Comparative Study between Pulsed and Steady-State DEMO

Toshihiro HAMADA, Kunihiko OKANO

Frontier Sciences, Univ. of Tokyo

Japan-US Workshop on Fusion Power Plants and Related Advanced Technologies with participations from China and Korea

27th Feb., 2013 at Kyoto University in Uji, JAPAN

E-mail hamada@ppl.k.u-tokyo.ac.jp

Research Goals

Pulsed tokamak reactor has some attractive advantages such that it could realize earlier than steady-state tokamak because of its technical simplicity. But its disadvantages could be so serious issues enough to abort its development. So we focused on the following 2 disadvantages: One is likely to cost high because of its largeness. Second is fatigue problem.

Disadvantages of pulsed are:

- To cost higher than Steady-State
  - because of its largeness
- To be so fatigued

Advantages are:

- To need less additional researches
- To be able to start constructing earlier
- To be less restriction of plasma or/and magnetism

Focused on as the research goals

Outline

1. Construction Costs without Fatigue
2. Design Window of CS Fatigue
3. TF Fatigue
4. Summary

Outline

1. Construction Costs without Fatigue
2. Design Window of CS Fatigue
3. TF Fatigue
4. Summary

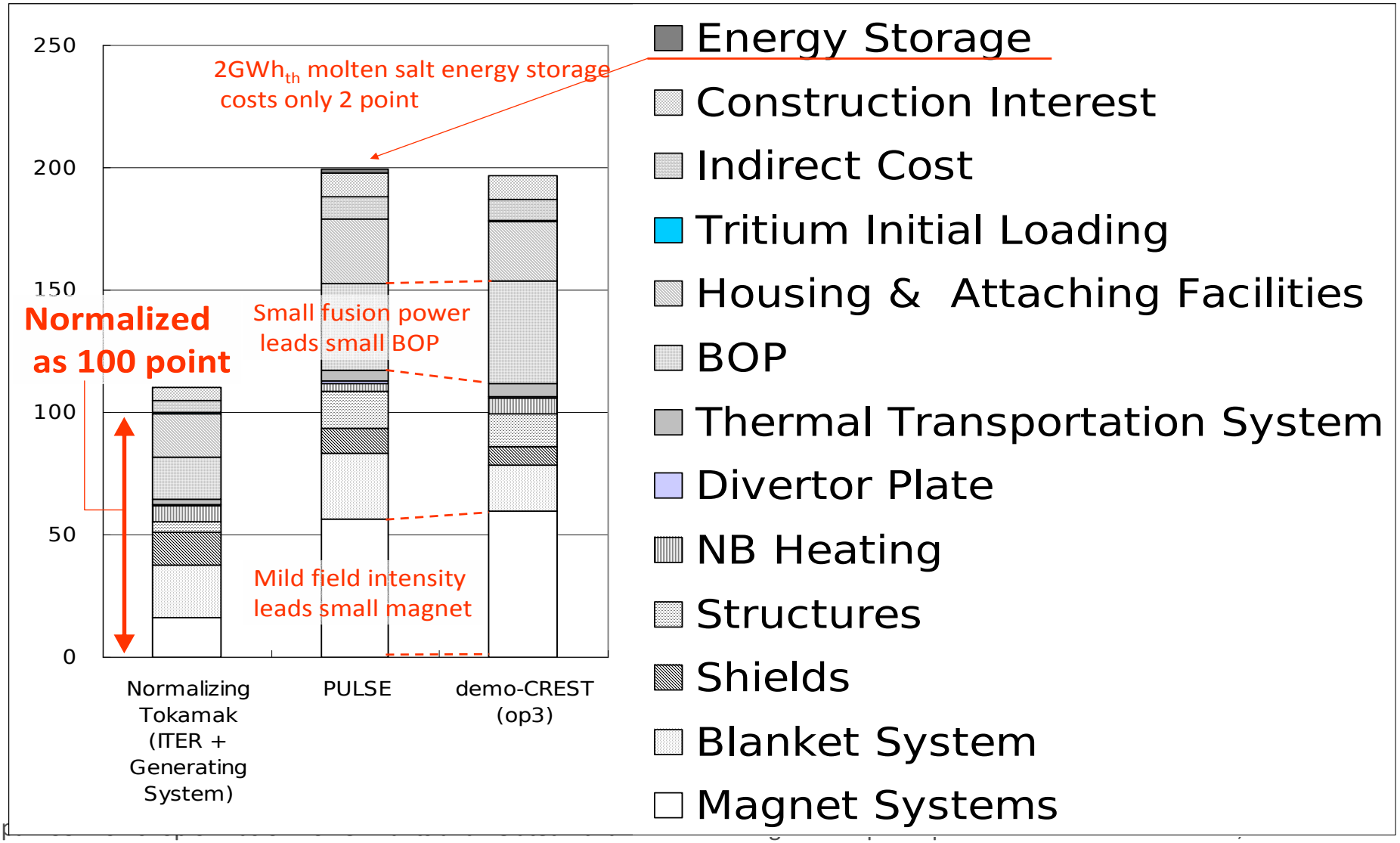
Design Parameters of Compared Reactors

- We chose 3 types of tokamak.
- One is iter, plus generating system. This system was used to define normalized cost.
- 2nd is a represent model of pulsed tokamak which is discussed in Broader Approach activity. That reactor have major radius of 10m, maximum toroidal field of 11.7T.
- 3rd is demo-CREST, this is a representative of steady-state tokamak, which has major radius of 7.25m, maximum toroidal filed of 16T.
- In those 2 reactors, overall outputs were fixed at 600MWe as comparison base.
- Also please note, magnetic field is of pulsed tokamak is relatively low intensity than steady state tokamak.

		Normalization · Tokamak (ITER + Generating System)	Pulsed Tokamak	Steady-State (demo-CREST op3)
Plasma and Reactor Parameters				
Fusion power	P_f (MW)	**500**	**1922**	**2463**
Electric output at sending out	P_e (MW)	**1**	**592**	**623**
Major radius	R_p (m)	**6.5**	**10.01**	**7.25**
Aspect ratio	A	3.82	4	3.4
Triangularity at the 95% flux surface	δ_{95}	0.4	0.33	0.35
Troidal field max	B_{tmax} (T)	**11.5**	**11.7**	**16**
Troyon coefficient	β_N	3.64	2.1	3.35
Turbine thermal efficiency	η_e (%)	33	33	33
NBI System efficiency	η_{nb} (%)	60	60	60
NB Power	P_{nb} (MW)	118	59	172
Total plasma current	I_p (MA)	8.4	18.1	15.6
Greenwald limit	$<n_{GW20}>$	0.93	0.922	1.1
Fraction of greenwald limit	f_{nGW}	0.823	0.82	0.825
Averaged ion density	$<n_{i20}>$	0.607	0.62	0.745
HH factor	H_{98y2}	1.29	0.788	1.265

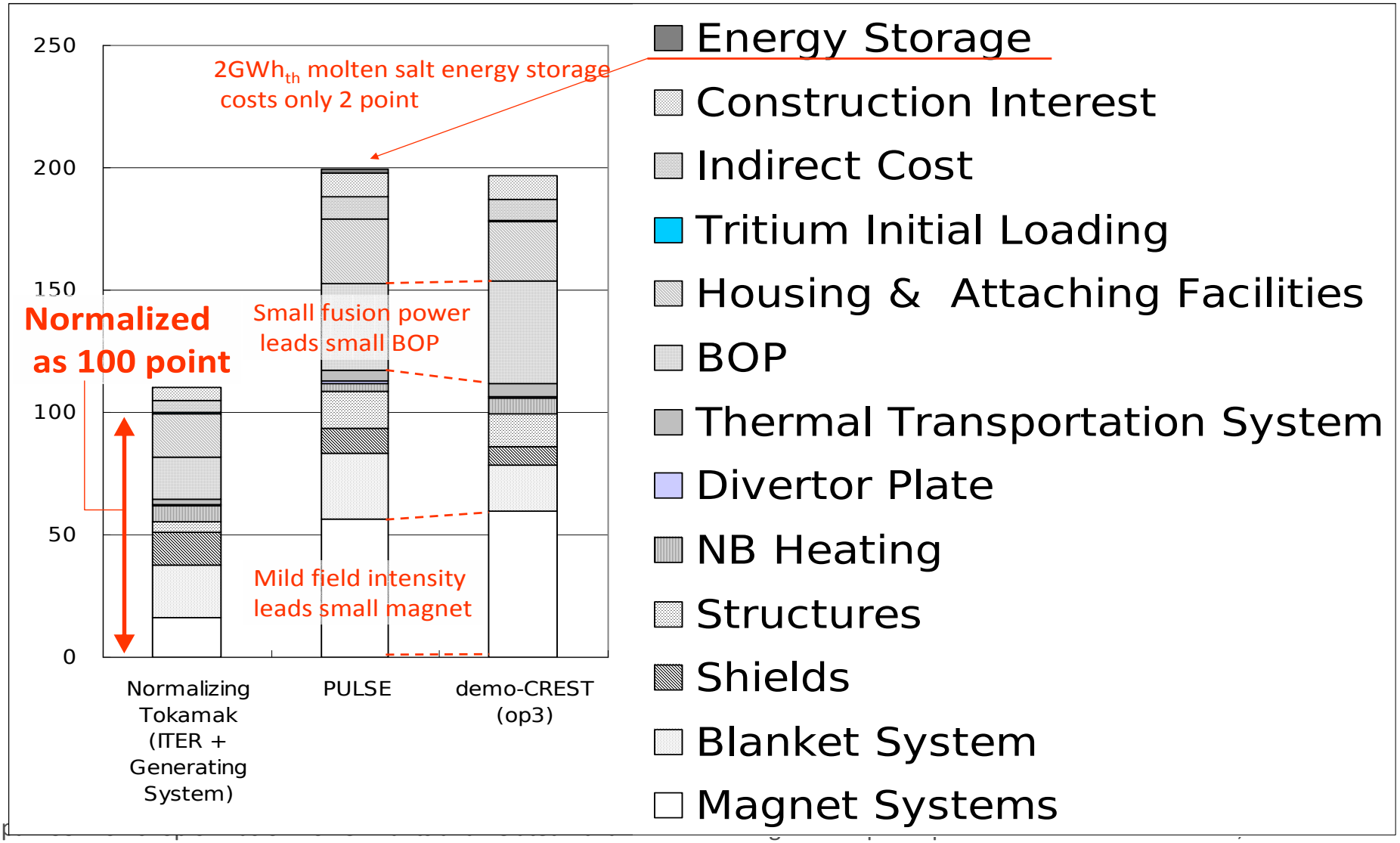
Calculation Result and Comparison of Costs

- This left bar is cost of iter plus generator system, calculated by FUSAC system code. And, this middle bar shows cost of pulsed tokamak representative. This right bar is of DEMO-CREST for steady-state tokamak.
- In this comparison, we defined this left bar as normalized cost of 100 points except the part beyond 100 points here, because it is interest cost.
- As you can see, the costs of pulsed and steady state tokamak were almost the same.
- I expected the cost of pulsed tokamak was higher than steady-state tokamak because of its largeness. But this conclusion denies my forecast. Pulsed reactor is proved not to be expensive.



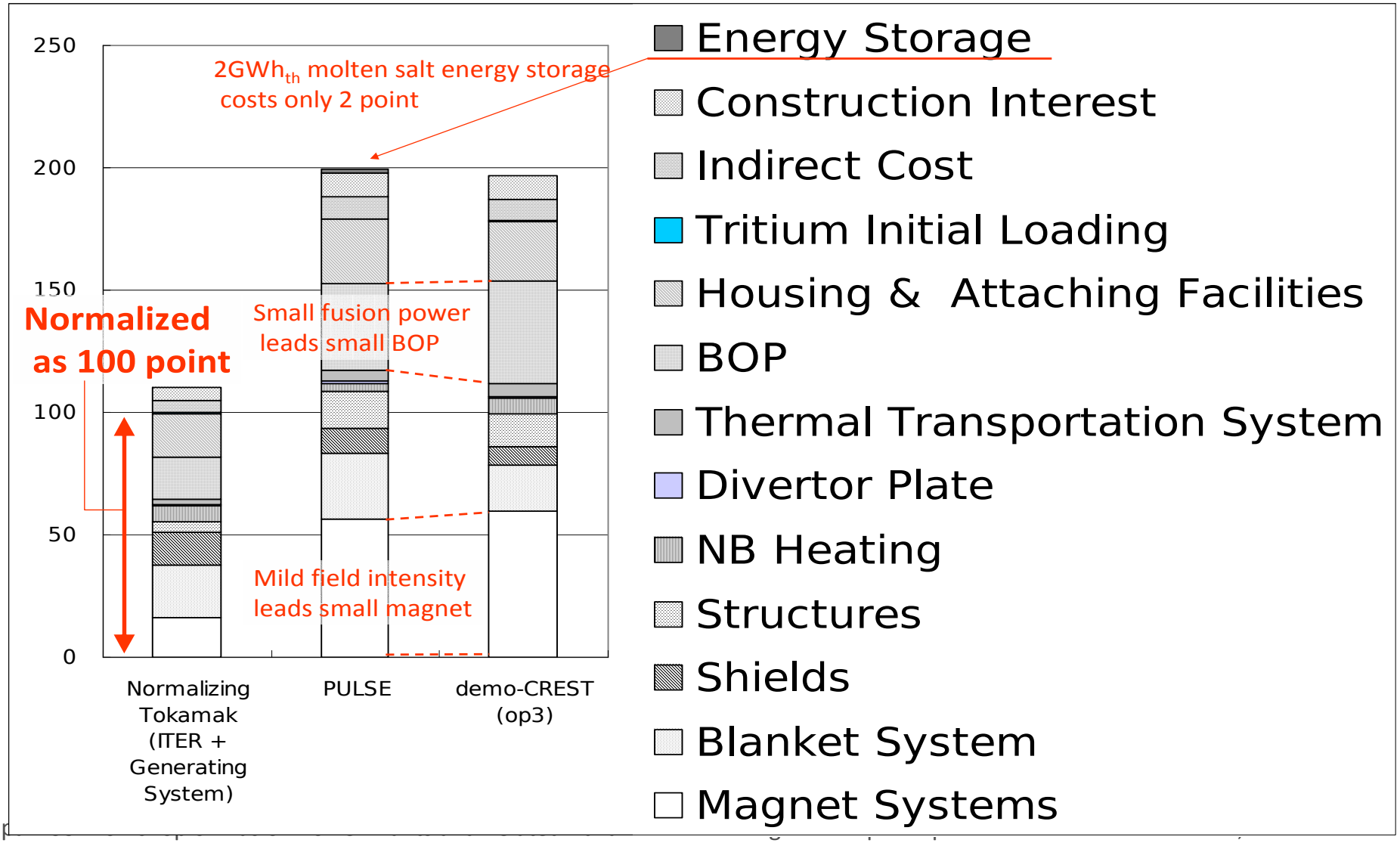
Calculation Result and Comparison of Costs

- Looking at the costs breakdown here, in pulsed tokamak, Magnet System cost is lower than that of steady-state, because of its relatively low toroidal field intensity.
- Also BOP is lower than steady-state. This comes from low fusion power by not requiring current drive system. BOP cost is derived by proportional calculation of fusion power in FUSAC system code.
- On the other hand, as expected, Shields, Structure, Blanket & Housing costs were higher than those of steady-state tokamak because of largeness of pulsed tokamak.



Calculation Result and Comparison of Costs

- I'd like to complement that thermal storage device have ***almost no impact to cost***. We assumed 2GWh thermal storage device of molten salt so as to compensate output stability, plant self-consumption and CS recharge power during dwell time.
- We estimated that it costs only 2 normalized cost. Namely the thermal storage device is not important issue in terms of cost.



Wrapping up - Cost Comparison

- Increased costs in pulsed tokamak are, Blanket, Structure, Shield & Housing costs.
- Decreased costs are Magnet System and BOP.
- Consequently, total costs between pulsed and steady-state tokamak are almost equal. This is the principal result of this section.

– Increased costs in pulsed tokamak:
  - Blanket
  - Structural materials
  - Shielding
  - Housing
    - Because of its large size, it is normally expected.

– Decreased costs in pulsed tokamak:
  - Magnet system
    - Because of lower intensity of toroidal field.
  - BOP devices
    - Because of low fusion power P_f

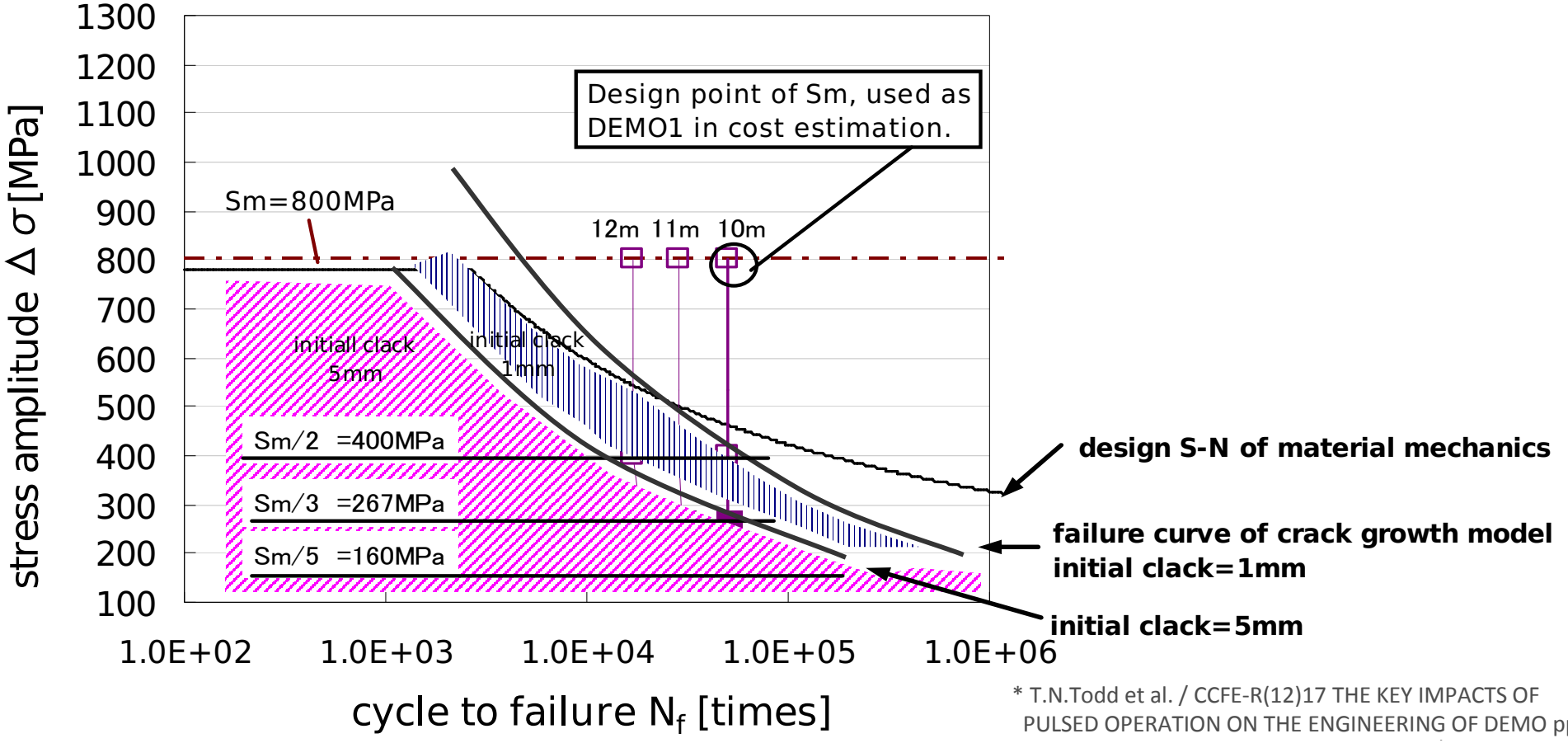
– Total costs are estimated ***almost equal***
  - because of canceling each cost out as shown above.
  - ***2GWth energy storage*** of molten salt have ***almost no impact to cost*** because of normalized cost of 2.

Outline

1. Construction Costs without Fatigue
2. Design Window of CS Fatigue
3. TF Fatigue
4. Summary

Scan of CS Design Window Using Fatigue Life Curve

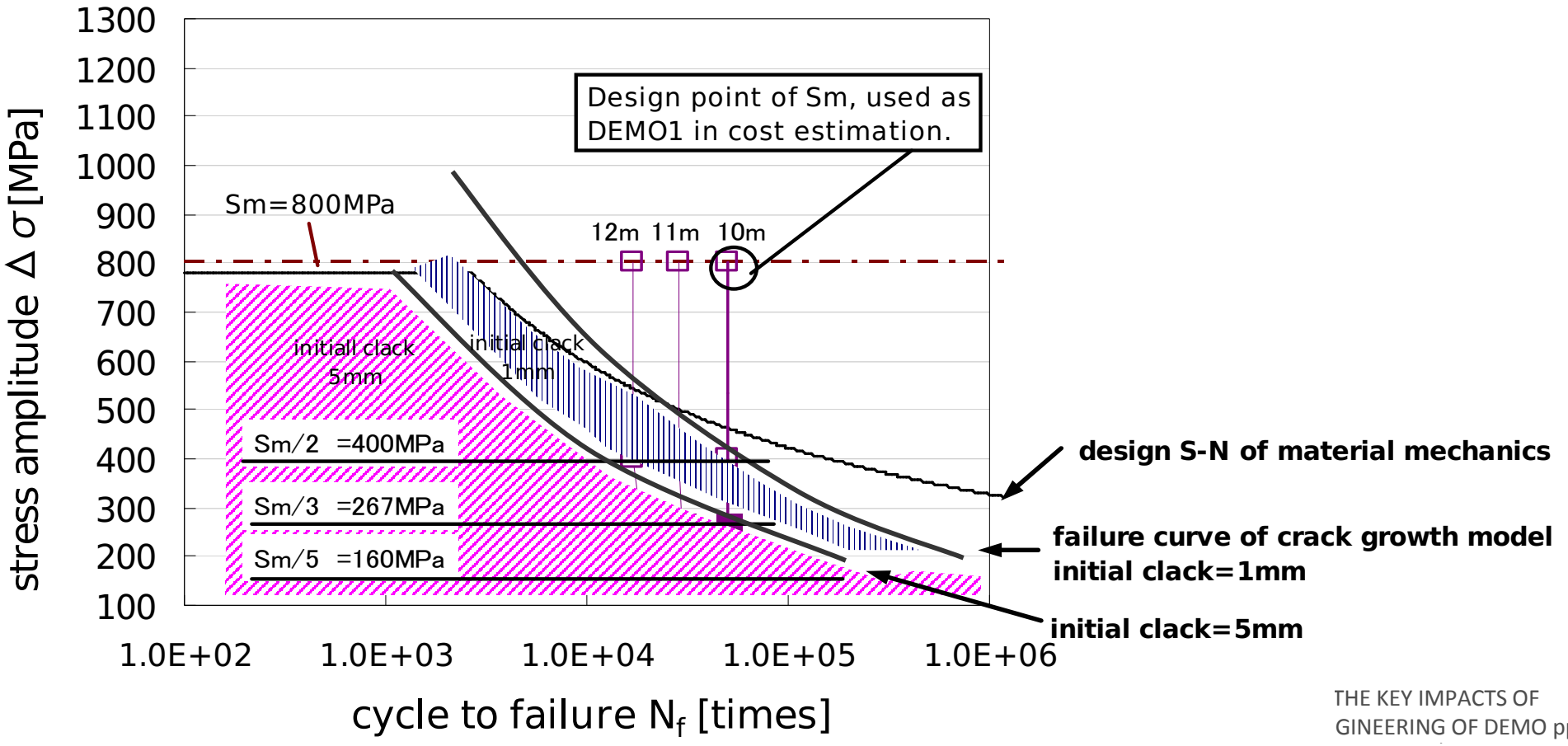
- We scanned CS design window using fatigue life curves of JJ1 cryogenic steel.
- In CS coil, its hoop force changes depending on the change in magnetic flux. That is principal factor of alternating stress and CS fatigue. We scanned the CS fatigue life by this figure, where X axis shows the number of cycles of alternating stress, and Y axis shows amplitude of alternating stress.
- There are 3 curves of JJ1 fatigue life on the figure. This one is design S-N curve of material mechanics. That indicates the relationship between/ number of cycles of alternating stress to failure/, and amplitude of the alternating stress. Namely, when amplitude of the alternating stress is 400MPa, fatigue life is about 200 thousand cycles.
- On the other hand, these 2 steep gradient curves are the fatigue life curves from crack growth model. The upper one is the curve assuming initial crack is 1mm. And the lower one is the curve assuming initial crack is 5mm. If we use the curve of 5mm, fatigue life will be 20 thousand cycles. As you have seen, Crack growth model could derive one order less cycle number than SN curve derives.



* T.N.Todd et al. / CCFE-R(12)17 THE KEY IMPACTS OF PULSED OPERATION ON THE ENGINEERING OF DEMO pp.48

Scan of CS Design Window Using Fatigue Life Curve

- We scanned the number of cycles in three major radius of 10m ,11m, and 12m giving various limits of design stress amplitude to System Code. The limits are Sm, one half of Sm, one third of Sm and one fifth of Sm, where Sm is design limit of static stress.
- As the result, limits of design stress amplitude have almost no impact to CS fatigue life. In case of 10m reactor, even if we chose the most severe curve of 5mm crack as a design condition, design stress can be reduced to one third of Sm.
- Because current density limit is so dominant that CS is enough thick to endure alternating stress. In case of 10m reactor, this figure tells fatigue life is about 50,000 cycles thru a 30-year operation and corresponding alternating stress limit is 300MPa, which is derived from the fatigue curve.
- This is the main conclusion of this page. And please remember 300MPa as limit of alternating stress of 10m pulsed reactor.

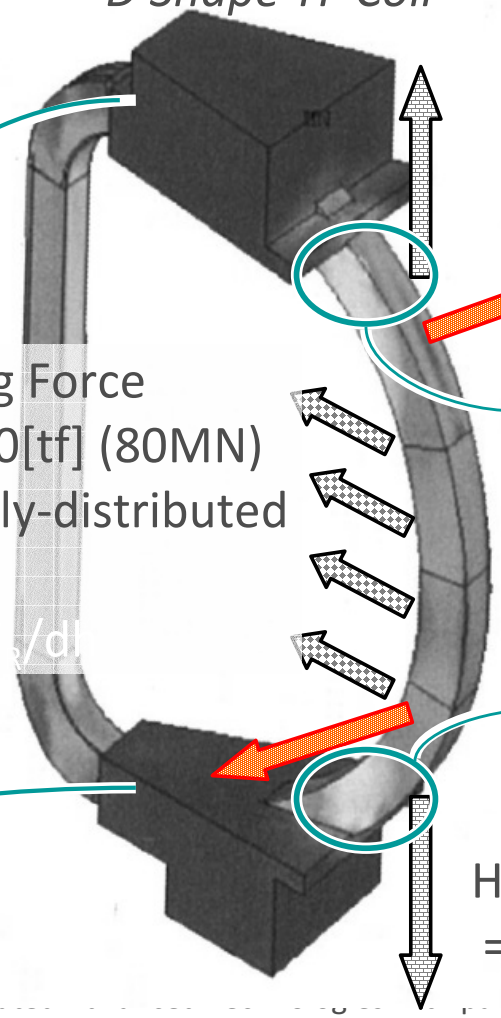


Outline

1. Construction Costs without Fatigue
2. Design Window of CS Fatigue
3. TF Fatigue
4. Summary

TF Coil Model for Discussing Stress

- This slide shows TF coil model for discussing about alternating stress on TF coil. We are interested in outer leg stress because alternating stress on TF acts only its outer leg. Here are 3 forces, which cause stress on TF outer leg.
- One is hoop force. This is about 140MN and acts vertical direction.
- Second one is centering force, that is 80MN toward the center. For calculation, we assumed this 80MN is total of uniformly-distributed load.
- Last one is the overturning force, that is 60 MN in circumferential direction. We assumed this overturning force as two point loads of 60MN. One is on the upper shoulder of outer leg toward right direction of this picture, as you can see here, and the other is on lower shoulder toward left direction.
- These overturning forces are supported by shear panels on upper and lower side of TF coil. So, the most severe stress and severe stress amplitude will occur on connecting border of TF coil and shear panel. This is corresponding to such as Cantilever Beam Problem.
- Next, we're going to focus on the total stress amplitude.



Overturning Force F_θ
= 5800[tf] (60MN)
(Modeled as point load)

Alternating Force

Centering Force
F_R = 8000[tf] (80MN)
(Uniformly-distributed load)

The most severe stress acts on aperture sides

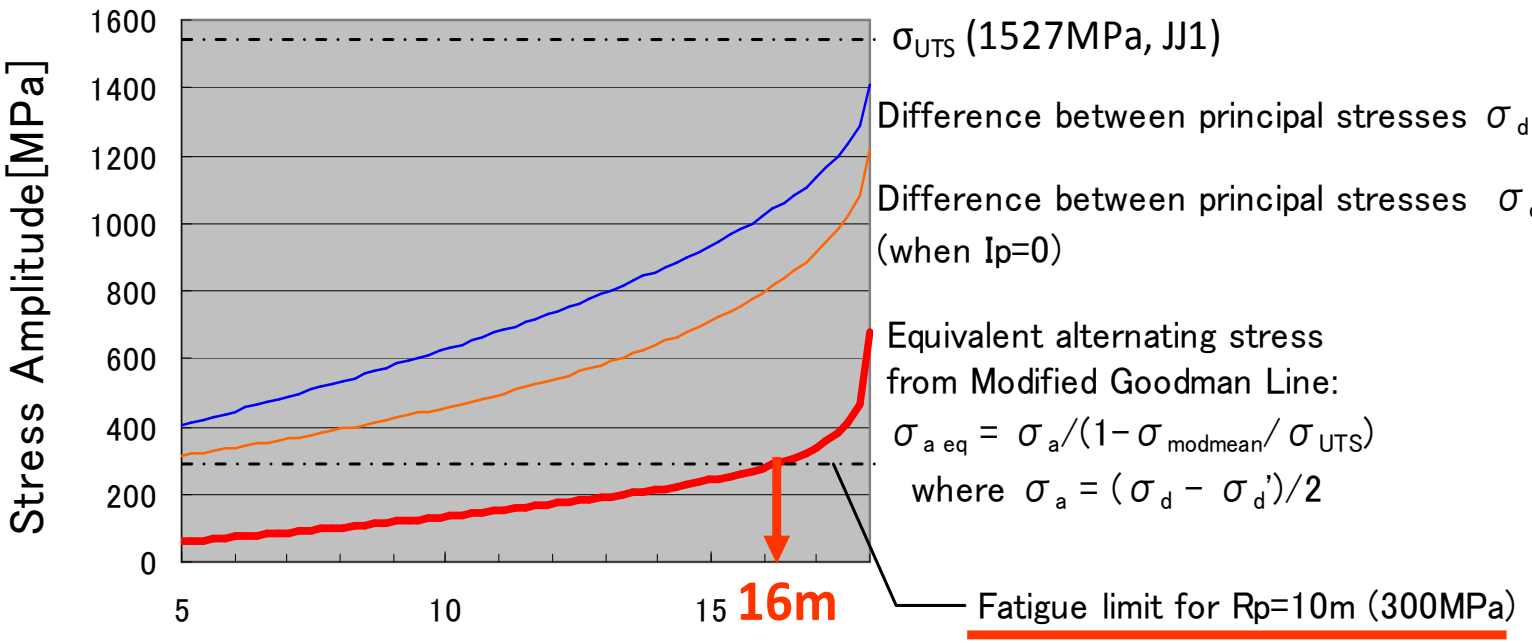
Alternating Stress
-> The target of research

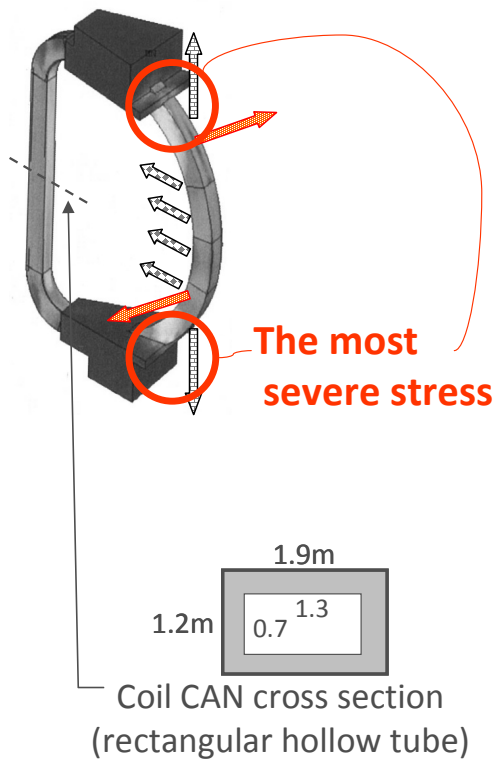
Assuming upper and lower side of TF are *fully fixed* by shear panel.

Hoop Force F_h
= 14000[tf] (140MN)

Fatigue of TF Aperture Sides

- This figure shows allowable length range of TF coil aperture between upper and lower shear panels. This is derived from allowable stress range, where X axis is length of aperture, Y axis is equivalent alternating stress at both sides of opening.
- This orange curve is the equivalent alternating stress. This is derived from our stress analysis using Modified Goodman Diagram and Tresca equivalent stress. And lower dashed line is 300MPa line, that is the design limit stress for a 30-year operation derived on the previous slide.
- Therefore, the intersection of those 2 lines indicates limit of aperture length and it is 16m. Namely we can allow aperture length up to 16m according to this figure.
- The upper length of 16m is not likely so severe condition but enough achievable condition. This is the conclusion of this slide. I'll skip explaining the other lines. if you'd like to learn about it, please find script of ***complement page 21*** later.

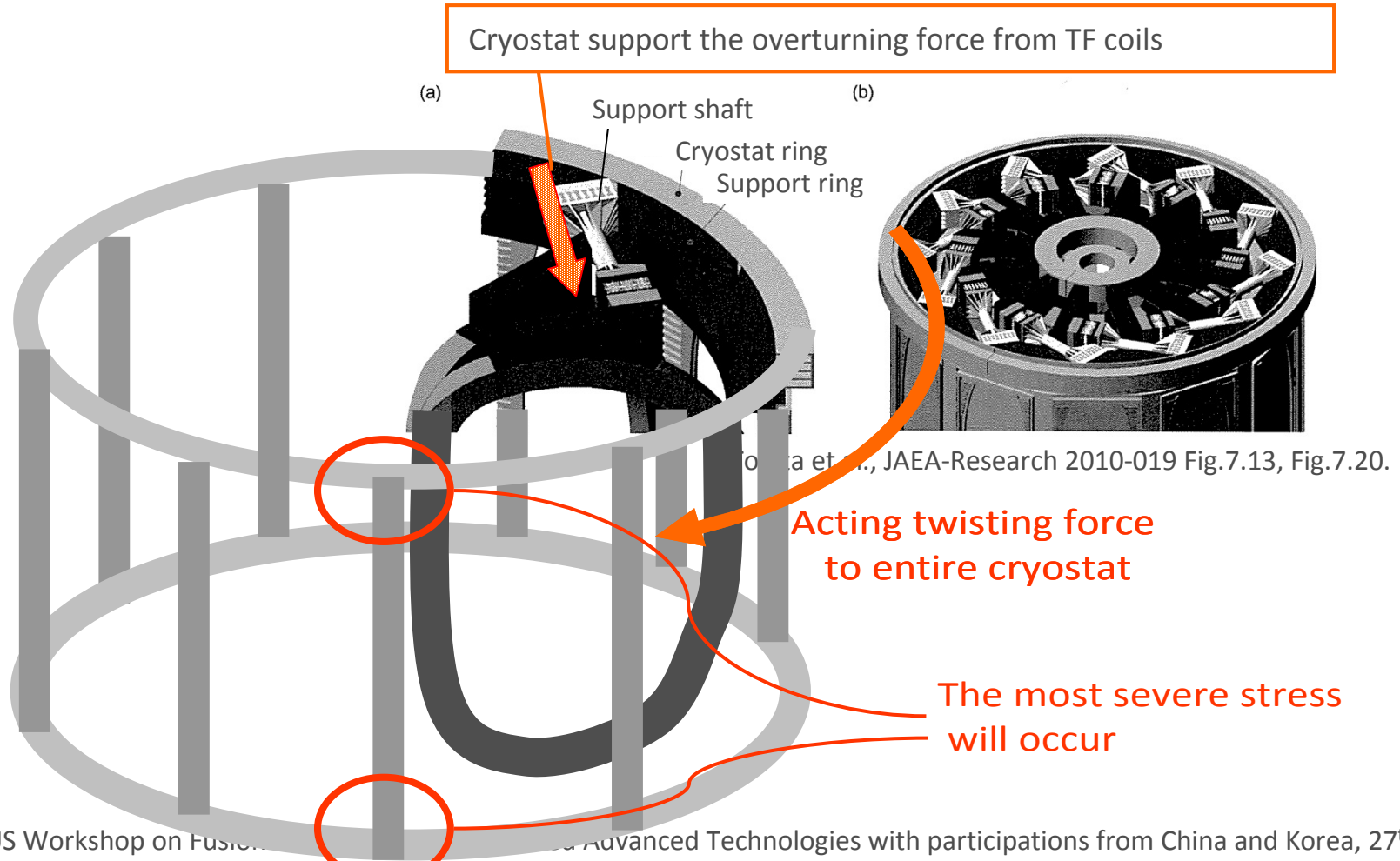




Bending stress on port sides of TF coil

Cryostat Skeleton as TF supporting structure

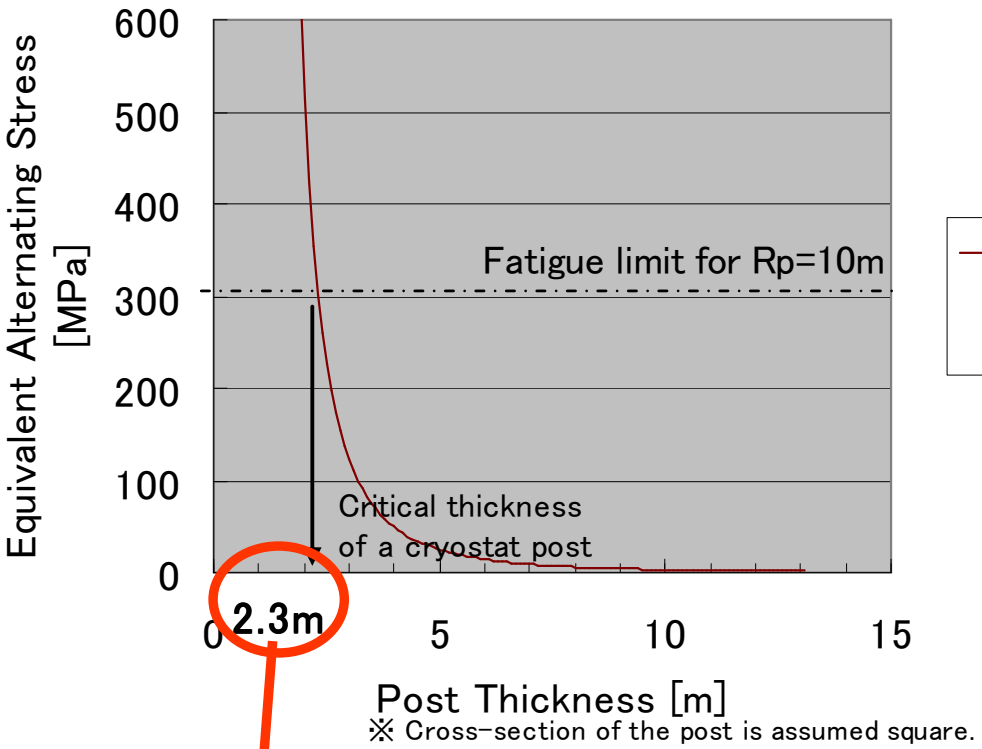
- Then we should explain about cryostat stress because we assumed to choose cryostat as a support structure of TF shear panel.
- Then, this is cryostat picture. The upper cryostat ring is connected to TF shear panel through support shaft. Thus the overturning force and centering force from TF coil is transmitted to the upper cryostat ring thru the support shaft. Consequently shear panel and TF coil are almost fully fixed.
- And then, this is complement of cryostat skeleton. Although it seems like a cage, could you please imagine this is cryostat skeleton. As lower cryostat ring is fully fixed on the ground, the transmitted overturning force thru support shaft acts to entire cryostat as twisting force in a circumferential direction. Therefore, stress on the post side is the most strong one. And it could be cause of fatigue. So we're going to clarify the stress now.



o a et al., JAEA-Research 2010-019 Fig.7.13, Fig.7.20.

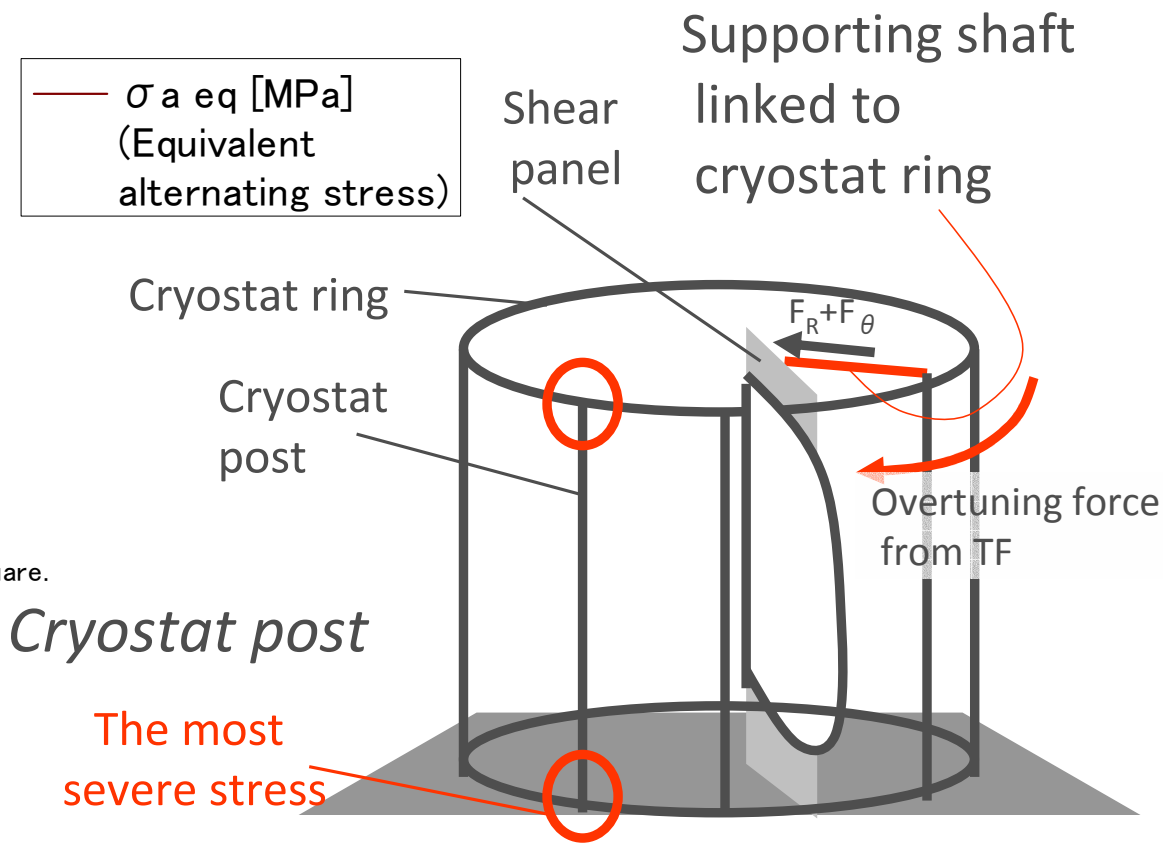
Cryostat Stress to support TF Bending Force

- The upper figure is a relationship between post thickness and stress on cryostat post side by overturning force. The lower figure is same skeleton model as previous page, so I will skip it. And so in the detail, the upper figure shows a relationship between equivalent alternating stress on a cryostat post and its allowable minimum thickness.
- If we assume its cross section is square, the minimum thickness so as to be less than 300MPa-stress is 2.3m. Although It is surely a problem. But the problem is so minimal that we can manage to solve it. In terms of cost, its increase is likely 3 normalized cost or less.



Bending stress on lower side of Cryostat post

Minimum thickness requirement of post thickness



Cryostat Skeleton Model

Outline

1. Construction Costs without Fatigue
2. Design Window of CS Fatigue
3. TF Fatigue
4. Summary

Summary and Remaining Issues

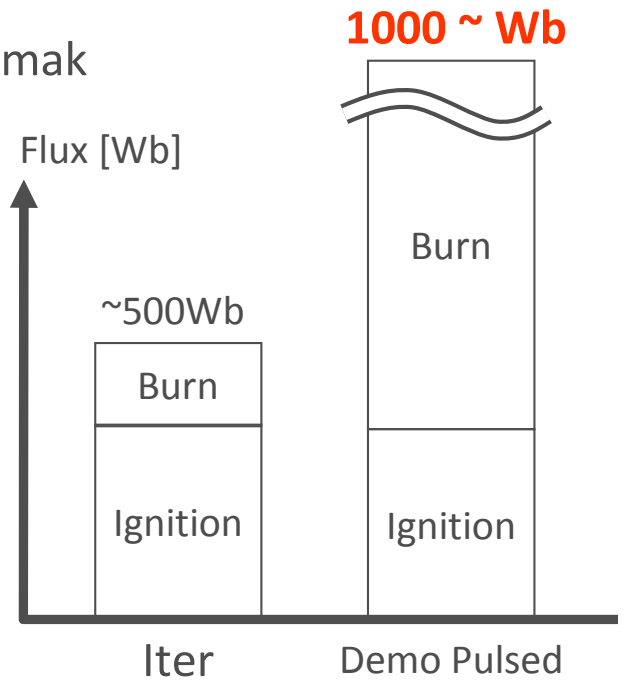
- 1st we discussed about construction cost. Then we've found that: -Total cost are almost equal in both type of tokamak reactors. -The cost of TF and BOP decreases because of mild field intensity and mild fusion power in case of pulsed reactor.
- On the other hand, The cost of Shield, Structure, Blanket & Housing increases. The cost of thermal storage for pulsed operation estimated 2 normalized cost or less.
- 2nd and 3rd discussion were about CS and TF fatigue problems, but they were not significant factor. On the other hand a few constraint and cost increase on cryostat pillar were found newly. It could push up the cost to about 3 normalized cost.
- As future works, cost comparison considering availability should be performed. Also we are focusing on a diverter problem, which is that field angle or strike point on diverter plate might be changed with change in CS flux during burn time.

[Summary]

- Cost
  - Total costs are almost equal in steady-state and pulsed tokamak
  - The cost of TF and BOP decreases
  - The cost of Shield, Structure & Blanket increases
  - The cost of thermal storage is 2 normalized cost or less.
- CS and TF fatigue
  - The fatigue is not significant in the both component
  - Stress on cryostat could push up cost a little

[Remaining Critical Issues for Pulsed Reactor]

  - Availability
  - Recharge Time, Recharge Generator Power
  - Field Angle Change on Diverter Plate



Flux Comparison Iter vs. Demo

~Thank you for your time~

Please feel free to ask me any question.

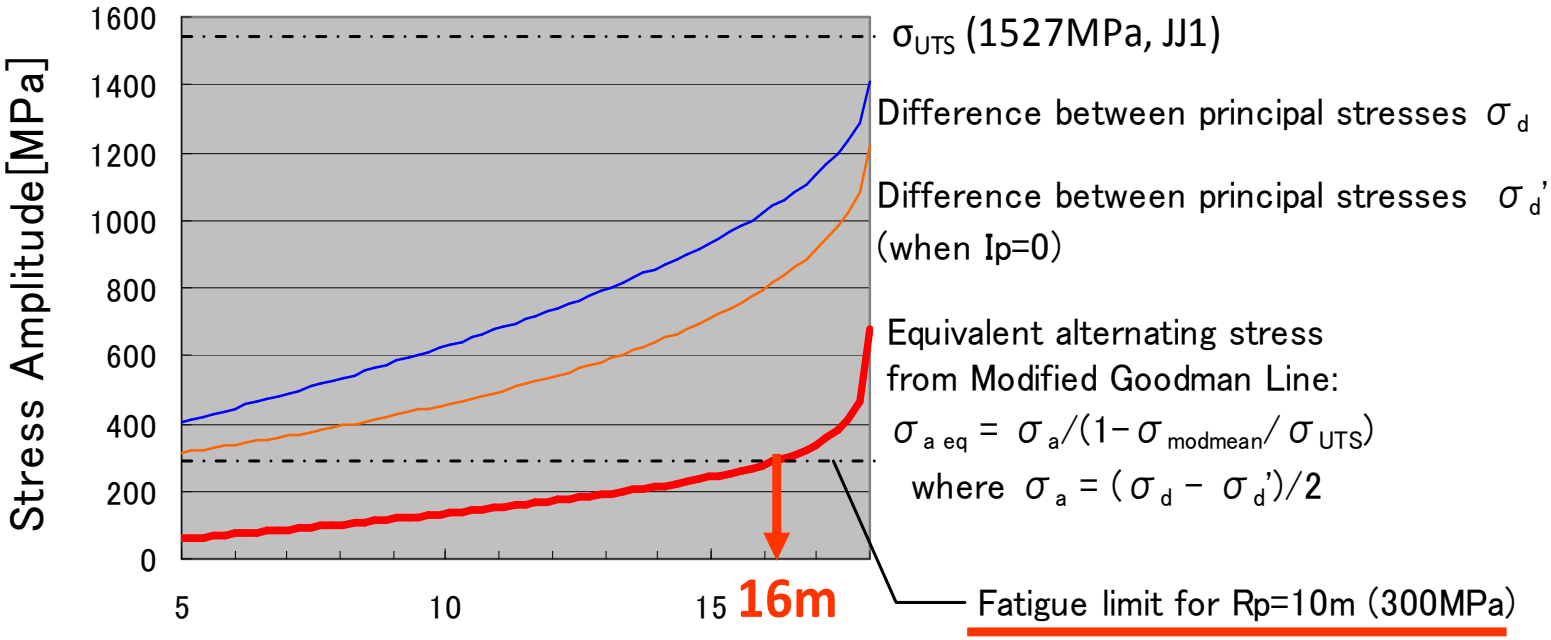
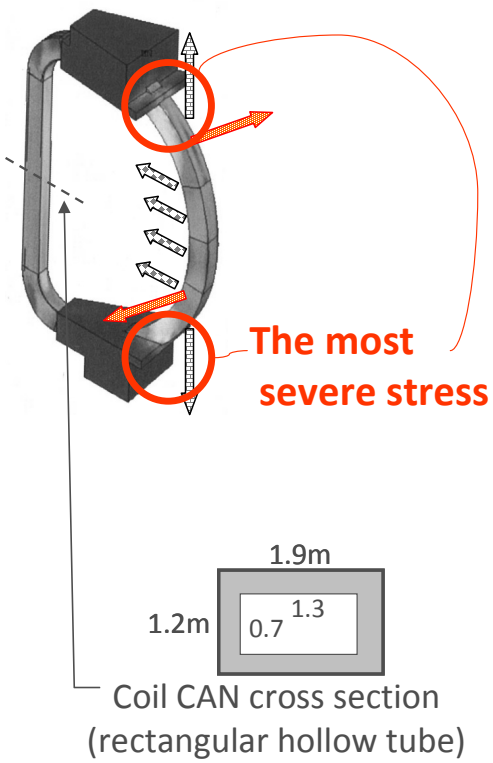
E-mail hamada@ppl.k.u-tokyo.ac.jp

Fatigue of TF Aperture Sides

COMPLEMENT OF PAGE 15

- And as complement, I'm going to explain about other lines.
- The upper two curves are difference between 2-dimensional principal stresses.
- The blue line is for flat top and the orange line is for Ip=0.
- Those difference is a base of derivation of Tresca equivalent stress.

- The upper dashed line is ultimate tensile stress, that of JJ1 is 1527MPa.
- This parameter is used for derivation of Modified Goodman Diagram.



Bending stress on port sides of TF coil