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M. ROBERTS, MANAGER
ORNL/W TNS PROGRAM

TNS DESIGN SPACE EXPLORATION HAS BROUGHT US A LARGE STEP CLOSER TO REALIZABLE REACTOR*

IAEA CONFERENCE AND WORKSHOP ON
FUSION REACTOR DESIGN
OCTOBER 12, 1977

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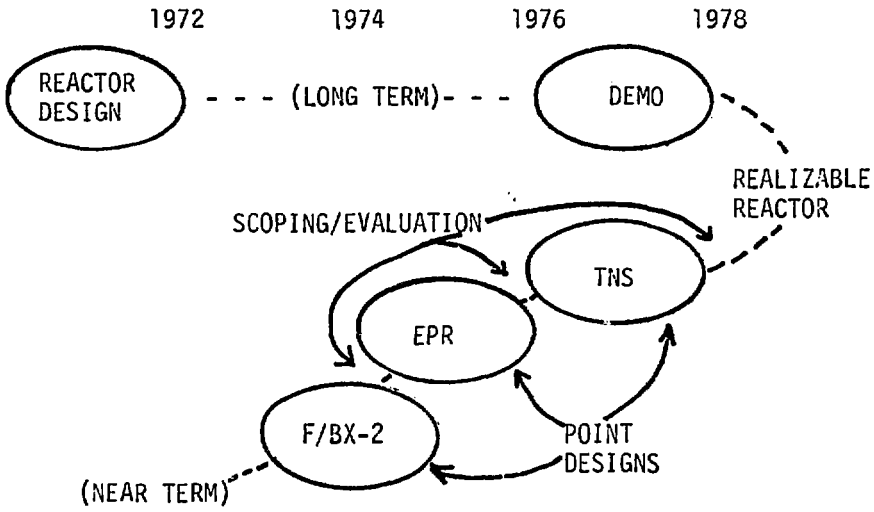
IN PAST FEW YEARS, ORNL ADVANCED DESIGN ACTIVITY
HAS BEEN EVOLVING TOWARD PRACTICAL
REACTOR DESIGN



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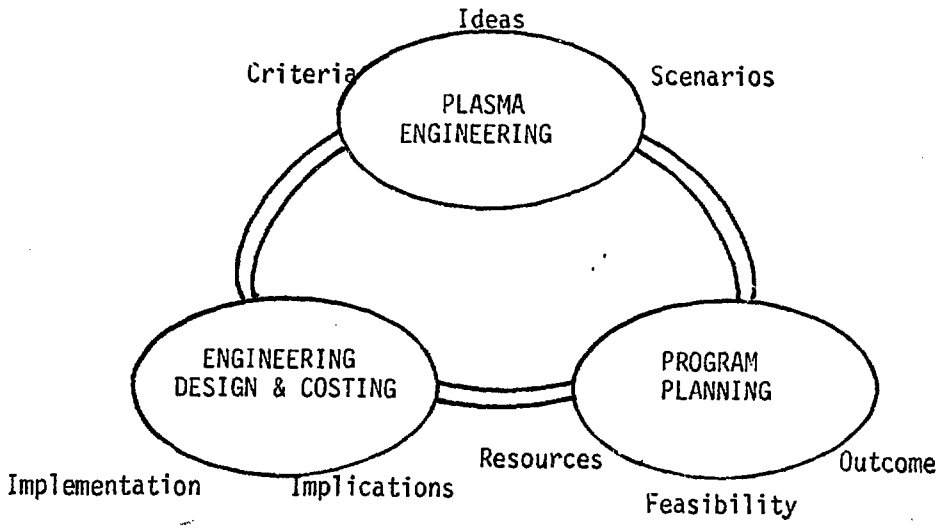
THREE INTERRELATED ACTIVITIES ARE BASIS
FOR CONTINUED EVOLUTION OF TNS DESIGN



SELF-CONSISTENT PICTURE SUPPORTS MEDIUM FIELD, "HIGH" BETA PLASMA MODEL

PLASMA MODEL

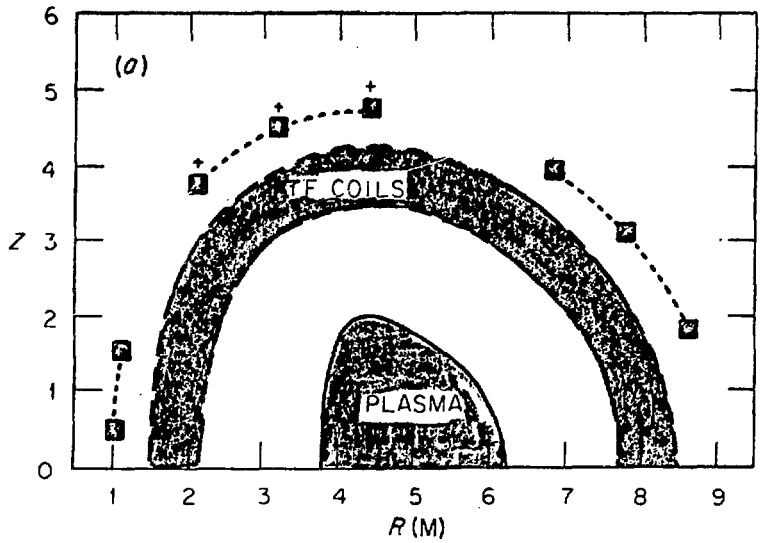
"HIGH" DENSITY	$\bar{N} > 10^{20} m^{-3}$	NEUTRON WALL LOADING (MW/m^2) 0.3-5.0
"MEDIUM" FIELD	$4T < B_T < 7T$	FUSION POWER (MW_{TH}) 100-2000
"HIGH" BETA	$5\% < \beta_T < 10\%$	

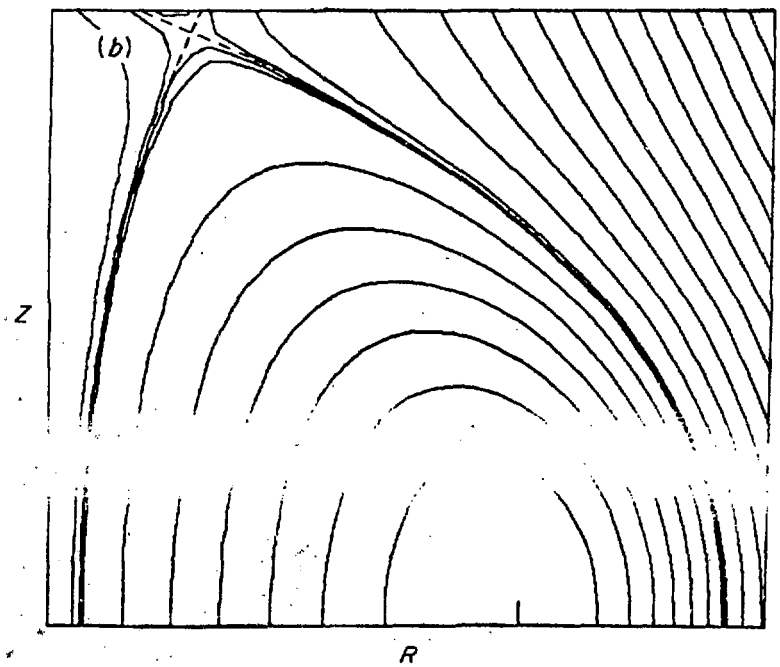
BASED ON SELF-CONSISTENT PROJECTIONS OF

- INTENSE NEUTRAL BEAM DRIVEN FLUX CONSERVATION
- PLASMA ELONGATION OF $b/a = 1.6$
- "ACCEPTABLE SCALING" - τ_{emp}, $10\ \tau_{TP}$
- $Z \gtrsim 1$

ORNL/DWG/FED-77149A

EQUILIBRIUM FIELD COILS THAT ARE INTERNAL OR EXTERNAL TO THE TOROIDAL FIELD COILS CAN BE USED TO MAINTAIN D-SHAPED HIGH $\bar{\beta}$ EQUILIBRIA





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CURRENT ESTIMATES FOR MHD BALLOONING MODE STABILITY ARE THAT STABLE $\overline{\beta}$ VALUES BETWEEN 5% AND 10% SHOULD BE ACHIEVABLE

- STABLE $\overline{\beta} = C(\sigma, \delta, \text{PROFILE})/Aq^2$
- $C \cong 1$ FOR CIRCULAR PLASMAS
- C CAN BE 2 OR 3 FOR NONCIRCULAR PLASMAS

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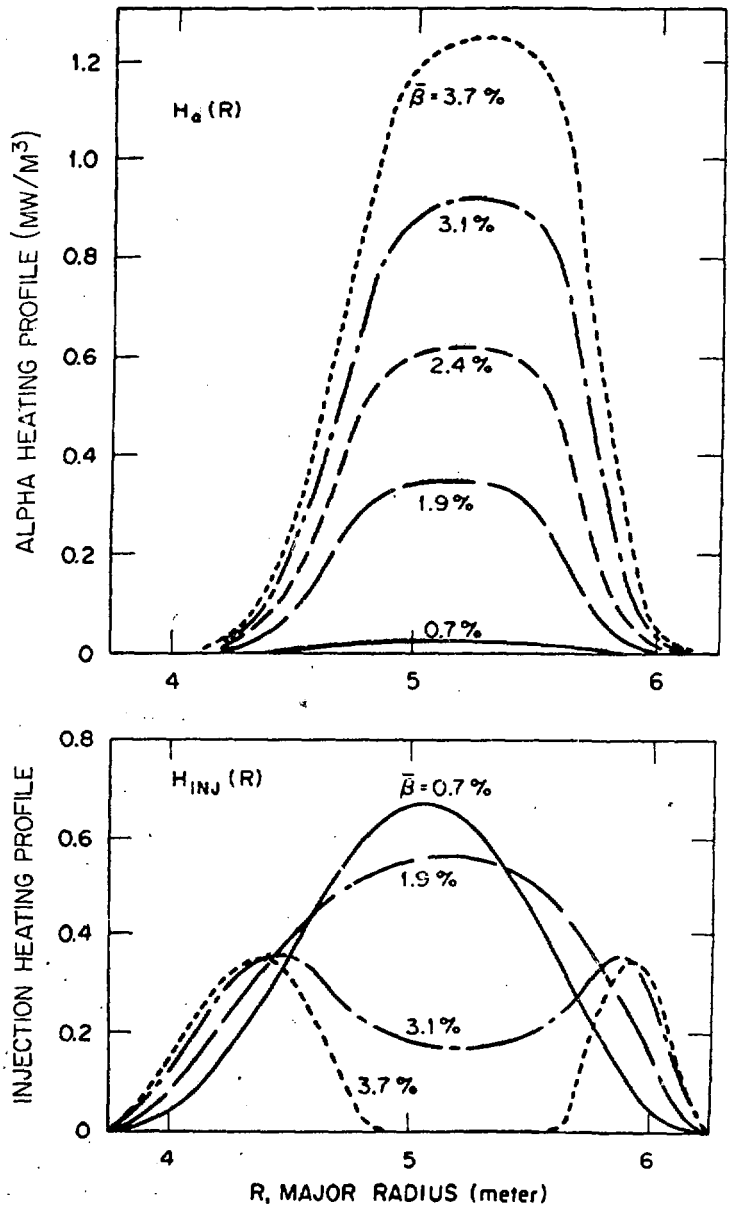
CENTRALIZED ALPHA-PARTICLE HEATING IN TNS HAS BEEN SHOWN TO EASE THE NEUTRAL BEAM PENETRATION REQUIREMENTS SO THAT 150 keV BEAMS SHOULD BE SUFFICIENT FOR $Z_{EFF} \lesssim 1.5$

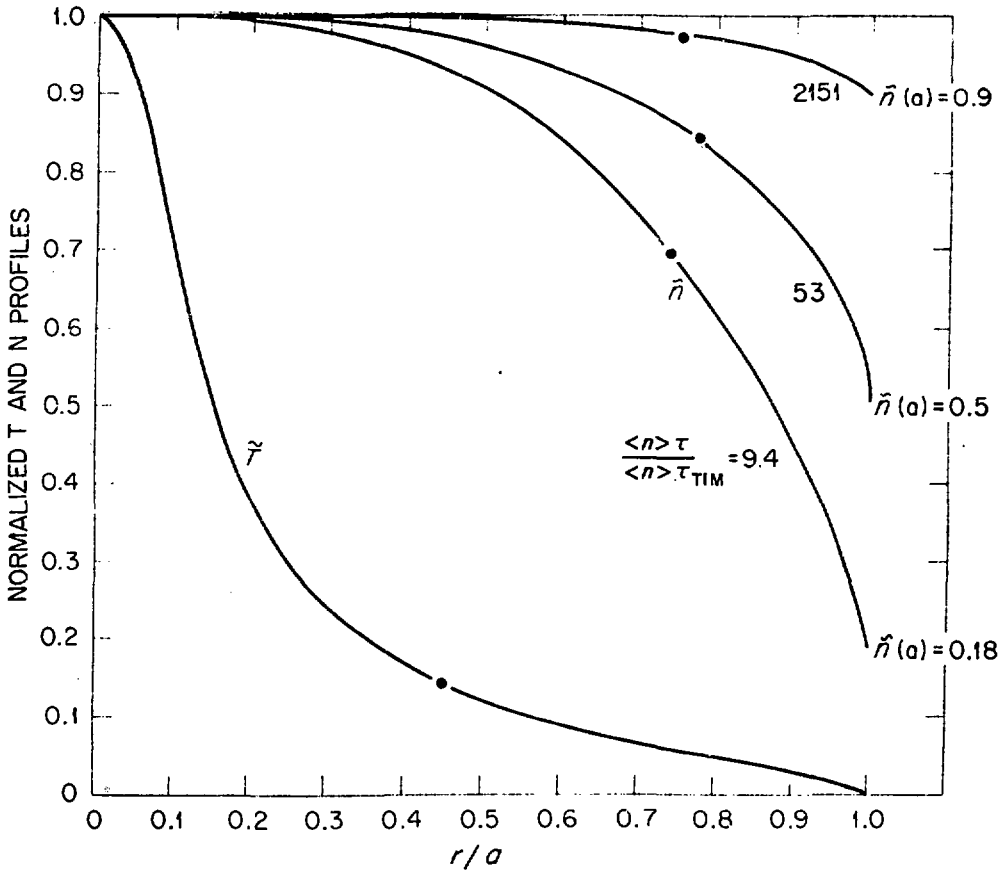


INCLUSION OF PROFILES HAS REDUCED PROJECTED BETA REQUIREMENTS FOR IGNITION

PARAMETERS FOR D-SHAPED TNS	UNIT	VALUES BASED ON 0-D MODEL	VALUES BASED ON 1-D TRANSPORT, MHD EQUIL + STAB.
Geometric	R_0, α, A, σ, B_T	Same	
$\overline{N}_{IGN + BURN}$	M^{-3}	2.2×10^{20}	$0.8\text{-}2.5 \times 10^{20}$
$\overline{T}_{IGN}$	KeV	11	4.0-7
$\overline{\beta}_{IGN}$	%	11	3-5
$\overline{\beta}_{BURN}$	%	15	3.5-10
NEUTRON WALL LOAD	MW/M^2	3.7	.3-5
TOTAL FUSION POWER	MW	1500	100-2000

ORNL-DWG 77-5021A

ONE-DIMENSIONAL EFFECTS HAVE BEEN SHOWN TO JUSTIFY THE USE OF THE ONE-TENTH TRAPPED PARTICLE MODE TRANSPORT (J. F. CLARKE)



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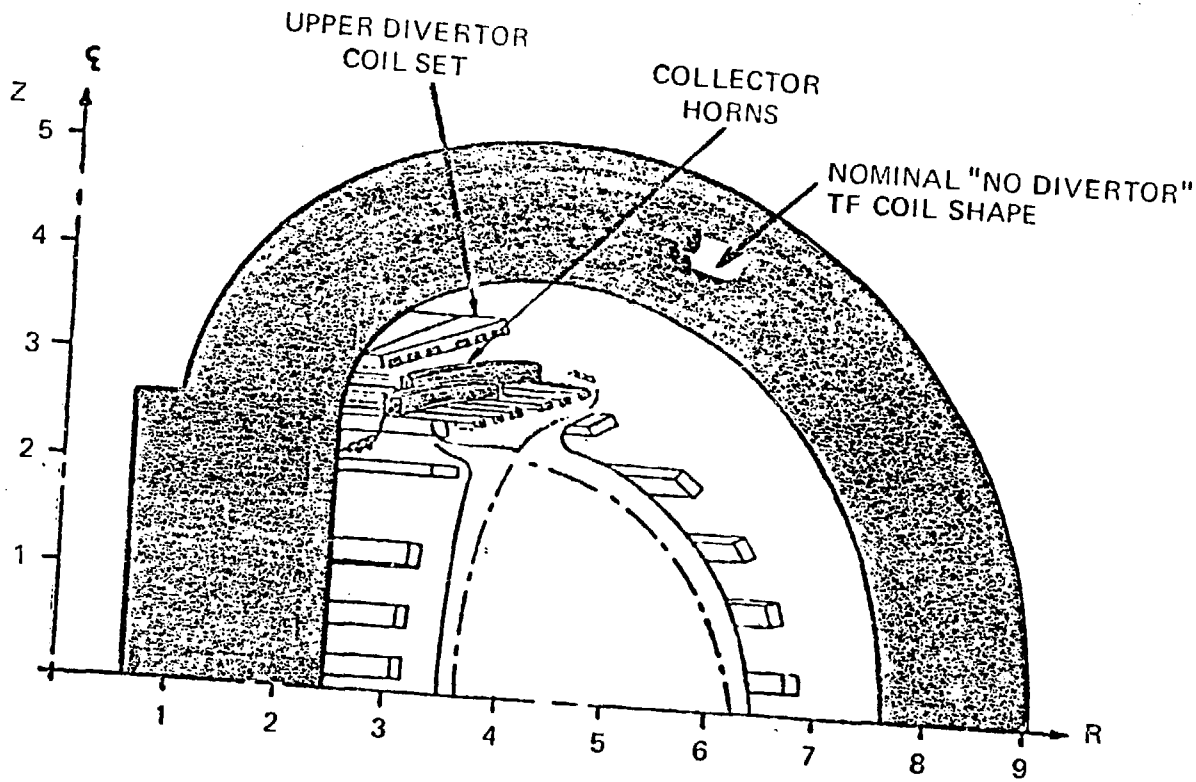
BASED ON A NOVEL COLLECTION SCHEME, A COMPACT POLOIDAL DIVERTOR DESIGN HAS BEEN DEVELOPED AND IS BEING EVALUATED

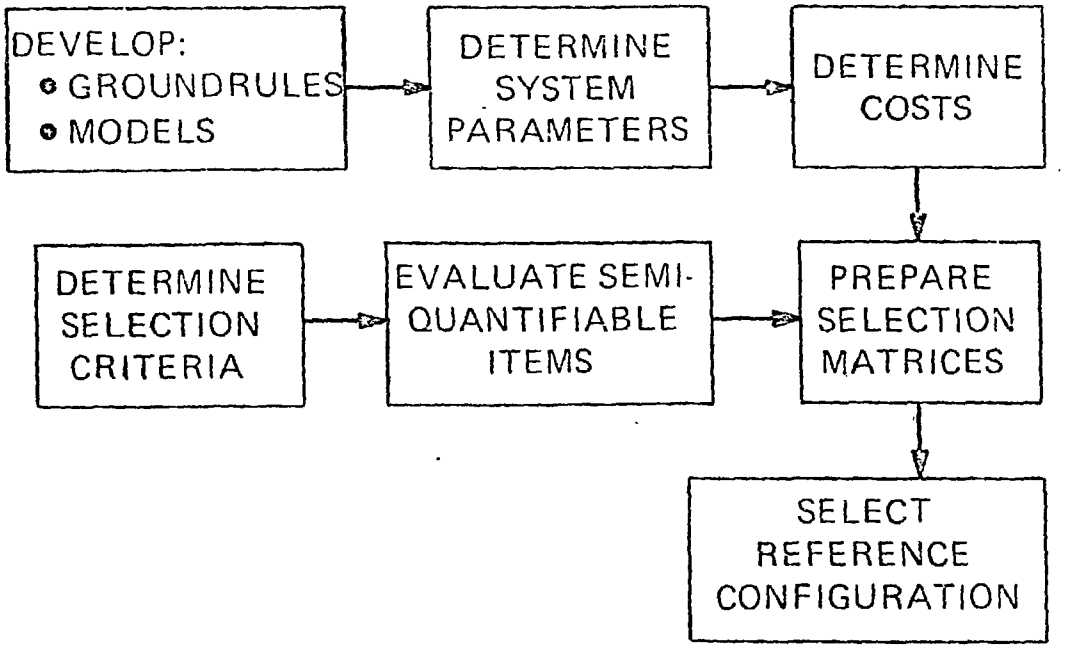


FED/VU-77214

PLASMA ENGINEERING MODELS POINT TOWARD ECONOMICALLY ATTRACTIVE PERFORMANCE

- SELF-CONSISTENT PICTURE SUPPORTS MEDIUM FIELD, "HIGH" BETA PLASMA MODEL
- ATTRACTIVE FCT CONCEPT APPEARS INCREASINGLY CREDIBLE THEORETICALLY WITH FEASIBLE PFS DESIGN
- DETAILED ENERGY DEPOSITION CALCULATIONS SUPPORT 150 KEV INJECTION TECHNOLOGY
- INCLUSION OF PROFILES HAS REDUCED BETA REQUIREMENTS AND SUPPORTED 0.1 TIM LOSSES
- COMPACT POLOIDAL DIVERTOR CONCEPT DEVELOPED WITHIN NOMINAL "D" TF COIL GEOMETRY

A DOCUMENTED PATH WAS DEVELOPED FOR QUANTITATIVE COST COMPARISON OF TF COIL TECHNOLOGY AND SIZE OPTIONS



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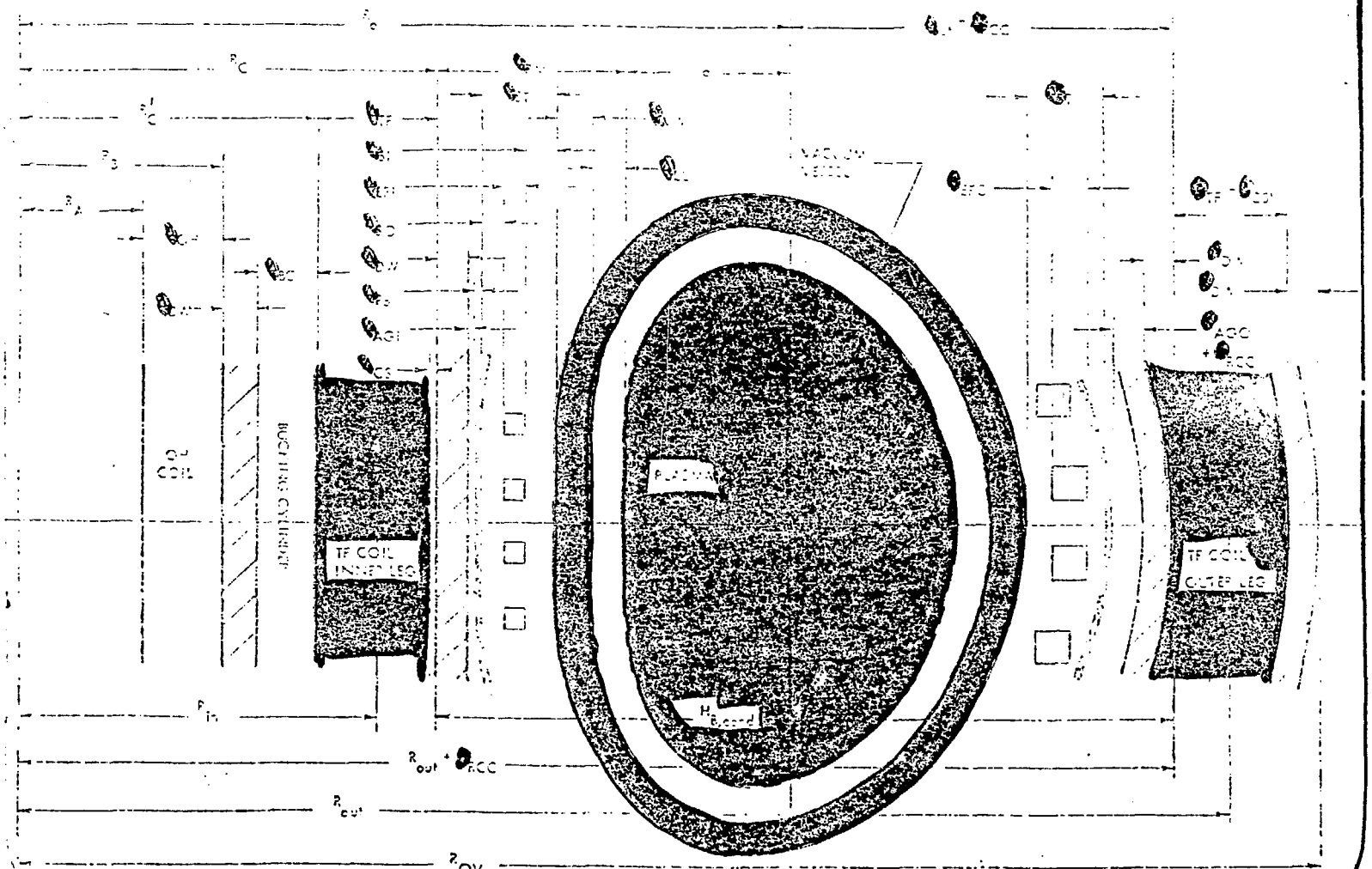
TF COIL ASSEMBLY LOGIC GIVES AN EXAMPLE OF THOROUGHNESS IN MODELLING

- INPUT
  - TF COIL TYPE AND NUMBER, PLASMA SPECIFICATIONS.
- DETERMINE
  - INNER TF LEG RADIAL CLEARANCES (10).
  - OUTER LEG RADIAL CLEARANCES (3).
  - RADIAL BUILD (3).
  - VERTICAL BORE CONSTANT TENSION D.
- CHECK
  - TO ENSURE THAT COMPONENTS FIT.
- ITERATE
  - AS NEEDED FOR CONSISTENCY.
- CALCULATE
  - MATERIAL VOLUMES AND COST OF ALL ASSEMBLY ELEMENTS.

SELF-CONSISTENT, DETAILED ENGINEERING REPRESENTATION
PROVIDES FIRM BASIS FOR LATER CONCLUSIONS

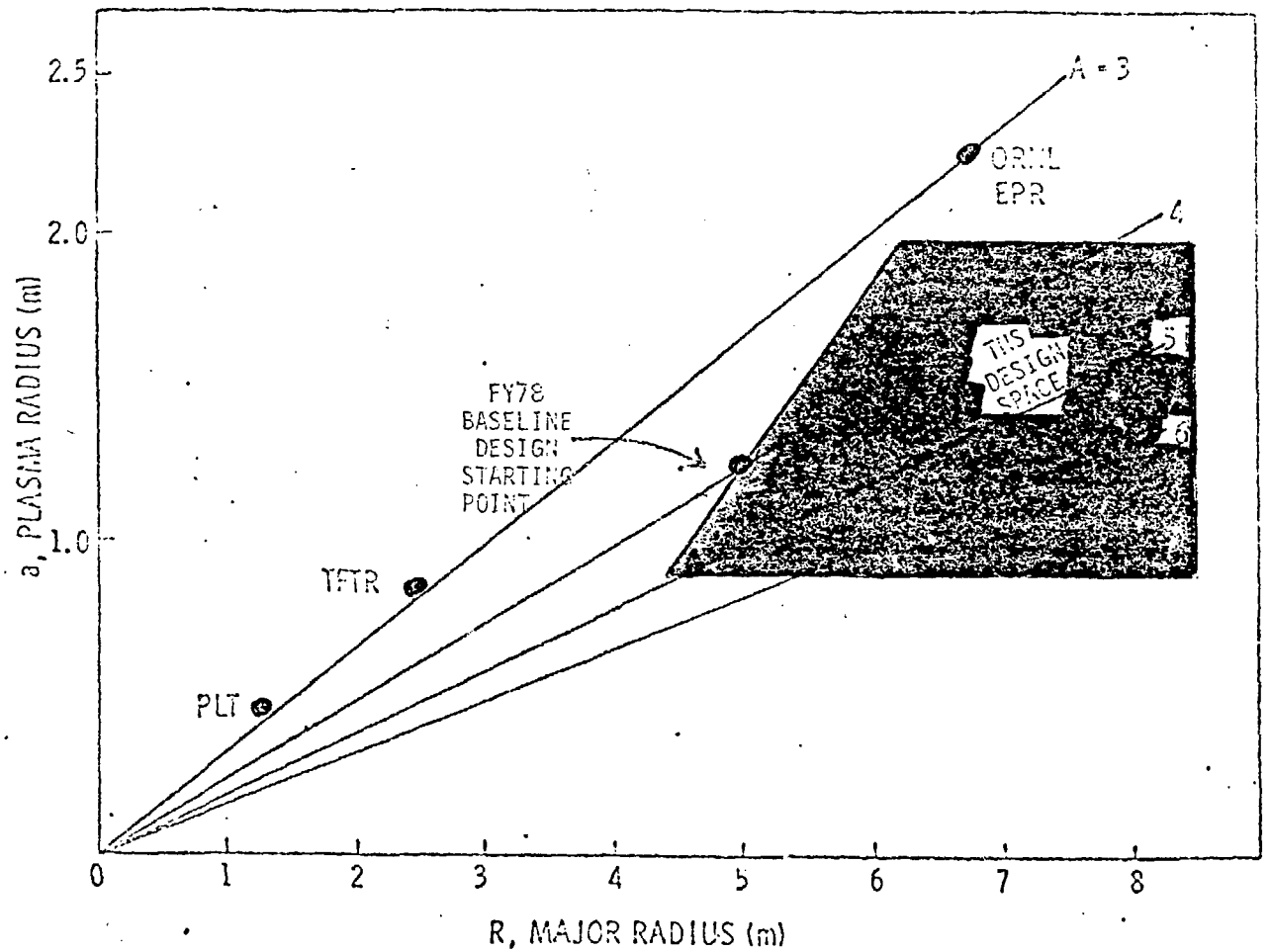


AS AN EXAMPLE OF THE EXTENT OF THE COSTING, THE REACTOR CELL ILLUSTRATES FIXED AND VARIABLE COSTING

ITEM	DIMENSIONS, M	UNIT COST	TOTAL COST, $
Plant System-Facility Buildings			
1. Reactor cell, cylinder with dome - containment	R_{RC}	$\$235.8/m^3$	Included elsewhere
300 ton polar crane	--	$1,890,000	1,890,000
Crane erection	--	$ 238,000	238,000
Remote systems operation	R_{RC}	$\$248/m^2$	$248\ \pi\ R_{RC}^2$
Reactor cell basement, utilized for service systems	$R_{RC} \times H_{BAS}$	$\$174/m^3$	$174\ V_{BS}$

2. NB Test Cell
3. Hot Cell
4. Mockup Assembly Bay
5. Transfer Bay
6. Utility Tunnel
7. M-G Building
8. Miscellaneous Buildings (12)

A BROAD DESIGN SPACE BRIDGING
TFTR AND EPR WAS THEN EXPLORED



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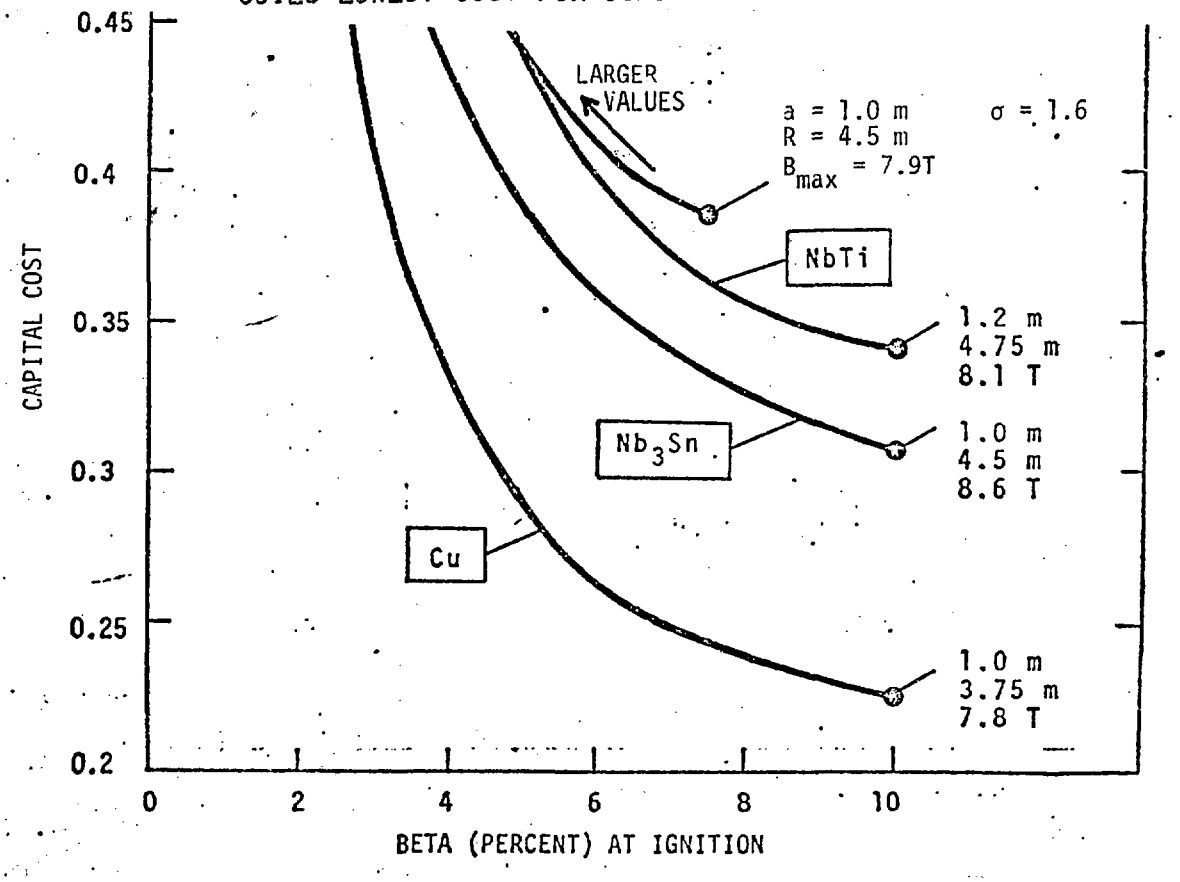
RESULTING COMPARATIVE COST CURVES INDICATE Cu COILS LOWEST COST FOR IGNITION OBJECTIVE



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CAPITAL COST COMPARISONS HAVE FORCED US
TO CONFRONT THE REAL QUESTIONS -
THE JUDGMENTAL ISSUES

QUANTIFIABLE	SEMIQUANTIFIABLE
✓ CAPITAL COST	MECHANICAL COMPLEXITY
✓ OPERATION COST	TECHNICAL RISK
SIZE	ASSEMBLY/MAINTENANCE
? PERFORMANCE	OPERATIONAL FLEXIBILITY
SCHEDULE	COST/SCHEDULE RISK
	REACTOR TECHNOLOGY
	EXTRAPOLATABILITY

FED/VU-77219

TF COIL TECHNOLOGY CHOICE BECOMES (AGAIN) FUNCTION OF OBJECTIVES AND PERSPECTIVE

PERFORMANCE / OBJECTIVE	$\beta < 5\%$	$\beta > 5\%$
IGNITION	Cu 10-12T	Cu 8-10T
REACTOR FOCUS	Nb_3Sn 11-13T	Nb_3Sn:NbTi 8-10T:8-10T $\$_{CAP} \leq \$_{CAP}$

WITH OBJECTIVE OF AGGRESSIVE FUSION POWER POWER PROGRAM IN MIND, OUR RECOMMENDATION IS FOR MEDIUM FIELD, HIGH BETA, Nb_3Sn BASED SYSTEM

- LATEST PLASMA ENGINEERING CALCULATIONS SUPPORT HIGH PERFORMANCE AT $4 < B < 7T$, at $5 < \bar{\beta} < 10\%$
- Nb_3Sn AT 8-10T LOW STRESS REQUIREMENT
- Nb_3Sn HAS LOWER REFRIGERATION REQUIREMENTS THAN NbTi
- Nb_3Sn HAS EXTRAPOLATABILITY
- Nb_3Sn BEING DEVELOPED WITH NbTi THROUGH LCP
- NbTi AVAILABLE AS BACKUP WITH MORE COST
- Cu AVAILABLE AS FURTHER BACKUP WITH LONG-TERM PROGRAM COST

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SYSTEMS ENGINEERING HAS PROVIDED QUANTITATIVE BASIS FOR PLASMA SIZE AND TF COIL TECH. CHOICES

- DOCUMENTED PATH DEVELOPED FOR QUANTITATIVE COMPARISON
- SELF-CONSISTENT (NON-OPTIMIZED) ENGINEERING MODELS DEVELOPED FOR EACH SUBSYSTEM IN ENTIRE PLANT
- COSTING ALGORITHM DEVELOPED FOR EACH MAJOR COMPONENT
- RELATIVE COST NOW AVAILABLE AS FUNCTION OF PLASMA SIZE, PERFORMANCE AND COIL TECHNOLOGY

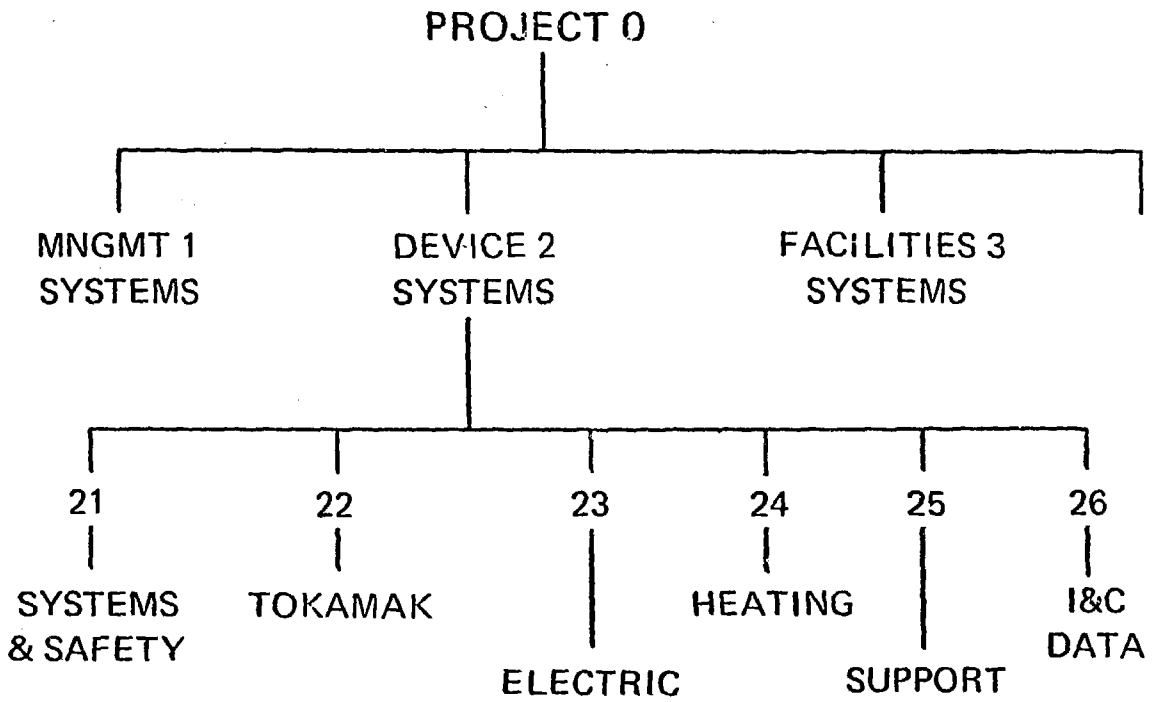
FED/VU-77222

SYSTEMS ENGINEERING HAS PROVIDED QUANTITATIVE BASIS FOR PLASMA SIZE AND TF COIL TECHNOLOGY CHOICES (continued)

- PROCESS OF QUANTIFYING THE JUDGEMENTAL FACTORS CONTINUES TO BE INCOMPLETE
- THEREFORE, QUANTITATIVE RESULTS MUST BE HEAVILY IMPACTED BY JUDGEMENT OF VARIOUS OBJECTIVES
- WITH OBJECTIVE OF AGGRESSIVE FUSION POWER PROGRAM IN MIND, OUR RECOMMENDATION IS FOR A MEDIUM FIELD, HIGH BETA, Nb_3Sn BASED SYSTEM

ORNL-DWG 77-5775

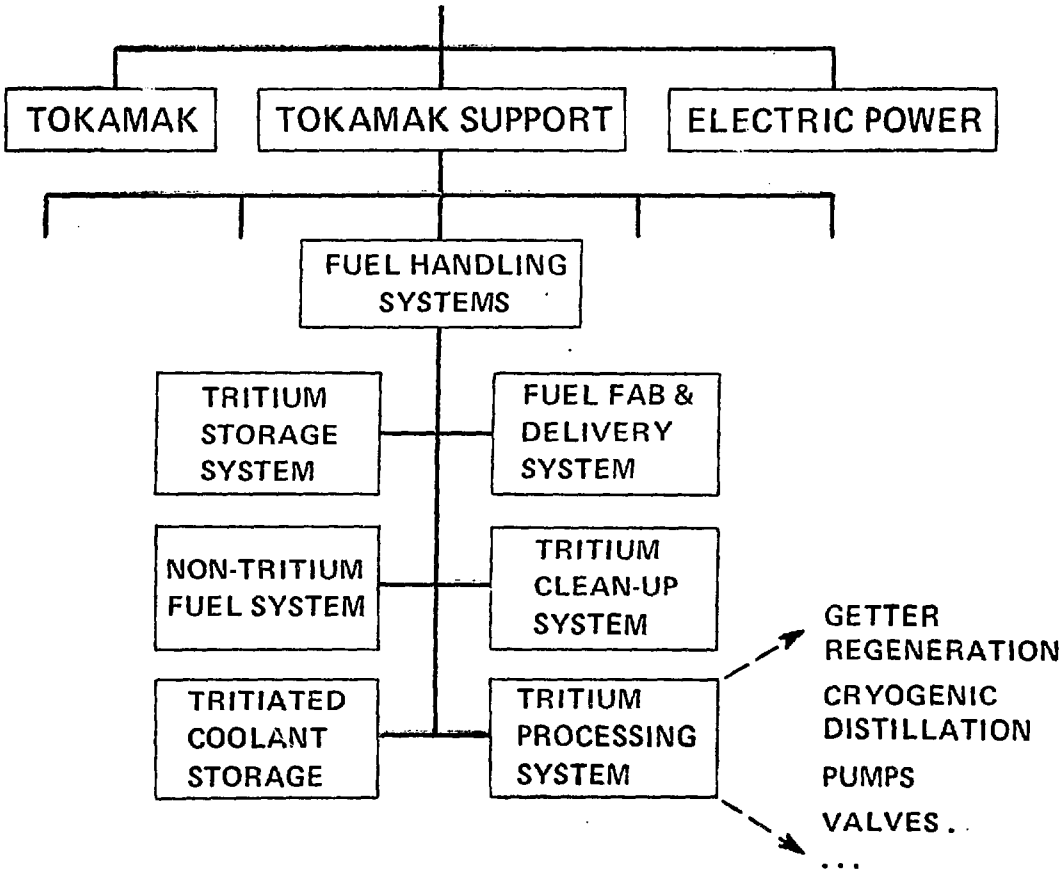
TO ORGANIZE PROJECT TASKS, ESTABLISHED COMPREHENSIVE WORK BREAKDOWN STRUCTURE (WBS)



SUBJECT
NO.
3M CATALOG NO. 1
3M CENTER, ST. P.
MADE IN U.S.A.

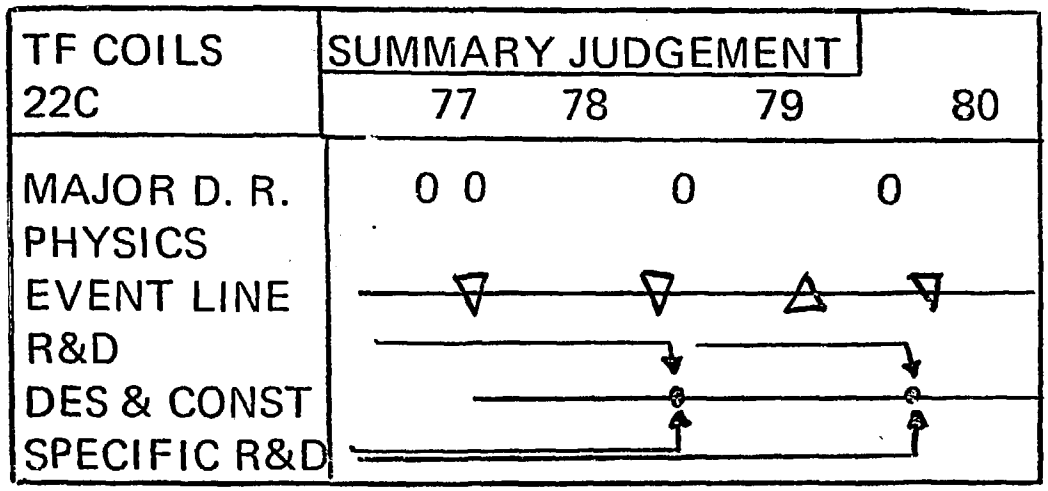
ORNL-DWG 77-4255

DESIGN MODEL IS BETTER THAN ANY HERETOFORE –
DETAIL IS DEVELOPED AT FOURTH LEVEL –
COMPONENTS AND PROCESSES



ORNL-DWG 77-6466

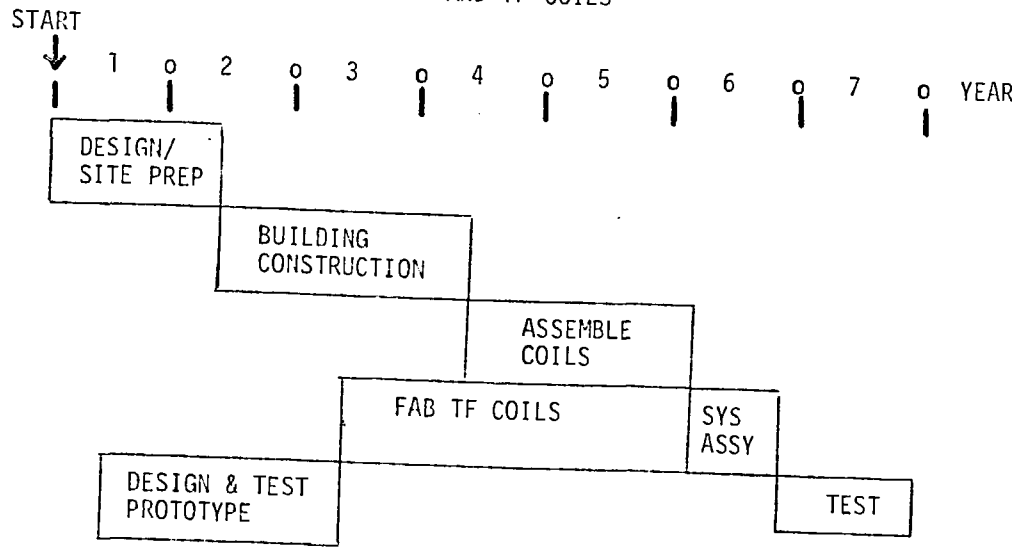
PART 2 - DEVELOPS WBS SCHEDULES AS FOCUS FOR ALL WORK ELEMENTS FOR NEEDS & PLANS & COMMENTARY



SUBJECT
CATALOG NO. 15 - 1
3M CENTER, ST. PAUL.
MADE IN U. S. A.

FED/VU-77223

QUANTIFIABLE CRITICAL PATH WAS FOUND TO BE MAIN BUILDING AND TF COILS



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AS IN COSTING COMPARISON, QUANTITATIVE
SCHEDULE EXERCISE HAS ILLUMINATED REAL ISSUE -
HOW TO MAKE PROGRAM DECISIONS

PRESENT ← t = ? →			0 -- 5 -- 10 YEAR
EXPERIMENTAL/	$\beta/\sigma/B$	?	BUILDINGS
THEORETICAL/	SITE/CONTRACTOR	?	ASSEMBLY-TEST
TECHNOLOGICAL	OBJECTIVES	?	COILS
PROGRAMS	RISK [IMPURITIES, FUELING, Nb_3Sn]	?	OTHER SYSTEMS

ORNL-DWG 77-5772R2

BUT, FROM HERE, GAPS DO EXIST IN THE PHYSICS PROGRAM

- COHERENT FORMULATION OF IMPURITY EFFECTS AND CONTROL PROGRAM IS ESSENTIAL
- EXPERIMENTAL PROGRAM ON HIGH β, HIGH T, CONFIGURATION MAINTENANCE ESSENTIAL
- COORDINATED, CLEARLY DEFINED EXPERIMENTAL PROGRAM PLANS ESSENTIAL
- STRONG APPLIED THEORETICAL SUPPORT PROGRAM IN IMPURITY DYNAMICS, PLASMA TRANSPORT AND ESPECIALLY COUPLED CODES

ORNL-DWG 77-6460

WITH TWO EXCEPTIONS, TOKAMAK SYSTEMS ARE UNDER CONTROL

	BASE	PLAN*	TIMELY	SOURCE
VAC. VES	V	V	V	TFTR/IND
STRUCT.	V	V	V	TFTR/IND
TF COILS	V	V	?	LCS/LCP, ETC
PF COILS	V*	V*	V*	PDX, TFTR
SHIELD	V	V	V	ORNL
IMP. CONT.	X			
MOCKUP	V	V	V	TFTR, IND

*NORMAL COILS ASSUMED FOR ASSESSMENT

BJECT
3M CATALOG NO. 15-1006
3M CENTER, ST. PAUL, MIN
MADE IN U.S.A.

ORNL-DWG 77-5777R

IN TECHNOLOGY, SEVEN NEW PROGRAMS OR STUDIES ARE NECESSARY IN ANY DESIGN PLAN

PROBLEM	PROGRAMS
PULSE LENGTH	–NB SWITCH TUBE
SPACE	–NB POWER PER UNIT
He/D/T	–COMPOUND GAS PUMPS
$	–PF ELECTRICAL SYSTEMS
	STUDIES
?	CONFIGURATION SENSING & CONTROL
?	ABNORMAL OPERATION
?	LIMITER MATERIALS

FED/VU-77226

PRINCIPAL ENGINEERING QUESTION IS
THAT OF ROUTE TO RELIABILITY

GOAL IS POWER PLANT RELIABILITY
TO DATE - EXPERIMENTAL PHYSICS DEVICES

HOW DO WE EVOLVE TO RELIABLE D-T OPERATION?

WE PROPOSE:

- TFTR EXPERIENCE
- SPECIFIC TNS MOCKUPS
- UTILITY PERSONNEL INVOLVEMENT
- DIRECTED S/C DEVICE EXPERIENCE
- FIRM KNOWLEDGEABLE DESIGN STANCE

IS THIS ENOUGH?

FED/VU-77227

PROGRAM PLANNING HAS DEVELOPED A DRAFT OF INTEGRATED TNS SCHEDULE/R&D PLAN

- PROJECT ENGINEERING BASED ON DETAILED W.B.S.
- ENG/TECH INTERFACE DEVELOPED FOR EACH DEVICE W.B.S. SYSTEM
- MASTER SCHEDULE EXERCISE DETERMINED BUILDINGS/TF COILS TO BE QUANTIFIABLE CRITICAL PATH
- PLASMA PHYSICS AND DECISION MAKING PROBABLY TRUE CRITICAL PATHS

FED/VU-77224

PROGRAM PLANNING HAS DEVELOPED A DRAFT OF INTEGRATED TNS SCHEDULE/R&D PLAN (continued)

- ASSOCIATED R&D NEEDS ANALYSIS HIGHLIGHTED BOTH STRENGTHS AND SPECIFIC GAPS IN:

  PHYSICS
  TECHNOLOGY
  ENGINEERING

FED/VU-77200

A CONSISTENT SET OF PHYSICS ASSUMPTIONS HAS BEEN ESTABLISHED FOR THE OAK RIDGE MEDIUM FIELD IGNITION REACTOR AT B_T = 4.3 T

PARAMETERS REFINED WITH 1-D TRANSPORT, MHD EQUILIBRIUM AND STABILITY CALCULATIONS

	LOW β	IGNITION	BURN
$\overline{\beta}$ (%)	1.0	3.0-5.0	3.5-10.0
I_P (MA)	4.0	4.5-5.5	
$\overline{N}$ (CM^{-3})	$0.3\text{-}0.5 \times 10^{14}$	$0.6\text{-}2.5 \times 10^{14}$	
$\overline{T}$ (keV)	1-2	4-7	5-10
COLLISIONALITY	0.14-0.98	0.01-0.15	
$\overline{n}\tau$ (CM^{-3} SEC)			$0.6\text{-}3 \times 10^{14}$
$P_{D\text{-}T}$ (MW)			100-2000
$P_{D\text{-}T}/V$ (MW/M^3)			0.4-8.0
W_L (MW/M^2)			0.3-5.0

INCREASED FLEXIBILITY OF REACTOR OPERATION CAN BE BUILT IN BY USING B_T = 6-7 T (Nb_3Sn COILS)

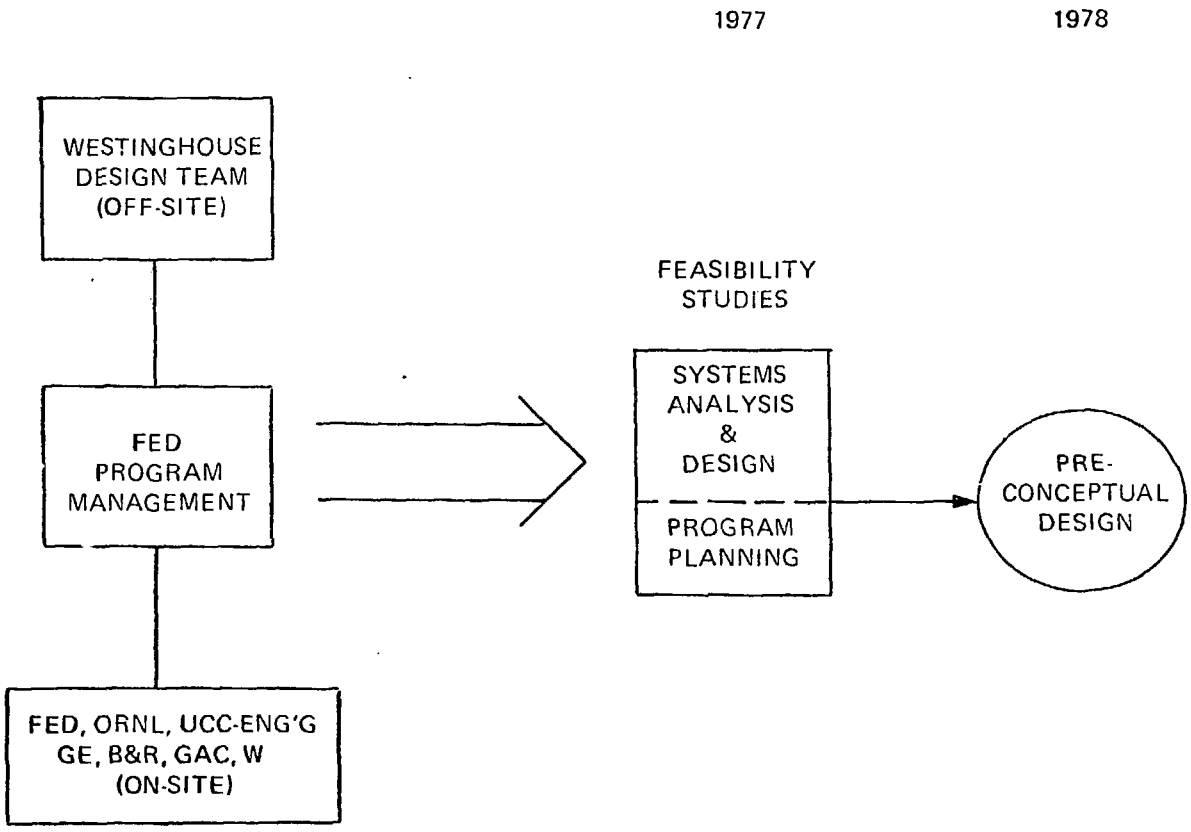
FED/VU-77228

BASED ON THIS PAST YEAR'S WORK, OUR CURRENT WORK TASKS CONFRONT MAJOR GO/"DIFFICULT" GO DESIGN TASKS

- WE START FROM AN ATTRACTIVE, SUPPORTABLE MEDIUM FIELD, HIGH β, BASELINE DESIGN
- CONCENTRATE OUR EFFORTS IN THREE AREAS THAT APPEAR TO BE HOLDING UP PROGRESS:
  - MECHANICAL FEASIBILITY
  - SIMPLIFIED POLOIDAL FIELD SYSTEM
  - INTEGRATED TNS/R&D SUPPORT PROGRAM

ORNL/DWG/FED-77186

THE TNS PROGRAM IS AN ORNL/INDUSTRY EFFORT FOCUSED ON INITIATING PRE-CONCEPTUAL DESIGN FOR THE IGNITION PHASE



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TNS DESIGN SPACE EXPLORATION HAS BROUGHT US A LARGE STEP CLOSER TO REALIZABLE REACTOR

- PLASMA ENGINEERING MODELS POINT TOWARD ECONOMICALLY ATTRACTIVE PERFORMANCE
- SYSTEMS ENGINEERING HAS PROVIDED QUANTITATIVE BASIS FOR PLASMA SIZE AND TF COIL TECH. CHOICES
- PROGRAM PLANNING HAS DEVELOPED A DRAFT OF INTEGRATED TNS SCHEDULE/R&D PLAN
- BASED ON THIS YEAR'S WORK, OUR CURRENT WORK TASKS CONFRONT MAJOR "GO/DIFFICULT GO" DECISION ISSUES
- INDUSTRIAL PARTICIPATION IS BEING USED TO STRENGTHEN THE EARLY DESIGN PROCESS