Life Cycle Assessment for Energy Payback of Spherical Tokamak Reactors

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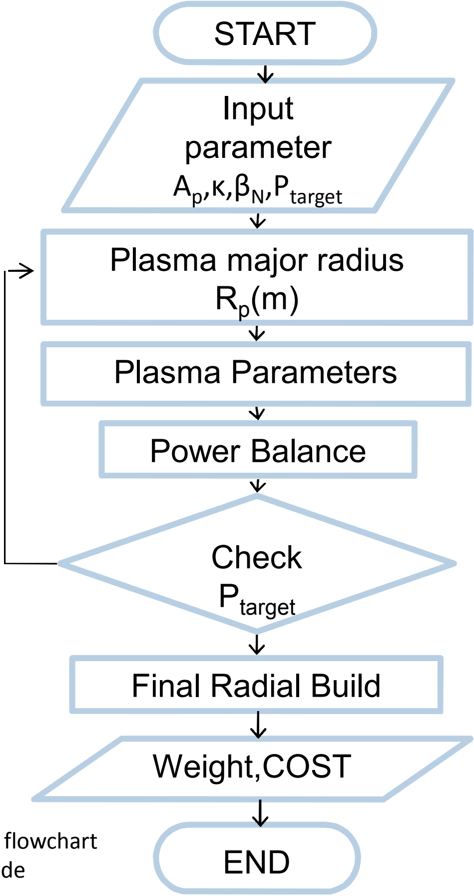
Motivation

1. In order to realize the fusion energy plant, high social acceptability is required.
2. In the previous study, we have evaluated the COE (Cost of Electricity), carbon dioxide emission, and the EPR (Energy Payback ratio) of each reactor, tokamak, helical, spherical tokamak.
3. We need use the energy effectively, because it is limited. The EPR is the evaluating how a power plant produces effectively from the lower input energy. Thus the effect of social conditional change on the EPR is considered to be smaller than that on the COE. In this study, we analyze the EPR in particular.
4. We had known that the COE of compact tokamak reactor is lower than that of the others. But the EPR of that is not known in detail.
5. From the above, we evaluated the EPR of spherical tokamak and compact tokamak reactors with low aspect ratio in this study.

Method of analysis



START

Input parameter $A_p, \kappa, \beta_N, P_{target}$

Plasma major radius R_p(m)

Plasma Parameters

Power Balance

Check P_{target}

Final Radial Build

Weight,COST

END

Fig1. The flowchart of PEC code

Physics, Engineering and Cost (PEC) code

- First, we input some parameters which design the plasma shape.
- If the net electrical power achieves the target value (typically 1GWe), the plasma radius is decided. And then, the Radial build is decided. (The radial build is the thickness of the components for radial direction.)
- The fusion island weight and the total cost of the components are evaluated.

- **Life Cycle Assessment**

  We evaluate from resources supply to decommission.

About Energy Payback Ratio (EPR)

The EPR means outputting energy efficiency. The EPR is defined as ratio of output energy to input energy. Input energy is as follows.

$$EPR = \frac{E_{output}}{E_{const.} + E_{operation} + E_{fuel} + E_{replace} + E_{Decon.}}$$

Construction

Input energy into the construction = The weight or cost of each components × Energy intensity [TJ/t] or [TJ/M$]

Fusion Island (FI)	**material**
First wall/blanket/shield	
Spherical Tokamak (ST)	SiC (like ARIES-ST)
Tokamak Reactor (TR)	SiC (like ARIES-AT)
magnet normal (NC)	Cu (Center-Post), Al
super (SC)	Nb_3Sn
vacuum vessel	SS

A part of the Balance of Plant (BOP)	**Formula [TJ]**
turbine	$240.3 * \left(\frac{P_{egross}[MW]}{1200}\right)^{0.83} * 6.31$
primary coolant system	$233.9 * \left(\frac{P_{th}[MW]}{3500}\right)^{0.55} * 5.49$

$$EPR = \frac{E_{output}}{E_{const.} + E_{operation} + E_{fuel} + E_{replace} + E_{Decon.}}$$

Operation

The energy requirements for operation including fixing and maintenance is evaluated.

The operation energy is assumed as **5% of input construction energy every year**.

Replacement

- The energy requirement for **blanket, divertor, and a part of the NBI** exchanges is evaluated. Only the case of ST has to replace the **center post**.
- The frequency of replacement is decided with the neutron wall load.

Fuel

The fusion reactors in this study use the deuterium-tritium reaction.

The tritium is bred in the blanket. Thus we consider the amount of deuterium consumed in fusion reaction.

Energy intensity of Deuterium is 140 [TJ/t].

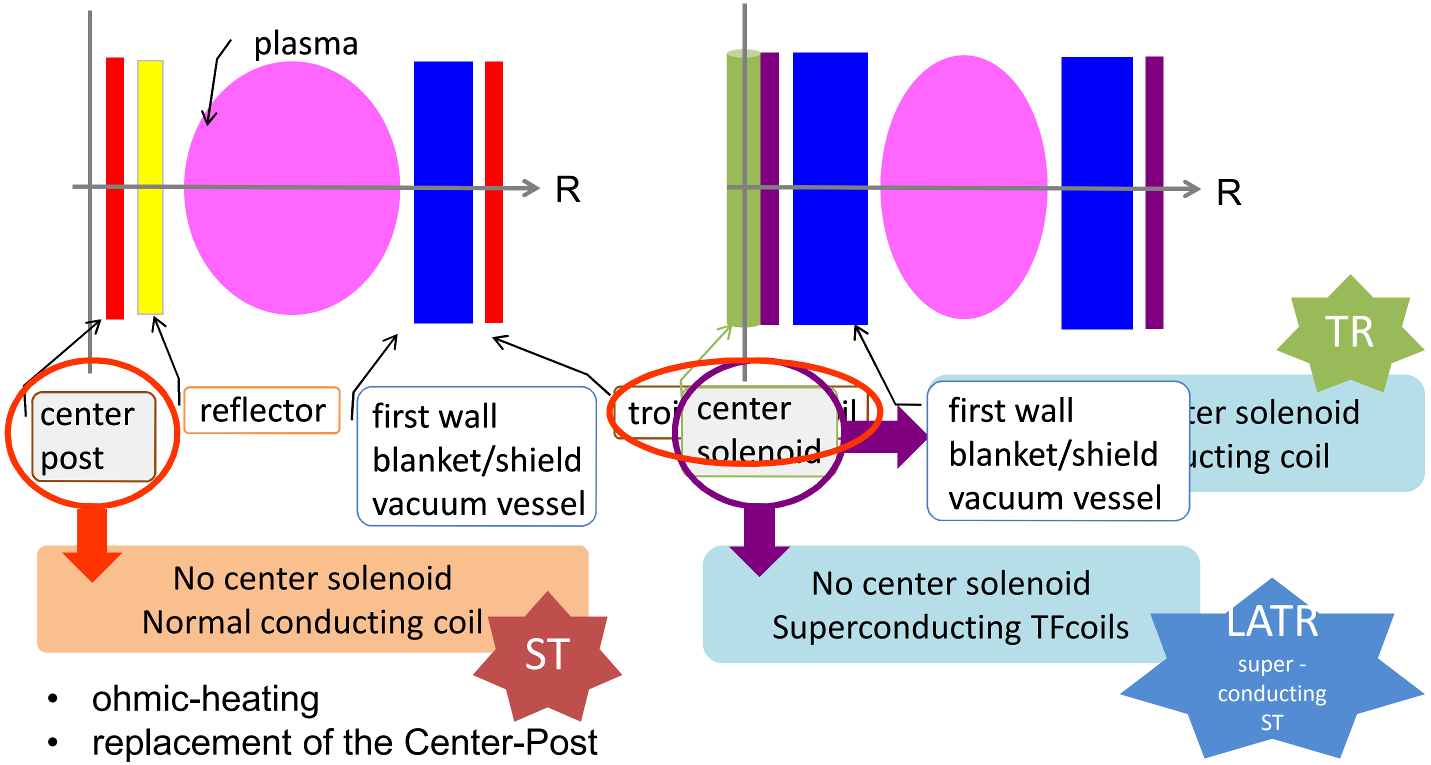
Decommission&Decontamination

We assumed that the decommission cost is 0.5M$.

We multiply the decommission cost by energy intensity of industry waste disposal .

Reactor models

- Spherical Tokamak Reactor(ST)
- Tokamak Reactor



center post

reflector

first wall
blanket/shield
vacuum vessel

No center solenoid
Normal conducting coil

troi center il
solenoid

first wall
blanket/shield
vacuum vessel

ter solenoid
ucting coil

No center solenoid
Superconducting TFcoils

- ohmic-heating
- replacement of the Center-Post

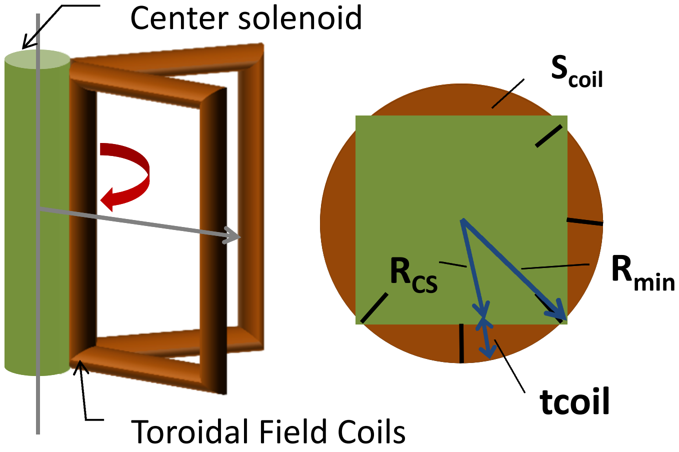
The design of the TFCoils

The cross section of toroidal field coil is calculated from the coil current. This upper equation describes the relationship of the coil current and toroidal field coil cross section.

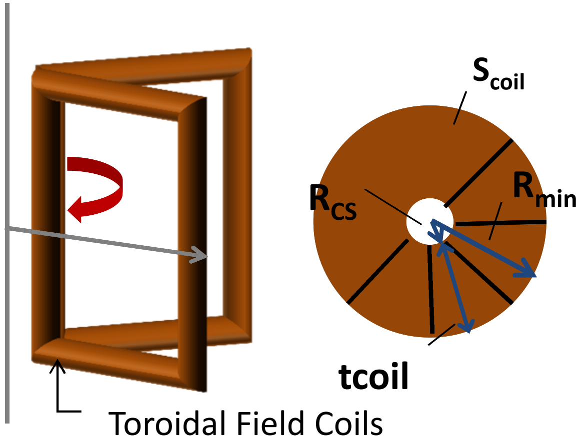
$$I_{coil} = 2\pi R_p B_T / \mu_0 = 5 \times 10^6 R_p B_T$$

$$S_{coil} = I_{coil} / J_{max}$$

Major plasma radius: R_p[m]
toroidal field: B_t [T]
maximum coil current density: J_{max}[MA/m^2]
coil current: I_{coil} [MA]

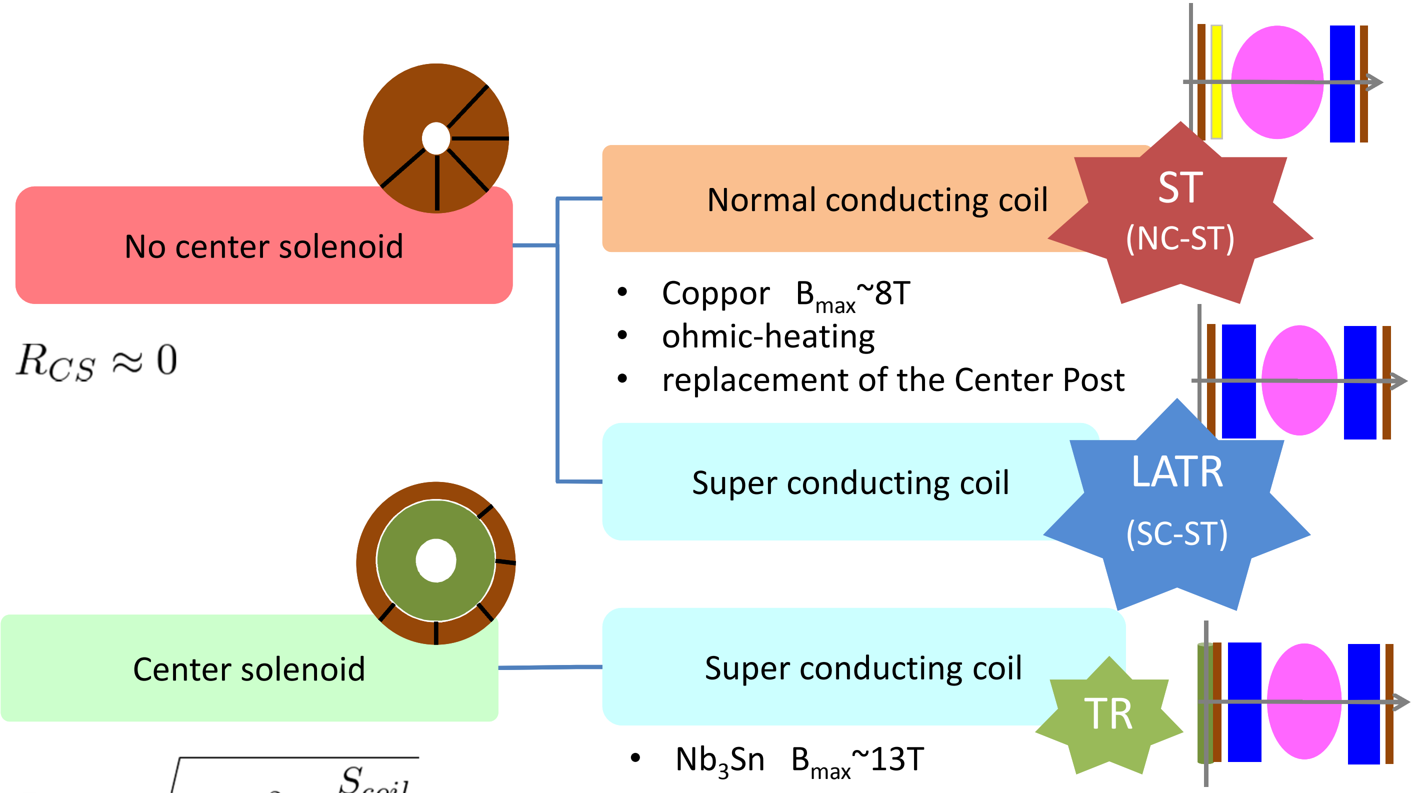


$$R_{CS} = \sqrt{rmin^2 - \frac{S_{coil}}{\pi}}$$



$$R_{CS} \approx 0$$

Classification of reactor types



No center solenoid

$R_{CS} \approx 0$

Normal conducting coil

ST

(NC-ST)

- Coppor B_{max}~8T
- ohmic-heating
- replacement of the Center Post

Super conducting coil

LATR

(SC-ST)

Center solenoid

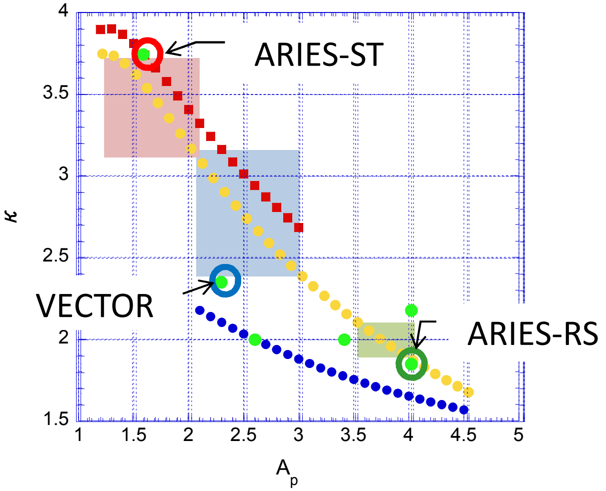
Super conducting coil

TR

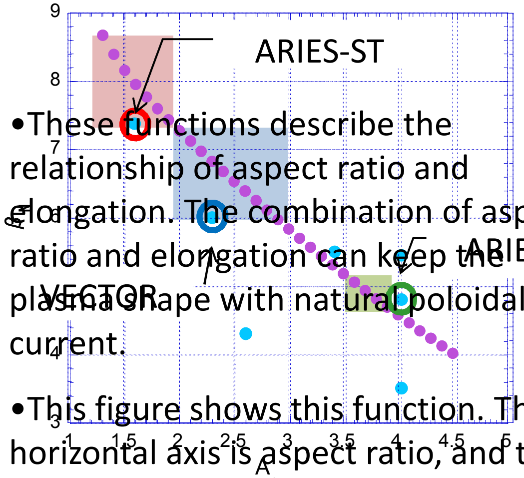
- Nb_3Sn B_{max}~13T

$$R_{CS} = \sqrt{rmin^2 - \frac{S_{coil}}{\pi}}$$

Analysis range of κ and β_N



P.C.P. Wong, et al;FTP2/17 Sorrento (2000).



- These functions describe the relationship of aspect ratio and elongation. The combination of aspect ratio and elongation can keep the plasma shape with natural poloidal coils current.
- This figure shows this function. The horizontal axis is aspect ratio, and the vertical axis is elongation. The line in red shows the case of ST, and the blue line is fitted into that of TR.
- To consider the situation of both ST and TR, we assume a new fitting line in yellow.

Fitting Tokamak Reactors

1.2<A_p<7.0 1.5<κ<6.0

$$\kappa_{PEC} = \kappa \times (-0.04A_p + 1.04)$$

$$\kappa^* = \kappa(0.05A_p + 0.55)$$

- We substituted elongation for the equation and evaluated β_N

$$\beta_N = 10.0(b_0 + b_1\kappa + b_2\kappa^2 + b_3\kappa^3)coth\left(\frac{d_0 + d_1\kappa}{A^m}\right)\frac{1}{A^n}$$

$b_0 = -0.7748$ $d_0 = 1.8524$
$b_1 = 1.2869$ $d_1 = 0.2319$
$b_2 = -0.2921$ $m = 0.6183$
$b_3 = 0.0197$ $n = 0.5524$

Y.R.Lin-Liu et al; Nucl. Fusion 44 (2000) 635.

ST		
A_p	**κ**	**β_N**
1.2	3.75	9.02
1.4	3.69	8.40
1.6	3.54	7.96
1.8	3.35	7.60
2.0	3.17	7.28

LATR		
A_p	**κ**	**β_N**
2.2	2.99	6.98
2.4	2.82	6.68
2.6	2.66	6.40
2.8	2.52	6.12
3.0	2.39	5.85

K.Tobita et al; JAEA-Research 2010-019 (2010).

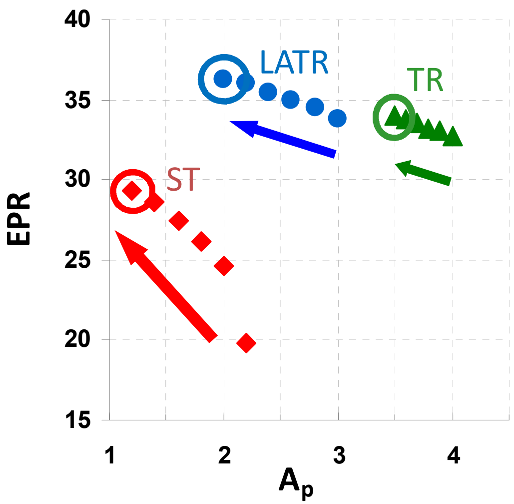
TR		
A_p	**κ**	**β_N**
3.5	2.10	5.19
3.6	2.05	5.07
3.7	2.01	4.95
3.8	1.96	4.83
3.9	1.91	4.71
4.0	1.87	4.59

Results

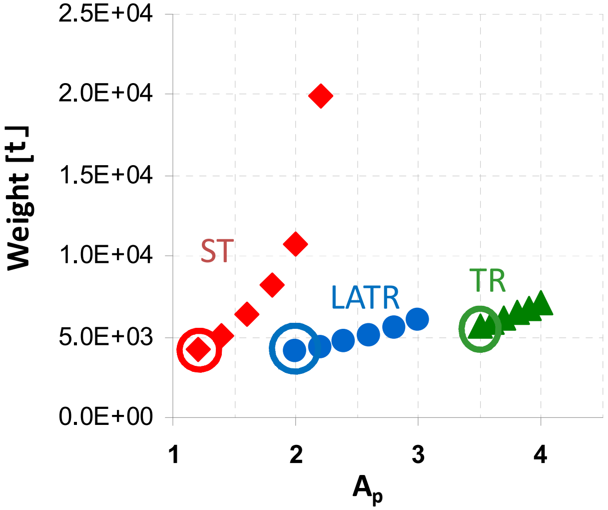
Aspect ratio dependence of the EPR

We show you that the relationship of aspect ratio and the EPR. We use the parameter, aspect ratio ,elongation, and normalized beta which evaluated in the previous slide.

Aspect ratio dependence of the EPR.



Aspect ratio dependence of the fusion island weight.



In the case of all reactors the lower aspect ratio is, the higher EPR is. The fusion island weight increase with increase of aspect ratio. And then, the lowest fusion island weight of each reactor are almost same. But the EPR of each reactor is different. In the next slide, we describe the reason with three typical reactor models.

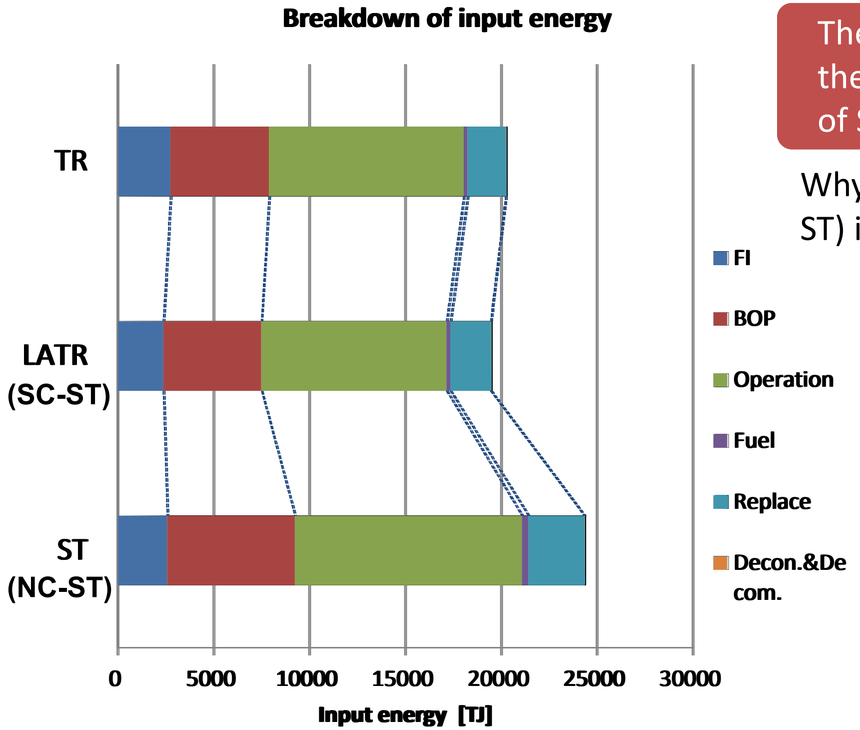
Output parameters of three typical models

	①ST	②LATR	③TR
reactor models	ARIES-ST -like	VECTOR -like	ARIES-RS -like
plasma aspect ratio A_p	1.6	2.3	4
plasma vertical elongation κ	3.74	2.35	1.85
normalized beta β_N	7.38	6	4.8
magnetic field at the coil B_{max} [T]	8	13	13
maximum coil current density [MA/m3]	10	30	30
major toroidal radius R_p [m]	4.08	4.70	6.51
minor plasma radius a_p[m]	1.31	1.33	1.20
newtron wall load [MW/m^2]	5.22	2.97	2.83
total thermal power p_{th} [MW]	3748	2351	2356
net electrical power p_{enet} [MW]	993	995	991
EPR	28	34	33

Three typical models; ARIES-ST, VECTOR, and ARIES-RS.

- Input parameter of aspect ratio, elongation, and normalized beta are as same as that of each original reactor.
- Net electrical power is 1GWe.
- Major toroidal radius of ST is the smallest.
- Total thermal power of ST is the highest.

Input energy breakdown of three typical reactor models



The input energy of LATR(SC-ST) is the lowest, and the input energy of ST(NC-ST) is the highest.

Why the input energy of the ST(NC-ST) is the highest?

- **BOP Energy of ST is the highest**

  P_{th} of ST is the highest because ohmic-heating energy is lost. Therefore the cost of BOP by P_{th} scaling is high.
- **Replace energy of ST is the highest**

  ST needs replace the center post every three years.

The EPR of LATR (SC-ST) is better.

Summary and future plans

◆ **Summary**

- **We designed ST(NC-ST),TR and LATR(SC-ST) using PEC code.**
- **We surveyed the EPR of ST(NC-ST), LATR(SC-ST), and TR with scalling aspect ratio**

  The EPR of ST(NC-ST) which aspect ratio is from 1.2 to 2.0 is lower than that of LATR(SC-ST) and TR. Now, we know that the EPR of LATR(SC-ST) is better.

- **We evaluated the EPR of three typical models, ARIES-ST, VECTOR, and ARIES-RS.**

  Input energy, especially balance of plant and replacement energy of ST(NC-ST) was most required.

◆ **Future plans**

- **We try to evaluate the EPR of the superconducting ST.**

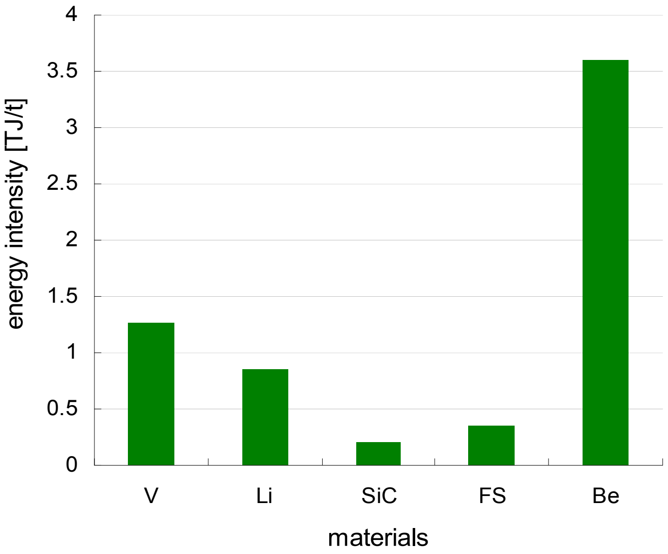
We hope this study will contribute for the establishment of the evaluating indicator for the social acceptability of fusion power plants.

	ST	LATR	TR
plasma aspect ratio	1.6	2.3	4
plasma vertical elongation	3.74	2.35	1.85
normalized beta	7.38	6	4.8
magnetic field at the coil [T]	8	13	13
maximum current density at the coil[MA/m3]	10	30	30
total useful thermal power pth [MW]	3748	2351	2356
gross electrical output power penet [MW]	993	995	991
fusion power density[MW/m3]	6.14	5.09	5.74
HH-factor	1.98	1.82	1.31
newtron wall load [MW/m2]	5.22	2.97	2.83
major toroidal radius Rp[m]	4.08	4.70	6.51
minor plasma radius ap[m]	1.31	1.33	1.20
total COE (PEC)[mill/kWeh]	99.1	78.2	82.1

		ST	LATR	TR
22.1	fusion reactor equipment	2601.2	2403.3	2777.3
22.1.1	FW/blanket/reflector	94.8	175.4	190.2
22.1.2	shield	596	561.8	633.4
22.1.3	magnets	560.6	302.3	440.6
22.1.4	current drive & heating	495.2	495.2	495.2
22.1.5	primary structure & support	75.9	152	221.6
22.1.6	vacuum systems	116.5	166.9	184
22.1.7	power supply	257.8	257.8	257.8
22.1.8	impurity control & divertor	84.5	4.8	5.1
22.1.9	direct energy conversion	0	0	0
22.1.10	ECRH breakdown system	14.4	14.4	14.4

		ST	LATR	TR
20	land & land rights	0	0	0
21	structures & site facilities	472.3	441.3	443.8
22.2	main heat transport systems	1992.4	1541.7	1543.4
22.3	auxiliary cooling system	22.6	14.2	14.2
22.4	radioactive waste management	32.2	20.2	20.2
22.5	fuel handling and storage	387.8	387.8	387.8
22.6	other reactor plant eqt.	30.9	19.4	19.4
22.7	instrumentation and control	177.3	177.3	177.3
23	turbine plant equipment	2307.7	1367.8	1370.1
24	electric plant equipment	703.7	554	554.5
25	misc. plant equipment	347	260.1	260.4
26	heat rejection system	0	126.3	126.3
27	special materials	178.6	203.7	215.2
91	construction services & eqt.	663	546.3	578
92	home office engr. & services	287.3	236.7	250.5
93	field office engr. & services	331.5	273.2	289

Energy intensity & Blanket Model

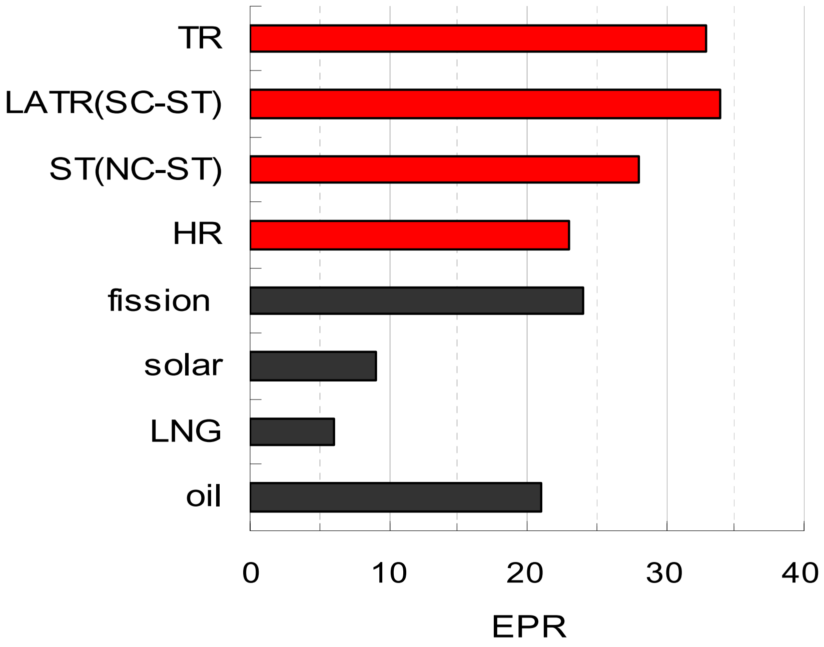


	ST	TR
Models	ARIES-ST like	ARIES-AT like
Structure	SiC,FS	SiC
Breeding	LiPb	LiPb
Energy intensity[TJ/t]	0.240	0.222

S.W.White:UWFDM-1093,University of Wisconsin (1998)
K.Tokimatsu: Fusion Engineering and Design 48 (2000) 483-498

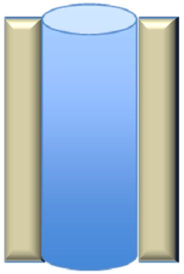
Compare with the other power plants

The EPR of fusion reactors are compared with that of other power plants



- The EPR of fusion reactors are as same as that of fission power plants.

CSC needs the cross section for the magnetic field flux



$$\Phi = L_P * I_P = B_{max} * S$$

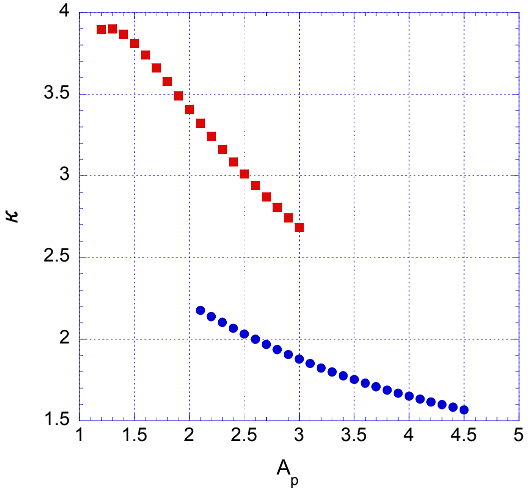
$$L_P = \left(\ln\left(8A_p/\kappa^{\frac{1}{2}}\right) + l_i/2 - 2\right) R_P$$

The thickness of blanket and shield

$$qwall\!: Neutron\ Wall\ Load[MW/m^2]$$

$$ttotal = 0.1 \times qnwall + 0.9$$
$$tblanket = ttotal \times fblanket$$
$$tshield = ttotal \times (1 - fblanket)$$
$$fblanket = 0.6(\mathrm{ST})$$

Analysis range of κ and β_N



$1.2<A_p<7.0$ $1.5<\kappa<6.0$

$$\kappa = \left(0.277 + \frac{9.127}{A_p} - \frac{5.748}{A_p^2}\right)$$

P.C.P. Wong, et al;FTP2/17,Sorrento (2000).

Fitting Tokamak Reactors

$$\kappa^* = \kappa(0.05A_p + 0.55)$$

K.Tobita et al; JAEA-Research 2010-019 (2010).

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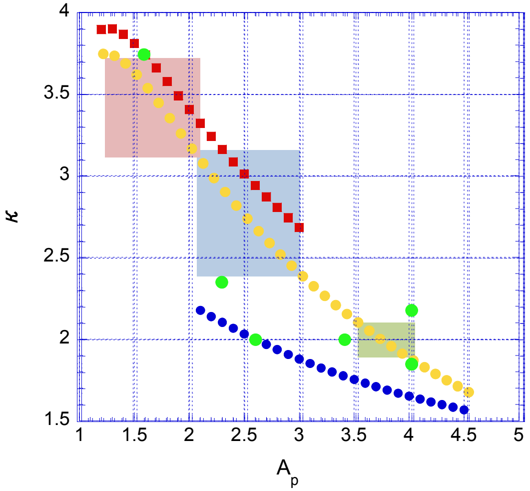

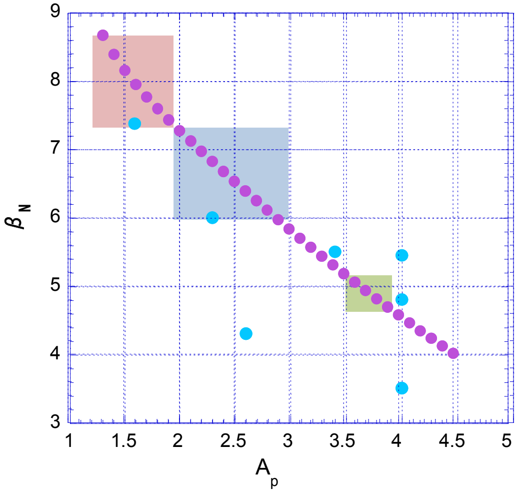

$1.2<A_p<7.0$ $1.5<\kappa<6.0$

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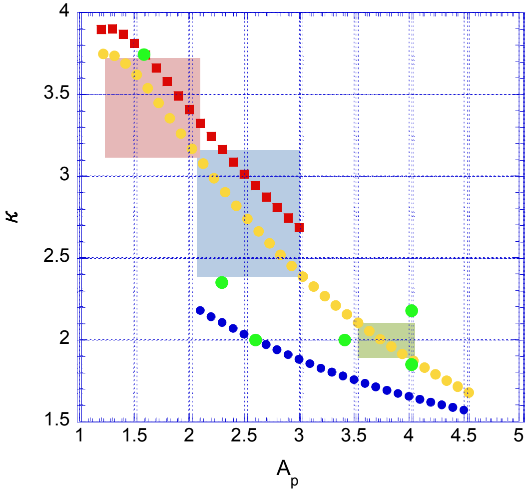

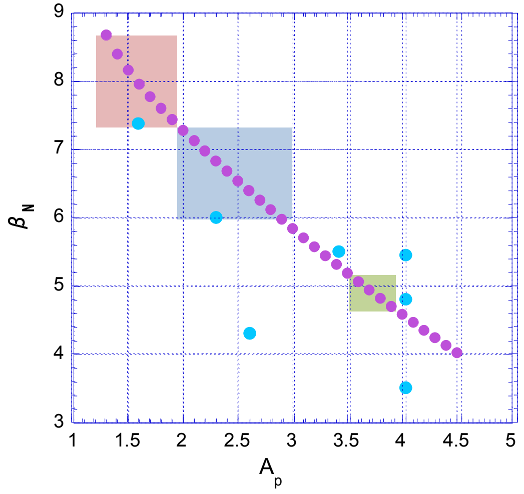

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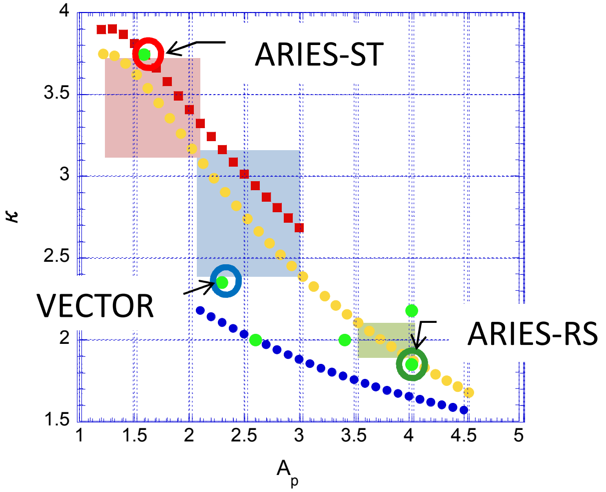

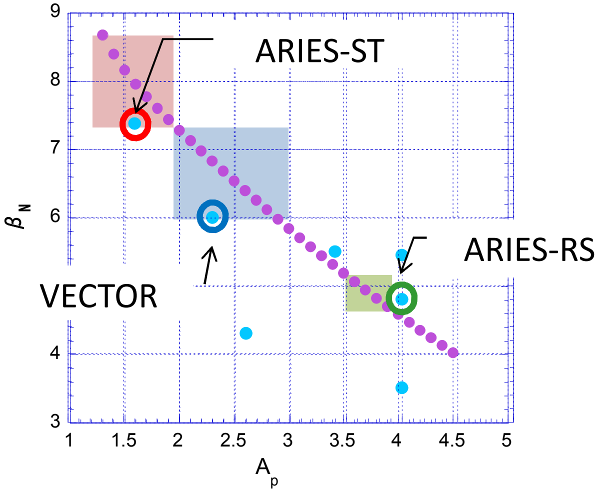

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