FUSION ENGINEERING DESIGN CENTER

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CONF-8711144--1-Vugraphs

DESIGN SENSITIVITIES & TRADE OFFS*

R. L. REID
FEDC/ORNL

CONF-8711144--1-Vugraphs

DE88 003773

ITER DESIGN MEETING
LAWRENCE LIVERMORE NATIONAL LABORATORY
LIVERMORE, CALIFORNIA

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*RESEARCH SPONSORED BY THE OFFICE OF FUSION ENERGY, U.S. DEPARTMENT OF ENERGY, UNDER CONTRACT DE-AC05-84OR21400 WITH MARTIN MARIETTA ENERGY SYSTEMS, INCORPORATED.

MASTER

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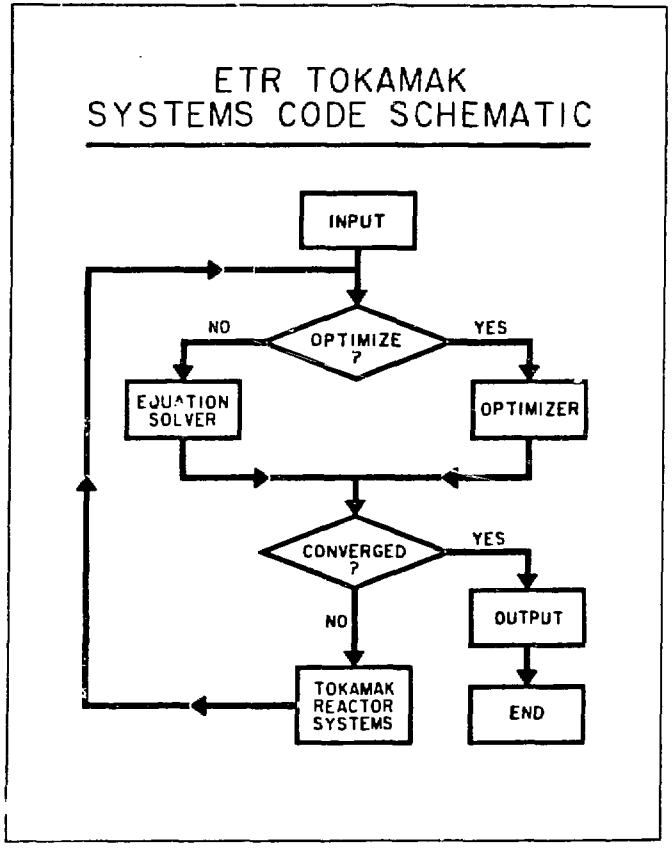
RECENT SYSTEMS ANALYSIS ACTIVITIES HAVE FOCUSED ON:

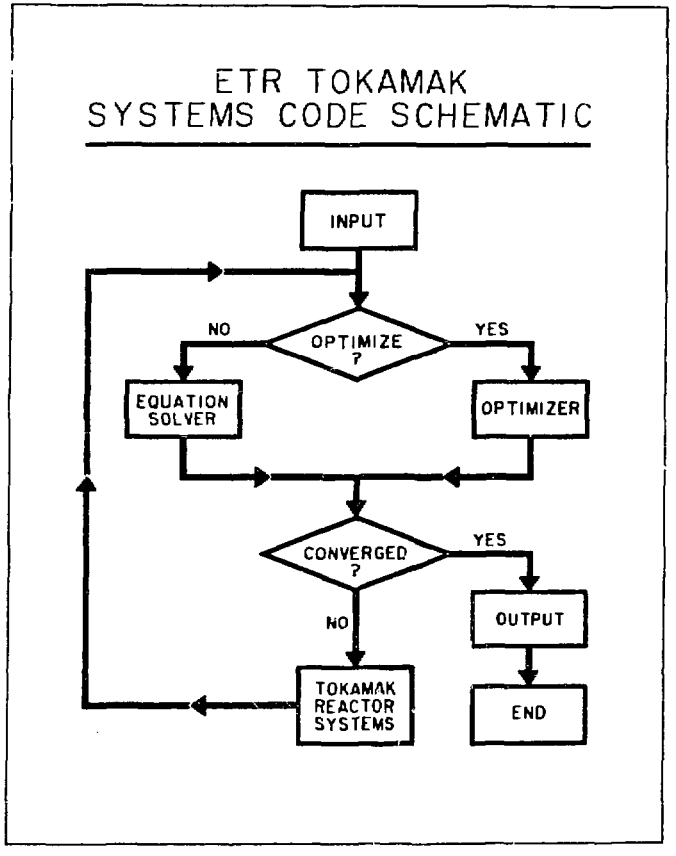
- COMPARING CANDIDATE ETR CONFIGURATIONS (BENCHMARK)
- PERFORMING SENSITIVITY ANALYSIS (OPTIMIZATION MODE)

BENCHMARK MODE



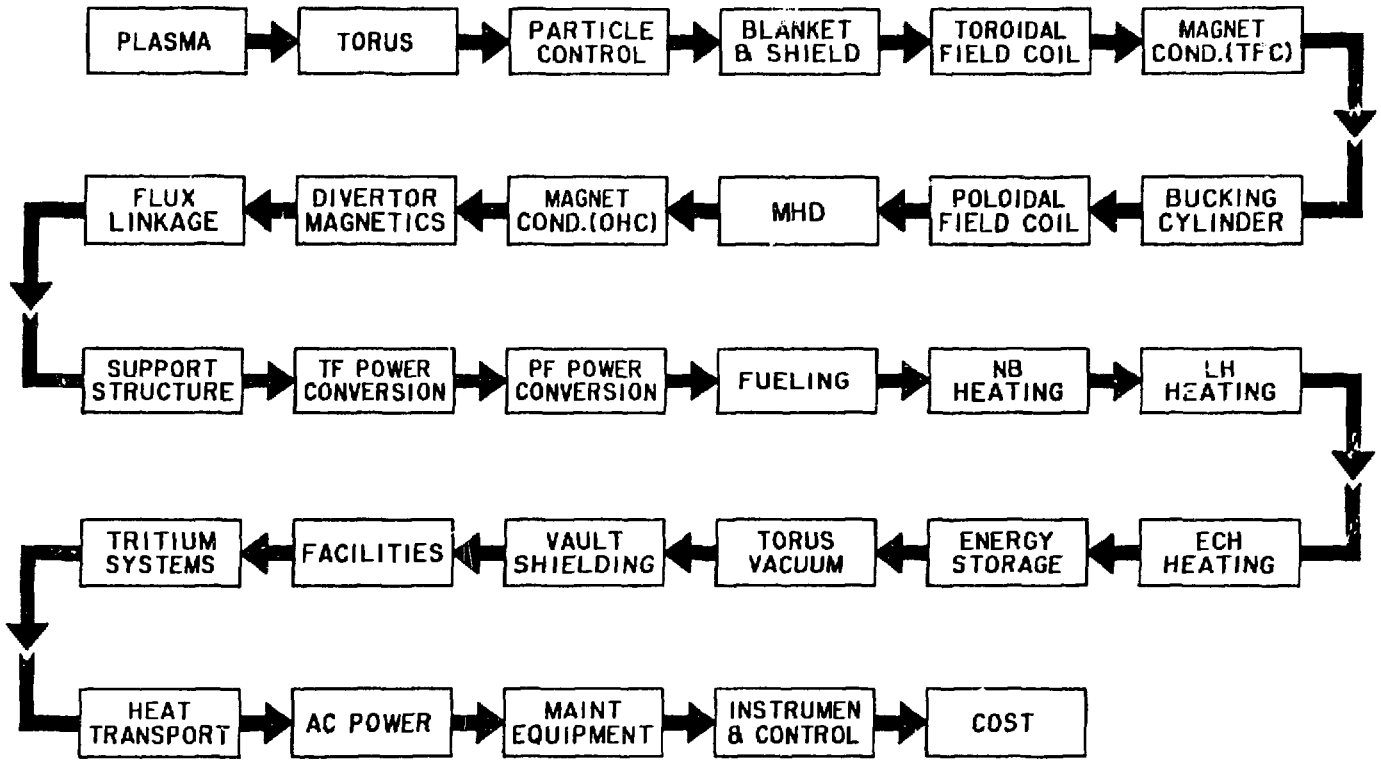
- ITERATE SAME NUMBER OF VARIABLES AS CONSTRAINTS
- INPUT RADIAL BUILD, PLASMA CHARACTERISTICS (DENSITY, TEMPERATURE, Z_{EFF}), FIELD-ON-AXIS, ETC.
- COMPUTE PERFORMANCE LEVELS (FUSION POWER, BETA, STRESS, VOLT-SEC AVAILABILITY, ETC.)
- CALIBRATE LIMITS

OPTIMIZATION MODE



- ITERATE MORE VARIABLES THAN CONSTRAINTS
- INCORPORATE UPPER AND LOWER BOUNDS ON ALL VARIABLES BEING ITERATED
- SPECIFY A FIGURE OF MERIT TO BE MAXIMIZED OR MINIMIZED
- INPUT PHYSICS AND ENGINEERING REQUIREMENTS (WALL LOADING, FUSION POWER, VOLT-SEC CAPABILITY, MAXIMUM STRESS), ETC.
- COMPUTE RADIAL BUILD, FIELD-ON-AXIS, COIL CURRENTS, ETC., WHICH SATISFIES DESIRED FIGURE OF MERIT

TOKAMAK REACTOR SYSTEMS FLOW DIAGRAM



INTOR-LIKE DESIGNS:MAJOR FEATURES

FEATURE/PARAMETER	INTOR	NET	FER	TIBER	OTR
Major Radius,m	5.0	5.18	4.42	3.0	6.3
Minor Radius,m	1.2	1.35	1.25	0.83	1.5
Ignited (I) or Q	I	I	Q >20	Q > 5	Q > 5
Operating Mode	Induct.	Induct.	Hybrid	Non-ind.	Induct.
Pulse Length, s	150	>200	800	CW	600
Impurity Control	SN	DN/SN	SN	DN	SN
Elongation	1.6	2.2/1.6	1.7	2.4	1.5
Triangularity	0.25	0.7/0.3	0.2	0.4	0.3
Plasma Current, MA	8.0	10.8	8.7	10.0	8.0
Fluence, MWy/m^2	3.0	0.8	0.3	3.0	5.0
Tritium Breeding	>0.6	>0.3	None	>1.0	>1.05
Plasma Heating	ICRH	(TBD)	(TBD)	LH+NB	ICRH

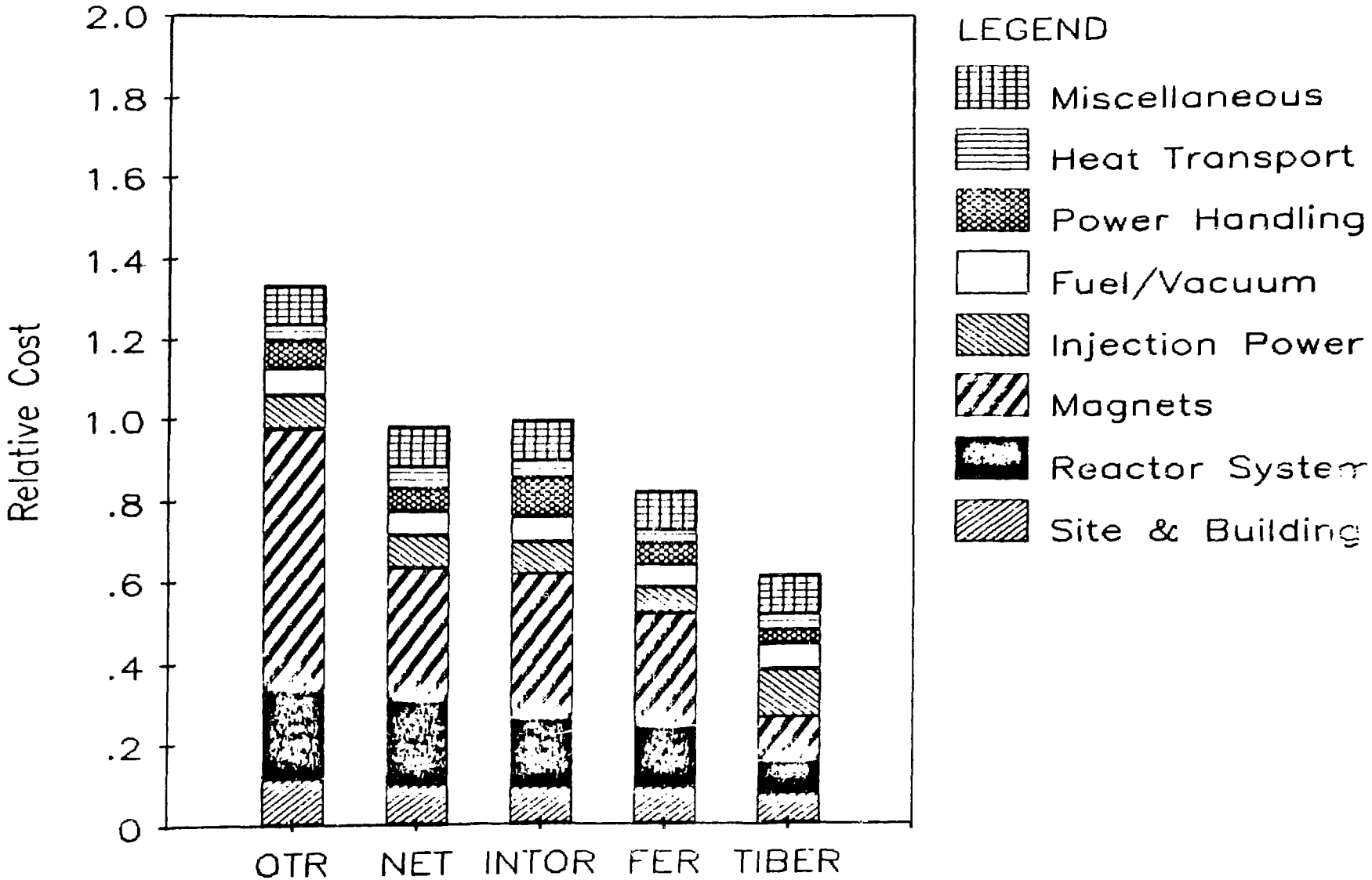
COMPARISON OF BENCHMARK CALCULATIONS

ITEM	INTOR	NET	FER	TIBER	OTR
Major Radius, m	5.0	5.18	4.42	3.0	6.3
Minor Radius, m	1.2	1.35	1.25	0.83	1.5
Plasma Current, MA	8.0	10.2	8.7	10.0	8.0
Field on Axis, T	5.5	5.0	4.6	5.55	5.8
Density, DT, 10^{20} m^{-3}	1.4	1.3	1.0	0.8	1.4
Temperature, keV	10.0	10.0	12.0	16.0	8.0
TF Coil Thickness, cm	67	70	68	49	110

Maximum Field, TF, T	11.0	10.8	11.4	10.8	12.0	10.0	12.0	11.1	12.0	11.8
Magnetic Energy, GJ	25.0	19.9	25.0	22.2	14.0	11.6	4.0	5.0	45.0	38.7
Current Density, TF, A/cm^2	2540	2970	2200	2467	3300	2990	4000	4390	3500	3055
Maximum Field, OH, T	8.0	8.8	11.0	10.1	12.0	10.9	14.0	13.8	8.0	7.6
Fusion Power, MW	584	584	650	652	406	405	314	308	500	504
Wall Load, MW/m^2	1.3	1.2	1.0	0.99	1.1	0.9	1.1	1.2	0.8	0.7
Beta, %	4.9	5.0	5.6	5.6	5.3	6.6	6.0	7.0	3.2	3.5
Required V-s	112	109	181	149	50	140	58	66	200	184

(Left Column = Published Value; Right Column = Calculated Value)

Direct Cost Comparison of INTOR–Like Devices



TIBER SENSITIVITY STUDY

- PERFORM BENCHMARK
- FIND THE MINIMUM COST TIBER
- DO SENSITIVITIES ABOUT THE MINIMUM COST TIBER
- EXAMPLES:

  BETA LIMIT COEFFICIENT
  PLASMA PROFILES
  WALL LOAD
  Q VALUE
  ELONGATION
  SHIELD THICKNESS
  SCRAPEOFF THICKNESS
  TF COIL MAGNET FIELD
  TF COIL MAGNET STRESS

PHYSICAL QUANTITIES USED AS VARIABLES IN THE OPTIMIZATION PROCEDURE

MAJOR RADIUS

ASPECT RATIO

PLASMA BETA

PLASMA DENSITY

PLASMA TEMPERATURE

FIELD ON AXIS

OH COIL BORE

OH COIL THICKNESS

OH COIL CURRENT DENSITY

TF COIL THICKNESS (INCLUDING CASE)

TF COIL CASE THICKNESS

TF COIL CURRENT DENSITY

WINDING PACK VOID FRACTION (OH AND TF FRACTIONS)

WINDING PACK COPPER FRACTIONS (OH AND TF COIL FRACTIONS)

WINDING PACK STEEL FRACTIONS (OH AND TF COIL FRACTIONS)

FIXED INPUT ITEMS FOR TIBER

TROYON BETA LIMIT COEFFICIENT	3.3*
ELONGATION (AT SEPARATRIX)	2.4
TRIANGULARITY (AT SEPARATRIX	.4
EDGE q -BAR	2.3
TEMPERATURE (DENSITY) PROFILE FACTOR, P	.58 (1.02)
Z_{EFF}	2.1
INNER (OUTER) SCRAPEOFF (M)	.082 (.142)
INNER (OUTER) SHIELD (M)	.48 (1.52)
TF-OH COIL GAP (M)	0.
INNER (OUTER) FIRST WALL + GAP THICKNESS (M)	.02 (.02)
INNER (OUTER) TF COIL - SHIELD GAP (M)	.02 (.01)
NUMBER OF TF COILS	16

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*LIMIT CALIBRATED FROM TETRA BENCHMARK OF TIBER

INEQUALITY CONSTRAINTS USED IN TIBER STUDIES

INEQUALITY:		
BETA	<	TROYON LIMIT
DENSITY	<	GREENWALD LIMIT
FUSION POWER/ INJECTION POWER	>	4.7 (*)
WALL LOAD (MW/M^2)	>	1.23 (*)
INDUCTIVE V-s CAPABILITY/ PLASMA - LI	>	.94 (*)
NONINDUCTIVE CURRENT DRIVE (FRACTION OF TOTAL CURRENT)		1.0
TF COIL TRESCA STRESS (MPA)	<	850 (*)
OH COIL TRESCA STRESS (MPA)	<	625 (*)
TF (OH) COIL CURRENT DENSITY SUPERCONDUCTOR LIMITS FOR: J (B, STRAIN, TEMPERATURE) HEAT TRANSFER QUENCH PRESSURE QUENCH TEMPERATURE RISE	<	X .85* (1.12*)
TF (OH) COIL CONDUCTOR STABILITY MARGIN (MJ/CM^3)	>	300
TF COIL RIPPLE AT PLASMA (%)	<	1.0

(*) LIMIT FOUND FROM TIBER BENCHMARK RUN

PARAMETERS FOR THE BENCHMARKED TIBER POINT
AND THE "OPTIMIZED" TIBER-LIKE DEVICE

QUANTITY	TIBER	OPTIMIZED TIBER
PHYSICS:		
MAJOR RADIUS (M)	3.00 +	2.73 *
ASPECT RATIO	3.60 +	4.05 *
PLASMA CURRENT (MA)	10. *	8.03 *
FIELD ON AXIS (T)	5.55 +	6.43 *
PLASMA BETA (%)	7.2 *	6.2 ⊠
ELECTRON TEMPERATURE (KEV)	15.7 +	16.4 *
ELECTRON DENSITY (10^{20} M-3)	1.06 +	1.16 *
FUSION POWER (MW)	308 *	233 *
NEUTRON WALL LOAD (MW/M^2)	1.23 #	1.23 ⊠
PLASMA VOLUME (M^3)	96 *	57 *
Q (A)	4.7 #	4.7 ⊠
RADIAL BUILD (M) :		
OH COIL	1.07 +	.96 *
TF COIL	.49 +	.49 *
INNER SHIELD	.48 +	.48 +
MINOR RADIUS	.83 +	.67 *
TF COIL:		
OVERALL CUR. DEN. (MA/M^2) (B)	20.7 *	23.7 ⊠
STORED ENERGY (GJ)	5.0 *	4.8 *
PEAK FIELD (T)	11.1 *	12.3 *
CONDUIT STRESS	850 #	850 ⊠
STABILITY MARGIN (MJ/CC)	540 *	300 ⊠

PARAMETERS FOR THE BENCHMARKED TIBER POINT
AND THE "OPTIMIZED" TIBER-LIKE DEVICE (CONTINUED)

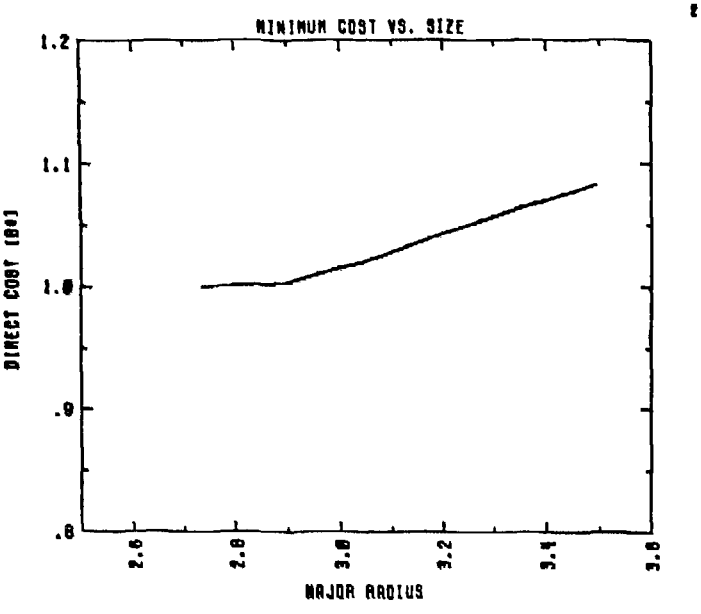
OH COIL:

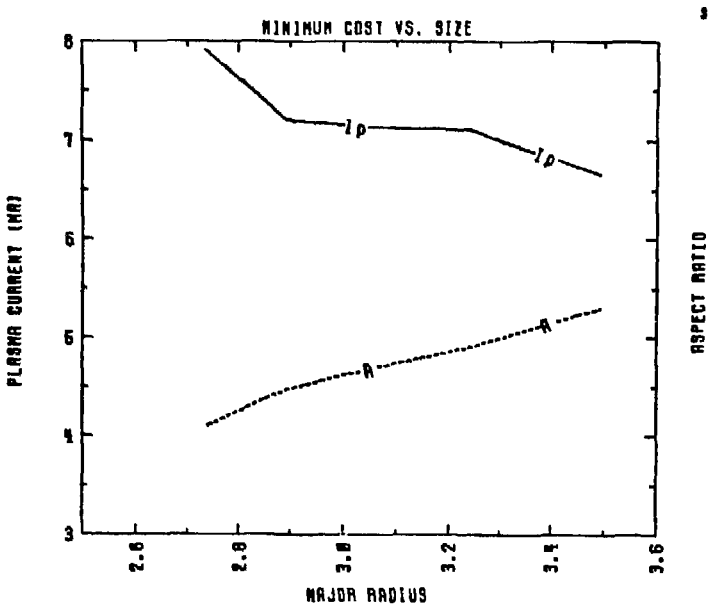
OVERALL CUR. DEN. (MA/M^2) (B)	27.8 *	30.1 ⊠
PEAK FIELD (T)	13.8 *	12.8 *
CONDUIT STRESS (MPA)	625 #	625 ⊠
STABILITY MARGIN (MJ/CC)	300 *	300 ⊠

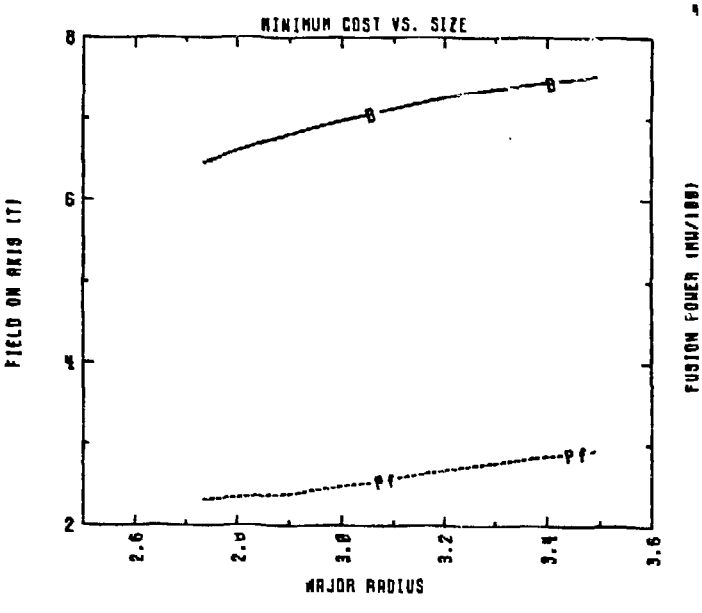
+ FIXED INPUT ITEM
* CALCULATED QUANTITY
# QUANTITY CALCULATED IN THE BENCHMARK RUN AND SUBSEQUENTLY USED AS A LIMIT
⊠ CALCULATED QUANTITY IN AN OPTIMIZATION RUN WHICH IS AT A LIMIT
(A) Q = FUSION POWER / INJECTION POWER
(B) THE HEAT TRANSFER EFFECT WAS THE LIMITING CONSTRAINT

TIBER

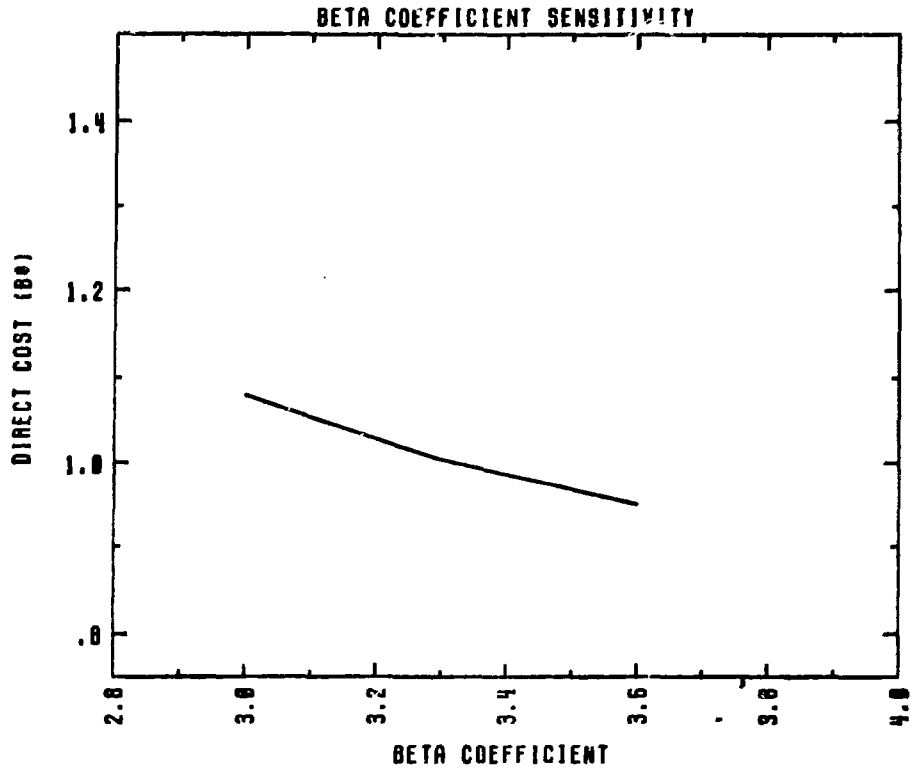
Minimum cost vs size



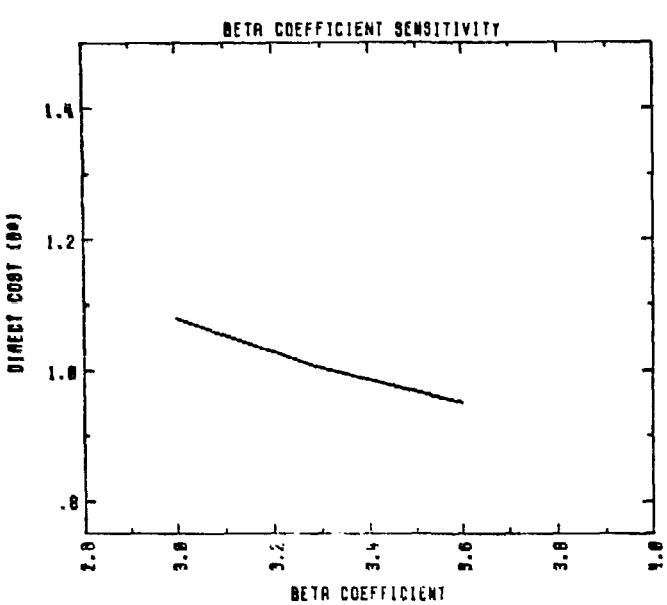


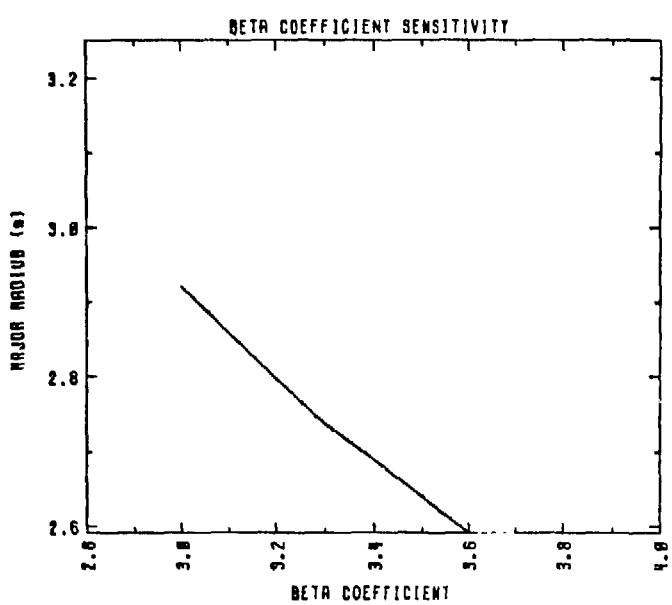


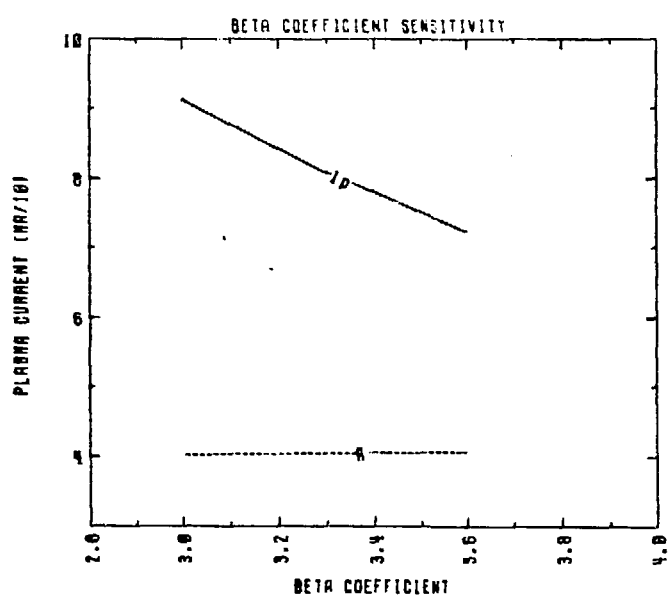
Minimum Cost vs Troyon Coefficient

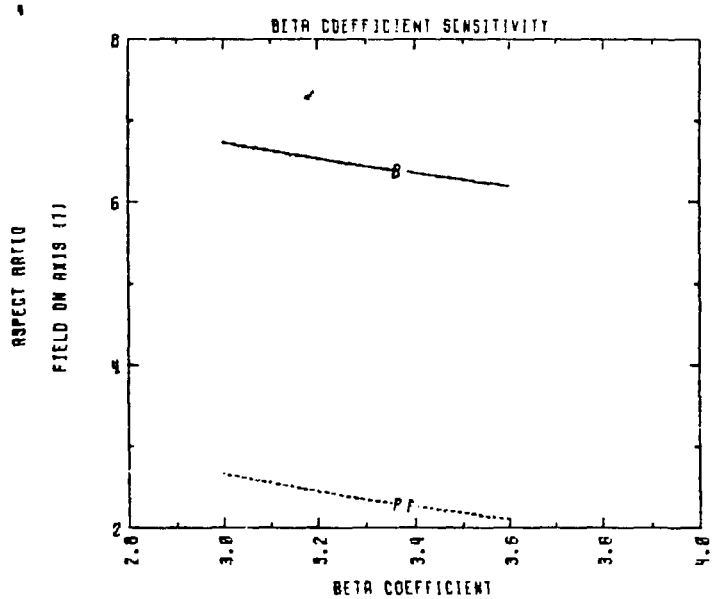


$$\beta = g \frac{I}{aB}$$

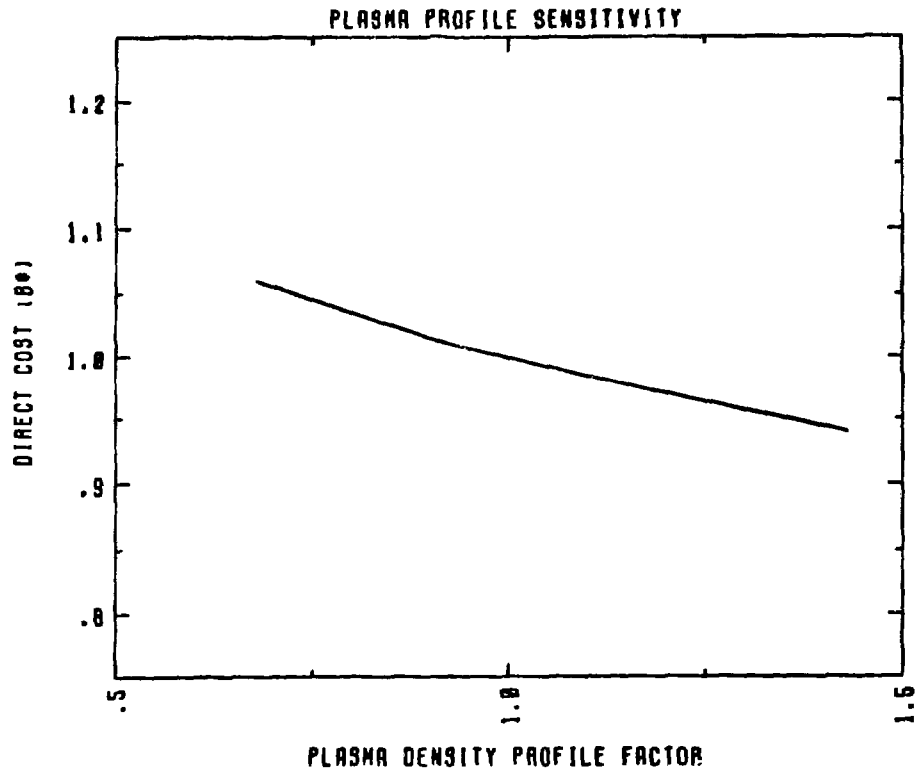

BETA COEFFICIENT SENSITIVITY
DIRECT COST ($B)
1.4
1.2
1.0
.8
2.0
3.0
3.2
3.4
3.6
3.8
4.0
BETA COEFFICIENT


BETA COEFFICIENT SENSITIVITY
MAJOR RADIUS (m)
3.2
3.0
2.8
2.6
2.0
3.0
3.2
3.4
3.6
3.8
4.0
BETA COEFFICIENT

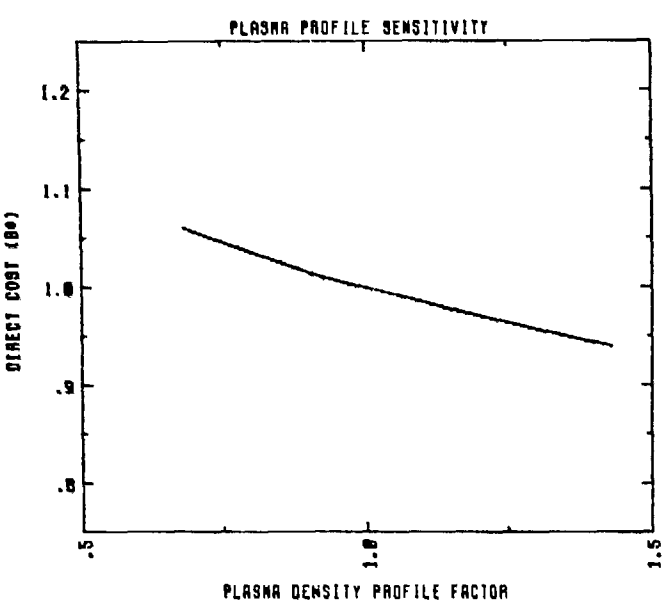

BETA COEFFICIENT SENSITIVITY
PLASMA CURRENT (MA/10)
10
8
6
4
ID
A
2.0
3.0
3.2
3.4
3.6
3.8
4.0
BETA COEFFICIENT

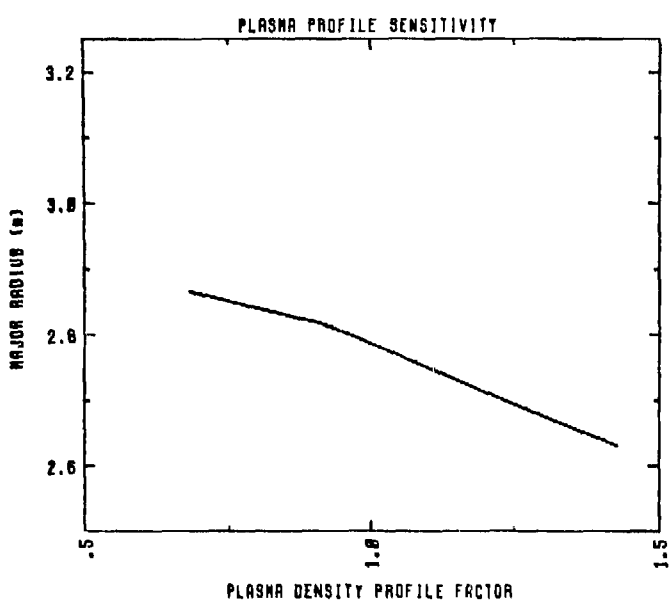

BETA COEFFICIENT SENSITIVITY
ASPECT RATIO
FIELD ON AXIS (T)
FUSION POWER (MW/100)
8
6
4
2
B
PF
2.0
3.0
3.2
3.4
3.6
3.8
4.0
BETA COEFFICIENT

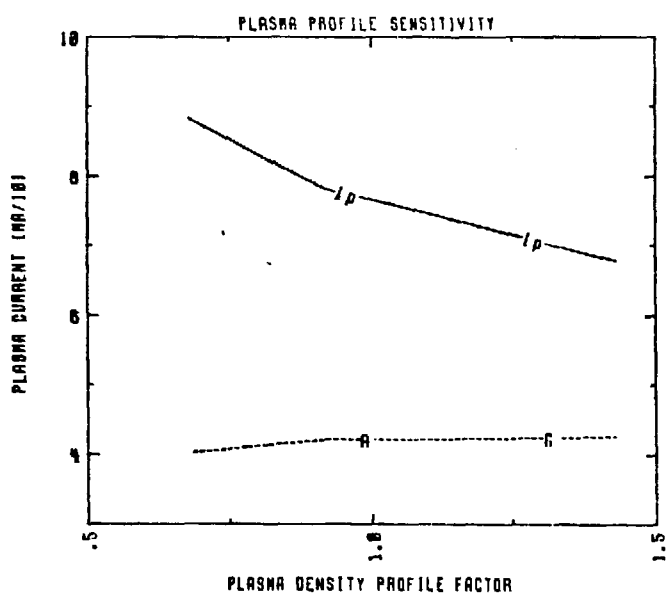
Minimum Cost vs Plasma Profiles

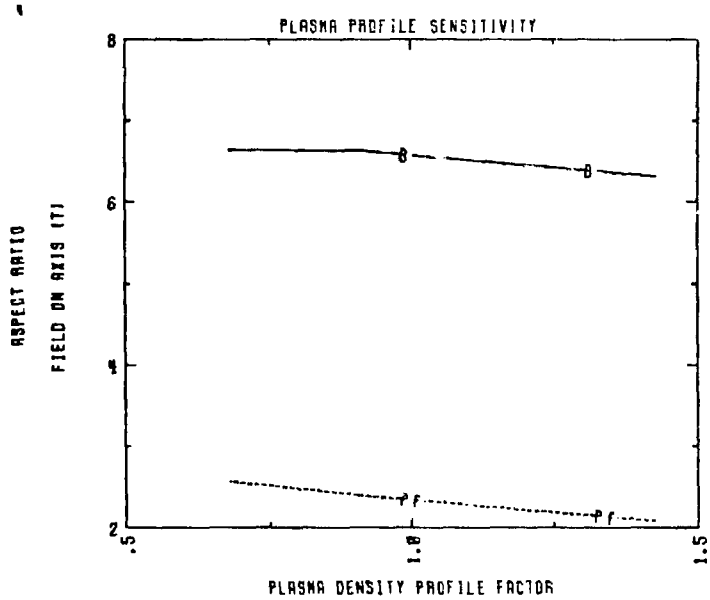


$$n \propto \left(1 - \left(\frac{r}{a}\right)^2\right)^{\alpha}$$

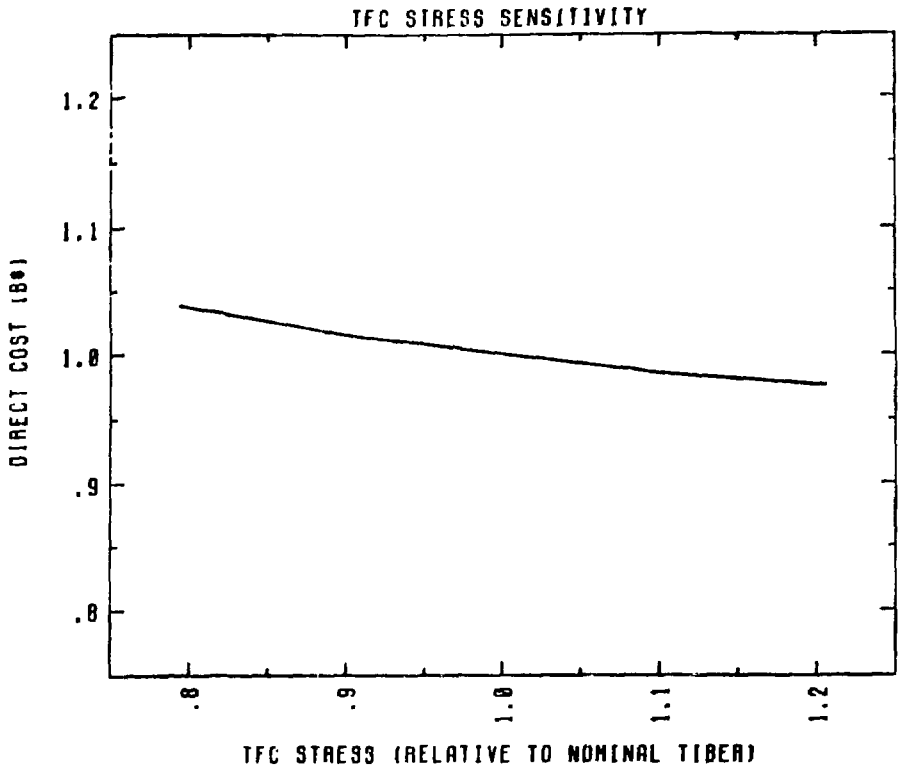

PLASMA PROFILE SENSITIVITY
DIRECT COST ($B)
1.2
1.1
1.0
.9
.8
.5
1.0
1.5
PLASMA DENSITY PROFILE FACTOR

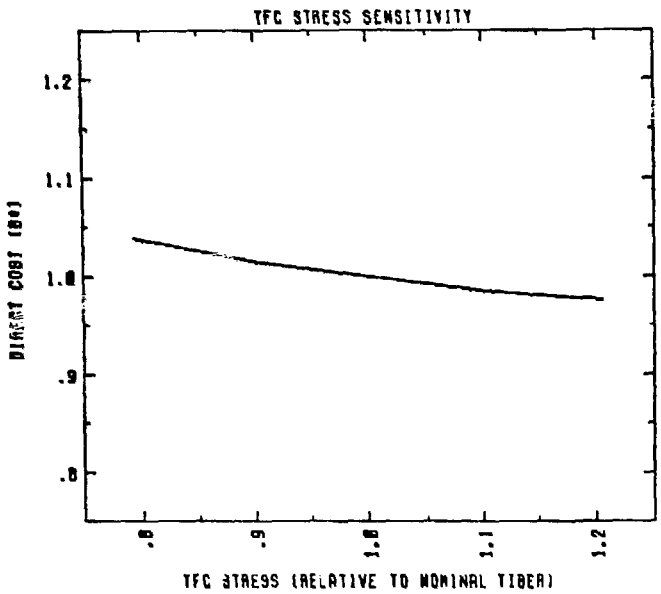

PLASMA PROFILE SENSITIVITY
MAJOR RADIUS (m)
3.2
3.0
2.8
2.6
.5
1.0
1.5
PLASMA DENSITY PROFILE FACTOR

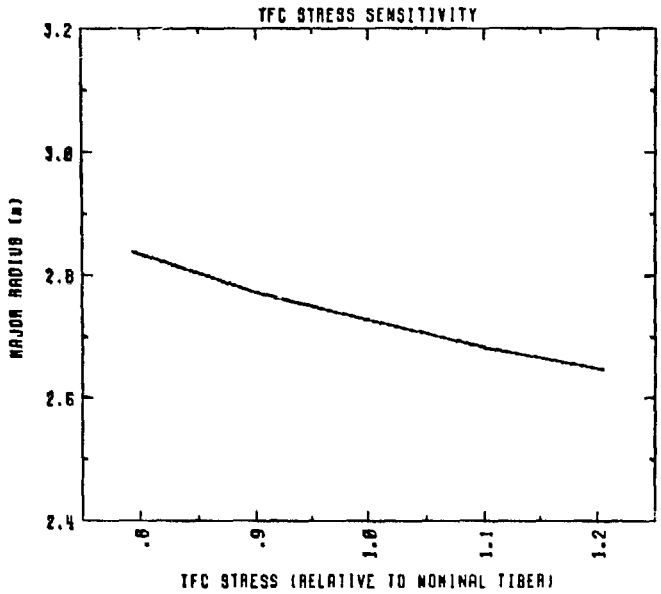

PLASMA PROFILE SENSITIVITY
PLASMA CURRENT (MA/10)
10
8
6
4
Ip
Ip
A
A
.5
1.0
1.5
PLASMA DENSITY PROFILE FACTOR

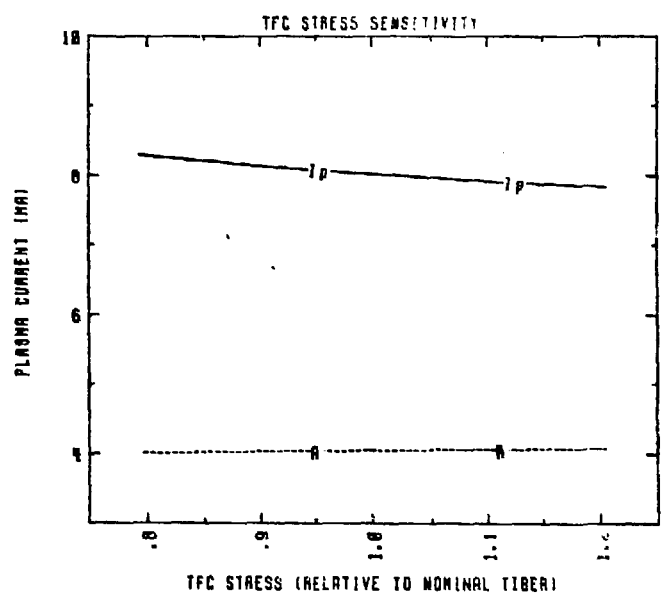

PLASMA PROFILE SENSITIVITY
ASPECT RATIO
FIELD ON AXIS (T)
FUSION POWER (MW/100)
8
6
4
2
B
B
F
F
.5
1.0
1.5
PLASMA DENSITY PROFILE FACTOR

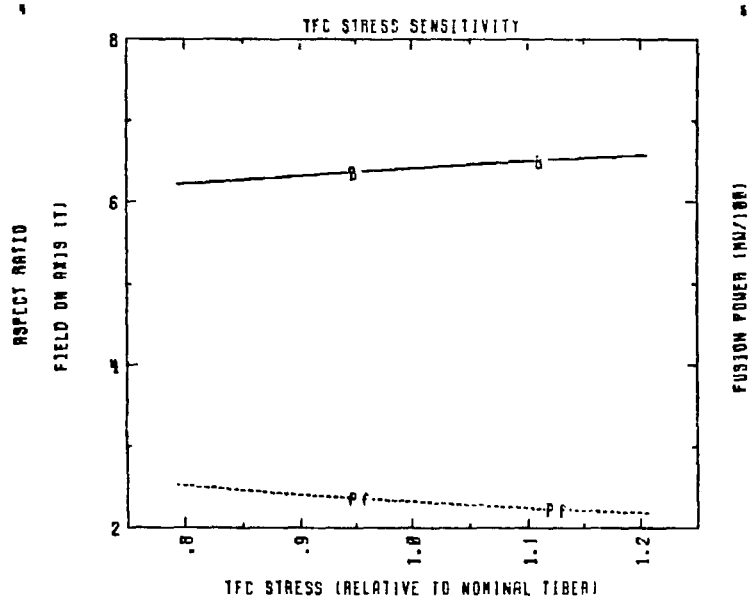
MINIMUM COST VS. TF COIL STRESS



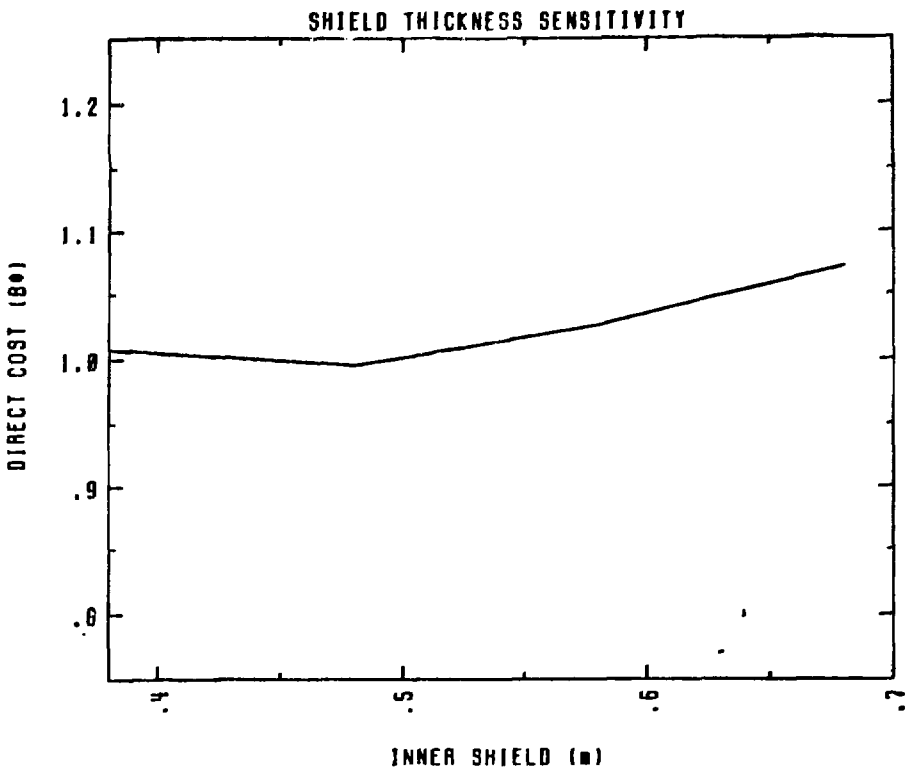

TFC STRESS SENSITIVITY
DIRECT COST (B$)
1.2
1.1
1.0
.9
.8
.8
.9
1.0
1.1
1.2
TFC STRESS (RELATIVE TO NOMINAL TIBER)

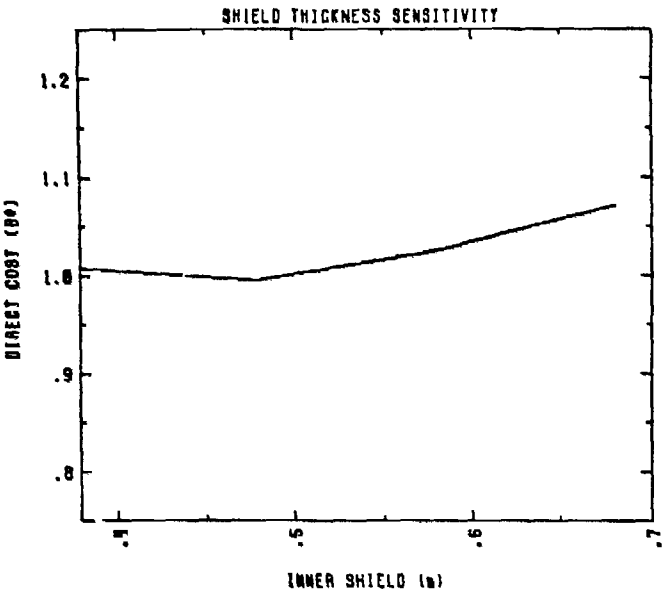

TFC STRESS SENSITIVITY
MAJOR RADIUS (m)
3.2
3.0
2.8
2.6
2.4
.8
.9
1.0
1.1
1.2
TFC STRESS (RELATIVE TO NOMINAL TIBER)

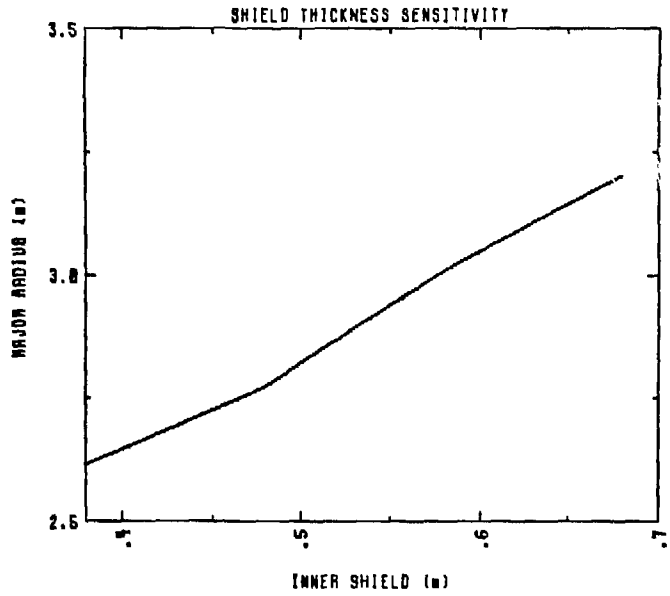

TFC STRESS SENSITIVITY
PLASMA CURRENT (MA)
10
8
6
4
Ip
Ip
A
A
.8
.9
1.0
1.1
TFC STRESS (RELATIVE TO NOMINAL TIBER)

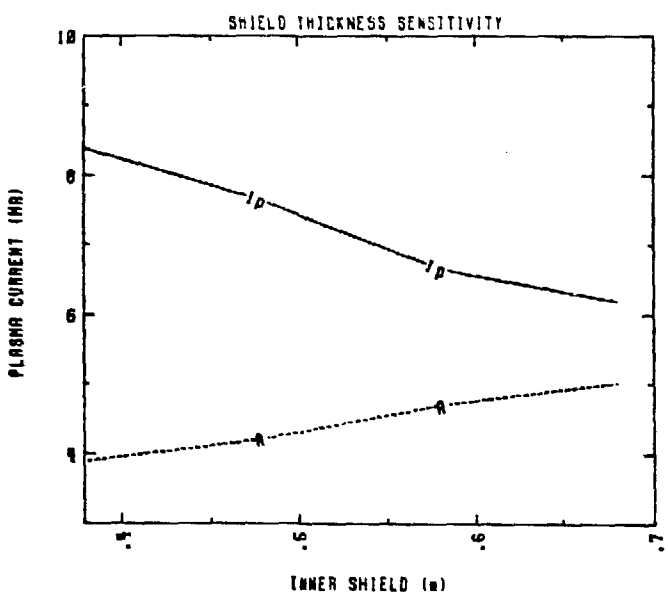

TFC STRESS SENSITIVITY
ASPECT RATIO
FIELD ON AXIS (T)
FUSION POWER (MW/100)
8
6
4
2
B
B
Pf
Pf
.8
.9
1.0
1.1
1.2
TFC STRESS (RELATIVE TO NOMINAL TIBER)

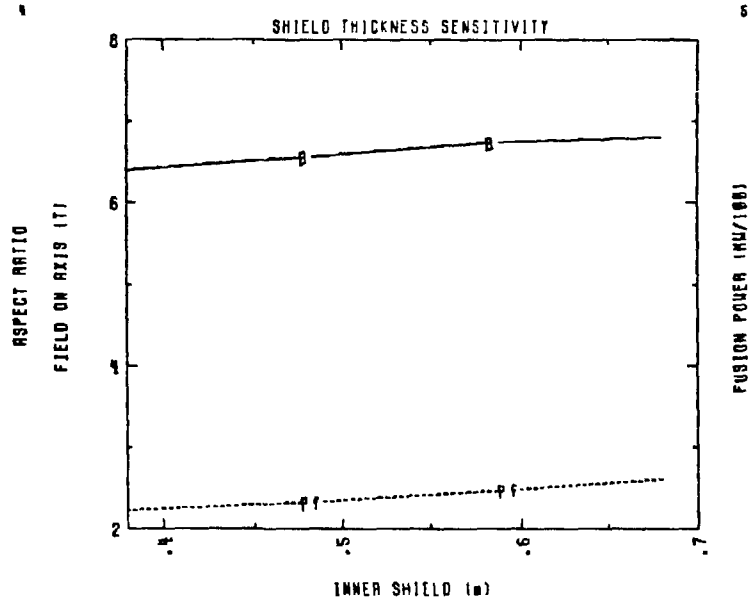
Minimum Cost vs Inner Shield Thickness

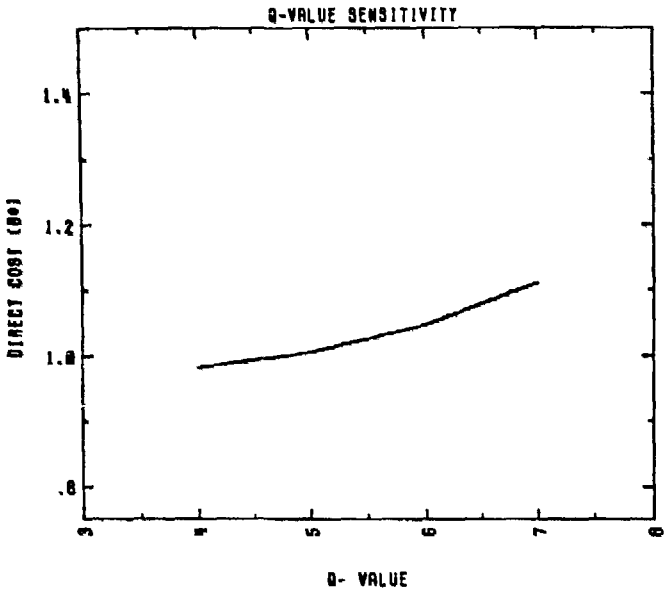


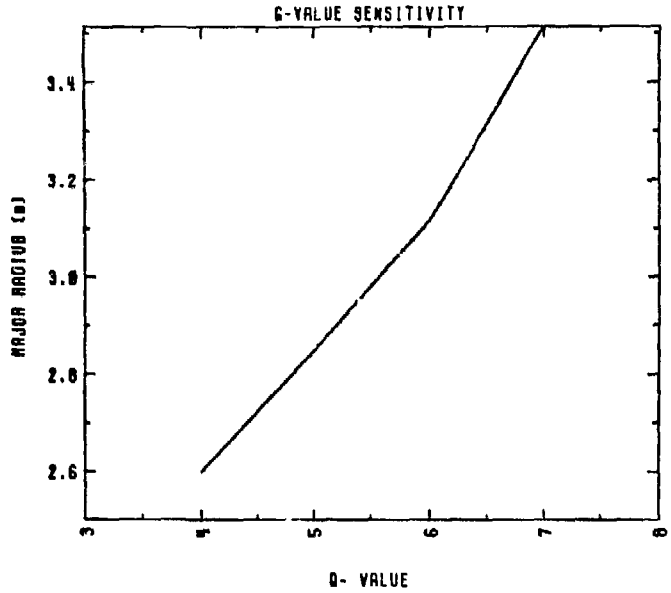

SHIELD THICKNESS SENSITIVITY
DIRECT COST (B$)
1.2
1.1
1.0
.9
.8
.4
.5
.6
.7
INNER SHIELD (m)

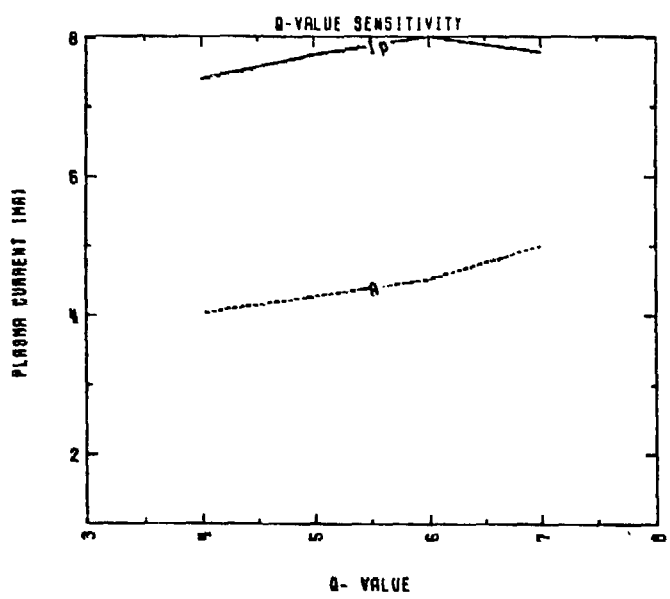

SHIELD THICKNESS SENSITIVITY
MAJOR RADIUS (m)
3.5
3.0
2.5
.4
.5
.6
.7
INNER SHIELD (m)

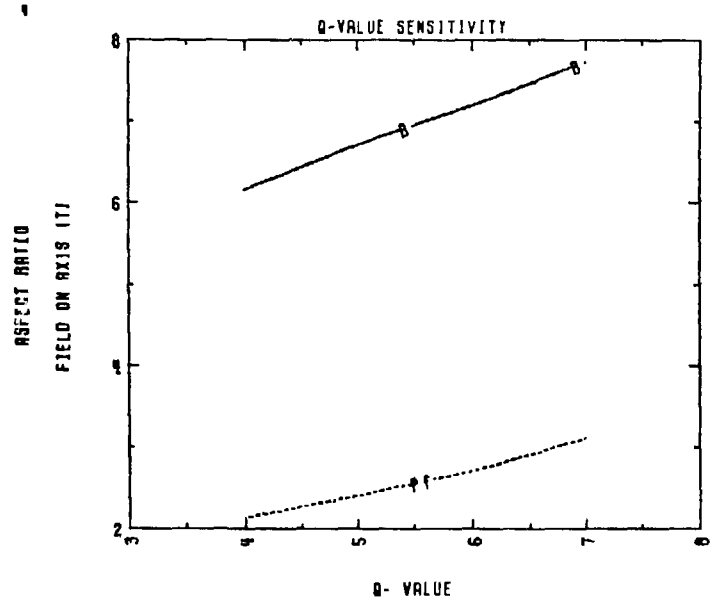

SHIELD THICKNESS SENSITIVITY
PLASMA CURRENT (MA)
10
8
6
4
Ip
Ip
A
A
.4
.5
.6
.7
INNER SHIELD (m)


SHIELD THICKNESS SENSITIVITY
ASPECT RATIO
FIELD ON AXIS (T)
FUSION POWER (MW/100)
8
6
4
2
B
B
Pf
Pf
.4
.5
.6
.7
INNER SHIELD (m)

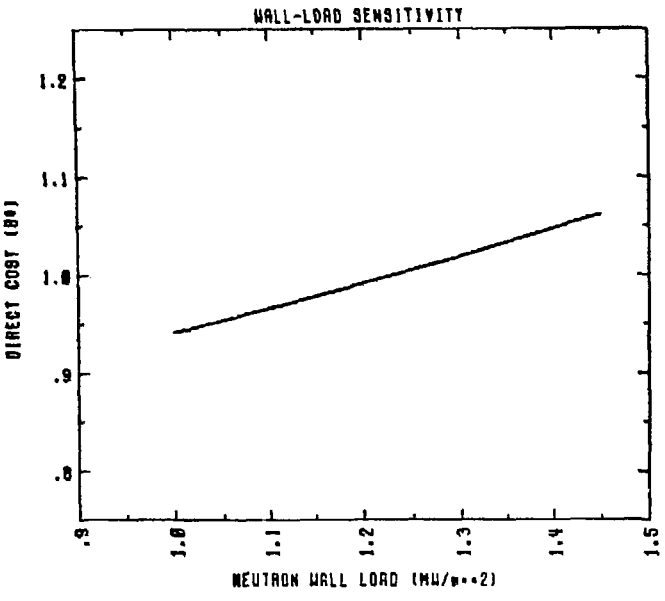

Q-VALUE SENSITIVITY
DIRECT COST (B$)
1.4
1.2
1.0
.8
3
4
5
6
7
8
Q- VALUE

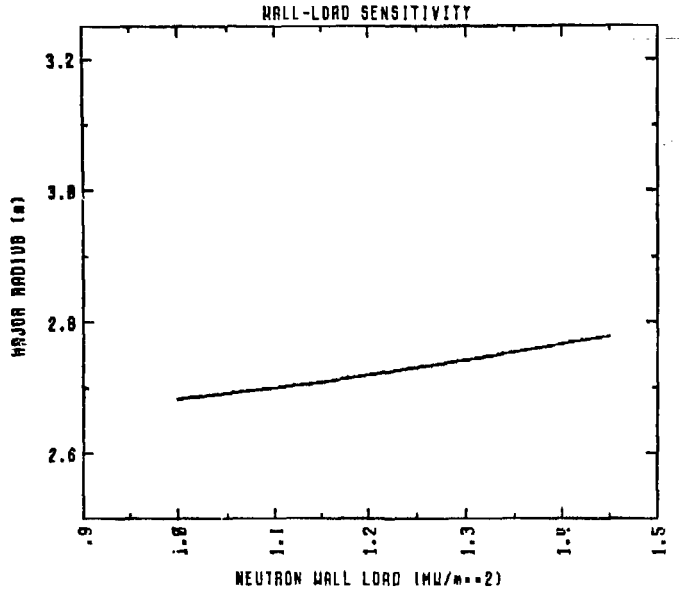

Q-VALUE SENSITIVITY
MAJOR RADIUS (m)
3.4
3.2
3.0
2.8
2.6
3
4
5
6
7
8
Q- VALUE

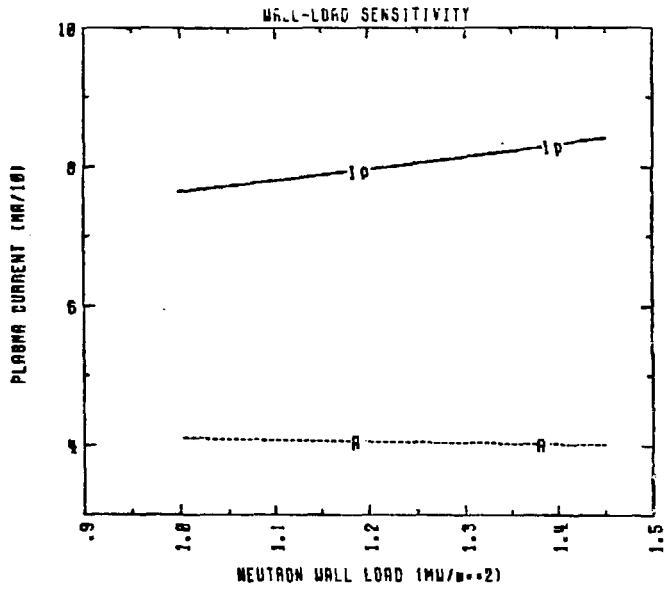

Q-VALUE SENSITIVITY
PLASMA CURRENT (MA)
8
6
4
2
Ip
3
4
5
6
7
8
Q- VALUE

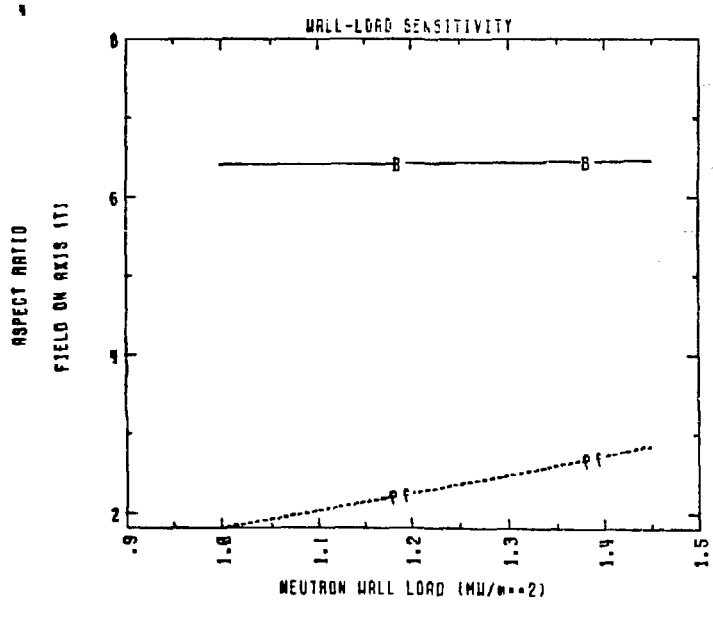

Q-VALUE SENSITIVITY
ASPECT RATIO
FIELD ON AXIS (T)
FUSION POWER (MW/100)
8
6
4
2
B
B'
P
3
4
5
6
7
8
Q- VALUE

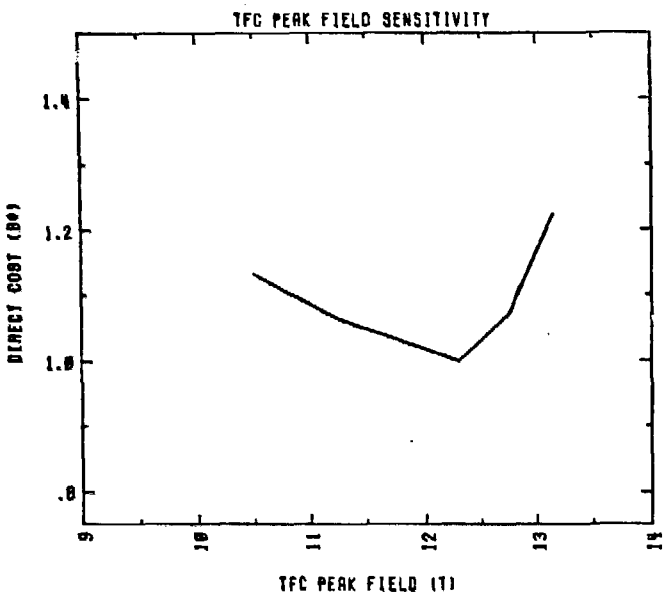
WALL LOAD SENSITIVITY

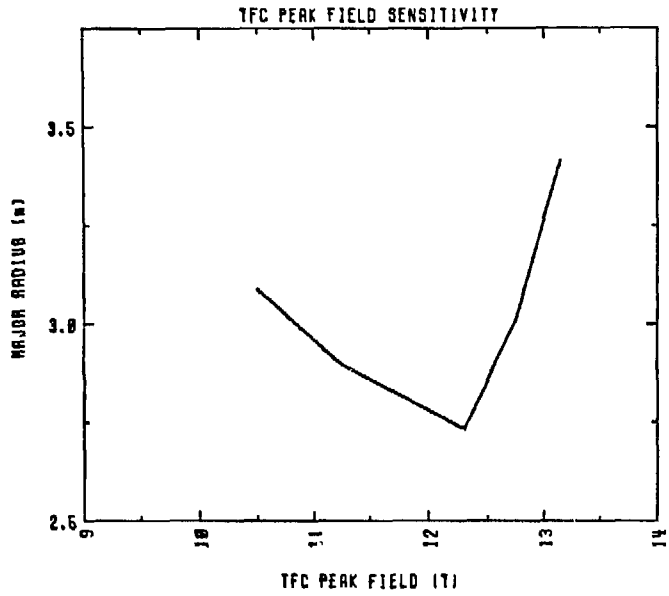


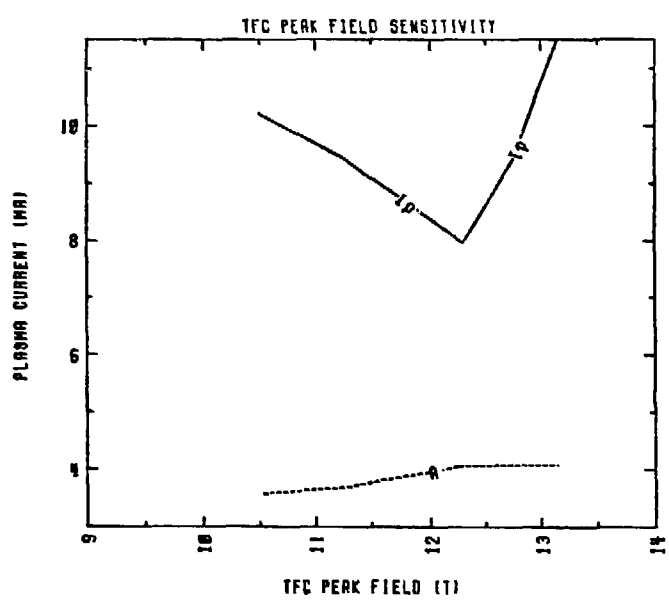


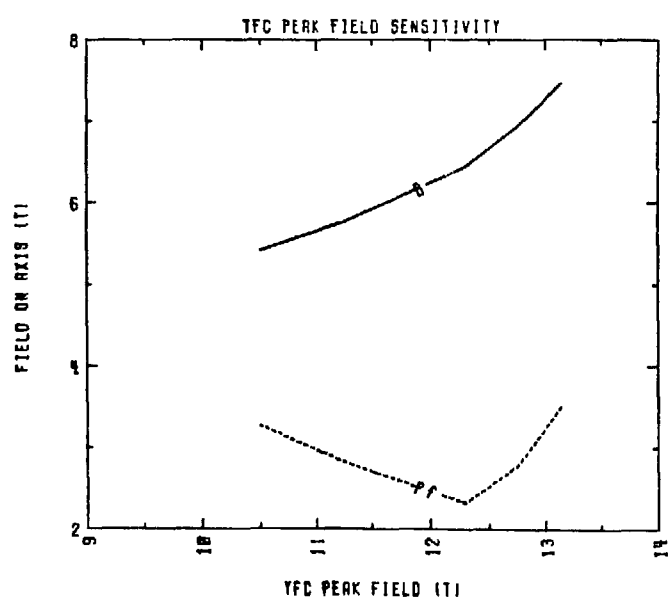





TFC PEAK FIELD SENSITIVITY
DIRECT COST (B$)
1.4
1.2
1.0
.8
9
10
11
12
13
14
TFC PEAK FIELD (T)


TFC PEAK FIELD SENSITIVITY
MAJOR RADIUS (m)
3.5
3.0
2.5
9
10
11
12
13
14
TFC PEAK FIELD (T)


TFC PEAK FIELD SENSITIVITY
PLASMA CURRENT (MA)
10
8
6
4
Ip
Ip
A
9
10
11
12
13
14
TFC PEAK FIELD (T)


TFC PEAK FIELD SENSITIVITY
ASPECT RATIO
FIELD ON AXIS (T)
FUSION POWER (MW/100)
8
6
4
2
B
Pf
9
10
11
12
13
14
TFC PEAK FIELD (T)

SUMMARY OF THE TIBER COST SENSITIVITIES

QUANTITY VARIED	% CHANGE-COST / % CHANGE-QUANTITY
BETA LIMIT COEFFICIENT	- .70
Z_{EFF}	+ .34
WALL LOAD	+ .33
PLASMA ELONGATION	- .30
Q-VALUE	+ .23
PLASMA PROFILES	- .16
SHIELD	+ .21
TF STRESS	- .15
INNER SCRAPE-OFF	+ .05
TF COIL SUPER-CONDUCTOR LIMITS	- .06

FIXED INPUT ITEMS FOR ITER STUDY

TROYON BETA LIMIT COEFFICIENT	3.0
ELONGATION (AT SEPARATRIX)	2.3
TRIANGULARITY (AT SEPARATRIX)	.4
EDGE $\bar{q}$ -BAR	3.0
TEMPERATURE (DENSITY) PROFILE FACTOR, P (A)	1.0 (.5)
Z_{EFF}	1.5
INNER (OUTER) SCRAPEOFF (M)	.10 (.12)
INNER (OUTER) SHIELD (M)	.55 (1.10)
TF-OH COIL GAP (M)	.03
INNER (OUTER) FIRST WALL + GAP THICKNESS (M)	.02 (.042)
INNER (OUTER) TF COIL - SHEILD GAP (M)	.06 (.31) (B)
NUMBER OF TF COILS	16

(A) PROFILES ARE PROPORTIONAL TO: (PAROBOLIC)^P

(B) OUTER GAP DETERMINED BY TF COIL RIPPLE CONSTRAINT

INEQUALITY CONSTRAINTS USED IN THE ITER OPTIMIZATION

INEQUALITY:

BETA	<	TROYON LIMIT
DENSITY	<	GREENWALD LIMIT
FUSION POWER / INJECTION POWER		---
WALL LOAD (MW/M^2)	>	1.0
IGNITION MARGIN (KAYE-GOLDSTON WITH H FACTOR = 2.0)	>	1.3
PLASMA CURRENT (MA)	>	15.
INDUCTIVE V-s CAPABILITY / PLASMA - LI	>	1.6
NONINDUCTIVE CURRENT DRIVE (FRACTION OF TOTAL CURRENT)	>	0. (A)

INEQUALITY CONSTRAINTS USED IN THE ITER OPTIMIZATION
(CONTINUED)

TF COIL TRESCA STRESS (MPA)	<	500
OH COIL TRESCA STRESS (MPA)	<	500
TF (OH) COIL DURRENT DENSITY SUPERCONDUCTOR LIMITS FOR:	<	
J<B, STRAIN, TEMPERATURE) HEAT TRANSFER QUENCH PRESSURE QUENCH TEMPERATURE RISE	<	X 1.0 (1.0)
TF (OH) COIL CONDUCTOR STABILITY MARGIN (MJ/CM^3)	>	300
TF COIL RIPPLE AT PLASMA (%)	<	1.5

(A) ALL ITER CASES ASSUME 40 MW EXTERNAL HEATING AT 3$/W

PARAMETERS FOR A CANDIDATE ITER POINT.

QUANTITY	ITER
PHYSICS:	
MAJOR RADIUS (M)	4.40 *
ASPECT RATIO	3.00 *
PLASMA CURRENT (MA)	15.8 *
FIELD ON AXIS (T)	5.40 *
PLASMA BETA (%)	4.3 *
ELECTRON TEMPERATURE (KEV)	8.2 *
ELECTRON DENSITY (10^{20} M^{-3})	1.47 *
FUSION POWEER (MW)	791 *
NEUTRON WALL LOAD (MW/M^2)	1.34 *
PLASMA VOLUME (M^3)	415 *
Q (A)	---
IGNITION MARGIN (B)	1.3 *
RADIAL BUILD (M):	
OH COIL	1.62 *
TF COIL	.41 *
INNER SHIELD	.55 +
MINOR RADIUS	1.47 *

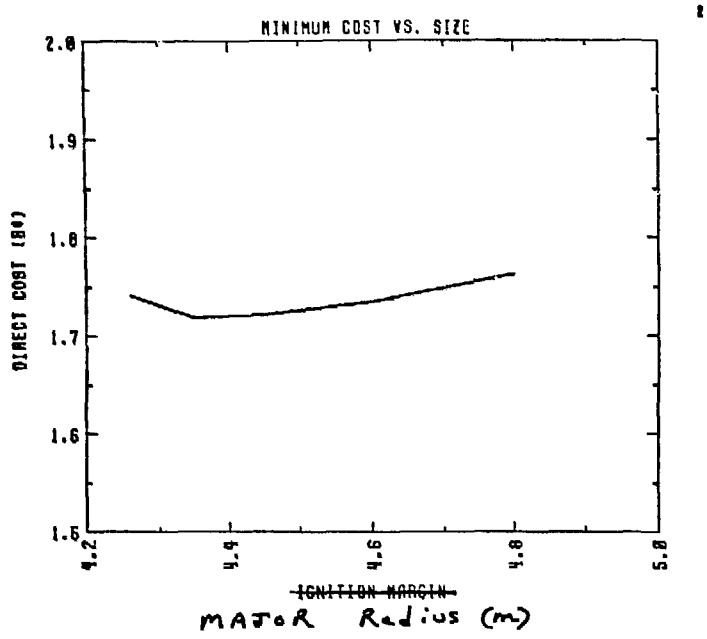
PARAMETERS FOR A CANDIDATE ITER POINT (CONTINUED)

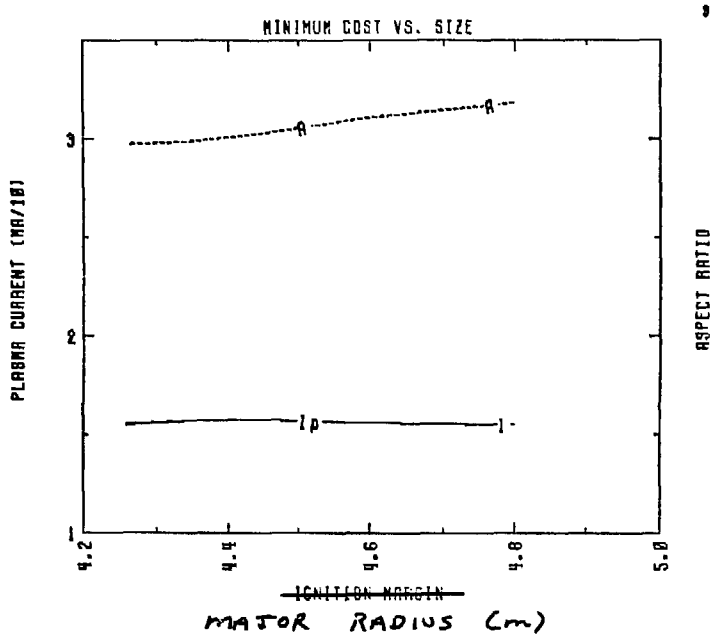
QUANTITY	ITER
TF COIL:	
OVERALL CURRENT DENSITY (MA/M^2) (C)	18.3 ⊠
STORED ENERGY (GJ)	14.9 *
PEAK FIELD (T)	10.9 *
CONDUIT STRESS	500. ⊠
STABILITY MARGIN (MJ/CC)	300. ⊠
OH COIL:	
OVERALL CURRENT DENSITY (MA/M^2) (C)	22.5 ⊠
PEAK FIELD (T)	10.8 *
CONDUIT STRESS (MPA)	500. ⊠
STABILITY MARGIN (MJ/CC)	300. ⊠

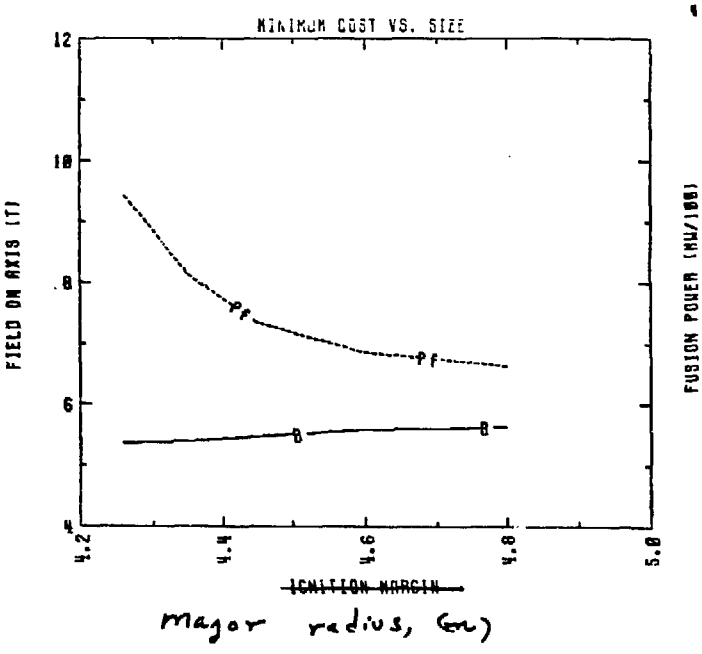
+ - FIXED INPUT ITEM
* - CALCULATED QUANTITY
# - QUANTITY CALCULATED IN THE BENCHMARK RUN AND SUBSEQUENTLY USED AS A LIMIT
⊠ - CALCULATED QUANTITY IN AN OPTIMIZATION RUN WHICH IS AT A LIMIT
(A) - Q = FUSION POWER / INJECTION POWER
(B) - KAYE-GOLDSTON IGNITION MARGIN USING H-FACTOR = 2.0
(C) - THE HEAT TRANSFER EFFECT WAS THE LIMITING CONSTRAINT

ITER

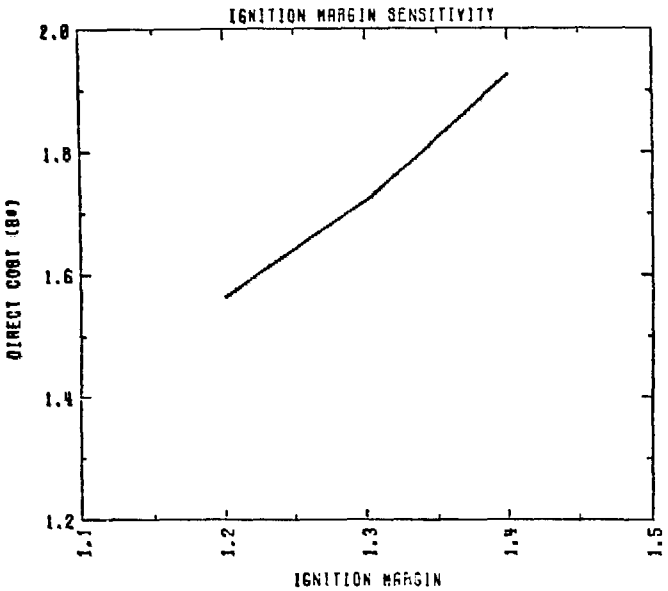
MINIMUM COST VS MAJOR RADIUS

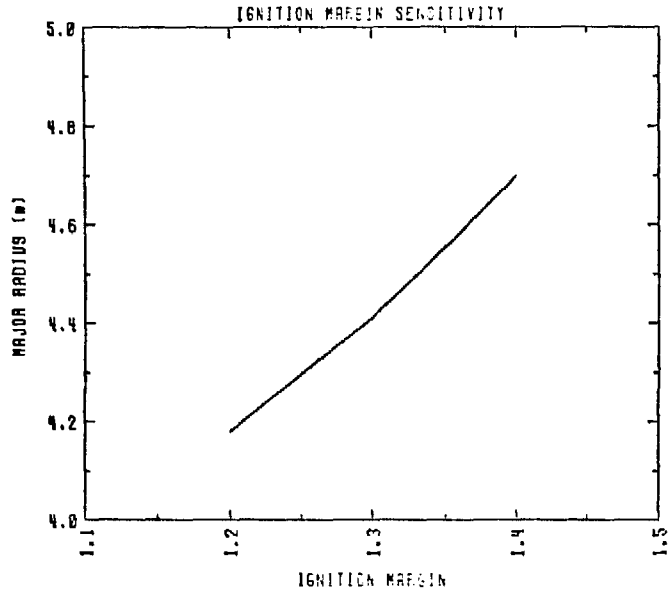


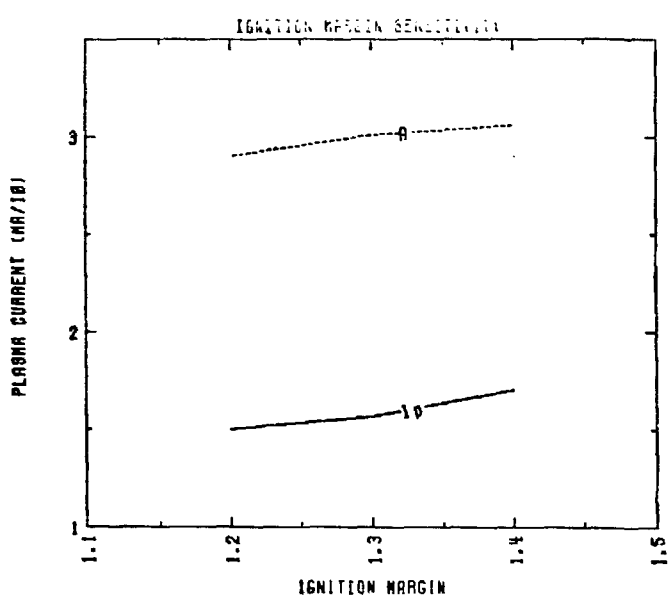


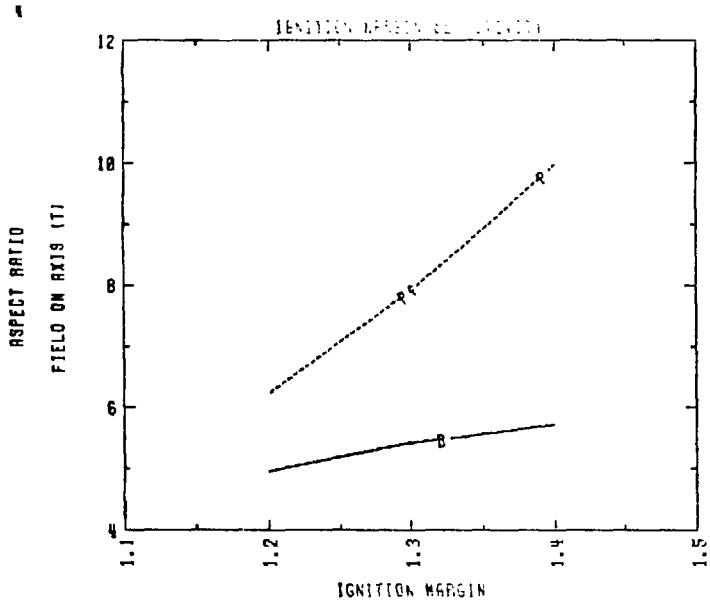


IGNITION MARGIN SENSITIVITY

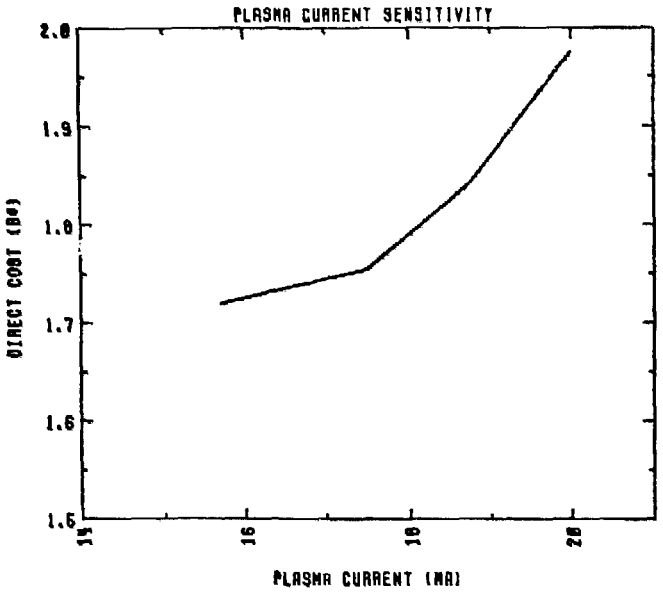


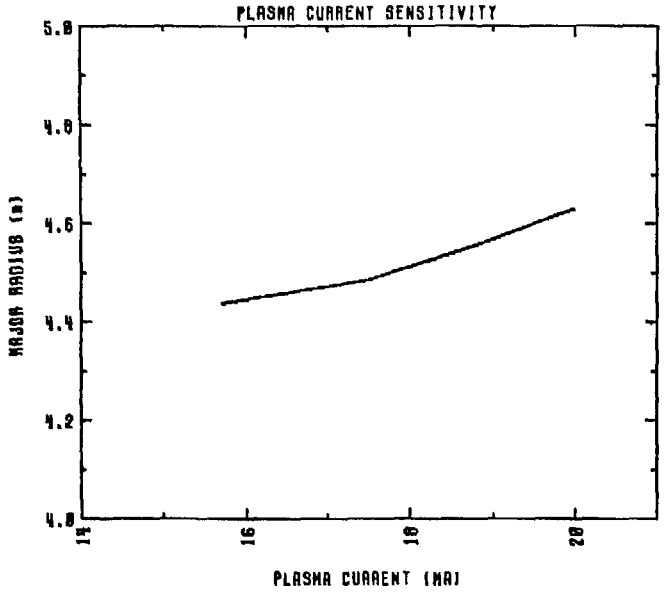


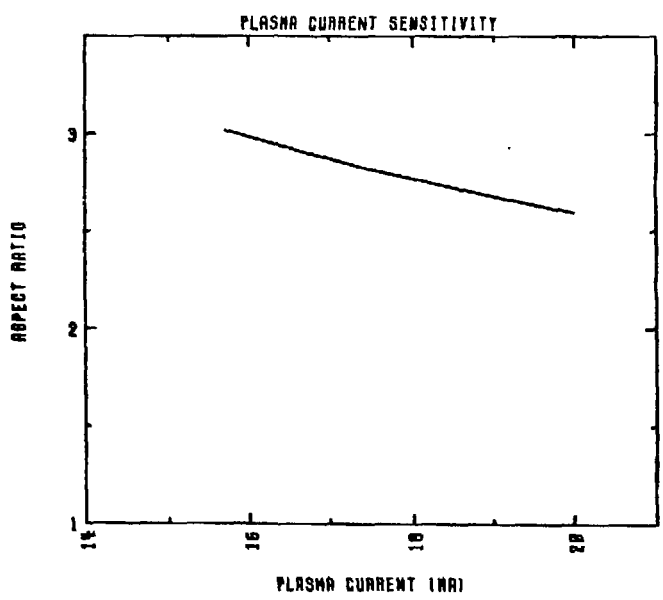


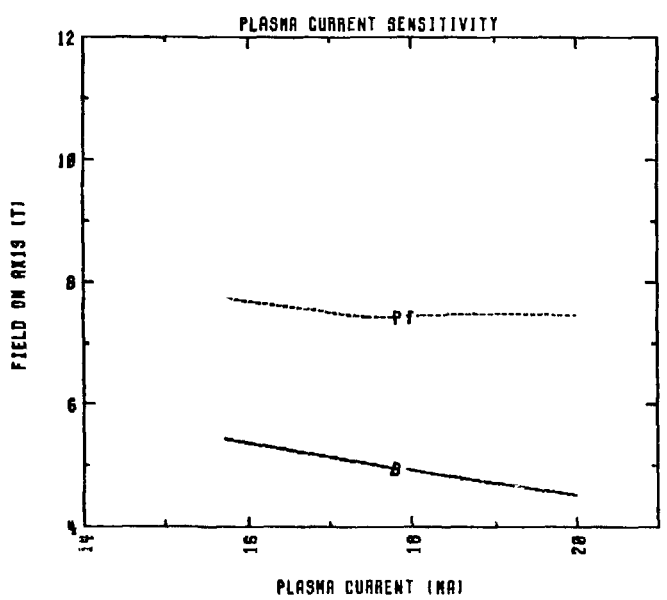


PLASMA CURRENT SENSITIVITY

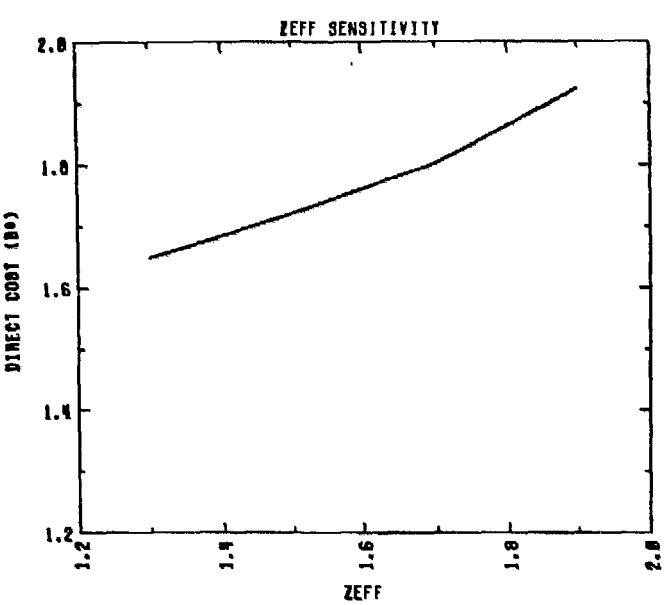


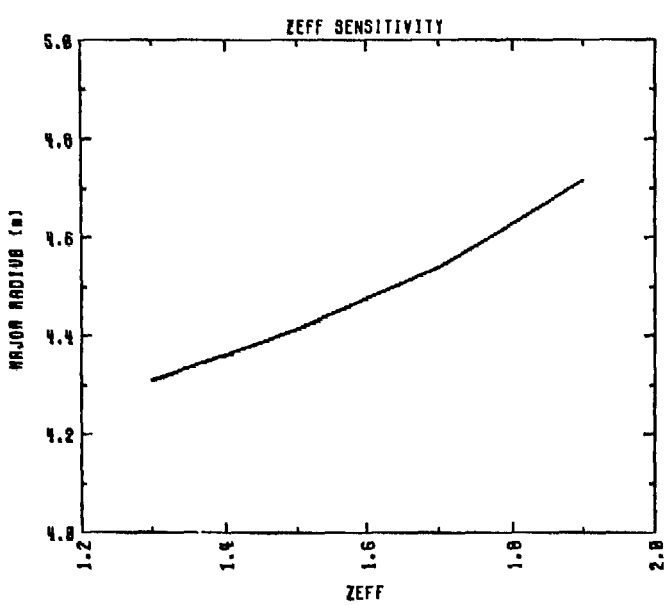


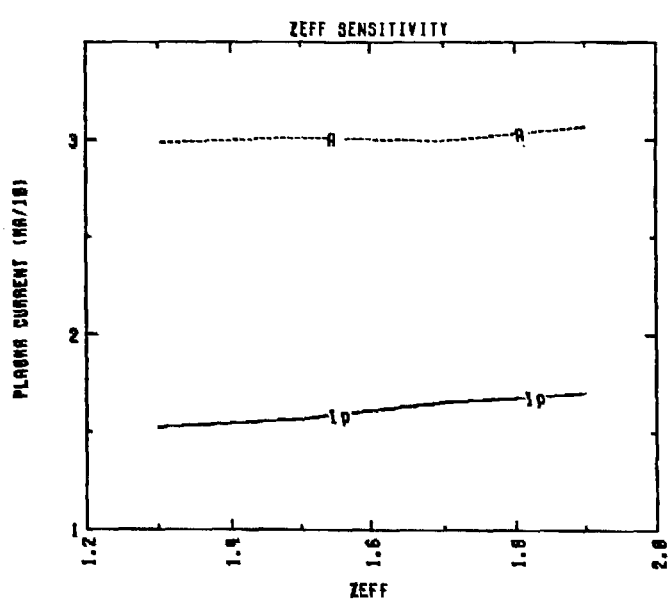


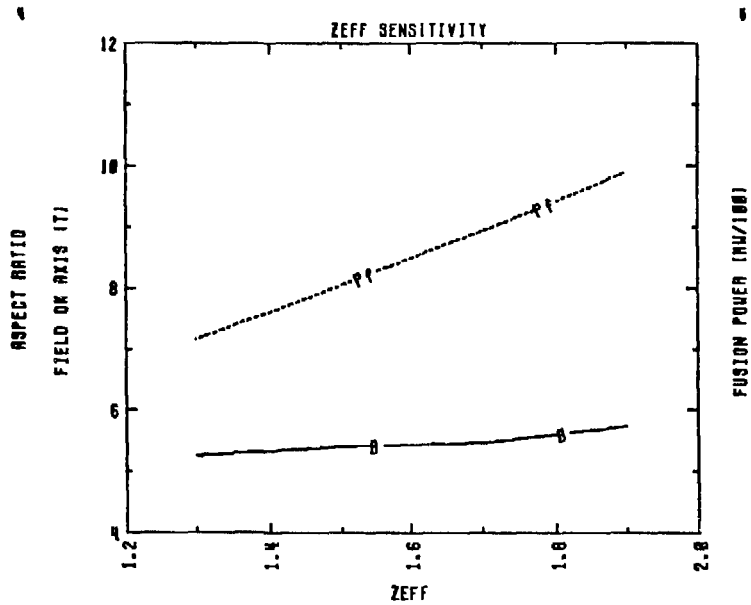


ZEFF SENSITIVITY

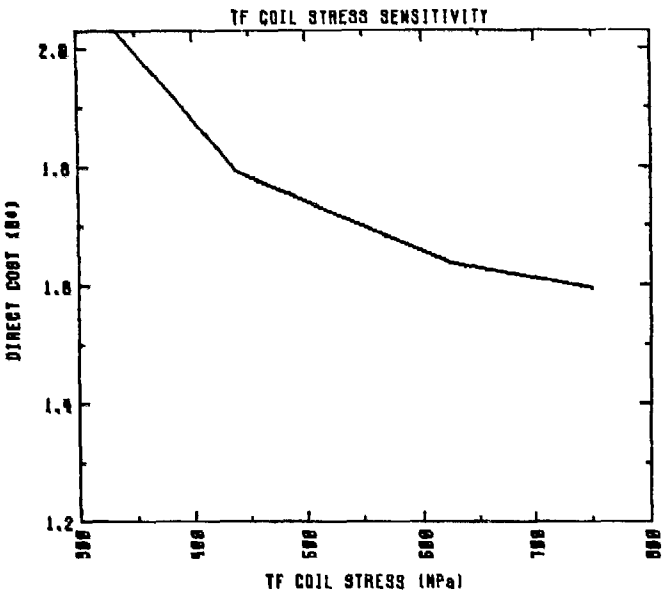


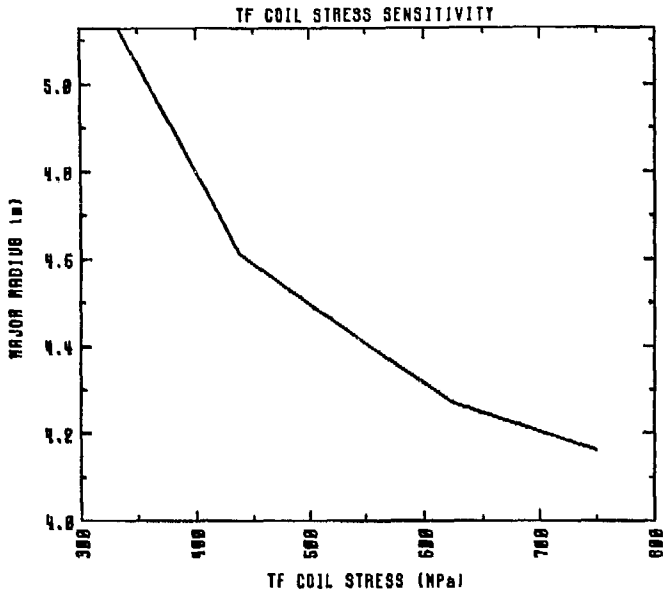


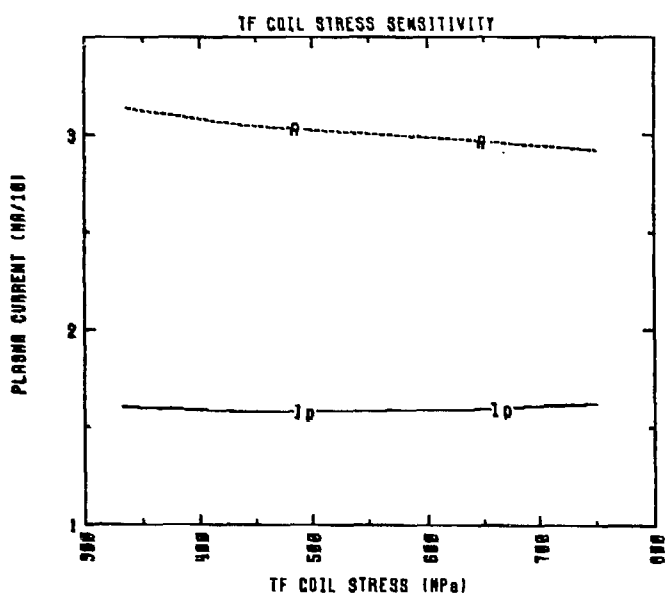


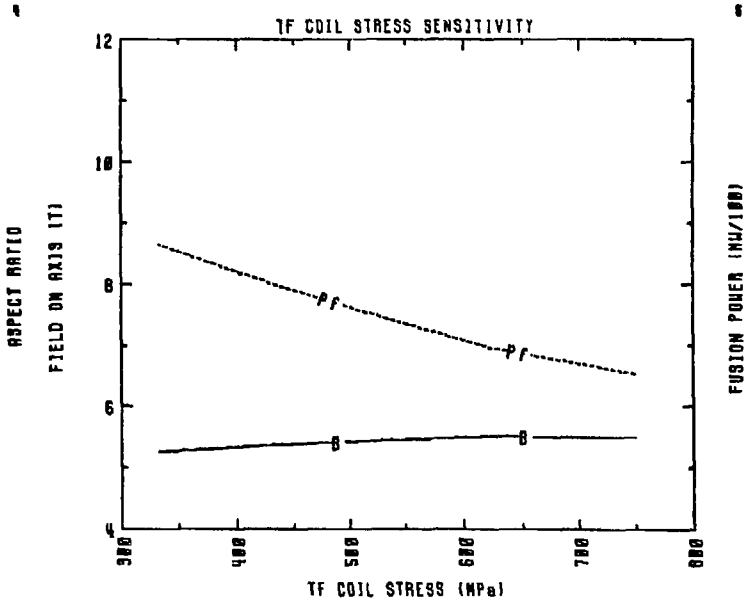


TF STRESS SENSITIVITY









SUMMARY OF THE ITER COST SENSITIVITIES

QUANTITY VARIED	% CHANGE-COST / % CHANGE-QUANTITY
IGNITION MARGIN	+ 1.4
PLASMA CURRENT	+ .40
Z_{EFF}	+ .41
PLASMA PROFILES	- .22
COIL STRESS	- .26
TF COIL SUPERCONDUCTOR LIMITS	- .06
INNER TF COIL-SHIELD GAP	+ .04

SUMMARY

- TETRA CODE IS FLEXIBLE ENOUGH TO PERFORM A WIDE VARIETY OF STUDIES.

- BENCHMARKS OF ETR-TYPE DEVICES IS GENERALLY GOOD.

- COST COMPARISONS SHOW INTOR, NET, AND FER HAVE SIMILAR COSTS; TIBER IS ABOUT 40% LESS COSTLY; OTR IS ABOUT 40% MORE EXPENSIVE.

- SENSITIVITY STUDIES INDICATE WHICH DESIGN ISSUES ARE MOST CRUCIAL.