Costing of magnets
or
How can the costs of ARIES be that much smaller that those of ITER

L Bromberg and J.H. Schultz

ARIES CTF meeting

UCSD

March 3-4, 2008

Topics

- Costing options for magnets
  - Resistive
  - Superconducting
- Irradiation limits for superconductors
- Costing methodologies

Magnet performance

- A large increase in performance in Post-ITER magnets is needed (~ 5x better than ITER) for DEMO to be convincing (*i.e.* prove economic attractiveness)
  - Specific magnet mass decreases by a factor of ~ 2
  - Specific magnet cost needs to decrease by > 2.5

Figure of Merit	Units	ITER	ARIES-AT	Ratio
\$/Wth	(\$/W)	20	1.9	10.5:1
M_{sc}/W_{th}	(g/W)	1.8	0.4	2.5:1
W_m/W_{th}	(s)	21.6	8.2	2.63:1

Resistive Magnets Costing

PCAST study group magnet cost analysis

Magnet Component	(Units)	Value
Manufacturing	($/kg)	56
Copper conductor	($/kg)	12
Magnet Systems Copper Superconducting	 ($/kg) ($/kg)	 68 82
BPX TF Coils	($/kg)	65
TFTR TF Coils	(FY89 $/kg)	103
TFTR TF Cases	(FY89 $/kg)	77
DIII TF Coils	(FY89 $/kg)	98
PF Coil Manufacturing	($/kg)	41
PF Coil System	($/kg)	105
BPX PF Coils	($/kg)	59
TFTR PF Coils	(FY89 $/kg)	180
DIII PF Coils	(FY89 $/kg)	84
Post-PCAST Cancelled Projects		
TPX TF Coils	($/kg)	139
TPX PF Coils	($/kg)	232
TPX CS Coil	($/kg)	332
TPX TF Coils	($/J)	0.11
GEM Solenoid	($/kg)	32
GEM Solenoid	($/J)	0.032

ARIES-RS TF $100/kg
$0.006/J

Near term resistive tokamak (FIRE)

Magnets

12 Magnets	107.8	RULE	FIRE	units
1.1 TF coil	**93.7**			
1.1.1 Conductor	6.8	0.09*(Conudctor mass)	75.4	(tonnes)
1.1.1.1 Inner leg	0.9	0.001*(MInner leg)*20	45.7	(tonnes)
112 case	25.1	0.098*(Mcoil cases)	257	tonnes
113 Shear plate	21.6	0.0618*(Mshear plates)	349	tonnes
114 Insulation	2.9	0.07*(Mass insulation)	41.4	tonnes
115 Coil fabrication	30.2	0.4*(Conductor mass)	75.4	tonnes
116 Connections	6.2	0.02*Nconnections	312	
12 PF Coils	**7.50**			
121 PFC conductor and fab	2.32	0.0116*(total kAmp-m-T)	199.6	(kA-km-T)
122 PFC support	1.95	0.0119*(PFC supports)	163.6	(tonnes)
123 PFC connections	3.24	0.01*(PFC Connections)	324	
13 OHC	**6.63**			
131 OH conductor	3.57	2.667*(Conductor length)	1.34	(km)
132 OHC insulation	0.04	0.035*(Minsulation)	1.28	(tonnes)
133 OHC fabrication	1.72	0.2*Mconductor	8.59	(tonnes)
134 TFC Bearing plate	0.00		0.00	
135 OHC connections	1.30	0.01*NOHconnections	130	
14 Coil Structure	**5.84**			
141 Gravity support	2.42	0.036*(Mgravity support)	67.3	(tonnes)
142 Intercoil structure	3.42	0.035*(Mintercoil structure)	97.8	(tonnes)

Near term resistive tokamak (FIRE)

Power conditioning equipment

		RULE	FIRE	
4.1 Coil power supply	**166.6**			
411 TFC Supplies	**59.3**			
4111 Transformers	5.8	4.76*0.000059*(1000000*PowerTF)^0.7	1.45	(GVA)
4112a TF Rectifiers	46.8	0.06*P_TFtotal	781	(MW)
4112a Internal Dump Power Supplies	0	0	0	
4113a Resistors	0	0	0	
4112b Interruptors	0	0	0	
4112b Dump Resistors	0	0	0	
4114 I&C (M$)	0	0	0	
4115 Bussing	6.7	4.76*0.0283*(LengthTFbusing*ITFconductor)	49.5	kA km
412 PFC Power Supply	**107.3**			
4121 Main Power Supplies	49.0	4.76*211000*PpeakPF_MVA*0.000001	48.7	MVA
4122 I&C	0	0	0	
423 Bussing	11.9	4.76*109*IpeakPF*LengthPFbus*0.001	22.9	kA km
41324 Burn power supplies	1.3	4.76*0.000001*49*NPFcircuits*(PresistivePF/NPFcircuits)^0.7	5618	
4125 Breakers	17.6	?		
4126 Resistors	0.6	4.76*0.2*500*EnergyPF*0.000001	1266	MJ
4127 AC Breakers	27.0	4.76*810000*NPFcircuits*0.000001	7	

Near term SC tokamak (FIRE 6)

Refrigerator and leads

Leads		RULE	FIRE VI	units
M$, VCL's TF	3.6	kA-lead TF*5000*0.000001	713.3	kA-lead
M$, VCL's PF	4.3	kA-lead PF*5000*0.000001	864	
M$, Cryogenic Refrigerator	29.2	(0.063/4.2)*(1000*P_refrigerator)^0.7	50	kW
M$, VCL liquefier	7.4	(0.063/4.2)*(1000*P_liquifier)^0.7	6.3	kW

Superconducting Magnet Costing

Cost of MRI/SMES magnets

System	Status	Stored Energy	Cold Mass	Cost	$/kg	$/J
		(MJ)	(tonne)	(M$)	($/kg)	($/J)
MRI	Commercial	4.0		0.35		0.075
SMES/Anchorage	Demo/ Cancelled	1800	690	18	26	0.01 ($0.57/W)
SMES/KY	Demo/ Final Design	100		30 (system) 16 (magnet)		0.3 0.16

Cost of ITER magnets

ITER System	Stored Energy	Cost	$/J (1989)	$/J (1999)
	(GJ)	(M$)	($/J)	($/J)
TF	97.5	1244	0.0128	0.0213
CS		263		
PF	25 (PF+CS)	222	0.0194	0.0323

ITER and TPX magnet figures of merit

Coil System	Stored Energy (GJ)	Mass (tonnes)	Mass/Energy (g/J)
	ITER CDA		
TF	40.7	6,960 +1500, OOP structure	0.209
PF	18.7		
	ITER EDA		
TF	108	11,100 (with BC) +5000, OOP structure	0.148
PF	25.3	3069	0.121
TF+PF	133.3	19,000	0.143
	TPX		
TF	1.05	138.6 (structure) 51.1 (windings)	0.181
PF	0.113	39.0 (windings) 9.0 (structure)	0.425
TF+PF	1.163	237.1	0.204

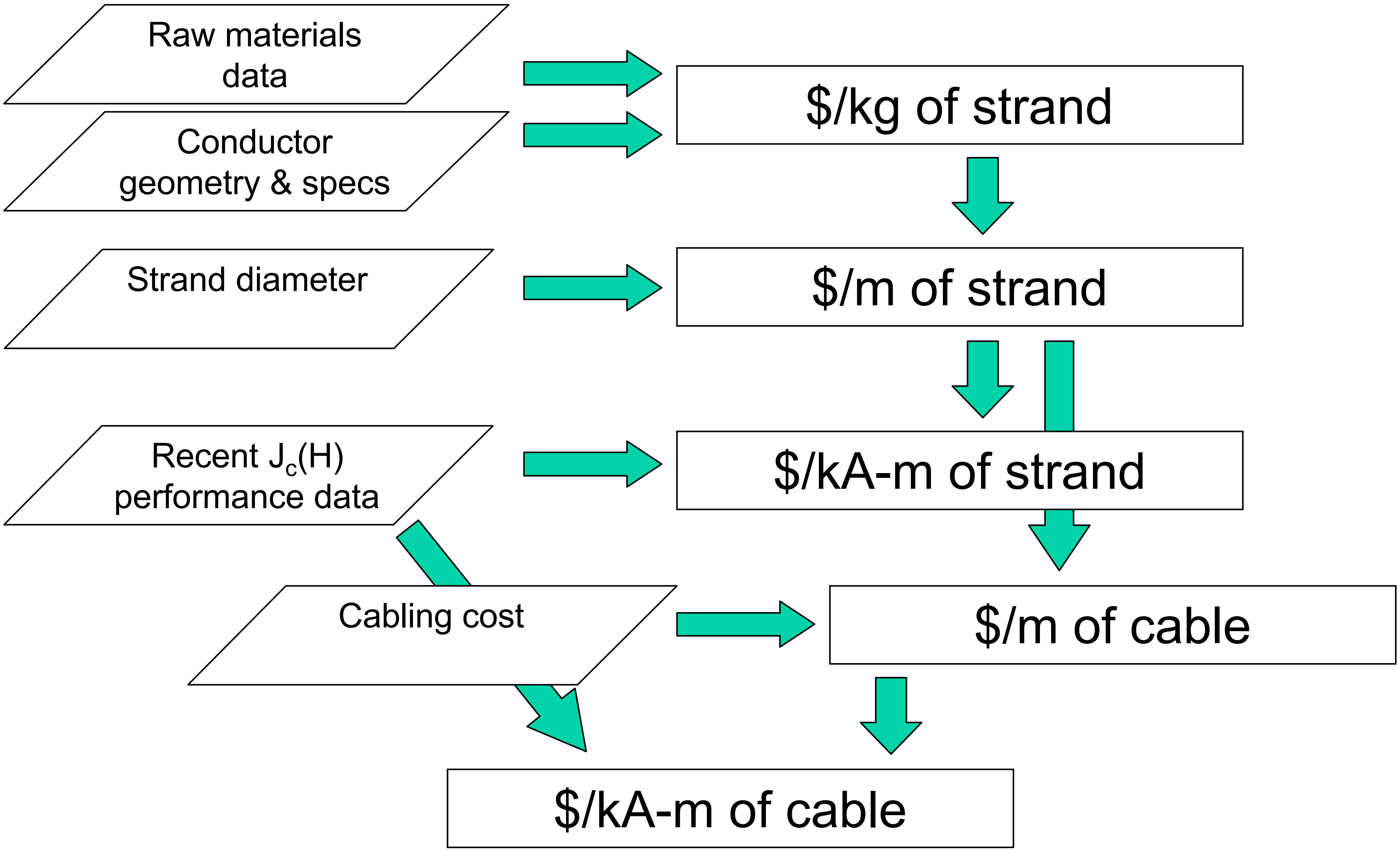
Option: Use Energy ==> Mass ==> Costing

Specific costs of the CS model coil

Subsystem	Parameter	Cost	Specific Cost
Inner Module			
Strand	6.5 tonnes	$7.8 M	$1200/kg
Jacket	2.5 km (25 tonnes?) 12.2 kg/m CS1 8.65 kg/m CS2	$2.5 M	$1000/m $100/kg
Coil (fab, tooling, development)	39 tonnes	$17 M	$436/kg (44 cents/g)
Subtotal	39 tonnes	$26.3 M	$674/kg (67 cents/g)
Outer Module			
Strand	7.41 tonnes?	$6.9 M	$930/kg
Jacket	2.85 km 29 tonnes?	$2.8 M?	$1000/m
Coil	50 tonnes?		
Subtotal	50 tonnes?	$26 M?	$520/kg?
Precompression Structure	70 tonnes	$0.8 M	$11.4/kg (1.1 cents/g)
Buffer Zone	18.2 tonnes		
CS Model Coil			
	600 MJ	$60 M?	$0.1/J?
	177.2 tonnes	$60 M?	0.295 g/J $338/kg ($0.34/g)

Bottom's up Cable Costing

Costing Methods for SC cable



Cost analyses of superconductors for high-field magnets, Lance Cooley, LTSW 2003, Monterrey CA

PIT(Powder_in_Tube) strand costs

LHC-NbTi		Nb_3Sn 4.2 K	Bi2212 4.2 K	MgB_2 4.2 K	H-Nb_3Sn 4.2 K	H-MgB_2 4.2 K
	Conductor raw materials cost					
	filament cost, $/kg	* $170	** $400	$500	$200	$50
	stabilizer cost, $/kg	$5	$175	$5	$5	$5
	reactants cost, $/kg	* $200	$0	$0	$0	$0
	diffusion barrier cost, $/kg	$0	$0	$5	$420	$10
	ancillary material cost, $/kg	$0	$0	$1,000	$0	$20
$66	***Conductor raw cost, $/kg***	*$83.50*	*$214.21*	*$252.59*	*$83.50*	*$19.50*
27¢	***Conductor raw cost, $/m***	*$0.35*	*$0.93*	*$1.01*	*$0.36*	*$0.06*
	Strand performance data					
	non-stabilizer J_c at field, A/mm^2					
	5	6400	2400	1500	12650	4000
	8	3600	2200	500	6820	1800
	10	2550	2030	150	5100	1000
	12	1780	2000	60	3150	500
	15	1050	1900	2	1680	100
	20	200	1800	0	425	0
	Strand raw performance index $/kA-m					
	5	*$0.11*	*$1.47*	*$0.90*	*$0.06*	*$0.03*
	8	*$0.20*	*$1.61*	*$2.69*	*$0.11*	*$0.07*
	10	*$0.28*	*$1.74*	*$8.96*	*$0.14*	*$0.12*
21¢ @ 5T	*12*	*$0.39*	*$1.77*	*$22.41*	*$0.23*	*$0.24*
	15	*$0.67*	*$1.86*	*$672.37*	*$0.43*	*$1.19*
	20	*$3.51*	*$1.96*	*>Hc2*	*$1.72*	*>Hc2*

* Reflects recent VAC/SMI bid and extruded tube quote

** Reflects recent presentation by Hasegawa at MT-18

PIT cable costs

	Nb_3Sn	Bi2212	MgB_2	H-Nb_3Sn	H-MgB_2
	4.2 K	4.2 K	4.2 K	4.2 K	4.2 K
Strand raw cost, $/kg	*$83.50*	*$214.21*	*$252.59*	*$83.50*	*$19.50*
Strand raw cost, $/m	*$0.35*	*$0.93*	*$1.01*	*$0.36*	*$0.06*
Strand cost relative to LHC Nb-Ti	*1.3*	*3.5*	*3.8*	*1.4*	*0.2*
Production cost scaling factor	825%	805%	225%	225%	225%
Relative to LHC Nb-Ti	*3.7*	*3.6*	*1.0*	*1.0*	*1.0*
Scaled strand cost, $/kg	*$688.88*	*$1,724.39*	*$568.33*	*$187.88*	*$43.88*
Recent purchase prices, $/kg					
Scaled strand cost, $/m	*$2.90*	*$7.49*	*$2.27*	*$0.82*	*$0.13*
			$0.50		
Cabling cost, $/m	*$3.00*	*$3.00*	*$3.00*	*$3.00*	*$3.00*
Scaled cable cost, $/m	*$107.31*	*$272.53*	*$84.71*	*$32.53*	*$7.76*
Cable final performance index at field, $/kA-m					
5	*$2.06*	*$29.82*	*$2.96*	*$0.32*	*$0.24*
8	*$3.66*	*$32.53*	*$8.88*	*$0.59*	*$0.53*
10	*$5.17*	*$35.26*	*$29.60*	*$0.78*	*$0.95*
12	*$7.41*	*$35.79*	*$74.00*	*$1.27*	*$1.91*
Scanlan data				*$1.50*	
15	*$12.56*	*$37.67*	*$2,219.94*	*$2.38*	*$9.53*
20	*$65.92*	*$39.76*	*(>Hc2)*	*$9.40*	*(>Hc2)*

Used this in ARIES ST

ARIES ST magnet costing

Superconductor cost	$/kg	500	120
SC	m^3/m	4.80E-05	4.80E-05
	kg/m	0.3888	0.3888
	Cost @ 12 T, 4.2 K	194.4	46.7
Stabilizer cost	$/m	8.5	8.5
Diffusion barrier cost	$/m	1.6	1.6
Insulating and cabling	$/m	100	38
Total conductor	$/m	304.6	94.8
	$/kA m @12 T 4.2 K	7.6	2.4
Scaled	$/kA m	10.2	3.2
Cost of coils, all periods	M$	30.2	9.4
Total conductor cost (direct)	M$	102	32

Detailed costing of PF coils for ARIES-AT

Conductor	Self-supporting PF coils		
Strands	25.4	IM	12.7
Coat	6	LCE	2.3
Cabling	13.6	LCE	5.2
Waste	11.3		0
Sheath	5.3	LCE	2
Encapsulation	3.7	LCE	1.4
Additional material	0.9		0
Conductor subtotal	**66.3**		**23.8**
$/ kA m			1
Winding pack			
Insulation	2.2	LCE	0.8
Tooling	4.2		0
Winding	50.9	LCE	19.6
Dummies	7.1		0
Heat treatment	0.7	LCE	0.3
Leads	1.2	LCE	0.4
Winding pack subtotal	**132.6**		**44.9**
$/ kA m			1.9
Support	19.4	LCE	7.5
Engineering	43.6		0
Hardware/engineering	**195.6**		**52.4**
Contingency	58	20%	10.5
PACE direct	253.6		62.9
PACE G&A	22.6	10%	6.3
OPEX	8.7		0
TOTAL in M$	**285**		**69.2**

HTS development/extrapolated costs

Technology Attributes	Near-Term Goals (present – 2007)	Mid-Term Goals (2008 – 2011)	Long-Term Goals (2012 – 2015)
Critical current	250 A/cm, 77 K, sf 125 A/cm, 65 K, 2 T	500 A/cm, 77 K, sf 250 A/cm, 65 K, 2 T	1000 A/cm, 77 K, sf 500 A/cm, 65 K, 2 T
Cost/Performance Ratio	$400/kA-m, 77 K, sf $800/kA-m, 65 K, 2 T	$50/kA-m, 77 K, sf $100/kA-m, 65 K, 2 T	$10/kA-m, 77 K, sf $20/kA-m, 65 K, 2 T
Wire Length	100 m	1000 m	>1000 m
AC Losses	1 – 2 W/m	0.5 – 1.0 W/m	< 0.50 W/m

Structural Materials
Costing

- Incoloy 908 has been the preferred conductor for Nb_3Sn today because of manufacturing method
  - wind and react
  - requires high temperature processing of conductor for extended period of times
  - matches thermal contraction coefficient to SC
- Incoloy is expensive ($40/kg), compared with SS ($10-20/kg)
  - suffers from oxygen induced corrosion

Summary

- Cost of magnets in fusion reactors are about a factor of 6-10 less expensive than comparable magnets today
- Conservative design of today's magnets makes them substantially more expensive
  - Conservatism can be decreased with experience
- Innovations in both strands and manufacturing could decrease the costs in 5-20 years by a factor of 10.
- Costing of TF magnet should be done in terms of $/J, instead of $/kg.
- Further innovations can decreased cost even more

Superconducting Magnets

- Increase the performance of the individual materials & components by increasing:
    - allowable current density
    - working stress
    - maximum electric field
- Greatest potential improvements in
    - superconducting strand and cable
        - cost reduction factor of 3-10 is possible
    - magnet structure improvements in
        - design and manufacturing techniques
        - material properties

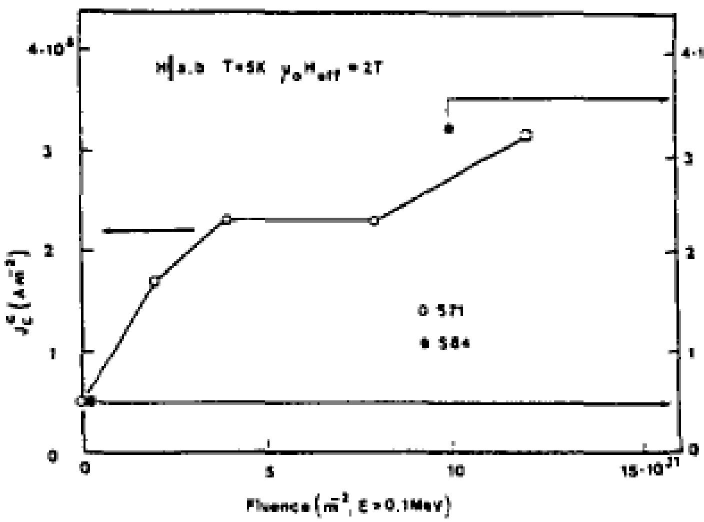
Resistive Magnets

- Resistive magnets discussed for both near, intermediate and long term (*i.e.*, fusion reactor) applications
- Challenges and opportunities:
    - Development of cheap strong, castable conductor alloys with good fatigue properties.
    - Improved high field designs (improved structure, conductors, configuration, active presses, etc.)
    - Improved compact high current demountable joints.
    - Development of reliable compact sliding joints.
    - Development of optimized designs for intense active cooling
    - Scale model of high performance tokamak magnet systems
    - Improved insulation (generic)
    - Development of advanced manufacturing techniques (generic)

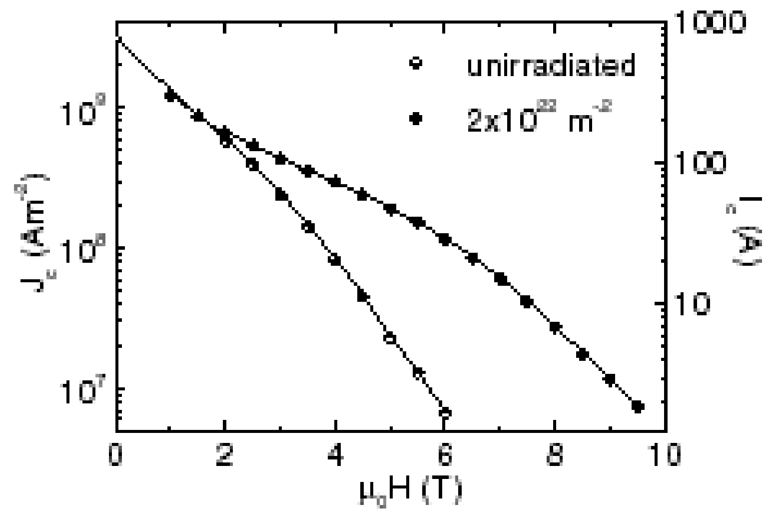
Irradiation Limits

Jc Enhancement of Hi Tc by Irradiation

YBCO



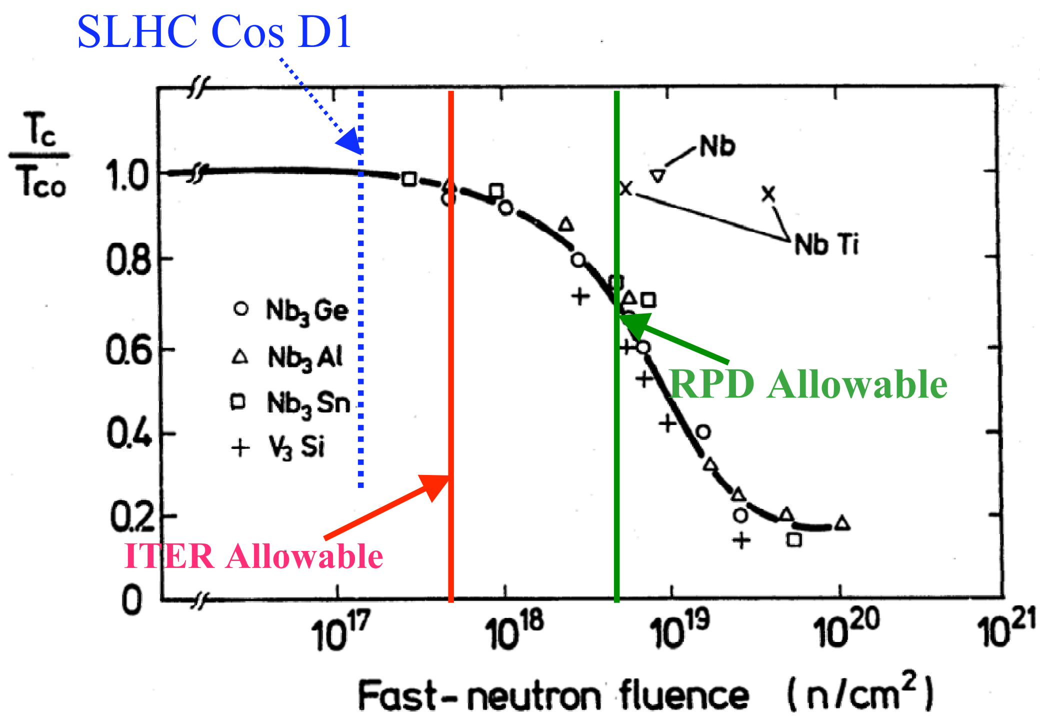
MgB2

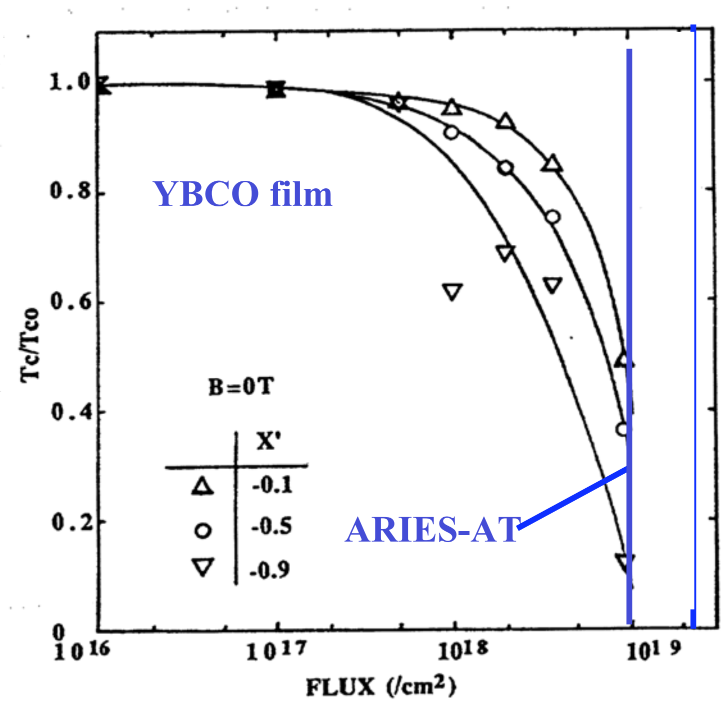


J_c, YBCO, MgB_2 enhanced by n^o irradiation, out to 2 x 10^{22}/m^2

Little, if any, J_c data out to 10^{23}/m^2

Neutron Degradation of T_c, A15's and YBCO





- All A15's have same T_c/T_{co} degradation vs. fluence
  - 1-2 orders of magnitude more sensitive than NbTi
- YBCO films have faster T_c/T_{co} degradation than A15's

Radiation resistance of fusion magnet materials, Schultz, J.H., 20th IEEE Symposium on Fusion Engineering (Oct. 2003)

	Technology Readiness Level	Description
1.	Basic principles observed and reported.	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.
2.	Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
3.	Analytical and experimental critical function and/or characteristic proof of concept.	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4.	Component and/or breadboard validation in laboratory environment.	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared to the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.
5.	Component and/or breadboard validation in relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment. Examples include "high fidelity" laboratory integration of components.
6.	System/subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in simulated operational environment.
7.	System prototype demonstration in an operational environment.	Prototype near, or at, planned operational system. Represents a major step up from TRL 6, requiring demonstration of an actual system prototype in an operational environment such as an aircraft, vehicle, or space. Examples include testing the prototype in a test bed aircraft.
8.	Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.
9.	Actual system proven through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. Examples include using the system under operational mission conditions.

Not a grand-challenge, but…

Magnets TRL for tokamaks

CSMC (US/Japan)

TF Model coil

ITER:

Operation with pulses, radiation fields, plasma operation (disruptions)

Not enough lifetime, but more pulses than a reactor

Random thoughts on costing methodology

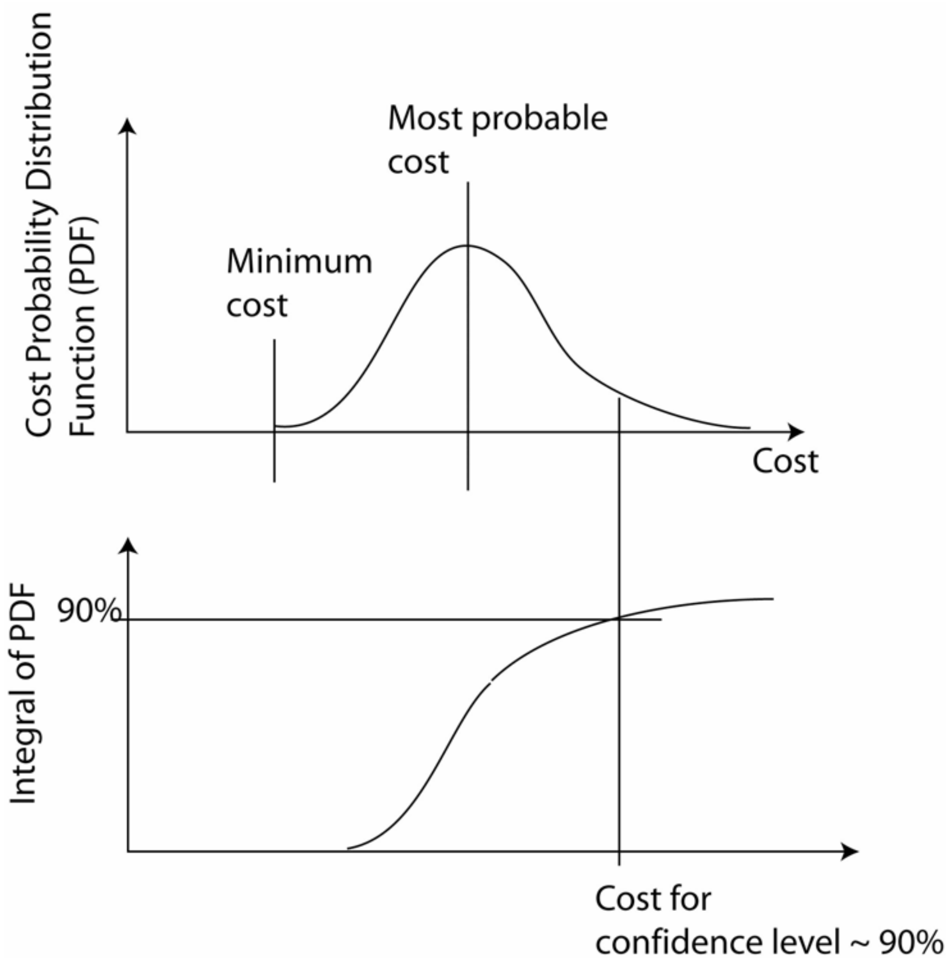
Means of obtaining minimum cost, most likely cost and cost spread

L. Bromberg

Costing in the presence of uncertainty

- In reality, the costing of the components of a fusion reactor is an estimate that has substantial uncertainty
- Recently, there has been substantial progress in making estimates of these type of systems:
  - Provide cost information that contains both an estimated cost and an uncertainty for all components
- Use a MonteCarlo approach to determining the cost of the system
  - Assign cost of different elements of reactor according to probability distribution of unit costs
  - Randomly assign cost for the different elements, each according to its probability distribution function
    - Each simulation event (cost) is recorder and process is repeated multiple times, in order to determine a probability distribution function of the total cost.
  - Cost methodology provides both an average cost, most probable cost as well as an uncertainty in the costing

Cost determination within a given confidence level



Costing with of fusion commercial reactors using MonteCarlo

- Method can be used for costing of components, such as large ceramic components, that have a large deviation in cost because of manufacturing difficulty (some elements inexpensive, others expensive due to the need of substantial repair).
- Method can also be used to determine impact of construction time, including interest rate effects on cost of construction
- Effect of learning curve
- Determining R&D needs for cost uncertainty minimization
    - elements resulting in largest uncertainty of total cost

Figures of merit of real and imaginary magnets

Magnet	Stored Energy	Mass	Mass/Energy
	(MJ)	(tonnes)	(kg/kJ)
Ignitor TF	1309	96 (magnet) 436.8 (magnet+clamps)	0.073 0.334
TFTR, TF	1366	580	0.425
PLT, TF	251	98	0.78
PDX, TF	182	73	0.401
ATC, TF	16.7	26	1.56
Alcator A, TF	24	5.8	0.335
Alcator C, TF	95	17.7	0.372
Ormak, TF	4.5	10	2.2
ISX-A, TF	19.4	12.0	0.618
ISX-B, TF	13.5	12.0	0.889
JET, TF	940	380	0.404
Zephyr, TF	1200	300	0.25
LCP	650	290	0.446
MFTF	409	341	0.834
Tore Supra	640	206	0.322
NMR Solenoid	0.4	0.082	0.205
FED	16300	4040	0.248
STARFIRE	50000	6000	0.12
WITAMIR	60,300	8,358	0.139
NUWMAK	35,700	1,540	0.043
UWMAK III	117,000	6,564	0.056
UWMAK II	233,000	25,508	0.109
UWMAK I	216,000	23,800	0.11