Comparative Economics Studies on Magnetic Power Plants

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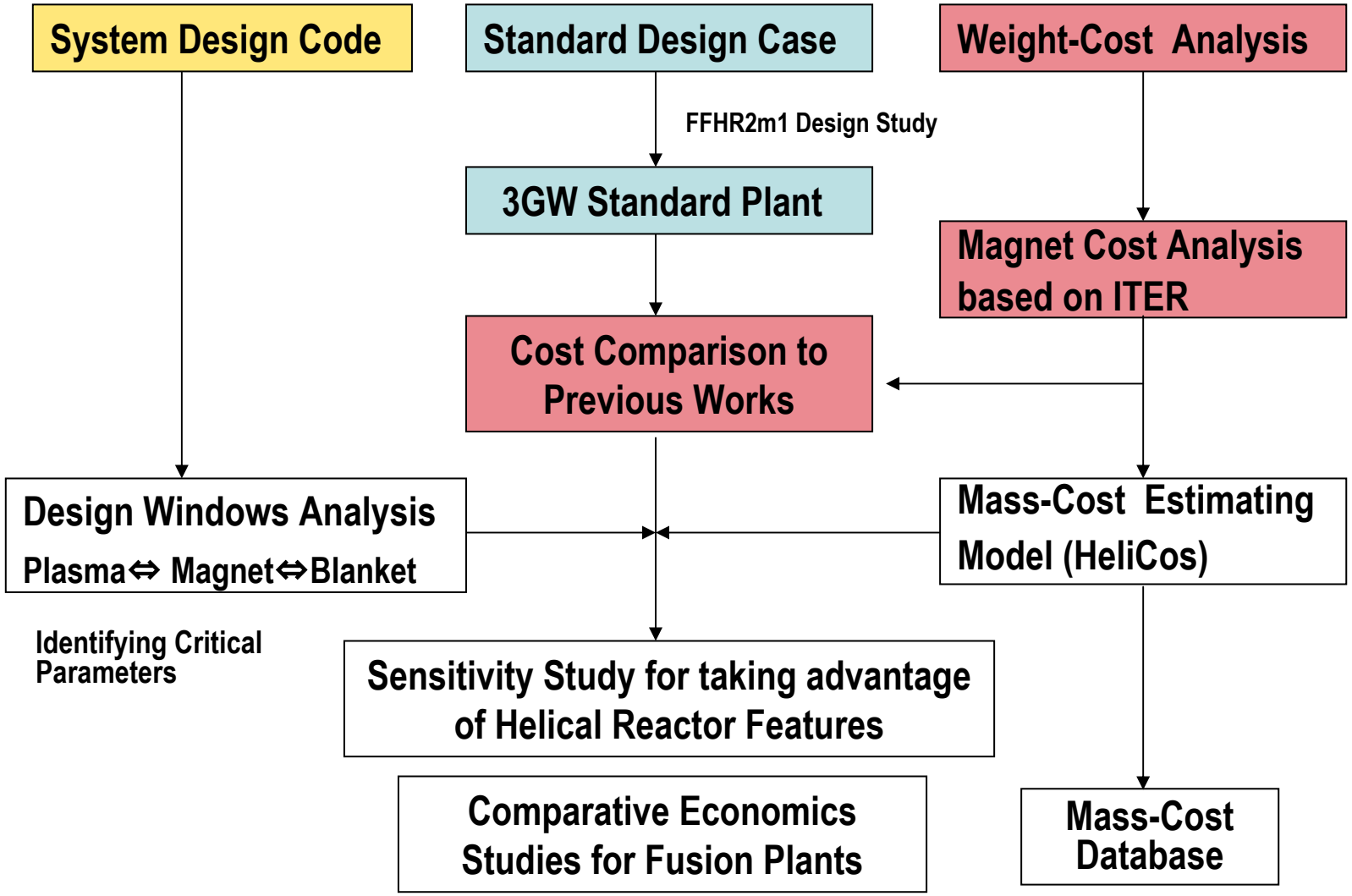
Introduction

- Previous Design Windows Analysis with Cost Model
  - Cost models combined system design codes have been studied with considering the relationships between plasma and reactor system parameters.
  - Generomak for Tokamak and other MFE plants (J. Shefield1986), PEC code for Helical Reactor (K. Ymazaki and T. Dolan 2004), and for Laser Fusion Plants (Y. Kozaki1993, 2002) , and system design studies in ARIES.
  - Most of their results shown the importance of mass power density , and suggested the directions to much higher beta and higher neutron wall loading. But the design windows directed to compact MFE power plants are severely limited by critical constraints of diverter heat loads, neutron wall loads, and tritium beading ratios.
  - In design windows analysis cost scaling laws are important. We should consider not only scale merits but also scale demerits, which may be necessary to another sense that plasma scientists and conventional power plant engineers get used to.
- We have much experience on costs of fusion device through preparing ITER construction. Now we can discuss the costs of magnet and major facility with some reality with ITER data base.
- We think a shape of double helical coil is simple and natural. Natural shape is beautiful, and important for cost effective engineering design. Then we studied the design windows of LHD type- helical reactors which have double helical coil.
- Based on FFHR design studies we have been studying a standard helical reactor design that can be referenced for technical and economics assessment, and discussing R&D roadmaps for fusion energy.

System Design and Mass-Cost Estimating Model (HeliCos)
-Tasks for developing methodology and studying design windows-



Major design parameters, their relationships, and constraints

1) Energy confinement scaling ISS95 and H_{iss} factor

$\tau_E = 0.26 P^{-0.59} n_e^{0.51} B_0^{0.83} R^{0.65} a^{2.21} \iota_{2/3}^{0.4}$ (ISS95) , H_{iss}~1.5 attained experimentally

2) Magnet Design

- Polarity l=2, Field periods m=10, Coil pitch parameter γ=1.15~1.25 base case
- $\langle B_T \rangle / B(Rc)$ =0.29 for R/a=4, j=25
- $B_{max}/B(Rc) = 0.4819 + 0.41847(a/H) + 0.0066851(a/H)^2$
  for m=10, γ=1.25, W/H=2 (W: width of HC, H: height of HC)

3) Fusion power balance $Pf = n_T n_D \langle \sigma v \rangle Vp * 17.58MeV * 1.602 * 10^{-19} (J/eV)$
Density profile, He, D, T, and impurity fractions.

4) Key limiting conditions for high plasma performance : β=3~5%, density limit.

5) Blanket space and Tritium breading ratio, $(a_c - a_p) > 1.2$ m

6) Neutron wall load and Diverter heat load

Standard Design Parameters of LHD type Helical Reactor

Major design items	LHD (4T)	FFHR2m1 1.9 GW	Standard 3GW
Polarity/Field periods l / m	2 / 10	2 / 10	2 / 10
Coil pitch parameter	1.25	1.15	1.15
Coil major Radius Rc m	3.90	14.0	14.0
Plasma major radius Rp m	3.75	14.0	14.0
Plasma radius a_p m	0.61	1.73	1.73
FW minor radius a_{FW} m	0.71	1.83	1.83
Magnetic field B0 T	4.00	6.18	6.18
Max. field on coils Bmax T	9.20	13.25	13.25
Coil current density j MA/m2	53	26.6	26.6
Coil width/height W/H	1.56	2	2
Magnetic energy GJ	1.64	120.00	120.00
Plasma stored energy GJ		0.54	0.68
Average beta $<\beta>$		2.8	3.6
ISS95 τ_E S		0.80	0.69
H factor		1.96	1.81
Electron density ne(0) 10^{19} m^{-3}		26.7	33
Temperature Ti(0) keV		15.6	15.8
Fusion power GW		1.90	3.00
Neutron wall load MW/m^2		1.50	2.37
Blanket space m	0.12	1.20	1.20

Key design parameters for standard power plants

- P_{net} 1.164 GWe
- P_{fusion} 3.0 GW
- Coil major Radius Rc = 14 m
- Magnetic field B0 = 6.18T
- Magnetic energy 120 -135GJ

- Considering the same magnet-size-plants for a standard case based on FFHR-m1 design study

- High density plasma than FFHR2m1 for high power density

  (n_e= 26.7→ 33.0)

- Neutron wall load

  1.50 (FFHRm1) → 2.37 MW/m^2

Table 1. Analysis on Weight and Cost of Magnet Systems based on ITER (1kIUA=144Yen)

TOKAMAK Coil Systems	Elements		ITER Report 2002			ITER FDR 1999		
								Cost MYen
C1. TF coil Nb3Sn/Cu (Cu ratio: 1)	Conductor	Strands						
		Conduit						
	Radial Plate							
	Winding (Weight)							
	Coil Case							
C2. CS Coil Nb3SnCu Cu ratio: 1	Conductor	Strands						
		Conduit						
	Radial Plate							
	Winding (Weight)							
	Coil Case							
C3. PF coil NbTi/Cu Cu ratio: 1	Conductor	Strands						
		Conduit						
	Radial Plate							
	Coil Case & Support		*862*	*2.9*	*2,499*		*3.8*	
C4. Coil Supports								
C5. Other Systems (Feeders etc.)					6,739			
Total Weight & Direct Cost			1016 6	*10.6*	107, 641	2187 8	12.6	275, 346

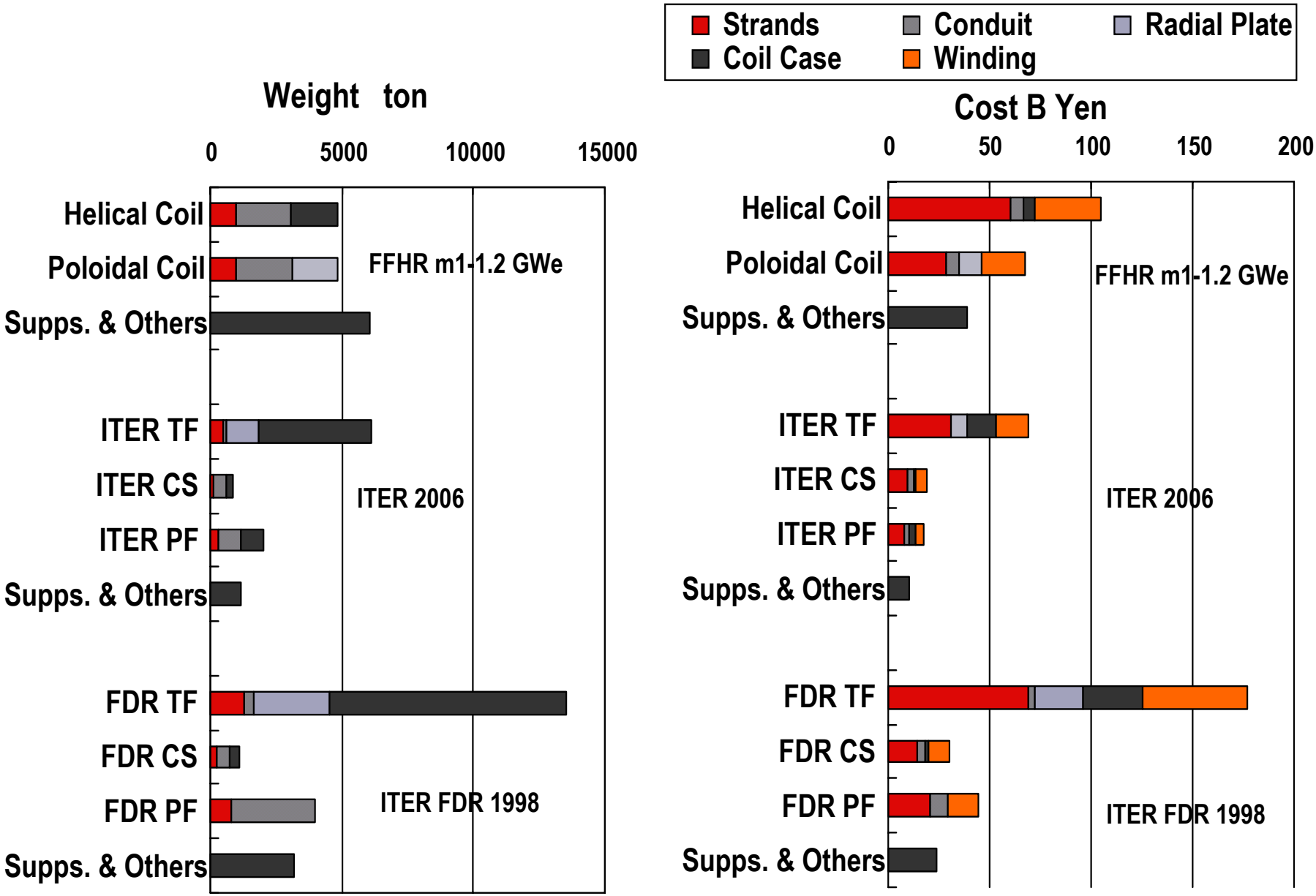
Coil systems elements weights are calculated based on design technical data. Cost values in italic are calculated by using cost data shown in ITER Report, FDR cost and unit cost data by Mitchell 1999.

Table 2. Estimation on Weight and Cost of Helical Reactor Magnet Systems based on FFHR-m1 Design Study and ITER Magnet Cost

Coil Systems	Elements		Weight ton	Unit Cost Myen/ton	Cost MYen
C1. Helical Coil Nb3Al/Cu (Cu ratio: 1)	Conductor	Strands	960	63.3	60,723
		Conduit	2,077	2.9	6,023
			3,037	*22.0*	66,747
	Winding		3,037	10.7*	32,431
	Coil Case		1,770	3.3	5,809
			4,807	*21.8*	104,987
C2. Poloidal (OV& IV)Coil NbTi/Cu (Cu ratio: 3)	Conductor	Strands	1,001	28.9	28,929
		Conduit	2,092	2.9	6,067
			3,093	*11.3*	34,995
	Radial Plate		1,717	6.5	11,163
	Winding		4,810	4.4*	21,165
	Coil case		0		
			4,810	*14.0*	67,324
C3. OV& IV Coil Support			6,085	3.3	20,081
C4. Other Coil systems 0.1*Sum(C1:C3)					19,239
Total Weight & Direct Cost			15,702	*13.5*	211,631

*We consider winding unit cost of Helical Coil is 1.2 times that of Tokamak Coil, and Poloidal Coil is 1/2 as same.

Magnets Weight and Cost of Tokamak and Helical Reactor



Cost estimation of SSTR and FFHR-2m magnets with IFTEC Cost Model and ITER unit cost

systems	elements	cost items	specifications	unit cost MYen/ton	weight ton	Cost M Yen	ITER MYen/ton	Cost M Yen
	SSTR cost estimated by Kozaki, 1992 (IFTEC, Institute for Future Technology and JAERI)						ITER cost basis	
C1. TFCoil	S1. TFCoil (NbTi)3Sn	S11. Nb3SnStrands	16T, Cu/nonCu=2.33, 34m×180×16=98km	48.00	700	33,600	63.3	44,310
		S13.Conduit, Winding		48.00		33,600	8.9	23,630
	S2.TFCoil NbTi	S22.Nbi Strands	5 T , Cu/nonCu=4.4, 37m×64×16=38km	24.00	300	7,200	29.0	8,700
		S23Conduit, Winding		24.00		7,200	3.6	3,503
	S3.Coil Case, others	S31. JN1material		1.00	8,240	8,240		
		S32. Processing		2.00		16,480	3.3	27,192
					9,240	106,320		107,334
C2. PF, CS, EFCoils	S1. PF Coil	S1. PF NbTi線	CSCoil40kA,7T,33.2km	41.00	370	15,170	28.9	10,693
	S2. CS, Efcoil	S2. Conduit, Winding	EFCoil40kA,5.5T,64.7km	6.00	2000	12,000	6.4	12,800
					2,370	27,170		23,493
C3. Others	Current leads, Cables					13,666		8,738
Total Weight and Direct Cost					11,610	147,156		139,565

systems	elements	cost items	specifications	unit cost MYen/ton	weigh tton	Cost M Yen	ITER MYen/ton	Cost M Yen
	FFHR-2m3GW cost estimation using IFTEC Cost Model						ITER cost basis	
C1. Helical Coil	S1. Helical Coil Nb3Al	S11. Nb3Al Strands	13T, Cu/nonCu= 1 134m×30×16×2 =128.7km, CICC winding	48.00	960	46,080	63.30	60,723
		S12. SUS Conduit		4.00	2,077	8,308	2.90	6,023
		S13. Nb3Al winding		15.17		46,080	10.70	32,431
	S2. Coil Case	S21.SUS材料費	–	4.00	1,770	7,080	3.30	5,809
					4,807	107,548		104,987
C2. PF Coil	PFCoil	S1. NbTi Strands	56.kA, 7T, 91km	24.00	1,001	24,024	28.90	28,929
		S12. SUS Conduit, R.P, Case		4.00	3,814	15,256	2.90	17,230
		S13. NbTi CICC winding		4.99		24,024	4.40	21,165
					4,810	63,304		67,324
C3. OV& IV Coil Support				3.00	6,085	18,255	3.3	20,081
C4. Others						17,085		19,239
Total Weight and Direct Cost					15,702	208,018		211,631

Cost estimation based on magnet weight and ITER unit cost

-using the same algorithm of ARIES cost methods to compare previous works-

M$ 2003

Cost Acc. No. & Title	FFHR-3GW * Estimated by Magnet Weight & ITER unit cost	FFHR-3GW Estimated by PEC code mass calculation and ARIES unit cost (T.Dolan and K.Yamazaki, 2004)	Helical 4.5GW
20 Land & land rights	12.7	12.7	12.7
21 Structures and Site facilities	344.7	344.7	450.3
22 Reactor Plant Equipment	3509.4	2427.0	2798.1
221 Fusion Reactor Equipment	2967.5	1748.8	2090.2
2211 first Wall and Blanket	343.1	198.6	259.4
2212 shield	178.4	194.7	254.3
2213 magnets	1996.5	947.0	956.7
2214 heating	63.3	63.30	168.8
2215 primary structure & support	129.6	129.6	169.3
2216 vacum systems	152.3	152.3	198.9
2217 power supply	51.7	51.7	67.6
2218 impurioty controll & diverter	11.6	11.6	15.2
222 Main heat transport system	400.4	400.4	523
223-7 Other reactor systems	277.9	277.9	363
23-7 Turbine Plant & others	602.1	602.15	913.20
90 Total Direct & engineering Cost	4469.0	3386.6	4070.9
91-97 Indirect Cost	3235.6	2451.89	2947.33
99 Total Plant Capital Cost	7704.6	5838.48	7018.23
Capital cost	97.3	73.7	59.7
Operation cost	10.0	10.0	7.7
Replacement cost	3.4	3.4	3.4
Fuel cost	0.02	0.02	0.02
Decomissioning	0.61	0.61	0.61
COE (mill/kWh)	110.7	87.1	70.9

Summary

- **We are developing a cost model combined with system design code of helical reactors (HeliCos). We considered a 3GW helical power plant based on FFHR-m1 design study, and estimated the weights and costs of major systems.**

- **We evaluated the cost of magnet systems of helical reactors using the data of ITER magnet costs. The results show the similar weights and costs of magnets between Helical and Tokamak reactors.**

- **Economics studies show that it is misunderstanding to consider helical coils are too expensive to achieve power plants. But in the next studies on design windows we must consider the critical issues, such as diverter heat loads, plasma boundary layer conditions and allowable blanket spaces with required tritium breading ratio, which are very sensitive to reactor size and weight.**