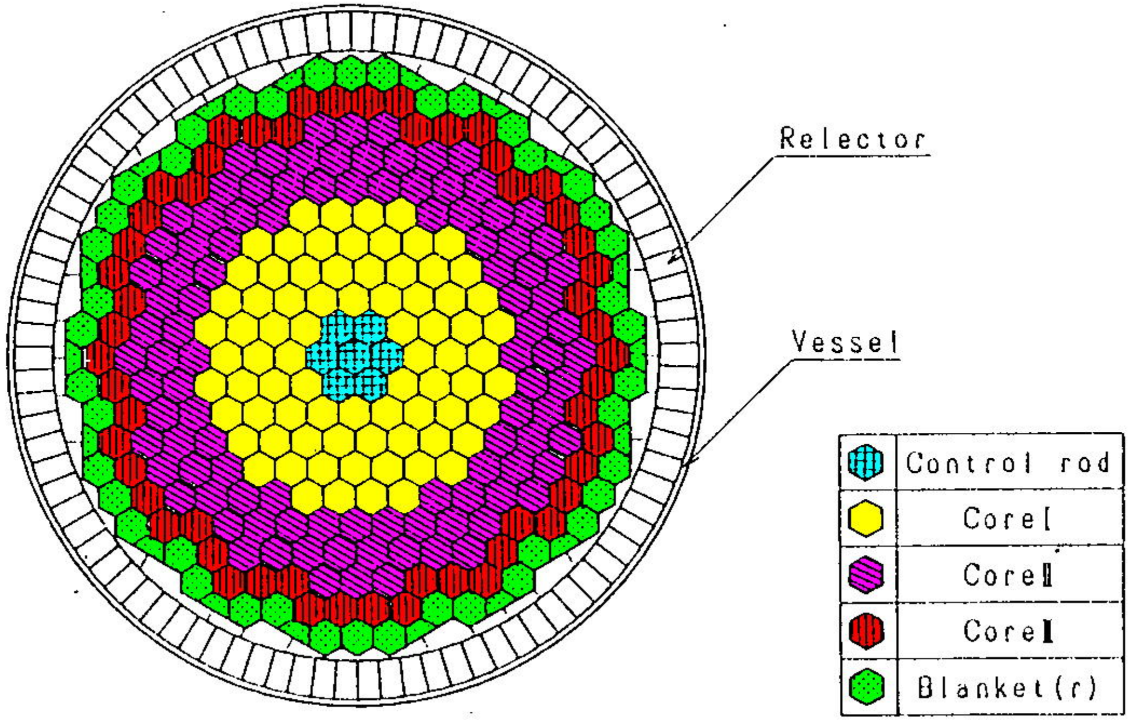
superFUJI plant condition

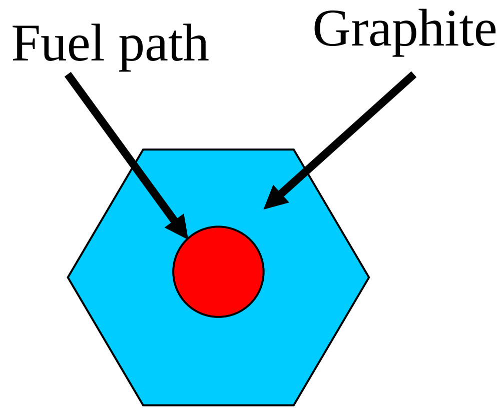
Thermal output	2,272 MWt
Electric output	1,000 MWe
Thermal efficiency	44.0%
Reactor vesse1 Diameter / Height	9.9 m / 6.7 m
Power density	7.2 MWt/m3



superFUJI core concept

Region	Maximum radius	Graphite fraction
Core-I	2.3m	93vol%
Core-II	3.4m	90vol%
Core-III	3.9m	85vol%
Blanket	Thickness 0.4m	80vol%



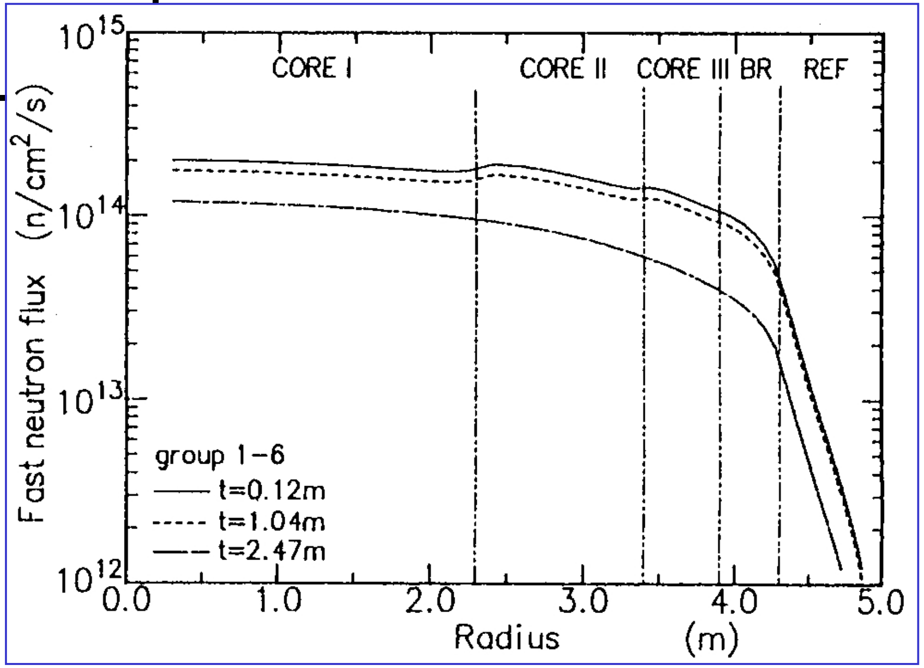


superFUJI design results

Fuel salt composition mol%	$LiF-BeF_2-ThF_4-UF_4$ 71.8-16.0-12.0-0.2*
Inventory(primary loop) ^{233}U Th Graphite	$62m^3$ 1.5 ton* 90.2 ton* 837 ton
Conversion Ratio	0.98*

*: Initial condition

Fast & epi-thermal neutron flux



superFUJI conclusion

1	1GWe FUJI is feasible.
2	Conversion Ratio is 0.98 or less.
3	Core Graphite requires replacement at 20 years (assuming 75% load factor).

(#2 and #3 can be improved as FUJI-U3.)

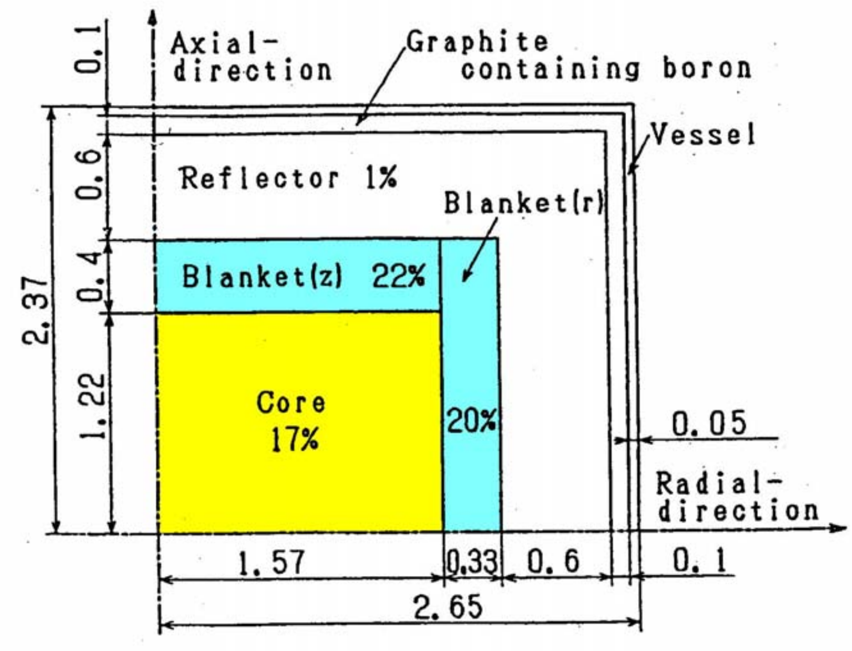
(3)

FUJI with Pu Fuel

"Neutronic Examination on Plutonium Trans mutation by a Small Molten-Salt Fission Power Station", K. Mitachi, et al., part of IAEA TECDOC-840, 1995

FUJI-Pu plant condition

Thermal output	250 MWt
Electric output	100 MWe
Thermal efficiency	40%
Reactor vesse1 Diameter / Height	5.3 m / 4.7 m
Power density	6.8 MWt/m^3

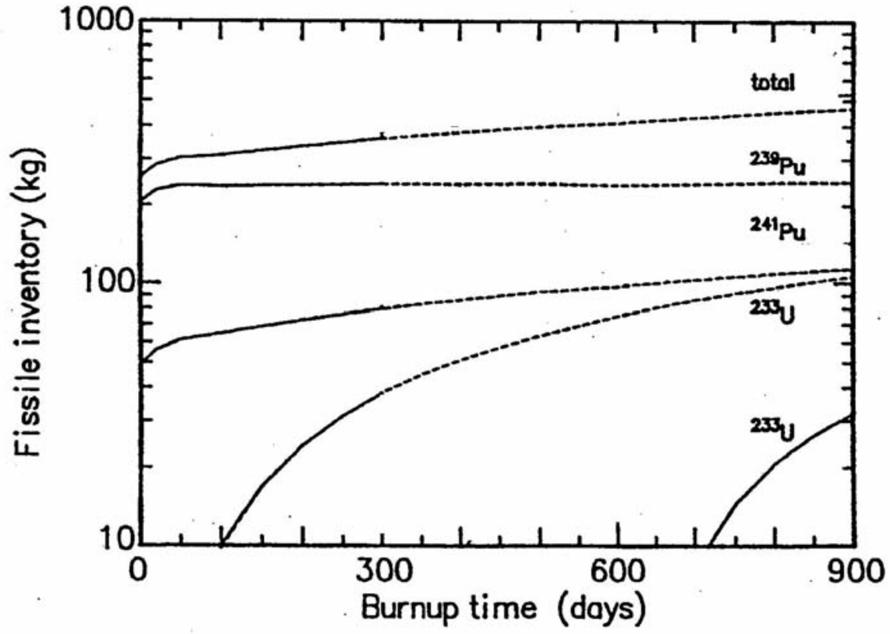


Fuel salt composition,mol%	$LiF-BeF_2-ThF_4-PuF_3$ 71.8-16.0-12.0-0.25*
Inventory(primary loop)	12.0m^3
Fissile Pu	0.275 ton**
Th	17.3 ton*
Graphite	167 ton

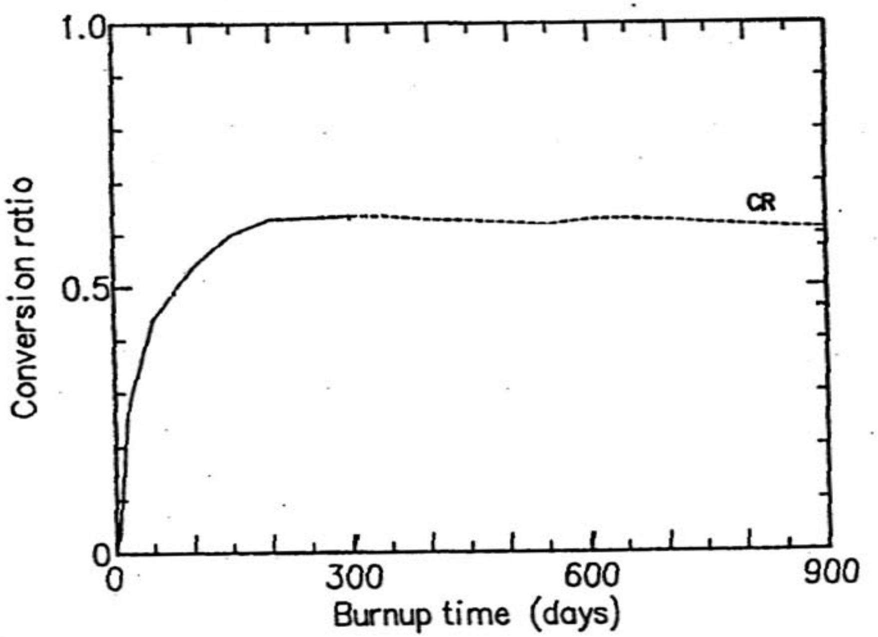
*: Initial condition. **:Pu from PWR 33GWd/t fuel.

FUJI-Pu design results

Fissile inventry vs. Time



Conversion ratio vs. Time



(Time behaviour for 900 Effective Full Power Days)

FUJI-Pu Material balance

	Initial	Feed (up to 900d)	Residual (at 900days)	Net production (R-I-F)
Pu fissile	254 kg	350 kg	360 kg	-244 kg
U fissile (+^{233}Pa)	0	0	112 kg	112 Kg
Th	17.4 ton	0.13 ton	17.4 ton	-0.1 ton
Conversion Ratio			0.61	

FUJI-Pu conclusion

If normalized to 1GWe with 1-year(365days) operation, FUJI-Pu can decrease 991 kg Pu-fissile, and produce 455 kg U-fissile.

normalized to 1GWe/year operation by a factor 4.06 (=1,000/100 x 365/900)

(4)

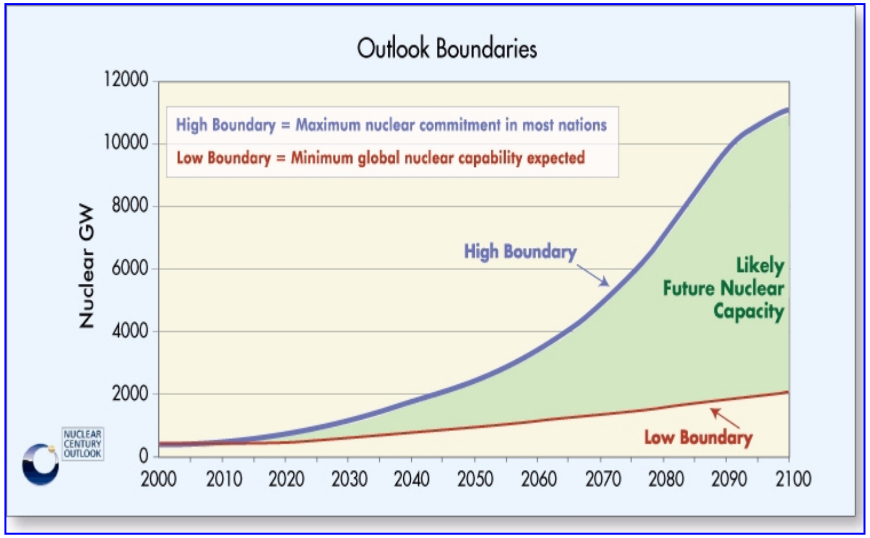
Related Thorium Fuel Cycles

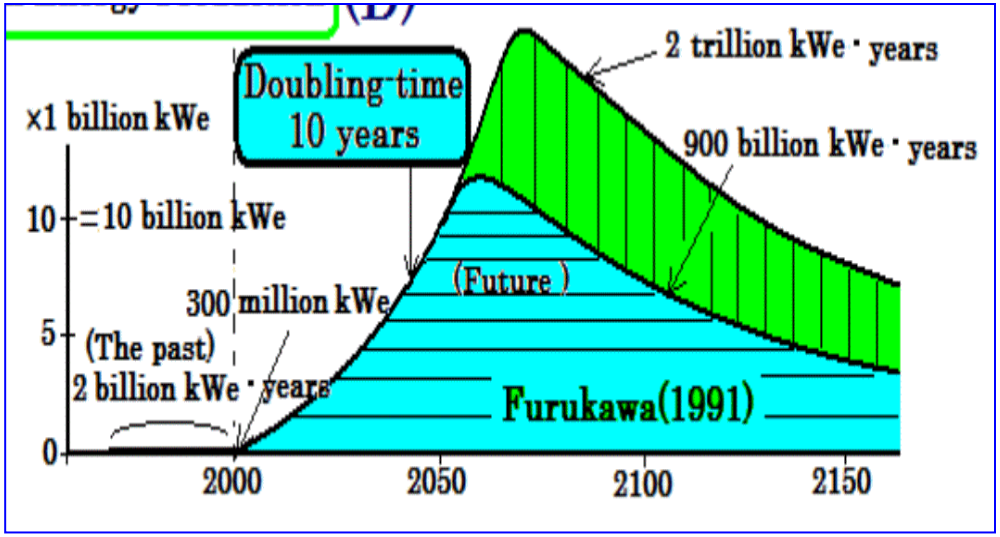
"A road map for the realization of global-scale thorium breeding fuel cycle by single molten-fluoride flow"

K. Furukawa, et al, Energy Conversion and Management 49 (2008)

Huge installation is required

World Nuclear Association suggests world nuclear capacity at year-2100 is about 10TWe (=10,000 x 1GWe plant). (Nuclear Century Outlook, 2009/12)
This is almost 30 times larger than current nuclear capacity.
Furukawa's estimate is similar at year-2065. (Energy Conv. & Man. 49, 2008)
So, huge fissile is required.





AMSB by proton beam of 1GeV/300mA can produce about 1ton/year U233.
So, 1,000 AMSBs can start 100x1GWeMSRs/year, and achieve 10,000 reactors after 100 years.

(5)

Summary

Summary

1	Small sized FUJI and 1GWe superFUJI have been studied.
2	FUJI can achieve self-sustaining (CR=1.0) with U233.
3	MSR can start with Pu, from LWR reprocessed fuels.
4	Huge number of MSR can start by U233 produced in AMSB.
5	MSR can operate with U235, as was shown in Denatured-MSR design by ORNL. This will help larger installation of MSR, if we do not have enough U233 or Pu-fissile as a startup fuel. (our future study)

Thank you for the attention!
Any questions/comments?