LEGIBILITY NOTICE

A major purpose of the Technical Information Center is to provide the broadest dissemination possible of information contained in DOE's Research and Development Reports to business, industry, the academic community, and federal, state and local governments.

Although a small portion of this report is not reproducible, it is being made available to expedite the availability of information on the research discussed herein.

171
5/8/86 JS①

I - 26070

ORNL/FEDC-86/1

29

DF-1699-3

INTERIM REPORT ON THE ASSESSMENT OF ENGINEERING ISSUES FOR COMPACT HIGH-FIELD IGNITION DEVICES

MASTER

FUSION ENGINEERING DESIGN CENTER

OAK RIDGE NATIONAL LABORATORY

Operated by MARTIN MARIETTA ENERGY SYSTEMS, INC.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

ORNL/FEDC-86/1

Dist. Category UC-20 c,d

FUSION ENERGY DIVISION

ORNL/FEDC--86/1

DE86 010060

INTERIM REPORT ON THE
ASSESSMENT OF ENGINEERING ISSUES FOR COMPACT HIGH-FIELD IGNITION DEVICES

Edited by

C. A. Flanagan
Fusion Engineering Design Center

Date Published - April 1986

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under Contract No. DE-AC05-84OR21400

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

CONTENTS

ABSTRACT.....	xiii
ACKNOWLEDGMENTS.....	xv
CONTRIBUTING AUTHORS.....	xvii
1. INTRODUCTION AND SYSTEMS OVERVIEW.....	1
1.1 INTRODUCTION.....	1
1.2 SYSTEMS OVERVIEW.....	2
1.2.1 Key Features.....	2
1.2.2 Key Parameters.....	4
1.2.3 Key Engineering Issues.....	5
1.2.4 Poloidal Field Coil System.....	6
1.2.5 Toroidal Field Coil Features.....	8
1.2.6 Operating Scenario.....	9
1.2.7 Energy and Power Requirements.....	10
1.2.8 RF Heating Requirements.....	13
1.2.9 Diagnostics and Instrumentation.....	13
1.2.10 Other Systems.....	14
1.2.11 Repairability.....	14
1.2.12 Conclusions.....	15
2. LIMITER AND FIRST-WALL ENERGY REMOVAL.....	17
2.1 INTRODUCTION.....	17
2.2 HEATING CONDITIONS.....	17
2.3 DESIGN CONCEPTS AND OPERATING LIMITS.....	22
2.4 EVALUATION OF LIMITER DESIGN CONCEPTS.....	24
2.5 KEY ISSUES.....	29
2.6 CONCLUSIONS.....	32
3. COMMON-BASIS STRUCTURAL ANALYSIS OF THE COMPACT IGNITION DEVICES.....	35
3.1 INTRODUCTION.....	35
3.2 PROPOSED GUIDELINES FOR ALLOWABLE STRESSES.....	35
3.3 STRUCTURAL ANALYSIS.....	37
3.3.1 MIT LITE (1.76 m-Major Radius).....	39

3.3.2	ISP 0424.....	41
3.3.3	Ignitor A (January 1985).....	41
3.3.4	Alcator C.....	44
3.3.5	TF Analysis Summary.....	49
3.4	OH CENTRAL SOLENOID ANALYSIS.....	50
3.5	STRUCTURAL ASSESSMENTS.....	51
3.6	CONCLUSIONS.....	52
4.	FABRICATION AND ASSEMBLY.....	55
4.1	FACTORS INFLUENCING FABRICATION AND ASSEMBLY.....	55
4.2	SEGMENTATION COMPARISON.....	55
4.3	TOLERANCE REQUIREMENTS.....	56
4.4	MATERIALS TO BE FABRICATED.....	57
4.5	SIZE AND WEIGHT OF COMPONENTS.....	58
4.6	MACHINING ASSESSMENT.....	59
4.7	ADHESIVE BONDING ASSESSMENT.....	63
4.8	LARGE VACUUM VESSEL MANUFACTURING ASSESSMENT.....	63
4.9	FABRICATION OF LARGE PRECISION STRUCTURES.....	68
4.10	ASSEMBLY ASSESSMENT.....	68
4.11	SUMMARY.....	70
5.	REPAIRABILITY.....	71
5.1	FEATURE COMPARISON.....	71
5.2	REPAIR APPROACH.....	72
5.3	TEST CELL LAYOUT.....	73
5.4	VACUUM VESSEL ACCESS.....	76
5.5	TEST CELL COMPONENTS.....	81
5.6	KEY ISSUES.....	86
5.7	CONCLUSIONS.....	87
6.	COMPACT IGNITION DEVICE COST ASSESSMENTS.....	89
6.1	INTRODUCTION.....	89
6.2	COSTING APPROACH.....	89
6.3	PROCEDURE.....	90
6.4	COST ELEMENT DEFINITIONS.....	90

6.5	METHODOLOGY.....	92
6.6	ASSUMPTIONS/GROUNDRULES.....	95
6.7	EXISTING SITE RESOURCES.....	95
6.8	COST ASSESSMENTS.....	95
6.9	CONCLUSIONS.....	100
Appendix A. DESCRIPTION OF THE IGNITOR CONCEPT.....		101
A-1.	INTRODUCTION.....	103
A-2.	TORUS DESCRIPTION.....	103
A-3.	TF COIL SYSTEM.....	108
A-4.	PF COIL SYSTEM.....	108
Appendix B. DESCRIPTION OF THE PPPL ISP 0424 CONCEPT.....		113
B-1.	INTRODUCTION.....	115
B-2.	TORUS DESCRIPTION.....	115
B-3.	TF COIL SYSTEM.....	115
B-4.	PF COIL SYSTEM.....	120
Appendix C. DESCRIPTION OF THE MIT WATER-COOLED LITE CONCEPT.....		123
C-1.	INTRODUCTION.....	125
C-2.	TORUS DESCRIPTION.....	125
	Toruz Assembly.....	129
	Precompression System.....	129
C-2.1	TF Coil System.....	131
C-2.2	PF Coil System.....	133
C-2.3	Vacuum Vessel/FW/Limiter System.....	136
C-2.4	Torque Structure.....	136
C-2.5	Liquid Nitrogen-Cooled Concept.....	139
Appendix D. RECOMMENDATIONS OF THE PHYSICS IGNITION PANEL.....		141
D-1.	OBJECTIVES.....	143
D-2.	PLASMA CONFIGURATION.....	143
D-3.	MHD CONSTRAINTS.....	143

D-4.	ENERGY CONFINEMENT.....	143
	D-4.1 Minimum Toroidal Field Strength and Machine Size.....	144
	D-4.2 Minimum Plasma Current.....	146
D-5.	IMPURITY CONTROL.....	147
D-6.	PULSE LENGTH.....	147
D-7.	PLASMA FUELING, HEATING, AND CURRENT DRIVE.....	147
D-8.	DISRUPTION SCENARIOS.....	148
D-9.	TOTAL NUMBER OF PULSES.....	148
D-10.	BURN CONTROL.....	148
D-11.	PORT SIZE.....	148
D-12.	MACHINE PARAMETERS.....	149

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1.1	MHD equilibrium of the PF coil system.....	7
1.2	Operation scenarios for (a) Ignitor C, (b) ISP 0424 and (c) LITE.....	11
2.1	Typical compact ignition tokamak in which inboard first wall forms the limiter surface.....	18
2.2	The relationship between peak heat flux and limiter shape...	20
2.3	Sensitivity of peak heat flux to e-fold distance.....	21
2.4	Limiter and first-wall design options.....	23
2.5	Thermal and combined stress variation with vacuum vessel temperature.....	23
2.6	Graphite vaporization rate variation with surface temperature.....	25
2.7	Transient thermal response of graphite tiles and stainless steel vacuum vessel.....	26
2.8	Maximum temperature vs (a) tube spacing and (b) skin thickness.....	28
2.9	Maximum temperature vs tile thickness.....	30
2.10	Heating duration vs heat flux.....	30
2.11	Cooldown time vs heat flux.....	31
3.1	Two-dimensional finite element models.....	38
3.2	In-plane and out-of-plane loads for LITE (8.5 T).....	40
3.3	In-plane and out-of-plane loads for ISP 0424 (8.95 T).....	42
3.4	In-plane and out-of-plane loads for Ignitor (12.5 T).....	45
4.1	Considerable warpage that occurs when one side of a cold- worked copper plate is machined.....	60
4.2	Tolerances of 0.001 in. held in the D-III finger, jointly match-machining and hand fitting.....	61
4.3	The D-III TF coil plates being machined at General Dynamics/Convair	62
4.4	The D-III TF coil centerpost, an adhesive bonded structure..	64

<u>Figure</u>		<u>Page</u>
4.5	Large PF coils being assembled at GA Technologies	65
4.6	Photo of TFTR vacuum vessel illustrating a segmented vessel.....	66
4.7	The D-IIID vacuum vessel	67
4.8	Photo of TFTR overall structure illustrating large tokamak support structure feasibility.....	69
5.1	Typical test cell layout, elevation view.....	74
5.2	Typical test cell layout, plan view.....	75
5.3	RM-10 master control station.....	77
5.4	RM-10 slave assembly.....	78
5.5	TFTR maintenance manipulator.....	79
5.6	Port size that restricts access.....	80
5.7	Acid fractionator module.....	82
5.8	Photo of acid fractionator module	83
5.9	Photo of pump installation	84
5.10	Computer-aided design to expedite development.....	85
6.1	Cost estimate assembly procedure.....	91
6.2	Cost estimate methodology.....	93
A-1	Ignitor reference design.....	104
A-2	Ignitor sector module.....	105
A-3	Original Ignitor design: coil positions and flux surfaces for (a) plasma initiation and (b) end of pulse.....	109
A-4	Tilted solenoid design ($\delta = 0.2$): coil positions and flux surfaces for (a) plasma initiation and (b) end of pulse.....	110
B-1	PPPL ISP 0424 design.....	116
B-2	ISP 0424 complete vacuum vessel assembly.....	119
B-3	Internal EF coils for ISP 0424; coil positions and flux surfaces for (a) plasma initiation and (b) end of pulse.....	121

<u>Figure</u>	<u>Page</u>
C-1 MIT LITE general arrangement.....	126
C-2 MIT LITE elevation view.....	127
C-3 Typical sector of TF coils plus vacuum vessel/first wall.....	130
C-4 TF bunch arrangement.....	132
C-5 FEDC specified coil positions and flux surfaces for (a) plasma initiation and (b) end of pulse.....	134
C-6 Vacuum vessel/first wall/limiter system.....	137
C-7 MIT LITE alternate torus structure.....	138

LIST OF TABLES

<u>Table</u>	<u>Page</u>
1.1 Key features.....	3
1.2 Key parameters.....	4
1.3 Key engineering issues.....	6
1.4 Features of TF coils.....	8
1.5 Running loads of TF coils.....	9
1.6 Energy and power requirements.....	12
2.1 Peak heat fluxes.....	22
2.2 Key parameters in inertially cooled limiter design.....	27
2.3 Key design issues.....	29
2.4 Disruption heating conditions.....	32
3.1 Common basis material strengths (MPa).....	37
3.2 Stress summary for the TF throat region of LITE at 8.5 T and 300 K.....	39
3.3 Stress summary for the TF throat region of ISP 0424 at 8.95 T and 300 K.....	43
3.4 Stress summary of the TF throat region of Ignitor A at 12.5 T and 77 K.....	46
3.5 Structural sensitivities of the Ignitor TF coil.....	47
3.6 Summary of results for the TF throat region of Alcator C at 300 K.....	48
3.7 Structural performance of Alcator C through 1984.....	49
3.8 Summary of results for TF throat region.....	49
3.9 OH central solenoid - ideal coil analysis.....	50
3.10 Ignitor central solenoid sensitivity.....	51
4.1 Size and weight of components.....	58
5.1 Key feature comparison of compact ignition device.....	71
5.2 Typical components requiring remote repair.....	72
6.1 Existing PPPL resources summary.....	96
6.2 Cost assessment of compact ignition devices.....	98
6.3 Cost assessment of compact ignition devices.....	99

TablePage

A-1	Major parameters of Ignitor (January 1985 reference) device.....	106
A-2	Ignitor radial and vertical build.....	107
A-3	PF coil positions and current.....	111
B-1	Major parameters of ISP 0424 ignition device.....	117
B-2	ISP 0424 radial and vertical build.....	118
B-3	Coil currents for ISP 0424 design with internal EF coils..	122
C-1	Major parameters of water-cooled LITE device.....	125
C-2	MIT LITE radial and vertical builds.....	128
C-3	Coil currents for water-cooled LITE for FEDC specified coil positions.....	135
C-4	Plasma parameters for water-cooled LITE at end of pulse for FEDC specified coil positions.....	135

ABSTRACT

Several concepts have been under investigation as candidates for a near-term tokamak ignition experiment. All concepts are compact (1- to 2-m major radius) and feature high-field, high-plasma current operation. During approximately the past year, scoping studies have been under way by three different groups; these include the Ignitor Concept guided by Prof. B. Coppi of the Massachusetts Institute of Technology (MIT), the LIIE Concept guided by Dr. Dan Cohn (MIT), and concepts studied at the Princeton Plasma Physics Laboratory (PPPL) in the Ignition Studies Project guided by Dr. John Schmidt. In June 1985, an Ignition Design Point Workshop was hosted by the United States, at which the status of the studies was summarized for an international review panel. The advocate groups presented the status of the design efforts. The current understanding of the physics data base was reviewed. Also, a session was devoted to a preliminary assessment of the engineering issues associated with such compact high-field devices.

The engineering issues addressed at the workshop included the overall configuration, layout, and assembly; limiter and first-wall energy removal; magnet system structure design; fabricability; repairability; and costs. In performing the assessment, the primary features and characteristics of each concept under study were reviewed as representative of this class of ignition device. The emphasis was to understand the key engineering areas of concern for this class of device and deliberately not attempt to define an optimum design or to choose a best approach.

The assessment concluded that compact ignition tokamaks, as represented by the three concepts under study, are feasible. A number of critical engineering issues were identified, and all appear to have tractable solutions. The engineering issues appear quite challenging, and to obtain increased confidence in the apparent design solutions requires completion of the next level of design detail, complemented by appropriate development programs and testing.

ACKNOWLEDGMENTS

The Compact Ignition Tokamak Studies benefit from the valuable contributions being made by the engineers and scientists who are involved in this program at national fusion institutions. We would like to acknowledge these many contributions from this broad-based participation. We would also like to acknowledge the particular guidance and support of Philip M. Stone and the Fusion Systems Branch of the Office of Fusion Energy, U. S. Department of Energy.

CONTRIBUTING AUTHORS

Section

1. C. A. Flanagan, FEDC
2. J. R. Haines, FEDC
3. D. B. Montgomery, MIT
4. F. A. Puhn, GA Technologies
5. C. A. Trachsel, McDonnell Douglas
6. W. R. Hamilton, FEDC

Appendix

- A. T. G. Brown, FEDC
- B. T. G. Brown, FEDC
- C. V. D. Lee, FEDC
- D. H. Furth, PPPL

1. INTRODUCTION AND SYSTEMS OVERVIEW

C. A. Flanagan, FEDC/Westinghouse

1.1 INTRODUCTION

During the period October 1984 to June 1985, several studies under way in the United States focused on compact, high-field tokamaks as a means to achieve ignition in the near term at low cost. The prime objective of such a near-term tokamak ignition experiment is to establish the physics of ignition and quasi-steady-state burn. In mid-June 1985, the United States hosted an Ignition Design Point Workshop at which the status of the United States studies was summarized for an international review panel. One session of this workshop was devoted to a preliminary assessment of the engineering issues associated with such compact high-field devices. The purpose of this report is to document the assessment presented at the workshop.

The tokamak studies performed by three different groups cover the range of compact high-field tokamaks discussed at the workshop. The concepts include (1) the Ignitor concept with leading advocate Prof. B. Coppi, (2) the series of LITE devices developed under the guidance of Dr. D. Cohn at Massachusetts Institute of Technology (MIT), and (3) the series of devices studied by the Ignition Studies Program under the guidance of Dr. J. A. Schmidt at Princeton Plasma Physics Laboratory (PPPL). Technical appendixes included at the end of this report briefly describe the three design concepts.

The session on Overview of Design Approaches assessed the engineering issues related to this class of compact high-field ignition machines. The primary features and differences of the various point designs were reviewed. The major unresolved issues and requirements necessary for resolution were identified. The design issues related to all of the point designs were discussed, and the issues were assessed by discussion of the point designs in parallel. There was a deliberate effort at this time not to define an optimum or pick a best design. The emphasis was to understand the present status of all the options. Identification and selection of a specific design approach will occur in

the future after additional design work has been completed. The assessment was distinguished by the fact that it was performed by independent engineers within the fusion community; however, these engineers had a close working relationship with the design teams.

This workshop followed an earlier international workshop held at Princeton on March 12-13, 1985. At this earlier workshop, a substantial consensus among the international participants was achieved relative to the major physics issues involved in the design of an ignition experiment. The March workshop established tentative physics objectives and design guidelines to be used for the compact ignition machines. This physics guidance is included as Appendix D.

The organization of this report follows the organization of the session at the Boston workshop on the Overview of the Design Approaches. Following this introduction and systems overview is a discussion in Sect. 2 of the limiter and first-wall energy removal. Section 3 deals with structural design and analysis, and Sect. 4 deals with fabrication and assembly. Section 5 covers maintainability. Costs are addressed in Sect. 6, and the conclusions are presented in Sect. 7. Appendixes A, B, and C contain brief descriptions of Ignitor, PPPL 0424, and LITE design points. Appendix D is the published physics guidance resulting from the March Workshop.

1.2 SYSTEMS OVERVIEW

This class of compact ignition devices is reviewed by major system and function to put into context the various design approaches. Three-dimensional perspective computer-aided design drawings were developed for each of the three design concepts and are included with the description of each design in the technical appendixes.

1.2.1 Key Features

The key features of the three design approaches are summarized in Table 1.1. The toroidal field (TF) coils for Ignitor are basically a continuous series of 96 plates. The PPPL ISP 0424 design currently has 14 TF coils, and the LITE design has 24 TF coils. All TF coils are

comprised of cold-worked, high-strength plates. The Ignitor concept employs a silver-copper alloy, the ISP 0424 concept uses conventional oxygen-free high-conductivity (OFHC) copper, and the LITE concept uses plates fabricated of OFHC copper except for the center leg, which is made from a high-strength beryllium-copper alloy.

Inertial cooling of the magnets with liquid nitrogen is assumed in the ignitor and ISP 0424 concepts; the LITE concept is based on active cooling using water. In addition, a version of LITE has been examined based on inertial cooling with liquid nitrogen.

A distinguishing feature of the ISP 0424 concept is the use of a slip joint in the TF coils to relieve the tension load on the inboard leg. As a consequence, an internal set of poloidal field (PF) coils, including the OH solenoid can be used. Also, the assembly of the device permits the installation of the vacuum vessel as a single welded unit. The other concepts use PF coils external to the TF coils; assembly of the device requires the use of vacuum vessel segments.

Table 1.1. Key features

	Ignitor	ISP 0424	LITE
Number of TF coils	96 plates (192 turns)	14	24
TF coils (Cold-worked, high-strength plates)	Ag-Cu	OFHC	OFHC Be-Cu
Magnet cooling	LN ₂	LN ₂	H ₂ O (LN ₂)
TF slip joint	No	Yes	No
Torque structure	Internal	External	External
PF coils	External	Internal	External
Vacuum vessel	Segmented	one piece	Segmented
Number of ports	12	14	23
Width of ports, m	0.10	0.44	0.22
Height of ports, m	0.80	0.95	1.3

A final key feature of the concepts is the number and size of ports provided. The larger ports are in the ISP 0424 and LITE concepts; these concepts provide for 14 and 23 ports with a port width of 0.44 and 0.22 m, respectively. The Ignitor port size is the smallest; there are 12 ports with a port width of 0.10 m. The port height varies from 0.8 to 1.3 m in the three concepts.

1.1.2 Key Parameters

The key parameters for the three concepts are listed in Table 1.2. Ignitor is the smallest device, with a major radius of 1.01 m and a plasma radius of 0.39 m. The ISP 0424 and LITE devices have a major radius substantially larger than Ignitor, yet still quite small even in comparison with existing machines. The major radius of ISP 0424 is 1.62 m with a plasma radius of 0.53 m, and the corresponding LITE parameters are 1.76 and 0.55 m, respectively.

Table 1.2. Key parameters

	Ignitor	ISP 0424	LITE
Major radius, m	1.01	1.62	1.76
Minor radius, m	0.39	0.53	0.55
Elongation	1.6	1.6	1.6
Triangularity	0.2	0.4	0.3
Field on axis, T	12.5	8.9	8.85
Plasma current, MA	9.6	7.8	7.0
Beta, %	1.2	5	4.6
Burn time, s	5.0	5.0	5.0
Fusion power, MW	108	305	300
Wall load, MW/m ²	4.0	5.6	5.3
RF power, MW	0 (to 10)	30	30
Total V-s supplied	20	26	30

All concepts assume an elongation of 1.6 and a triangularity that varies from 0.2 (Ignitor) to 0.4 (ISP 0424).

All of these concepts operate at high magnetic field at the center of the plasma. The ISP 0424 and LITE concepts are at about 9 T, and Ignitor is at a central field of 12.5 T. The associated plasma currents at full field are also large; LITE is at a plasma current of 7.0 MA, ISP 0424 is at 7.8 MA, and Ignitor is at 9.6 MA.

The average toroidal beta for LITE and ISP 0424 is about 5%; Ignitor assumes that ignition occurs while beta is still relatively low, at about 1.2%. The full-field, full-current burn length for LITE and ISP 0424 is 5 s; Ignitor assumes a burn scenario that achieves full field, full current for about 0.5 s, after which the field is reduced to about 7.5 T, and the burn continues for an additional 3-4 s. For the conditions stated, the associated fusion power for the devices is about 300 MW (wall loading of about 5 MW/m^2) for LITE and ISP 0424 and about 100 MW (wall loading of about 4 MW/m^2) for Ignitor.

Ignitor advocates the possibility of achieving ignition ohmically and does not rely on auxiliary power; however, up to 10 MW of rf power is identified as backup. About 30 MW of rf power is identified for LITE and ISP 0424.

The total volt-seconds supplied by the machines varies from about 20 for Ignitor to about 30 for LITE.

1.2.3 Key Engineering Issues

Several key issues are associated with this class of ignition devices. Table 1.3 lists seven that are considered important, particularly at this stage of the design. Subsequent sections more fully describe five of these key issues.

All of the concepts must address how to react the magnetically induced loads associated with these high-field approaches. Similarly, fabrication of the components represents an essential consideration for each concept. Because the plasma radius is small yet the fusion power is significant, the heat loads that must be accommodated are significant, and means to handle such loads must be identified, particularly in view of the desire to use inertial cooling.

Table 1.3. Key engineering issues

Magnet system structure design
Fabricability
Plasma chamber heat loads/insulation
Configuration layout, assembly
Access
Repairability
Costs

The approach to the overall configuration layout and method of assembly plays a major role in achieving the goals of the device at a minimum size. Usually, there is a trade-off between various considerations that determines how a given concept can be configured and assembled. Identifying such considerations and their importance to the concept is a major issue. Because these designs are all compact, the amount of access is decreased compared to the type of access typically desired in next-generation devices that have been studied during the past several years. Another consequence of the compact size and limited access is the issue of repairability.

Finally, there is a strong desire to minimize the overall cost of the machine, and this desire drives the approach being used to develop each concept.

1.2.4 Poloidal Field Coil System

Self-consistent magnetohydrodynamic (MHD) calculations using the same model and methodology were performed for each of the three concepts. The location and size of the individual PF coils were taken to be those suggested by the design teams. With this input and necessary device parameters, calculations were performed to confirm that each design satisfied MHD equilibrium. Figure 1.1 shows the arrangement of the PF coils for each of the concepts drawn to the same scale and also shows the plasma shape. Each design satisfies the MHD requirements with the plasma parameters identified and for the plasma shape

Fig. 1.1. MHD equilibrium of the PF coil system.

indicated. The volt-seconds supplied by each device are 20, 26, and 30 for Ignitor, ISP 0424, and LITE, respectively.

None of the PF coil systems has been optimized, and such studies would serve to improve the present (adequate) systems.

1.2.5 Toroidal Field Coil Features

The three concepts derive many of their distinguishing features from the approach to the TF coil system. Table 1.4 summarizes these features.

Table 1.4. Features of TF coils

Ignitor	ISP 0424	LITE
Precompression rings	Sliding joint	Self-supporting
Wedging/bucking	Primarily wedging	Wedging
Cold-worked, high-strength plates	Cold-worked, high-strength plates	Cold-worked, high-strength plates
Ag-Cu155	OFHC Cu	OFHC Be-Cu
External C-clamp	Partial case/panels	External torque structure

Ignitor uses precompression rings to achieve a preload on the TF coils. This accommodates the problem of center-leg tension. The ISP 0424 concept is investigating the use of a slip joint to essentially eliminate the tension load on the center leg of the TF coils; however, this requires the development of an acceptable slip joint to mechanically decouple the center leg from the remainder of the TF coil. The LITE concept relies on the use of wedged plates that are self-supporting. Ignitor requires a combination of wedging and bucking to accommodate and distribute the loads on the TF coils. The ISP 0424 design relies primarily on wedging. The resulting stress levels associated with the TF coil magnets are intimately tied to the approach adopted to react the magnetic loads. As discussed in Sect. 3, the stress levels can probably be accommodated based on the approach suggested to establish the design allowables.

The methods to react the magnetic loads vary among the designs. Ignitor uses an external C-clamp design concept; ISP 0424 uses a partial case on the outer TF leg combined with shear panels; and LITE uses an all-external torque structure. Additional detail is contained in the technical appendixes.

Table 1.5 presents a summary of the magnetically induced running loads for the three concepts. The total vertical load varies from about 400 MN for Ignitor to about 700 MN for ISP 0424. The total megampere turns (MAT) varies from about 65 for Ignitor to about 75 for LITE. The peak running load is about 10 MN-m for Ignitor, about half of that for LITE, and about a quarter of that for ISP 0424. The total torque is of the order of 350 to 450 MN-m for LITE and ISP 0424 and about 135 for Ignitor. The associated torque on the inner leg of the TF coil is 60 to 30 MN-m for LITE and ISP 0424 and about 10 for Ignitor. These loads for the nominal conditions were used to determine the associated stresses for the three designs. In addition, some sensitivity analyses were performed. A discussion of the methodology, allowables and calculated results is presented in Sect. 3.

Table 1.5. Running loads of TF coils

	Ignitor (24)	ISP (14)	LITE (24)
Total vertical load, MN	394	711	574
Total MAT	63.3	72.5	74.8
Peak running load, MN-m	10.4	2.6	5.7
Total torque, MN-m	134	442	336
Inner-leg torque, MN-m	9	30	61

1.2.6 Operating Scenario

The ISP 0424 and LITE concepts were developed to be compatible with the physics guidelines provided and confirmed at the earlier March workshop. The Ignitor concept was developed to provide the capability to achieve ignition using solely ohmic heating if possible. The associated burn-pulse operating scenario for the three concepts reflects the

concept assumptions. The LITE and ISP 0424 designs assume a ramp-up to full-field and full-current conditions followed by a 5-s burn. Subsequently, the burn pulse is terminated and the field ramped down again. The specific times for ramping the TF and PF fields have not been definitely established. Ignitor assumes ramping to full field and current followed by a 0.5-s burn at ignition at these conditions. Subsequently, the TF field is reduced to 7.5 T and the burn continued for about 3-4 s. The burn is then terminated and the field ramped down again. Here again, the specific times for ramping the TF and PF fields and the exact means of controlling the plasma when decreasing the TF field from 12.5 to 7.5 T have not been fully defined.

Figure 1.2 presents potential waveforms for operating scenarios for the three concepts. These waveforms have been used to model the burn pulse for each of the design concepts and to determine the power requirements of each device.

The details of the operating scenario and burn characteristics, the details of ramping and holding the TF field, the current waveforms of the PF coils and their relationship to the TF coils, and the balancing of the associated power requirements require additional study and development for each of the concepts. The preliminary scenarios developed to date are illustrative of the nature of the burn and the associated power requirements but are not definitive.

1.2.7 Energy and Power Requirements

The total energy storage and power supply requirements have been estimated for each of the three design concepts based upon the burn scenarios described in Sect. 1.2.6. These estimated requirements are compared to the available power at the PPPL site.

Table 1.6 summarizes the estimated requirements. The energy storage requirements in terms of gigajoules (GJ) are estimated at 2.5, 3.3, and 7.5 for Ignitor, ISP 0424, and LITE, respectively. It should be noted that Ignitor and ISP 0424 are nitrogen cooled and that this version of LITE is water cooled. About 4.5 GJ is available at PPPL. Accordingly, additional capacity would be required for the water-cooled LITE

Fig. 1.2. Operating scenario of (a) Ignitor C, 5-s burn; (b) ISP 0424, 5-s burn; and (c) LITE, 5-s burn.

concept. In terms of total megavolt-amperes, the estimated values are 1400, 800, and 1150 for Ignitor, ISP 0424, and LITE, respectively. The capability at PPPL is about 950 MVA. Accordingly, additional capability would be required for both Ignitor and LITE. An approach to minimize the cost of power supply equipment was evaluated. Based upon use of 2-kA, 15-kA modules, the required number of such power supplies was estimated to be 49, 29, and 47 for Ignitor, ISP 0424, and LITE, respectively. The number available at PPPL is 38, so additional power supplies would be required for both Ignitor and the water-cooled LITE.

Table 1.6. Energy and power requirements

	Ignitor	ISP 0424	LITE	Available at PPPL
<u>Energy storage</u>				
Gigajoules	2.5	3.3	7.5	4.5
Megavolt-amperes	1400	800	1150	950
<u>Power supply modules</u>				
(2 kV, 15 kA)				
Number	49	29	47	38
<u>Ac power (MVA)</u>				
Steady state	75	75	60	80

The ac power requirements, in terms of megavolt-amperes for steady state, are 75, 75, and 60 for Ignitor, ISP 0424, and LITE, respectively, and all are within the 80 MVA available at PPPL.

The impact of the additional energy storage and power requirements has been included in determining the cost estimates. None of these comparisons results in any issue of engineering feasibility, but these considerations are a factor in setting the final capital cost for each device.

1.2.8 RF Heating Requirements

Ignitor is advocated to be a mostly ohmically heated-to-ignition device. As such, no (or only very limited) auxiliary heating is claimed to be needed for the device. Up to 10 MW of ion cyclotron resonance heating (ICRH) as back-up is identified for Ignitor. For both ISP 0424 and LITE, 30 MW of ICRH is identified and included in the design description.

Several different launcher options, all conceptually different, have been identified for potential use in these devices. They include simple half-turn loops, half-turn loops recessed into the vessel wall, ridged waveguides, and cavities. The choice of launcher will be based upon the field level, the available space, the level of risk (or research and development), desired and near-term experience. There are a number of concerns about all launcher concepts. Such rf systems have not been built and operated; it is essential to obtain confirmation that such designs will perform as needed. Areas in which additional data, experience, or development are needed include neutron damage to insulators, plasma heat deposition and erosion, antenna modeling and design, high-power rf sources (frequencies greater than 80 MHz), mechanical accessibility, plasma coupling analysis, impurities from the antenna, and design for operation in the machine environment.

1.2.9 Diagnostics and Instrumentation

These compact devices will limit the space available and allocated for diagnostics. In order to obtain the necessary and desired physics and operating data to derive understanding about ignited plasma performance, a reasonable minimum amount of diagnostics must be provided. An estimate has been made that a reasonable minimum is to allocate three equally spaced sectors of the device for diagnostics use. Each sector should provide at least one vertical and five horizontal penetrations. A diameter of about 6 cm for each penetration is needed.

Such access for diagnostics can be provided horizontally by each design concept. The vertical access is more restrictive for all devices because of the compact size. Vertical access for diagnostics in Ignitor appears to be more of a challenge because of the small major radius.

Future design effort is needed on all device concepts to determine the diagnostic and instrumentation requirements and to specify locations where such diagnostics should be placed.

1.2.10 Other Systems

Each of the compact ignition concepts requires the integration of many other systems such as vacuum and vacuum pumping, heat transport and heat rejection, and fueling and fuel handling. These systems, which are essential to these compact devices, are within present engineering capability or are based on technologies currently being developed within the fusion program. As such, no engineering feasibility concerns are associated with the incorporation of such systems into this class of fusion devices.

1.2.11 Repairability

All concepts in this class of compact fusion ignition devices have no nuclear shielding close to the vacuum chamber. Upon initiation of deuterium-tritium operation, the devices will experience significant levels of activation so that hands-on repair, adjustment, or maintenance of any equipment or components will not be possible. All operations within this activated environment will require remote operation with remote equipment. None of the concepts has addressed the implications of the needed shielding, optimal placement of the shielding, the implications of remote repair and maintenance, or the identification of the equipment necessary to accomplish such repair or maintenance.

This need must be addressed to ascertain the overall implications for the device configuration, size, and cost. However, it is anticipated that the results of such an assessment will apply to each concept in approximately the same way, rather than differentially influence the evaluation of the concepts one to another.

Section 5 specifically discusses some of the major considerations associated with this aspect of this class of compact ignition machines.

1.2.12 Conclusions

The assessment of this class of compact ignition machines has identified several engineering issues that appear to be quite challenging to resolve. The major key issues include the overall configuration, assembly, access, and associated structural design. Also included are the ability to handle the estimated heat loads, the design of the vacuum vessel, and the issues of fabrication and repairability.

Each of the three design approaches has unique and attractive features. Developing increased confidence in the ability of each of these approaches to satisfy the performance objectives associated with a compact ignition machine will require more detailed engineering study, complemented in selected areas by tests of suggested approaches to specific engineering problems.

Overall, the assessment of the engineering issues associated with this class of design has not identified any issue for which a solution does not exist; all of the work performed to date indicates that the key issues appear tractable. Based on this assessment, proceeding with the next level of design is warranted for a compact ignition device within this class of machines.

2. LIMITER AND FIRST-WALL ENERGY REMOVAL

J. R. Haines, FEDC

2.1 INTRODUCTION

The compact size and ignited plasma operation planned for this class of devices lead to high heat loading of first-wall and limiter components. Designing an energy removal system for these components is a major concern. Results of a study to determine the feasibility of designing a limiter and first-wall system that can handle the severe heat loads are presented and discussed in this section.

A cross section of a typical compact ignition tokamak is shown in Fig. 2.1. The plasma limiter is formed by the inboard first wall, which is also used as the vacuum vessel. Combining these functions into a single structure reduces the major radius and overall device cost, but increases the design difficulty. A limiter blade located at the bottom of the device, similar to that proposed for FED¹ and TFCX,² was also considered in these studies. In addition to the advantages in device size and cost, the inboard location provides a larger area for energy removal and thus has lower peak heat fluxes. The major advantages of the bottom location are (1) ease of limiter installation and removal for maintenance and (2) ease of access to the limiter for pumping impurities. Since maintenance is given a low priority and active impurity control is judged to be unnecessary for the relatively short burn durations of these devices, the inboard location was selected as the reference design configuration.

2.2 HEATING CONDITIONS

The heat load to the limiter was assumed to be 80% of the total fusion-created, alpha-particle power. The distribution of this power through the scrape-off layer was estimated using the Schmidt³ model (exponential decay). The e-fold distance was assumed to vary with poloidal location in direct proportion to the poloidal variation in field gradient.

Fig. 2.1. Typical compact ignition tokamak in which inboard first wall forms the limiter surface.

A nominal e-fold distance of 15 mm at the outboard midplane location was used to calculate the heat flux distribution for several limiter shapes. Results for three types of inboard limiter shapes are shown in Fig. 2.2. The poloidally flat limiter has the highest peak heat flux. The limiter potentially can be contoured to maintain a uniform heat flux, at the nominal e-fold distance, over 160° of poloidal angle (referred to as the "constant" heat flux). A third option is a D-shaped, plasma-type limiter; this option has an intermediate peak heat flux. Using the ISP device as an example, the peak heat fluxes for the nominal e-fold distance on the flat limiter, "constant" heat flux limiter, and D-shaped limiter are 6.9, 3.3, and 5.3 MW/m², respectively (Fig. 2.2).

Sensitivities of peak heat fluxes to changes in the highly uncertain e-fold distance are shown in Fig. 2.3. If the e-fold distance is one-half its nominal value, the peak heat fluxes on the plasma-shaped limiter and "constant" heat flux limiter are about the same (6.7 MW/m²). Since the uncertainty in the e-fold distance may be more than a factor of two, the less sensitive plasma-shaped limiter is recommended.

For first-wall design purposes, the radiated heat load from the plasma was assumed to be 50% of the fusion alpha power. This power was assumed to be uniformly distributed.

Peak limiter and first-wall heat fluxes for the three ignition devices are shown in Table 2.1. Peak limiter design heat fluxes range from 1.9 to 6.7 MW/m². Note that the stated values for Ignitor are at a beta value of 1.2%. Operation at the critical beta limit would result in substantially higher values. The stated values for ISP and LITE are for operation at the critical beta. As discussed in the following sections, variations to this design heat flux were examined parametrically to determine design sensitivities and limits. Since the limiter heat fluxes are substantially greater than those expected on the remainder of the first wall and because the first-wall and limiter construction for these devices is essentially the same, attention during this feasibility study has focused on limiter energy removal.

Fig. 2.2. The relationship between peak heat flux and limiter shape.

Fig. 2.3. Sensitivity of peak heat flux to e-fold distance.

Table 2.1. Peak heat fluxes
(Plasma-shaped limiter, heat flux e-fold distance = 1/2 nominal value)

Device	Fusion power (MW)	Heating duration (s)	Peak heat flux (MW/m ²)	
			Limiter	First wall
ISP	305	5	6.7	0.6
LITE	300	5	6.1	0.5
Ignitor	30 (108)	5 (Peak)	1.9 (5.6)	0.2 (0.5)

2.3 DESIGN CONCEPTS AND OPERATING LIMITS

The limiter and first-wall designs for these devices specify graphite tiles attached to a cooled, stainless steel, vacuum vessel. Two configuration options are shown in Fig. 2.4. Since the burn duration for these devices is short and the requirements on cooldown time are minimal, a design with widely spaced coolant tubes attached to the vacuum vessel [Fig. 2.4(a)] was investigated as a "low-cost" cooling system approach. A more effective, but higher cost, double-wall coolant passage approach [Fig. 2.4(b)] was also analyzed.

Operating temperature limits for the stainless steel vacuum vessel and graphite tiles were established based on thermal/mechanical and erosion/plasma contamination considerations. Most of the vacuum vessel will be at a relatively low temperature (assumed to be 20°C) compared with the localized regions of peak limiter heating. Thus, the region of localized peak heating will be constrained, to some extent, from growing. The compressive thermal stress in this region is conservatively estimated, assuming a totally constrained structure.

The thermal stress and the total combined stress (thermal stress plus the assumed megapascal primary vacuum stress) are shown in Fig. 2.5. The fatigue stress design limit, based on operation at 3000 cycles, is based on experimental data⁴ and includes a factor of two reduction on the failure stress or a factor of ten reduction on the number of cycles to failure. The peak vacuum vessel temperature limit, based on fatigue, is about 210°C. The ASME Boiler and Pressure Vessel Code limit on combined stress (the lesser of twice the yield strength,

Fig. 2.4. Limiter and first-wall design options.

Fig. 2.5. Thermal and combined stress variation with vacuum vessel temperature.

or two-thirds of the ultimate strength) is also shown in Fig. 2.5. This limit is more restrictive than the fatigue limit and results in a peak allowable vacuum vessel temperature of 150°C.

The graphite tile temperature is assumed to be limited by the need to avoid contamination of the plasma by sublimated graphite. The graphite vaporization rate is shown in Fig. 2.6 as a function of temperature.⁵ Assuming that the graphite vaporized at a given temperature accumulates in the plasma (no losses from the plasma) for a period of 5 s, a limit of 2200°C is established, based on allowing the graphite content of the plasma to equal 1% of the D-T density. For design purposes, a graphite temperature limit of 2000°C is used. This rationale appears to be quite conservative, however, because of the sensitivity of vaporization to temperature; a less conservative estimate of the buildup would not substantially increase the temperature limit. For example, allowing the vaporization rate to increase by an order of magnitude results in an increase of less than 200 K in the maximum allowable temperature.

Radiation-enhanced sublimation⁶ is neglected in setting the graphite temperature limit. Observations on the Tokamak Fusion Test Reactor (TFTR) indicate that the plasma performance is unaffected by operation of graphite at temperatures of 2200°C. A more complete understanding of graphite temperature limits and plasma contamination is expected as soon as TFTR begins operation with the newly installed, large-area, graphite bumper limiter.

2.4 EVALUATION OF LIMITER DESIGN CONCEPTS

Thermal analyses were performed to establish the feasibility of limiter design concepts and to identify design constraints and limitations. Typical results of these analyses are shown in Fig. 2.7. This plot displays the transient thermal response of the graphite tile and stainless steel vacuum vessel. These predictions were made using the two-dimensional TOPAZ⁷ finite-element heat transfer program.

As shown in Fig. 2.7, the surface temperature of the graphite tile rises quickly during the 5-s burn pulse and cools rapidly during the 1200-s cooldown time chosen for this example.

Fig. 2.6. Graphite vaporization rate variation with surface temperature.

Fig. 2.7. Transient thermal response of graphite tiles and stainless steel vacuum vessel.

The stainless steel vacuum vessel does not respond significantly to the heating pulse during the burn period but reacts during the long cooldown phase. The peak temperatures ratchet higher during successive pulses in this particular case and eventually reach a cyclic steady state after the third consecutive pulse.

Key parameters that were varied in these studies are listed in Table 2.2. Results of these parametric studies are summarized in Figs. 2.8-2.11. The sensitivity of the stainless steel peak temperature to spacing between adjacent tubes is shown in Fig. 2.8 for a peak heat flux of 6 MW/m^2 , heating duration of 5 s, graphite tile thickness of 30 mm, and gap conductance between the tile and substrate of $10 \text{ W/m}^2\text{-K}$. The tube spacing must be relatively small, less than 0.05 m for this case.

Table 2.2. Key parameters in inertially cooled limiter design

Peak heat flux
Burn duration
Dwell time between burns
Tube spacing
Tile-to-vacuum vessel conductance
Tile thickness
Vacuum vessel thickness

The variation of the maximum stainless steel temperature with skin thickness for the double-wall panel design concept is shown in Fig. 2.8(b). At a heat flux of 6 MW/m^2 , the skin thickness can be 20 mm. This thickness should be more than adequate for structural purposes.

The effect of graphite tile thickness on peak graphite and stainless steel temperatures is shown in Fig. 2.9. For a heat flux of 6 MW/m^2 , the tile thickness must be greater than about 15 mm. The tile thickness must be increased to about 35 mm if the heat flux is expected to reach 12 MW/m^2 .

Fig. 2.8. Maximum temperature vs (a) tube spacing and (b) skin thickness.

The trade-off between heat flux and heating duration for the inertially cooled design is displayed in Fig. 2.10. Limits based on maximum graphite tile and stainless steel vacuum vessel temperatures are indicated in this figure. If a relatively low gap conductance (about $100 \text{ W/m}^2\text{-K}$) is established between the tile and substrate, all three devices considered have feasible operating conditions from the first-wall and limiter energy removal viewpoint.

Cooldown performance between burns is presented in Fig. 2.11. For a 5-s burn pulse at a heat flux of 6 MW/m^2 , the cooldown time must be greater than about 5 min. Otherwise, if consecutive burn pulses were to occur with less cooldown time, temperatures would ratchet to unacceptable levels. Also, as shown in Fig. 2.11, the required cooldown time becomes infinite as the heat flux approaches 12 MW/m^2 . This simply means that unacceptably high temperatures are reached after a single burn at 12 MW/m^2 .

2.5 KEY ISSUES

Key issues in the design of the limiter and first-wall energy removal system are listed in Table 2.3. Thermal shock caused by intense plasma disruption heating is a concern. These conditions are defined in Table 2.4 for the ISP device. In a simple model,⁸ thermal shock damage of the tiles is likely at the nominal conditions. However, the nature of the damage is not clear. Further experimental studies to explore the behavior of graphite at conditions similar to those expected during plasma disruptions are recommended.

Table 2.3. Key design issues

Thermal shock during disruptions
Tile-to-substrate attachment design
Graphite temperature limits
Toroidal tolerance requirements
Structural design

Fig. 2.9. Maximum temperature vs tile thickness.

Fig. 2.10. Heating duration vs heat flux.

Fig. 2.11. Cooldown time vs heat flux.

Tile-to-substrate attachment is a critical design variable. Fabrication methods to reliably establish and maintain the low conductances necessary for this case are required.

Graphite temperature limits continue to be an important quantity that is somewhat difficult to establish. Laboratory observations of chemical sputtering at temperatures between 400 and 600°C and radiation-enhanced sublimation at temperatures about 1000°C continue to point to disastrous results with the use of graphite. However, experience in real tokamaks does not bear this out. A more complete understanding, or at the very least a resolution of the question whether a large-area graphite limiter can operate at elevated temperatures, is expected during upcoming TFTR operations with the newly installed bumper limiter.

Table 2.4. Disruption heating conditions

Disruption phase	Energy duration (ms)	Density (MJ/m ²)
Thermal quench	1	3.8
Current quench	10	3.2

Because the inboard vacuum vessel serves as the limiter, tolerance requirements for establishing the vacuum vessel location must be within a small fraction of the scrape-off, e-fold distance of 15 mm. The feasibility and impact on vacuum vessel fabrication of meeting this requirement are addressed in Sect. 4.

Finally, the overall structural design of the limiter, in a manner to minimize the space used, must be addressed.

2.6 CONCLUSIONS

The power densities of the compact ignition devices are significantly higher than those of previous advanced tokamak design studies such as FED, INTOR, and TFCX. However, because of the large fraction of first-wall area used as limiter surface in the ignition device, heat fluxes are only slightly higher (about 6 MW/m²) than those previously considered.

The major difference between these limiter designs and previous designs is the cooling approach. Previous devices required steady-state energy removal, whereas because of the short burn duration expected for the compact ignition devices, the energy is absorbed in the temperature rise of the graphite tile during the burn phase and removed in the water coolant system during the relatively long dwell time between burns. Based on the results of these studies, inertially cooled limiter and first-wall designs appear feasible for the proposed compact ignition device heating conditions.

REFERENCES

1. C. A. Flanagan, D. Steiner, and G. E. Smith, eds., Fusion Engineering Device Design Description, ORNL/TM-7948/V2, Oak Ridge National Laboratory, Oak Ridge, Tennessee, December 1981.
2. J. R. Haines, TFCX Pumped Limiter and Vacuum Pumping System Design and Analysis, ORNL/FEDC-84/8, Oak Ridge National Laboratory, Oak Ridge, Tennessee, April 1985.
3. J. Schmidt, "Tokamak Impurity - Control Techniques," Comments Plasma Phys. Controlled Fusion 5, 225 (1980).
4. Materials Handbook for Fusion Energy Systems, DOE/TIC-10122, File Code Ab02-2401 (C-1).
5. Industrial Graphite Engineering Handbook, Union Carbide Corporation, Carbon Products Division, 1969.
6. J. Roth, J. B. Roberto, and K. L. Wilson, "Enhanced Sputtering of Graphite at High Temperature," J. Nucl. Mater. 122 & 123, 1447-52, (1984).
7. A. B. Shapiro, TOPAZ - A Finite Element Heat Conduction Code for Analyzing 2-D Solids, UCID-20045, Lawrence Livermore National Laboratory, Livermore, California, March 1984.
8. J. R. Haines and G. M. Fuller, "Thermal Shock Considerations for the TFCX Limiter and First Wall," pp. 1113-16 in Proceedings of the 10th Symposium on Fusion Engineering, Philadelphia, Dec. 5-9, 1983.

3. COMMON-BASIS STRUCTURAL ANALYSIS OF THE COMPACT IGNITION DEVICES

D. B. Montgomery, MIT

3.1. INTRODUCTION

An independent structural analysis of the candidate ignition devices was made based on a common set of design criteria. A particular version of each of the three ignition devices was studied, namely, a water-cooled LITE at 1.76-m major radius, ISP 0424, and Ignitor A in a January 1985 version. Four areas were covered in the study;

- the analysis basis, highlighting the stress criteria, design allowables, and analysis method;
- the results of the study, covering free-body diagrams with applied loads, finite-element, and local analysis;
- A comparison between the stress conditions of the ignition study concepts and the Alcator-C device; and
- An overall structural assessment of each concept.

3.2 PROPOSED GUIDELINES FOR ALLOWABLE STRESSES

A working document produced during the study suggests guidelines for allowable stresses. Selected material from those guidelines follows, and of particular note is the use of average stresses based on the belief that local stresses which may exceed yield will result in a plastic redistribution toward an average value.

It is also important to recognize that these proposed structural design criteria are strictly related to the special case of the compact ignition device magnets, which are designed for only 3,000 full-field pulses (and 100,000 70% full-field pulses), and should not be considered as generic criteria for all fusion magnets.

The ignition studies have the goal of establishing the engineering feasibility of one or more compact copper ignition devices. The degree of compactness is affected by the particular structural approach chosen and the level of allowable stresses. The allowable stress level is in turn related to the degree of risk allowed, which depends on the degree

to which material properties are known and controlled and the degree to which the structural behavior is predictable.

The allowable stress criteria recommended are generally less conservative than those in the ASME pressure vessel code, but they are considered to be appropriate to the compact ignition devices, provided that appropriate test and quality control programs are put in place, and provided that the structural behavior is monitored throughout the life of the device.

The various magnet coil design approaches under consideration are divided into two classes, the first, where an external structure is used (i.e., constrained), and the second, where no external structure is used (i.e., self-reacted). Different allowables are suggested for the two approaches.

In the case of a constrained coil using wedging, it is proposed that the applied stress be determined from the average value of transverse compression, the average value of axial tension, and the average value of out-of-plane shear. These three component averages should be combined to obtain an applied Tresca stress. The value of Tresca stress proposed should be the lesser of the following: 0.85 times the yield strength of the material in the inner leg, or 0.7 times the ultimate tensile strength, subject to the additional criterion that cyclic effects do not prove more limiting.

The static-load-allowable Tresca stresses in the external structure should conform to the criteria of the ASME Boiler and Pressure Vessel Code, namely one-third of ultimate or two-thirds of yield. It is appropriate to use such a conservative criterion for the external structure, as there is little negative impact on compactness and considerable overall safety gain.

In the self-reacted case, there is no external frame to limit the tension in the inner leg of the magnet, and hence it is appropriate for the allowables to be lower in this case.

It is proposed, again, that the average transverse compression, average axial tension, and average out-of-plane shear be combined into a Tresca stress. It is proposed that this stress be the lesser of the following: two-thirds of the yield stress for the material or 0.6 of

the ultimate, subject to the additional criterion that cyclic effects do not prove more limiting. The nonaverage "peak" stress should be examined against cyclic effects data for the material.

The material properties chosen for the common-basis structural analysis are given in Table 3.1. It is recognized that at this study level there is an incomplete data set for the properties of copper and copper alloys of appropriate cross section. More data must be available before final design, but for the present studies, reasonable judgment applied to available data must suffice.

Table 3.1. Common-basis material strengths (MPa)^a

	104 half-hard copper	155 silver copper	175 beryllium copper 0.5%
σ_y (300 K)	297	400	820
σ_y (200 K)	317	421	862
σ_y (80 K)	352	469	959
σ_u (300 K)	331	428	862
σ_u (200 K)	352	455	917
σ_u (80 K)	393	503	1007

^aConversions: MPa $\times$ 0.145 = ksi; MPa $\times$ 0.1 = kg/mm.

3.3 STRUCTURAL ANALYSIS

A two-dimensional (2-D) finite-element (FE) analysis of in-plane loads for the TF coils and support structure was carried out. In addition, strength-of-materials methods were used to analyze the TF coil inner leg under out-of-plane loading and the central ohmic heating (OH) solenoid stress levels. The 2-D FE models are shown in Fig. 3.1. In the case of LITE, the common-basis FE analysis was calibrated against their rather complete analysis, and agreement was good.

LITE

ISP 0424

IGNITOR

ALCATOR C

Fig. 3.1. Two-dimensional finite element models.

3.3.1 MIT LITE (1.76-m Major Radius)

The principal structurally related features of LITE are

1. self-supported coil against in-plane loads,
2. wedged TF inner legs,
3. use of Be-Cu alloy in TF inboard legs,
4. external torque structure, and
5. external PF coils.

The parameters used in the analysis were

$$\begin{aligned}
 R &= 1.76 \text{ m,} \\
 a &= 0.55 \text{ m,} \\
 B_0 &= 8.5 \text{ T,} \\
 I_p &= 7 \text{ MA,} \\
 B_{oh} &= 18.3 \text{ T.}
 \end{aligned}$$

These parameters lead to the in-plane and out-of-plane loads shown in Fig. 3.2 and in the stresses shown in Table 3.2.

Table 3.2. Stress summary for the TF throat region of LITE at 8.5 T and 300 K

In-plane loading (MPa)	
Average tensile stress	153
Average face pressure	-198
Average radial stress	-16
Out-of-plane loading (end of burn) (MPa)	
Torsional shear stress	27
Minimum required friction coefficient	-0.14
Combined stress (MPa)	
$\frac{\text{Average stress}}{\text{Allowable stress}}^a$	$\frac{355}{517} = 0.69$
Peak Tresca stress (MPa)	408

^a0.6 Ultimate controls, using copper 175 at 300 K

In-plane

24 TF COILS

74.8 MAT

574 MN VERT. LOAD

Out-of-plane (end of burn)

336 MN-M TOTAL M_x

61 MN-M CENTRAL
COLUMN TORQUE

Fig. 3.2. In-plane and out-of-plane loads for LITE (8.5 T).

3.3.2 ISP 0424

The principal structurally related features of ISP 0424 are

1. sliding-joint TF coil, with the majority of tensile load transferred to an external support;
2. wedged inboard legs, with minor load taken in bucking;
3. use of unalloyed OFHC copper;
4. partially encased coils with shear panels to support out-of-plane loads; and
5. internal PF coils.

The parameters used in the analysis were

$$\begin{aligned} R &= 1.62 \text{ m,} \\ a &= 0.53 \text{ m,} \\ B_0 &= 8.95 \text{ T,} \\ I_p &= 7.83 \text{ MA,} \\ B_{oh} &= 4.2 \text{ T.} \end{aligned}$$

These parameters give rise to the in-plane and out-of-plane loads shown in Fig. 3.3 and in the stresses given in Table 3.3.

3.3.3 Ignitor A (January 1985)

The principal structurally related features of Ignitor A are

1. precompression of TF coil inner leg through use of a multi-element external frame,
2. use of 155 silver-bearing copper TF coil,
3. OH solenoid used as bucking cylinder,
4. out-of-plane load carried through the external frame "C-clamp" assembly, and
5. PF coils external to the TF, internal to the external structure.

The parameters used in the analysis were

$$\begin{aligned} R &= 1.0 \text{ m,} \\ a &= 0.39 \text{ m,} \\ B_0 &= 12.5 \text{ T,} \end{aligned}$$

In-plane

Out-of-plane (End of burn)

Fig. 3.3. In-plane and out-of-plane loads for ISP 0424 (8.95 T).

Table 3.3. Stress summary for the TF throat region of ISP 0424
at 8.95 T and 300 K

In-plane loading (MPa)		
Average tensile stress		53
Average face pressure		-123
Average radial stress		-88
Out-of-plane loading (startup) (MPa)		
Torsional shear stress		17
Minimum required friction coefficient		0.14
Combined stress (MPa)		
<u>Average Stress</u>		183
Allowable stress ^a		231
		$\frac{183}{231} = 0.79$
Peak Tresca stress (MPa)		183
Joint area		
Running load (MN/m)		0.14
Equivalent transverse pressure (MPa)		2.1

^a0.7 Tensile ultimate controls using copper 104 at 300 K.

$$I_p = 10.0 \text{ MA,}$$

$$B_{oh} = 25 \text{ T.}$$

These parameters give rise to the in-plane and out-of-plane loads shown in Fig. 3.4 and in the stresses given in Table 3.4.

The Ignitor stresses in Table 3.4 are for an artificial case in which the coil is assumed not to change in temperature during the pulse, and thus to remain at the same temperature as the constraining support structure. In addition, an assumption of perfect fit-up and thus combined bucking and wedging occurs in the central TF region. Table 3.5 examines the sensitivity of the Ignitor stresses to these two assumptions by letting the TF coil rise to 200 K and assuming either pure bucking or pure wedging, which are the extremes of poor fit-up. We note that the allowables are exceeded only under pure wedging (i.e., a gap between the TF and the central solenoid against which the TF coil is expected to buck). Pure bucking, which has the lowest stresses, is not considered a viable option as some wedging is assumed to be necessary to support the out-of-plane loads.

The Ignitor central tension support rod was also examined, and average Tresca stresses of 900 MPa were found. We consider this stress level to be beyond reasonable practice and anticipate redesign during the next design phase.

3.3.4 Alcator C

The Alcator C device was analyzed to give a comparison of the allowables for the ignition devices with an operating magnet.

The principal structurally related features of Alcator C are

1. copper/steel sandwich turns,
2. copper yields on first cycle at 14 T and is precompressed by elastic steel,
3. keys ensure no slip at zero field,
4. precompression face pressure from external rings, and
5. "monolithic" continuous coil to take overturning moment.

In-plane

24 TF COILS

63.3 MAT

394 MN VERT. LOAD

Out-of-plane (end-of-burn) 134 MN-M TOTAL M_x 9 MN-M CENTRAL
COLUMN TORQUE

Fig. 3.4. In-plane and out-of-plane loads for Ignitor (12.5 T).

Table 3.4. Stress summary for the TF throat region of Ignitor A
at 12.5 T and 77 K

In-plane loading (MPa)	
Average tensile stress	49
Average face pressure	-172
Average radial stress	-121
Out-of-plane loading (MPa)	
Torsional shear stress	28
Minimum required friction coefficient	0.16
Combined stress	
<u>Average Tresca stress</u>	<u>228</u>
Allowable stress ^a	352 = 0.65
Peak Tresca stress	232

^aUltimate controls, using copper 155 at 77 K.

Table 3.5. Structural sensitivities of the Ignitor TF coil

Condition	Average applied stress (MPa)	<u>Average stress</u> Allowable stress
<u>77 K, 12.5 T ($\sigma_a = 352$ MPa)</u>		
Pure bucking	207	0.59
Perfect bucking and wedging	221	0.63
Pure wedging	572	1.62
<u>200 K, 12.5 T ($\sigma_a = 318$ MPa)</u>		
Pure bucking	159	0.50
Perfect bucking and wedging	248	0.78
Pure wedging	510	1.60
<u>200 K, 0 T ($\sigma_a = 318$ MPa)</u>		
Pure bucking	207	0.65
Perfect bucking and wedging	290	0.91
Pure wedging	262	0.82

The following parameters were used in the analysis and represent the highest levels at which the machine has operated. The machine design field values are given in parentheses.

$$\begin{aligned} R &= 0.64 \text{ m,} \\ a &= 0.17 \text{ m,} \\ B_0 &= 12.5 \text{ T (14 T),} \\ I_p &= 0.8 \text{ MA,} \\ B_{oh} &= 18 \text{ T (22 T).} \end{aligned}$$

These parameters give rise to the stresses in Table 3.6. We note from Table 3.6 that Alcator C has exceeded the "allowable" stresses by 20% at 12 T.

Table 3.7 gives the operating history of the machine, indicating 370 pulses at 12 T. The machine has never operated at 14 T, but were it to do so, the copper would yield on the first cycle as was anticipated and would then be placed in precompression by the steel sheets on subsequent cycles. Keys between the steel and copper were included to ensure the permanency of the precompression.

Table 3.6. Summary of results in the TF throat region of Alcator C at 300 K

In-plane loads (MPa)	12 T	14 T
Average tensile stress	165	224
Average face pressure	-110	-150
Average Tresca	275	374
Peak Tresca	278	379
Allowable stress (MPa)	228	228
$\frac{\text{Average Tresca}}{\text{Allowable stress}}^a$	1.20	1.64
$\frac{\text{Average Tresca}}{\text{Yield stress}}$	0.93	1.26
$\sigma_{TY} = 297 \text{ MPa measure}$		

^a 0.7 Ultimate controls, using 300 K.

Table 3.7. Structural performance of Alcator C through 1984

Field (T)	Number of pulses	Peak Tresca stress copper (MPa)	Peak stress tensile yield ^a
7-9	22,000	157	0.53
10	3,900	193	0.65
11	280	234	0.79
12	370	278	0.94
14	0	379	1.28

^a σ_{TY} = 297 MPa measured.

3.3.5 TF Analysis Summary

Table 3.8 summarizes the analysis of the throat regions of the four magnets. We note that the ratio of average stress to allowable for all the ignition devices is less than one for the cases treated. As discussed, however, these cases represent idealized cases, and further sensitivity studies are clearly called for.

Table 3.8. Summary of results for TF throat region

	Results (MPa)			
	Alcator C (12 T)	LITE	ISP	Ignitor
In-plane loading				
Average tensile stress	165	153	53	49
Average face pressure	-110	-198	-123	-172
Average Tresca stress	275	355	183	220
Peak Tresca stress	278	408	183	232
<u>Average stress</u>	1.2	0.69	0.79	0.65
Allowable stress				
Out-of-plane shear	--	27	17	28

3.4 OH CENTRAL SOLENOID ANALYSIS

A strength-of-materials analysis was conducted on the various OH central solenoids. The analysis is "ideal" in two important areas. First, the coils were assumed to be infinitely long and hence to have no axial compression from end effects. Second, the coils were assumed to have a 100% packing fraction and to be isotropic in properties. Table 3.9 gives the idealized stresses and compares them with allowables for the materials chosen in the designs. All factors are less than one for these idealized cases.

Again, the case of Ignitor is more complicated because the TF and OH coils interact in that design. In Table 3.9, both the TF and OH are assumed to be fully energized. Table 3.10 explores the sensitivity to other assumptions. We note that a gap between the TF and OH would result in overstressing of the OH (recall that such a gap would also result in an overstressing of the TF) and therefore must be prevented.

Table 3.9. OH central solenoid -- ideal coil analysis^a

	B (T)	D (m)	Average stress (MPa)	Peak stress (MPa)	Assumed tensile yield (MPa)	Peak stress tensile yield
ISP	4.2	1.9	83	90	297	0.3
LITE	18	1.02	186	303	821	0.37
Ignitor ^b	25	0.64	160	230	455	0.50
Alcator C ^c	18	0.30	102	226	297	0.76

^aInfinitely long coil, filling factor 100%.

^bTF energized.

^cMaximum operating field.

Table 3.10. Ignitor central solenoid sensitivity^a

Condition	Peak stress (MPa)	$\frac{\text{Peak stress}}{\text{Tensile yield}}$ ^b
OH on, TF on	230	0.50
OH off, TF on	204	0.45
OH on, TF off	454	1.00
OH on, TF gap	746	1.65

^a Infinitely long coil, filling factor 100%^b $\sigma_{TY} = 455$ MPa.

3.5 STRUCTURAL ASSESSMENTS

The structural assessments of the three devices are summarized here.

LITE

1. There is simple TF structural support of in-plane loads.
2. There is a direct structural relationship to Alcator data base.
3. Reasonable margins exist for in-plane, out-of-plane, and OH stresses.
4. Concept depends on material properties of Be-Cu plate, which has a limited data base for these sizes and thicknesses.
5. Concept requires careful control of plate taper, interface to torque structure, and plate weld detail.

ISP 0424

1. Demountable coil favors use of internal PF coils, which lead to more reasonably handled out-of-plane loads for divertor case.
2. The TF sliding joint unloads tension from the center leg, leading to a smaller machine using conventional copper.
3. Reasonable margins exist for in-plane, out-of-plane, and OH stresses.
4. The sliding joint must be developed to carry the necessary current and allow slip despite the high transverse pressure due to out-of-plane loads.

Ignitor A

1. Use of preload, an external frame, and a bucked design result in a more compact permissible design than either of the other approaches.
2. The fully trapped TF coil meets the structural criteria for in-plane loads and mid-range temperature rises, provided the assembly tolerances are properly controlled.
3. The OH solenoid, against which the TF is bucked, represents an active bucking post, dependent on the level of excitation and temperature changes.
4. The balance between bucking and wedging must be controlled to be between
 - partial wedging necessary to ensure support of out-of-plane twist in the inner legs, and
 - full wedging, which would result in excessive face pressure.
5. The TF inner legs must remain bonded, or be adequately wedged, to prevent bucking under preload.

3.6 CONCLUSIONS

From a structural point of view, each concept presents some level of engineering risk. We believe, however, that the next level of design,

coupled with a research and development (R&D) program on materials, bonding techniques, and sliding joints, will result in compact ignition devices with an acceptable level of engineering risk.

4. FABRICATION AND ASSEMBLY

F. A. Puhn, GA Technologies

4.1 FACTORS INFLUENCING FABRICATION AND ASSEMBLY

While numerous design features influence fabrication and assembly, the most significant ones are:

1. segmentation of the device,
2. tolerance requirements on both components and assemblies,
3. materials to be fabricated, and
4. size and weight of components and subassemblies.

Each of these major factors has been considered in the following assessment of the feasibility of fabrication and assembly of the three candidate design concepts.

4.2 SEGMENTATION COMPARISON

The ignition devices proposed use two distinctly different segmentation schemes. The ISP 0424 device employs a one-piece vacuum vessel and PF coils within the TF coil bore. The TF coil has demountable joints that allow access to these internal ring-like components. Assembly and disassembly utilize radial movement of the outer TF coil bundles and vertical movement of the internal components. This is a segmentation concept similar to that of D-III at GA Technologies.

The Ignitor and LITE concepts use another segmentation concept. These devices employ one-piece TF coil turns, with only the vacuum vessel located inside the TF coil bore. The vacuum vessel is made in wedge-shaped segments joined by welding in radial planes. Segments of the vessel are handled along with groups of TF coil turns. Each wedge-shaped vessel/TF coil subassembly is moved radially for assembly or disassembly of the tokamak. PF coils are external to the TF coil and are moved vertically during assembly or disassembly. This method of segmentation is similar to TFTR at PPPL and JET at Culham Laboratory.

Because all the proposed designs use methods of segmentation previously used on large tokamaks, segmentation is not a feasibility

issue. The type of segmentation chosen will influence the cost and the design of other systems, however.

4.3 TOLERANCE REQUIREMENTS

All the proposed designs use a wedge-shaped TF coil and structure in the center of the tokamak. Intimate contact between adjacent components is necessary over large surface areas to distribute stress. The components must be machined on most or all of their surfaces to close tolerances. Shims may be used for adjustment, but they too will be precision and highly stressed.

The tolerances have not been specified at this time. However, it is assumed that machining methods similar to those used to build tokamaks such as PDX and D-III will be used. The detail drawings and analysis should define a set of tolerances compatible with the materials, size of machined parts, and techniques normally used in industry. Appropriate shimming and tolerance adjusting methods will be incorporated into the design. The result will be a precision, but feasible, design concept.

The ISP 0424 incorporates a sliding joint in the TF coil. This will require precision machining over a relatively small surface area. The exact tolerance requirements for the joint will depend on the ability of the sliding contact elements to accept misalignment or motion perpendicular to the plane of sliding. These data will not be available until R&D work on the sliding joint is accomplished. Preliminary data on candidate joint contacts indicate a tolerance less stringent than that required in the precision finger joint used on D-III. A precision joint surface over a limited area is not a fundamental feasibility issue, but the fabrication costs for that detail remain somewhat uncertain at this time.

Ignitor relies on both wedging and bucking to support compressive loads in the inboard leg of the TF coil. Thus, the components must interface on both radial and circumferential surfaces to ensure proper sharing of loads. Several methods are possible to accomplish this, including machining at the subassembly level and shimming. The design details have not been specified, but feasible manufacturing methods

exist. The cost and schedule for this portion of the fabrication remain uncertain, pending additional design work. It should be noted that machining of the entire outer cylindrical surface of the D-III TF coil centerpost was accomplished after bonding into a 50-tonne assembly. Boring of the center hole of an Ignitor TF coil assembly would be a task of similar magnitude.

LITE uses a one-piece TF coil made of several different copper alloys. This coil also has steady-state cooling capability. The fabrication of splices in the coil material and interfaces to be diffusion bonded together for cooling passages are critical close-tolerance machining tasks. The LITE shares similar fabrication challenges with the other designs.

All the proposed designs rely on a reasonably uniform spreading of heat load over first-wall surfaces. This requires holding a tight tolerance on the first-wall contour with respect to the toroidal field lines. The tolerance must be significantly smaller than the scrape-off thickness of the plasma, implying a tolerance in the 1- to 2-mm range. Since the vacuum vessel shape and location and the tile dimensions all contribute to the final deviation from true position, it seems necessary to design a method of adjusting or shimming the final position of the first-wall tiles. Detail designs are not defined at this time, but methods for solving this problem exist and should prove reasonable to implement.

4.4 MATERIALS TO BE FABRICATED

Due to the high stress, all the designs propose high-strength copper for the TF coil. The alloys chosen require cold working to obtain the material properties. Cold-worked copper has reasonable machining and forming properties, but there are problems with residual stresses and spring-back.

All the designs will require high-strength structural material in local areas (such as joints). Nonmagnetic structural materials with high strength have been used in many previous tokamaks. There should be

no unusual problems using these materials since they have many other industrial applications.

The magnets and structural joints will require electrical insulation incorporating adhesive bonding for structural integrity. The sections of the coils typically transfer shear loads through bonded interfaces. Due to the high stresses anticipated, manufacturing techniques for bonded joints may be pushed close to the state of the art. Experience with bonded structure in the aerospace industry is expected to be utilized in the design and fabrication.

The various materials proposed are all within the current experience of industry, and therefore no feasibility issues exist. However, there may be some difficulty obtaining large sizes of high-strength, high-quality raw material. The lack of adequate-size material would require the incorporation of extra splices and joints.

4.5 SIZE AND WEIGHT OF COMPONENTS

The largest proposed ignition device is smaller than present large tokamaks such as D-III, TFTR, and JET. Thus, no problems in handling or manufacturing the largest components are anticipated.

The weights of the proposed device components are summarized in Table 4-1. The components to be lifted are within the capacity of ordinary large, industrial cranes. The moving of large components is also within industrial experience.

Table 4.1. Size and weight of components

Design	Largest component lifted	Largest component moved
Ignitor	Pre-compression ring, 36.5 tonnes	Reactor core half, ~150 tonnes
LITE	Pre-compression ring, 14.4 tonnes	Core segment, 35 tonnes
ISP 0424	TF coil segment, 18 tonnes	Centerpost (TF coil and solenoid), 110 tonnes

4.6 MACHINING ASSESSMENT

The three designs proposed all share the same difficulties with respect to machining:

1. close tolerance on large parts,
2. possible residual stress warpage, and
3. use of tough, high-strength materials.

All of these problems have been addressed in the past on other programs, and successful results were obtained.

The requirements for tight tolerances and the use of high-strength materials impact machining cost, not feasibility. The appropriate trade-off studies and design decisions will be made during detail design to minimize overall cost. Trial machining of particularly difficult components can be used to gain high technical confidence and reliable cost estimates prior to start of production.

Close-tolerance machining of large, cold-worked copper plates is difficult. Depending on the exact manufacturing process for the raw material, residual stresses can cause considerable warpage during machining. This was a significant problem in the machining of large 155-copper plates for the D-III TF coil (Figs. 4.1 through 4.3). The problem was solved by taking light cuts and straightening between cuts. In the critical demountable finger joint, match-machining and hand-fitting were used to achieve the required tolerances.

To avoid severe problems with warpage, a number of preliminary steps could be taken. These include:

1. machining of prototype plates;
2. consideration of alternative alloys and heat treatment to minimize residual stress in the raw material; and
3. optimization of manufacturing plan to minimize total cost, trading off straightening cost against extra machining allowance.

The designs all appear feasible from the standpoint of machining. Detail design and analysis are needed to fully assess the cost impact of tolerances. It is assumed that tolerances will be similar to those on

Fig. 4.1. Considerable warpage that occurs when one side of a cold-worked copper plate is machined.

Fig. 4.2. Tolerances of 0.001 in. held in the D-III finger, jointly match-machining and hand fitting.

Fig. 4.3. The D-III TF coil plates being machined at General Dynamics/Convair. These are similar in size and configuration to the inner TF coil legs of ISP 0424.

present-day tokamaks, since the functional requirements and the manufacturing processes are similar.

4.7 ADHESIVE BONDING ASSESSMENT

Structural adhesive bonding has been accomplished on many large coils on present-day tokamaks. Several manufacturing processes have been used, including vacuum impregnation and autoclave bonding. The D-III TF coil is an example of a large bonded coil, with a size and configuration similar to the TF coil of ISP 0424 (Figs. 4.4 and 4.5).

The potential problems with bonding relate to the high stresses expected in the ignition device. The traditional bonding materials and techniques may not be suitable for the new devices. If stress analysis indicates it is necessary, the ignition experiment may require additional testing of new bonding materials, techniques, and quality control. Materials and processes used for high-strength aerospace applications may be necessary to obtain the required properties. This will not be determined until design details and stress analysis are defined more completely. The preliminary analysis shows that stresses are higher than in most present-day tokamaks but that bonding techniques and materials are available to manufacture assemblies with suitable properties.

4.8 LARGE VACUUM VESSEL MANUFACTURING ASSESSMENT

Large vacuum vessels have been fabricated for existing tokamaks. TFTR and JET use segmented vacuum vessels, and D-IIID uses a one-piece vessel. All of these existing vessels are the same size as or larger than those required for the ignition devices (Figs. 4.6 and 4.7).

The requirements of a thin vessel-wall space envelope and a continuous first-wall tile surface imply close tolerance requirements for the vessel shape. This problem must be addressed with care to avoid excessive costs. The tolerances on the vessel interface surfaces must reflect previous manufacturing techniques in order to use the previous data base for cost-estimating purposes.

Fig. 4.4. The D-III TF coil centerpost, an adhesive bonded structure. The entire 50-tonne assembly was rotated on a turntable for machining of the cylindrical outer surface and for coil winding.

Fig. 4.5. Large PF coils being assembled at GA Technologies. They are similar in size to those required for an ignition experiment. These coils are vacuum impregnated inside a structural steel case.

Fig. 4.6. Photo of TFTR vacuum vessel illustrating segmented vessel.

Fig. 4.7. The D-IIID vacuum vessel. This one-piece Inconel 625 weldment is similar in size to the LITE and ISP 0424 and larger than the Ignitor vessel.

If remote segmentation of the vacuum vessel becomes a design requirement, another technical concern will arise. The assembly tolerances for the vessel joints will interact with first-wall contour tolerances. Additional realignment of first-wall tiles may be necessary following vessel reassembly. This may have an impact on manufacturing tolerances and design features for first-wall alignment.

Unless increased in later design iterations, the small, 10-cm-wide ports make vacuum vessel initial assembly a remote process on Ignitor. The ports on LITE seem marginally adequate for human access to the interior of the vessel. Man-size ports are desirable to minimize tooling cost and speed initial assembly of a segmented vacuum vessel.

4.9 FABRICATION OF LARGE PRECISION STRUCTURES

Large coil support structures have been fabricated for TFTR, D-III, JET, and other large tokamaks (Fig. 4.8). The tolerances and materials are similar to those required for an ignition experiment. The potential use of additional quantities of high-strength material will increase machining costs, but it is not a feasibility issue.

If remote handling is required for the structure, joints and interfaces may require tighter tolerances than previous tokamak designs. Remote handling of the structure is currently not included in the ignition device design criteria, but it could be considered in the future.

The proposed large preload rings are unconventional due to their size and amount of load carried. However, they appear feasible to construct, using conventional welding, forming, and machining techniques.

4.10 ASSEMBLY ASSESSMENT

Large tokamaks have been assembled with both segmented and one-piece vacuum vessels. Segmentation will not have a big effect on initial assembly, assuming suitable tooling is developed for joining segments of a multipiece vacuum vessel. Both the assembly sequences and the size and weight of components are within the experience base of the fusion community.

Fig. 4.8. Photo of TFTR overall structure illustrating large tokamak support structure feasibility.

Currently, remote handling of the major components of the tokamak is not a design requirement. If it were, traditional methods of tolerance adjustment during assembly might not be feasible. New methods of adjustment and closer assembly tolerances may be required.

Assembly tolerances for the first wall may be a concern, pending detail design of components. The first-wall contour must be held with respect to the toroidal field lines, requiring both precision assembly and a method of adjustment for tolerance buildup.

4.11 SUMMARY

The three ignition device designs, LITE, Ignitor, and ISP 0424, all have similar challenges of tight tolerances and high-strength materials. Differences do exist due to the TF coil and vacuum vessel segmentation concepts. The TF coil sliding joint requires additional tolerance control, but it eases assembly of the device. A segmented vacuum vessel eliminates the sliding joint in the TF coil. Fabrication and assembly of all three designs are feasible and close to the existing experience base.

There are three principal observations dealing with fabrication and assembly:

1. If new, high-strength adhesive bonding materials are required, new process development may be required.
2. If remote handling of major assemblies becomes a design requirement, tolerance adjustment at joints and interfaces may require new techniques.
3. The first-wall contour tolerances are a challenge impacting design, fabrication, and assembly.

5. REPAIRABILITY

C. A. Trachsel, McDonnell Douglas

Three compact ignition devices were evaluated to determine the feasibility of repairing this class of devices. The designs evaluated include the MIT LITE and Ignitor designs and the PPPL ISP 0424 design. Each device is located inside a shielded test cell without shielding. As a result, all device components will become radioactive and require remote repair operations.

5.1 FEATURE COMPARISON

A comparison of features requiring remote repair is shown in Table 5.1. Major differences include a prefabricated vacuum vessel on the ISP and segmented vacuum vessel designs that are joined during final assembly on the other two concepts. All vessels are covered on the interior with graphite tiles. An undefined, but possibly major, difference is in how precisely the tile mounting surfaces can be located and the effect this has on tile installation. The prefabricated PPPL ISP vacuum vessel design should provide a truer surface for tile mounting. The Ignitor device simplifies remote repair by not including RF heating, but the smaller port size restricts maintenance. This is discussed in detail later.

Table 5.1. Key feature comparisons of compact ignition tokamaks

Item	Configuration		
	LITE	Ignitor	ISP 0424
Vacuum vessel	Segmented	Segmented	One piece
First-wall/ limiters	Graphite tiles	Graphite tiles	Graphite tiles
Heating	RF and OH	OH	RF and OH
Number of ports	24	12	14
Port size	0.22 m x 1.3 m	0.10 m x 0.80 m	0.44 m x 0.95 m
Diagnostics, misc., and fueling	Not defined	Not defined	Not defined

The test cell components external to the TF coils such as diagnostics, fueling, switching, and cooling are not defined at this date. Therefore, a detailed assessment of remote repair for these designs is premature. However, there is no reason to believe that repair of these components should be substantially different among the device designs if good design practice is used.

5.2 REPAIR APPROACH

The designs locate shielding at the test cell wall, requiring remote operations on all components in the test cell. Components in the test cell are limited to those that must be located there and those that would require remote maintenance even if located outside the test cell. Typical in-cell components are listed in Table 5.2.

Table 5.2. Typical components requiring remote repair

First wall tiles and coatings
Rf antennae
Flange seals
Coolant connections
Electrical connections
Diagnostic equipment and auxiliaries
Vacuum pumps
Valves and vacuum windows
External coil leads

Remote replacement of the TF, EF, and OH coils and vacuum vessel components is not planned for the compact ignition devices. This permits use of a lower-cost remote repair system and simplifies the design. Special care must be taken to make these components reliable. Vacuum vessel leaks are a major concern.

Basic assumptions as to the approach that will be used in development of the repair system designs for a compact ignition machine are stated below.

The repair approach (e.g., TF coil, EF coil, and vacuum vessel repair requirements) must be established at the start of the project. Adequate resources must be allocated to ensure that requirements are met. Repair requirements cannot be delayed to save dollars or schedule and added later without degrading the repair system.

Repair must be treated as an additional performance criterion; an additional design iteration will be required to assess the ability to be repaired. This repair system and tokamak concepts must be designed together and finalized before hardware fabrication begins.

The compact devices do not count on invention of repair systems but rely on the use of known, viable concepts. Development is required to determine the exact design parameters and design configurations to be used. This development must be performed prior to firming up design features. For example, if remote welding of vacuum vessel segments is required, then stiffness requirements for proper alignment, built-in welder track size, etc., must be defined before final part fabrication is started.

Modular design using good remote design practice must be used. For example, designs should not require hand fit-up, but should include guide pins and push-pull design features. The number of components located in the test cell should be minimized to reduce the remote tasks required.

Extensive "shake-down" operations are planned to permit checkout of the maintenance equipment and elimination of "infant mortality" before components require remote repair.

5.3 TEST CELL LAYOUT

A typical test cell layout is shown in Figs. 5.1 and 5.2 for the compact device. It uses a polar crane located above a slotted rotating shield through which the crane and crane-mounted manipulator operate. During tokamak operation, the shield slot is blocked off. This prevents crane activation.

Tokamak repairs are accomplished by the crane-mounted manipulator and by a post-mounted manipulator that can be plugged into floor sockets near components and vacuum vessel ports.

Fig. 5.1. Typical test cell layout, elevation view.

Fig. 5.2. Typical test cell layout, plan view.

A transfer hatch is planned for moving test cell components to a hot cell that uses conventional through-the-wall manipulators. The manipulators inside the test cell will be controlled by operator control stations similar to that shown in Fig. 5.3. A typical manipulator arm is shown in Fig. 5.4. It includes television cameras and acoustic sensors and can include force feedback and computer assist as desired. Other arm designs will be required for specific tasks as the designs evolve.

Technology for developing the test cell manipulators and control stations is currently available and can be applied as soon as specific designs and requirements are defined.

5.4 VACUUM VESSEL ACCESS

All designs plan graphite tile replacement inside the vacuum vessel. Replaceable tile designs have not been defined and analyzed to date, but all three devices need a design. The design should be developed to be consistent with installation and removal using a single manipulator arm. Tile design will influence the tokamak radial build.

Tile replacement would be accomplished with a remote arm that uses technology developed for the JET arm and under development for the TFTR arm. The JET arm requires breach of the vacuum vessel. This simplifies arm development.

PPPL plans to have the TFTR arm, shown in Fig. 5.5, developed in two years. It operates in an antechamber that allows entry into the vacuum vessel without breach of vacuum. This permits surface analysis between shots and leak isolation and minimizes the bakeout time. A possible improvement to this design for compact devices would be computer-guided positioning. Manual operation for tile replacement is planned.

Significant port size differences exist in the three designs, as shown in Fig. 5.6. The present small port size of Ignitor requires a remote joint weld for final assembly of the vacuum vessel prior to activation because it does not permit personnel entry. The port provides marginal access for remote welder installation. A preliminary review of the access requirements indicated to the reviewer that a

Fig. 5.3. RM-10 master control station.

Fig. 5.4. RM-10 slave assembly.

Fig. 5.5. TFTR maintenance manipulator.

Fig. 5.6. Port size that restricts access.

minimum of 15 cm is required; however, the Ignitor group has stated that a device exists for remote welding that will fit through the 10-cm port. The small port also requires multiple-port entry for tile replacement, affecting the amount of diagnostics and equipment that must be removed for major tile replacement. The LITE and ISP designs permit manned access and single-port entry of a manipulator for tile replacements.

5.5 TEST CELL COMPONENTS

Diagnostic and test cell component designs will have to be developed in parallel with the device, and remote features must be incorporated. Hot cell experience exists to guide this design effort, but the designs will require more room and different designs than those used in previous fusion test devices.

Figure 5.7 shows an acid fractionator module which employs these design practices. In addition to using remote replaceable jumpers for coolant lines at the top of the module, it provides for remote replacement of a heat exchanger and pump that have high failure rates. The actual piece of hardware, shown in Fig. 5.8, is serviced by two overhead manipulator arms. Test cell components must use a similar modular design approach.

A detail view of the pump installation is shown in Fig. 5.9. It includes a coolant connection joint which can be operated by a single manipulator arm that fits a torque motor over a tapered hex bolt head. Additionally, guide pins are used at the pump base for positioning the pump.

Computer-aided design (CAD) modeling is a relatively new tool that can make design of maintenance equipment and modular components for remote repair much easier by providing rapid design evaluation and iteration capability. The model shown in Fig. 5.10 was generated, animated to show robot arm-motion requirements, and modified to meet requirements in less than four hours.

McDonnell Douglas has replaced the tube and cable mockup of the TAV-8B forward fuselage with a computer model and saved significant cost

Fig. 5.7. Acid fractionator module.

Fig. 5.8. Photo of acid fractionator module.

Fig. 5.10. Computer-aided design to expedite development.

and schedule in development. All fusion laboratories now have CAD systems in place for use in compact device development.

5.6 KEY ISSUES

Key issues require closer examination of specific components to identify those that require remote repair and to determine the design modifications necessary to accomplish remote repair. The shield location at the test cell wall increases the number of components requiring remote repair. A key question to be addressed is: Does lack of a need for TF, EF, OH, and vacuum vessel remote replacement make it possible to locate permanent shielding at the TF boundary and increase the use of hands-on maintenance, or does neutron streaming through ports negate its effectiveness?

The port size needed to get a welding head and the associated vessel joint positioning equipment in place must be examined more closely. A review by Diametrics indicated that a 10-cm access port would force these components into an extensive development program. A requirement for an increase in port size may affect machine radius.

All concepts require mechanically attached tiles that can be remotely replaced. A tile design development effort, including the remote arm selection, should be undertaken in the program so that tile thickness effects on the major radius are determined and port size is adequate.

A significant requirement in tile design may be the need to align the tile surface with the magnetic field lines. Tolerances in the vacuum vessel and magnetic centerline of the magnets may require tailored tiles that are fabricated by mapping magnetic surfaces after assembly of the magnets and the vacuum vessel.

Leak detection and isolation methods have not been addressed in the designs. Inability to replace the vacuum vessel remotely makes a leak detection system even more critical. A system including dual seals, intermediate pumping, separate manifolding, etc., should be defined.

The test cell components should be defined in detail so that a shielding location can be defined and the specific designs can be initiated to assure compatibility with repair.

5.7 CONCLUSIONS

The present concepts plan to use existing technology and can result in a remotely repairable compact ignition machine if adequate attention is given the task early in the design effort. This includes time for design iteration and development testing. CAD/CAM simulation and mock-ups must also be a part of this effort.

Prior to D-T operation, a period of full-up demonstration of remote repair can ensure repair capability and reduce the need for repair by allowing replacement of "infant mortality" items.

Remote replacement of the TF coil, EF coil, and vacuum vessel should be considered further before they are excluded. It may be possible to include design features which do not exclude future remote repair at a small additional cost.

6. COMPACT IGNITION DEVICE COST ASSESSMENTS

W. R. Hamilton, FEDC

6.1 INTRODUCTION

The purpose of the compact ignition device cost assessment activity was to develop preconceptual scoping cost estimates of a range of "minimum-cost" compact ignition devices, which are all assumed to be sited at the PPPL. In particular, this "range of devices" consists of the water-cooled MIT LITE device and the liquid nitrogen-cooled PPPL ISP device. A similar estimate is being developed for the Ignitor device.

The estimated plant and capital equipment (PACE) cost of the ISP device is \$258 million (FY 84 dollars), and the estimated PACE cost of the LITE device is \$288 million (FY 84 dollars). Further detail is presented in Sect. 6.8.

6.2 COSTING APPROACH

Past experience on fusion projects has demonstrated that "bottom-up" cost estimates of leading-edge-of-technology devices at the preconceptual design level are consistently low. This traditional estimating method involves summing the cost of the subsystem components, beginning with the smallest details and combining these into larger and larger assemblies until the entire subsystem is complete. The "bottom-up" method is an excellent cost-estimating method where the design has matured to a final level of detail and/or the components are standard, off-the-shelf items with accurately known costs. The absence of a mature design at the preconceptual level makes total "bottom-up" cost estimating very difficult at best, due to the inherent lack of design definition and detail.

The costing approach chosen for the compact ignition device cost assessments is judged to be more compatible with the preconceptual level of design definition and detail. This approach consists of using past cost experience from fusion projects and industry to project the cost of

these next-generation devices. Also, credit for buildings, facilities, and equipment items judged to be available at the PPPL site are factored into the cost estimates.

6.3 PROCEDURE

The procedure followed in assembling the compact ignition device cost assessment is depicted on the flowchart in Fig. 6.1. At the outset of the study effort, a procedure was developed in concert with the study participants for coordinating the costing activity, and a document was prepared that set forth the code of accounts/work breakdown structure (WBS) to be employed, assignment of responsibility to cognizant engineers for technical input to the estimates, a standardized component data sheet for data transfer, and a schedule for the costing activity.

At the point in the preconceptual design activity where quantities of material and equipment could be estimated, the cognizant engineers submitted the completed component data sheets, along with any supplementary material, to the FEDC cost engineer. This information served as the technical basis for the cost estimates. These component data sheets contained a listing of the available component/subsystem resources and required modifications to the existing resources, a hardware description and parameters list for the particular component/subsystem, and a suggested costing basis (optional).

This component/subsystem design data was then coupled with cost factors extracted from the FEDC historical cost data base and input to the FEDC Cost Estimation Spreadsheet, where the cost estimate was performed and cataloged. Approximately 130 account elements were used to generate the cost estimates.

6.4 COST ELEMENT DEFINITIONS

The FEDC Cost Estimation Spreadsheet was used to perform and catalog the compact ignition device cost assessments. This spreadsheet calculates the project PACE cost. PACE cost is defined in its simplest form as the total expense of constructing the plant and placing it into operation and includes the design, fabrication and procurement,

Fig. 6.1. Cost estimate assembly procedure.

installation, and subsystem preoperational testing phases of the project. PACE cost is composed of two subelements. direct cost and indirect cost.

Direct costs are those costs that are specifically identified with a permanent plant component, subsystem, or facility and include engineering cost, hardware cost, and installation cost. The engineering element of direct cost is defined to account for the first-of-a-kind, nonrecurring engineering design costs. Engineering cost includes design management/engineering/analyses, specification and drawing development, and tool design. Hardware cost includes the purchase price of commercially available equipment delivered to the site and the "build-to-print" cost incurred by the project. The "build-to-print" cost is defined to represent the purchase price of the component/subsystem if it were commercially available and includes management, materials, fabrication labor, subcontracted equipment, tooling, packaging and shipping, vendor testing, vendor manufacturing, and support engineering. Installation costs refer to the cost of craft labor used in assembly and on-site acceptance testing of permanent plant equipment and subsystems.

Indirect costs are those that are not specifically identified with permanent plant components, subsystems, or facilities but are incurred by the project as a whole. Subelements of indirect cost are such categories as project management, project systems engineering, project quality assurance, project safety and environmental engineering, construction management, on-site inspection, and laboratory management.

6.5 METHODOLOGY

The flowchart shown in Fig. 6.2 outlines the methodology used in the Cost Estimation Spreadsheet for generating the PACE cost estimates for the compact ignition devices. Design parameters and descriptive information for the particular component/subsystem were input to the spreadsheet from the component data sheets supplied by the cognizant engineers. Cost data were input to the spreadsheet for the specific component/subsystem from the FEDC historical cost data base file. The cost data base file is a catalog of cost coefficients, cost algorithms,

Fig. 6.2. Cost estimate methodology.

and "component take-off" costs formatted onto separate cost data sheets corresponding to specific components/subsystems. Each cost data sheet contains hardware, engineering, and installation cost data. The cost data input to the spreadsheet for a specific component/subsystem are chosen from the cost data base file based on the cost of a component/subsystem of similar configuration and type.

Three techniques were used to calculate the unit hardware cost for a specific component/subsystem. These costing techniques are unit costing, cost algorithms, and "component take-off" costing. Where a solid historical cost data base was available, the unit costing method was used, whereby the hardware cost is based on cost per unit (weight, surface area, power, etc.) of similar hardware. Where a good data base did not exist, the cost algorithm method was used. Cost algorithms are empirical costing equations, developed from experience on similar hardware, where the hardware cost is scaled as a function of component/subsystem design parameters. Where the component/subsystem was composed of standard items with accurately known costs, a "component take-off" method was used whereby the subsystem cost was based on the unit cost and quantity of the components that make up the subsystem. Engineering and installation costs are calculated as a function of the percentage of total hardware cost and added to it to yield the direct cost of the component/subsystem.

This procedure is followed for all elements in the code of direct cost accounts, after which the elements are summed to give the total direct cost of the project. The Cost Estimation Spreadsheet incorporates a standard code of accounts, developed at FEDC, as the basis for reporting the estimated component/subsystem costs. This code of accounts incorporates a mandatory account level, applicable to all magnetically confined fusion concepts and device types, below which additional generic accounts unique to the compact ignition devices were developed.

Factors for each individual indirect cost element are input to the spreadsheet, expressed as a percentage of direct cost, for calculation of the project total indirect cost. The percentages used in the estimates were derived from historical data from several sources. The

project indirect and direct costs are then summed to yield the project PACE cost.

6.6 ASSUMPTIONS/GROUNDRULES

The general assumptions and groundrules on which the cost assessments are based were developed in concert with and agreed to by the study participants and by Department of Energy/Office of Fusion Energy. These assumptions and groundrules are as follows:

- Only PACE costs were assessed. Research and development cost and operating costs were not addressed.
- The cost assessments were done in constant-year FY 84 dollars. No escalation was applied.
- Overall project contingency was not addressed.
- The existing PPPL site was assumed as the location of the compact ignition devices.
- Credit was taken for all usable existing site resources.
- The organizational scope of the project was that of a prime contractor responsible to a laboratory for engineering, procurement, and construction.

6.7 EXISTING SITE RESOURCES

The compact ignition device cost assessments assume that the device will be sited at the PPPL and that credit can be taken for existing site resources. Table 6.1 presents a summary listing of the resources that considered applicable to the compact ignition devices.

6.8 COST ASSESSMENTS

The results of the ISP and LITE preliminary cost assessments are shown in Tables 6.2 and 6.3 to different levels of detail. The cost assessments are based on the approach, methodology, assumptions and groundrules, and existing resources set forth in Sect. 6.2 through 6.7 and on the designs described in Appendixes B and C.

Table 6.2 shows the ISP and LITE cost assessments tabulated by four major direct cost elements and one indirect cost element. "Device"

Table 6.1. Existing PPPL resources summary

Facilities

- Auxiliary facilities
- Support facilities
- Site utilities

RF systems

- 21-MW rf power supply/transmitter modules (Fusion Materials Irradiation Test)
- 18-MW neutral beam power supplies

Power conditioning systems

- 38 power supply modules w/interface hardware
- PF system auxiliary equipment
- 12-MJ capacitor charge/discharge system
- 950-MVA motor-generated flywheel system
- Protection equipment

Heat transport/heat rejection systems

- 3480-gpm chilled water
- 9500-gpm unchilled water
- Deionizing equipment/demineralized water makeup
- 29-MW cooling tower
- Liquid nitrogen storage

Fuel handling system

- 50/1000-cfm room air detritiation systems
- 10-cfm glovebox detritiation system
- Receiving/storage/analytical gloveboxes
- Waste systems
- Compactor

Table 6.1 (continued)

Electric plant

- 200-MVA substation
- 150-KVA uninterruptible power system
- 12-MW backup power system
- Energy distribution system
- Utility energy supply

Instrumentation and control system

- Computer structure with peripherals
 - Consoles
 - CAMAC crates and modules, signal conditioning
-

Table 6.2. Cost assessment of compact ignition devices

Element	PPPL ISP	MIT LITE
Device	88.4 ^a	90.0
Power systems	7.7	33.8
Auxiliary heating	45.7	45.7
Other	86.3	85.2
Total direct cost	228.1	254.7
Total indirect cost	29.8	33.4
Total PACE cost	257.9	288.1

^a In millions of 1984 dollars.

Table 6.3. Cost assessment of compact ignition devices

Element	PPPL ISP	MIT LITE
Facilities	31.7 ^a	31.3
Vacuum vessel/first wall/ limiter/structure	31.0	30.0
Magnets	57.3	60.0
RF heating	45.7	45.7
Vacuum systems	6.2	6.2
Power conditioning systems	7.0	13.6
Heat transport	2.4	1.6
Fuel handling	8.9	8.9
I&C	13.2	13.2
Maintenance equipment	23.8	23.8
Electric equipment	0.7	20.2
Heat rejection	0.2	0.2
Direct cost	228.1	254.7
Indirect cost	29.8	33.4
PACE cost	257.9	288.1

^a In millions of 1984 dollars.

includes all the reactor island components: vacuum vessel/first wall, limiters, vacuum system structure, and magnets. "Power systems" include the electric plant and power conditioning equipment. "Auxiliary heating" consists of the ICRH systems. "Other" is composed of facilities, heat transport systems, fuel handling equipment, instrumentation and control (I&C), remote maintenance equipment, and heat rejection systems. The major difference in the estimated costs is in power systems, where additional electric plant equipment (substation) and source conditioning equipment is required to accommodate the larger electrical loads of the water-cooled LITE device. The ISP electrical load requirements are more compatible with existing electrical equipment capabilities at the PPPL site.

Table 6.3 shows the ISP and LITE estimated costs divided into major device subsystems. Systems assumed to be common to both devices are the rf heating system, fuel handling equipment, instrumentation and control, and maintenance equipment. Again, it can be seen that the major differences in the cost estimates are in the power conditioning equipment and electric plant equipment areas.

6.9 CONCLUSIONS

It is concluded that the preliminary cost assessments made of the water-cooled LITE device and the liquid-nitrogen-cooled ISP device are representative of the costs of this type of device. Historical cost data derived from actual cost experience were used to project the costs of the compact ignition devices. To obtain a more detailed estimate, a conceptual design of these devices must be generated and an effort to obtain input from industry on cost must be initiated.

Appendix A

DESCRIPTION OF THE IGNITOR CONCEPT

T. G. Brown, FEDC

A-1. INTRODUCTION

The key characteristics of the current Ignitor device consist of the application of preloads to the TF coil to balance the TF inboard leg vertical load and the combination of TF wedging and bucking of the OH solenoid to support the net TF coil centering load. These features are used to minimize the device size, consistent with past high-field, compact Ignitor device concepts. The general arrangement of the current Ignitor concept is shown in Fig. A-1, and an isometric view of a partial 30° sector is shown in Fig. A-2. Figure A-2 shows one port and openings for TF coil leads for each coil turn. Other options are being considered whereby only two leads (one entering and one leaving) would be associated with each sector. A summary of the major plasma parameters is shown in Table A-1. The radial and vertical build dimensions are listed in Table A-2.

A-2. TORUS DESCRIPTION

The vacuum vessel consists of an actively cooled stainless steel (double-wall or brazed tubes) vacuum vessel with 12 ports. The port opening measures 0.80 m high by 0.10 m wide at the midplane. In this version of Ignitor, the machine assembly begins by bringing together one-half of the machine made up of 30° sector modules consisting of the vacuum vessel and TF coil system. The vacuum vessel of adjacent sectors is welded together poloidally by a remote welder which gains access to the weld area through the sector ports. After each machine half is assembled (180°), the two halves are joined to form the full machine assembly. The sectors are assembled in this fashion to allow shear keying material to lock adjacent sectors together in order to react the net TF overturning moments. An alternate concept is being investigated whereby the overturning moment is reacted externally by shear connections between modules.

Mechanically attached graphite tiles on the inboard surface of the vacuum vessel serve as the first wall. Graphite tiles are also assumed on the top and bottom region inboard of the major radius.

Fig. A-1. Ignitor reference design.

Fig. A-2. Ignitor sector module.

Table A-1. Major parameters of Ignitor (January 1985 reference) device

Major radius, m	1.01
Minor radius, m	0.39
Aspect ratio	2.59
Triangularity	0.2
Elongation	1.6
Field on axis, T	12.5
Plasma current, MA	9.6
Safety factor	2.6
Beta, %	1.2
Burn time, s (at full field, full current)	0.5
Fusion power, MW	108
Wall load, MW/m ²	4.0
RF power, MW	0 (to 10)
Total V-s supplied	20

Table A-2. Ignitor radial and vertical build

Radial build			
Component	Thickness (cm)	Beginning (cm)	Ending radius (cm)
OH bore	20	0	20
OH solenoid	20	20	40
Gap	0	40	40
TF coil	19.5	40	59.5
Gap	1.2	59.5	60.7
Vacuum vessel/ first wall	1.3	60.7	62.0
Plasma	39	62.0	101.0
Plasma	39	101.0	140.0
Scrape-off	1.5	140.0	141.5
Vacuum vessel/ first wall	1.3	141.5	142.8
Gap	0.2	142.8	143.0
TF coil	15	143.0	158.0
Structure	37	158.0	195.0
Top vertical build (Bottom is symmetric)			
Component	Thickness (cm)	Beginning Z (cm)	Ending Z (cm)
Plasma	64	0	64
Scrapeoff	2.5	64	66.5
Vacuum vessel/ first wall	1.3	66.5	67.8
Gap	0.2	67.8	68
TF coil	15	68	83
Structure	67	83	150

A-3. TF COIL SYSTEM

The TF coil system (January 1985 reference) consists of 96 two-layer TF coil planes equally spaced toroidally (see Fig. A-2). The conductors are silver-bearing copper, and the full 30° sector is assumed to be epoxy impregnated. In the region of the vacuum vessel port openings, two adjacent TF coils are jogged to each side of the port to allow space to form the duct opening.

The TF coils are supported by external "C-clamp" wedged plates that form the main structural element of the device. These plates are prestressed radially inward by a wedge system that reacts the load against compression rings located at the upper and lower outboard region of the device.

During operation, the outward force acting on the TF coil outer leg unwedges the "C-clamp" plates and allows the system to react the preload as a downward force on the TF coil inner leg. A central laminated tie rod is used to provide additional preload.

The net centering force of the TF coil is supported by a combination of wedging and "bucking" against the OH transformer, which is wound on the central laminated steel core. A laminated steel winding layer is located on the outer surface of the OH coil to provide OH support when the OH is energized and the TF is not.

A-4. PF COIL SYSTEM

The reference poloidal field coil arrangement and flux surfaces used for plasma initiation and end-of-pulse are shown in Fig. A-3. This system is based on a separate OH, equilibrium field (EF) system. An alternate arrangement has been proposed by the FEDC (shown in Fig. A-4) which operates as a combined OH/EF system and allows the elimination of the upper and lower center coils. Table A-3 shows the PF coil positions and currents for these systems.

Fig. A-3. Original Ignitor design: coil positions and flux surfaces for (a) plasma initiation and (b) end of pulse.

Fig. A-4. Tilted solenoid design ($\delta = 0.2$): coil positions and flux surfaces for (a) plasma initiation and (b) end of pulse.

111/112

Table A-3. PF coil positions and current

Plasma Initiation			End of pulse		
R (m)	Z (m)	I (MA)	I (MA)	I/I _p	R · I (MA-m)
Original Ignitor design					
1.97	0.60	-0.42	-1.70	-0.20	3.3
1.95	0.75	0.80	-0.80	-0.09	1.6
1.97	0.90	-0.42	-1.70	-0.20	3.3
1.22	0.97	2.00	-2.00	-0.23	2.4
0.83	1.05	-3.08	3.08	0.36	2.6
0.45	0.75	9.10	-9.10	-1.06	4.1
0.29	^a	19.50	-19.50	-2.28	5.6
(b) Tilted solenoid design ($\delta = 0.2$)					
1.97	0.69	0.33	-4.18	-0.49	8.2
0.65	0.91	1.00	3.15	0.37	2.0
0.39	0.77	10.01	-10.01	-1.17	3.9
0.29		19.50	-19.50	-2.28	5.6

^a Solenoid width = 0.18 m; height = 1.0 m.

Appendix B

DESCRIPTION OF THE PPPL ISP 0424 CONCEPT

T. G. Brown, FEDC

B-1. INTRODUCTION

The salient feature of the PPPL ISP 0424 device is the incorporation of a sliding joint in the TF coil inboard region for the purpose of unloading the vertical load on the inner leg. This feature allows the machine size to be reduced plus allows the installation of a full prefabricated vacuum vessel and internal PF coils. The general arrangement of the ISP 0424 concept is shown in Fig. B-1. A summary of the major plasma parameters is shown in Table B-1. The radial and vertical build dimensions are listed in Table B-2.

B-2. TORUS DESCRIPTION

The vacuum vessel consists of an actively cooled structure made from single-curvature sections which are welded together to form a complete vacuum vessel assembly (see Fig. B-2). With the TF coil sliding joint located at the innermost region of the TF coil leg, a complete vacuum vessel assembly can be lowered over the assembled TF coil inboard legs. Fourteen large ports are formed in the vacuum vessel with port openings measuring 0.95 m high and 0.44 m wide at the midplane. Mechanically attached to the inboard wall is a limiter composed of machined graphite tiles. Graphite tiles are also provided on the top and bottom of the vacuum vessel.

B-3. TF COIL SYSTEM

The TF coil system consists of 14 copper plate coils formed in a modified "picture frame" shape. Demountable sliding joints are provided in each TF coil in the inboard region, allowing the vacuum vessel to be installed in one piece and permitting the installation of unjointed internal PF coils (see Fig. B-2). The 14 straight inboard coil legs are assembled together in an epoxy-impregnated prefabricated unit. The sliding TF coil joint allows the coil outboard of the inner straight leg to slide vertically under magnetic loads, decoupling the outboard TF coil vertical load from the inner coil leg. In so doing, the inner leg can be sized to support its own radial centering force with the absence of vertical load. Princeton has established a joint test program to investigate a number of candidate sliding joint concepts.

Fig. B-1. PPPL ISP 042% design.

Table B-1. Major parameters of ISP 0424 ignition device

Major radius, m	1.62
Minor radius, m	0.53
Aspect ratio	3.06
Triangularity	0.4
Elongation	1.6
Field on axis, T	8.9
Plasma current, MA	7.8
Safety factor	2.6
Beta, %	5.0
Burn time, s	5.0
Fusion power, MW	305
Wall load, MW/m ²	5.6
RF power, MW	30
Total V-s supplied	26

Table B-2. ISP 0424 radial and vertical build

Radial build			
Component	Thickness (cm)	Beginning radius (cm)	Ending radius (cm)
TF bore	23	0	23
TF winding	66	23	89
Gap	2	89	91
OH solenoid	8	91	99
Gap	4	99	103
Vacuum vessel/ first wall	6	103	109
Plasma	53	109	162
Plasma	53	162	215
Scrape-off	12	215	227
Vacuum vessel/ first wall	6	227	233
Gap	19	233	252
TF coil	77	252	329
Top vertical build (Bottom is symmetric)			
Component	Thickness (cm)	Beginning Z (cm)	Ending Z (cm)
Plasma	85	0	85
Scrape-off	12	85	97
Vacuum vessel/ first wall	6	97	103
Gap	50	103	153
TF coil	77	153	230

Fig. B-2. ISP 0424 complete vacuum vessel assembly.

A built-up welded strong back is provided to support each TF coil outer leg against the net magnetic outward load. The strong back structure in turn reacts this load against laminated stainless steel prestressed rings which surround the TF coil structure on the top and bottom of the device.

B-4. PF COIL SYSTEM

An optional set of internal poloidal field coils and corresponding flux surfaces used for plasma initiation and end of pulse are shown in Fig. B-3. The solenoid coils are wrapped around the prefabricated inner TF coil leg assembly, and the outer PF coils are positioned in place before the installation of the outboard TF leg/strong back structure. Table B-3 lists the PF coil positions and currents for this coil option.

(a)

(b)

Fig. B-3. Internal EF coils for ISP 0424: coil positions and flux surfaces for (a) plasma initiation and (b) end of pulse.

Table B-3. Coil currents for ISP 0424 design with internal EF coils

Plasma Initiation			End of pulse		
R (m)	Z (m)	I (MA)	I (MA)	I/I _p	R • I (MA-m)
2.30	0.75	0.61	-3.12	-0.39	7.2
1.45	1.35	0.00	0.35	0.04	0.5
0.95	^a	5.25	-5.25	-0.66	5.0

^a Solenoid width = 0.10 m; height = 1.60 m.

Appendix C

DESCRIPTION OF THE MIT WATER-COOLED LITE CONCEPT

V. D. Lee, FEDC

C-1. INTRODUCTION

The major features of the water-cooled LITE configuration are the 24 TF coils, a vacuum vessel/first-wall system within the TF bore, an external PF coil system, self-supporting TF coils, and an external torque structural system.

C-2. TORUS DESCRIPTION

The general arrangement of the LITE configuration is shown in Fig. C-1. The vacuum vessel/first-wall system and the PF coil system are not shown in this figure but are shown in the elevation view in Fig. C-2.

The major and minor radii of the LITE concept are 1.76 and 0.55 m, respectively, and the magnetic field on axis is 8.97 T. Initial studies for this concept feature a field on axis of 9.4 T. Therefore, some of the results discussed in later sections, specifically for the PF system, are shown at the 9.4-T field on axis. A summary of major plasma parameters is presented in Table C-1. The LITE radial and vertical builds are shown in Table C-2.

Table C-1. Major parameters of water-cooled LITE device

Major radius, m	1.76
Minor radius, m	0.55
Aspect ratio	3.20
Triangularity	0.3
Elongation	1.6
Field on axis, T	8.85
Plasma current, MA	7.0
Safety factor	2.6
Beta, %	4.6
Burntime, s	5.0
Fusion power, MW	300
Wall load, MW/m ²	5.3
RF power, MW	30
Total V-s supplied	30

Fig. C-1. MIT LITE general arrangement.

FUSION ENGINEERING DESIGN CENTER

Fig. C-2. MIT LITE elevation view.

Table C-2. MIT LITE radial and vertical builds

MIT LITE Radial build			
Component	Thickness (cm)	Beginning radius (cm)	Ending radius (cm)
OH bore	35	0	35
CH solenoid	34	35	69
Gap	1	69	70
TF coil	41	70	111
Gap	6	111	117
Vacuum vessel/ first wall	4	117	121
Plasma	55	121	176
Plasma	55	176	231
Scrape-off	4	231	235
Vacuum vessel/ first wall	4	235	239
Gap	22	239	261
TF coil	50	261	311
Top vertical build (Bottom is symmetric)			
Component	Thickness (cm)	Beginning Z (cm)	Ending Z (cm)
Plasma	88	0	88
Scrape-off	8	88	96
Vacuum vessel/ first wall	4	96	100
Gap	8	100	108
TF coil	44	108	152

Torus Assembly

Machine assembly consists of installing the OH solenoid coil and the three innermost bottom PF coils on the torque table, which is mounted on support columns. The bottom precompression ring, bottom bundle-to-bundle wedges (24), and the lower outer PF coil are then added to the torque table. These components are shown in Figs. C-1 and C-2.

The next components to be installed are the TF coils, along with the vacuum vessel/first-wall (FW) system. The components are installed in sectors of two TF coils, plus a 30° section of the vacuum vessel/FW system. A typical sector of these two components is shown in Fig. C-3. Adjacent sections of the vacuum vessel/FW are welded together, with the last weld being made through the access port opening of the vessel. The inboard leg of each TF bundle is wedge-shaped, with the nose of each bundle wedging against the two neighboring TF bundles to react the inward in-plane magnetic forces.

The upper outermost PF coil and the upper precompression ring are then installed on support columns in the radial plane of the TF coil bundles. Upper bundle-to-bundle wedges are lowered onto support cleats in the pie-shaped openings between the TF bundles. The top shear plate is then secured in place on top of the bundle-to-bundle wedges. The remaining three top PF coils and the external torque structure are the final torus components to be installed.

Precompression System

A system of screw jacks is installed in the upper and lower precompression rings, forming a dual-purpose system. First, the 48 screw jacks (24 upper and 24 lower) which mate with the outer face of each TF coil are used to provide a precompression load on each TF coil, forcing it radially inward. The precompression load induces a wedging contact pressure between the noses of adjacent TF coils. This contact pressure is used to transfer current from one TF coil to the next. An additional 48 screw jacks (24 upper and 24 lower) are used to apply a radially inward load on the coil-to-coil wedges. This preload by the wedges serves to ensure that all the TF coils, as well as individual plates

Fig. C-3. Typical sector of TF coils plus vacuum vessel/first wall.

within the coils, are compressed snugly together. Once the TF coils have been preloaded, mechanical shear connections between the wedges and the upper shear plate and the lower torque table are installed. Shear connections between the upper shear plate and the upper precompression ring and between the torque table and the lower compression ring are also installed. After this precompressed system has been secured, the mechanical screw jacks are unloaded to prevent additional loading of the precompression rings by in-plane magnet forces.

The shear connections described above form a load path to react the out-of-plane magnetic forces within the TF coils. The out-of-plane magnetic forces tend to twist the upper half of the TF coil in one toroidal direction while twisting the bottom half in the opposite direction. Therefore, out-of-plane forces cause the TF coils to push toroidally against the wedges that shear the load into the shear plate (or torque table) which, in turn, shears the load into the precompression rings. The external torque structure attached to both rings reacts the torque from the top precompression ring with the torque from the bottom precompression ring.

C-2.1 TF Coil System

The TF coil system for the LITE concept comprises 24 TF coils. Each TF coil is made up of 16 TF coil plate turns, for a total of 384 turns. A typical TF coil is shown in Fig. C-4.

Each TF coil is basically rectangular in shape. The external corners on the inboard side are chamfered, and all internal corners have large, well-rounded radii. The gross external dimensions are 2.41 m wide by 3.04 m high by 0.38 m thick, and the bore opening is 1.5 m wide by 2.16 m high. The wedge angle of the nose is 15° . Therefore, each of the 16 plates is tapered in the throat region, with the taper beginning at a machine radius of 0.7 m and continuing on a 0.9375° taper until a radius of 1.5 m is reached. At this point, each TF plate becomes a constant thickness of 0.024 m for the remainder of the turn. The 1.5-m machine radius becomes the bend line for the TF plates. At this point,

TF Bunch Arrangement

Fig. C-4. TF bunch arrangement.

the outer portion of each plate is bent to a plane parallel to a plane through the center of the TF coil.

Each TF coil plate turn is water cooled by two separate coolant circuits. One circuit cools the inboard leg half, requiring 10-13 parallel water coolant channels. The other circuit cools the outboard leg half. The plate turn is manufactured by machining one-half of each of the coolant channels in a left-hand and right-hand plate, each of which is half of the total plate-turn thickness. The right-hand and left-hand plates are then mated such that the half-coolant channels in each plate form a complete channel, and the two plates are diffusion bonded together. Additionally, the inboard leg half of each turn is made from CDA 175 beryllium copper, while the outboard leg half is CDA 104 OFHC copper in the half-hard condition. Electron-beam welds at the top and bottom are used to joint the inner half-turn with the outer half. The beryllium copper provides the high strength required for the inboard leg, while the OFHC copper on the outboard half provides higher conductivity, resulting in lower power loss. The insulating material between coil turns is GT-10-R insulation. Total TF coil system weight is 300 metric tons.

C-2.2 PF Coil System

The poloidal field coil design for LITE at a field on axis of 9.4 T was defined by FEDC. The coil positions and flux surfaces for plasma initiation and end of pulse are shown in Fig. C-5. The system consists of an OH coil and eight equilibrium field coils.

The FEDC MHD equilibrium code was used to compute equilibria for the LITE. Table C-3 shows the resulting coil currents for both plasma initiation and end of pulse. A current density of 3000 A/cm^2 was used to size the coils.

Fig. C-5. FEDC specified coil positions and flux surfaces for (a) plasma initiation and (b) end of pulse.

Table C-3. Coil currents for water-cooled
LITE for FEDC specified coil positions

Coil location		Plasma initiation	End of pulse		
R (m)	Z (m)	I (MA)	I (MA)	I/I _p	R · I (MA-m)
3.35	0.90	0.63	-2.94	-0.38	9.8
2.50	1.70	0.00	-1.80	-0.23	4.5
1.25	1.70	0.00	2.12	0.28	2.6
0.85	1.50	0.00	2.12	0.28	1.8
0.52	^a	31.50	-31.50	-4.11	16.4
					35.1

^aSolenoid thickness = 0.31 m; height = 2.75 m.

The weight of the OH coil was calculated to be 25 metric tons, and the weight of the eight equilibrium field coils is 63 metric tons.

The plasma parameters at the end of the pulse are given in Table C-4.

Table C-4. Plasma parameters for water-cooled LITE at end of pulse
for FEDC specified coil positions

Major radius, m	1.76
Minor radius, m	0.55
Elongation	1.60
Triangularity	0.30
External toroidal field on axis, T	9.40
Current, MA	7.66
Safety factor at axis	0.99
Safety factor at edge	2.67
Engineering beta, %	4.54
Poloidal beta	0.90

Volt-seconds available for startup, heating, and burn, V-s = 28.97.

C-2.3 Vacuum Vessel/FW/Limiter System

The vacuum vessel/FW/limiter system for the LITE concept, shown in Fig. C-6, consists of an actively cooled, double-walled vacuum vessel with graphite tiles mechanically attached to the surface of the vessel. The graphite tiles serve as a bumper limiter and are located on the inboard half (approximately 160° poloidal angle) of the vessel.

The tile thickness is estimated to be 30 mm, and the vacuum vessel walls are 5 mm each. Thin-wall ribs connecting the inner and outer walls of the vessel form coolant channels in the poloidal direction. Performance aspects of the vacuum vessel/FW/limiter system are discussed in Sect. 2.0.

Access ports provide for rf heating, fueling, diagnostics, and instrumentation and control functions. A total of 24 access ports is provided, one between each TF coil outboard leg. The access opening measures 1.30 m high by 0.22 m wide at midplane with a 1.4-m radial depth.

C-2.4 Torque Structure

The out-of-plane magnetic forces within the TF coils tend to twist the upper half of the TF coil in one toroidal direction while twisting the bottom half in the opposite toroidal direction. To react this torsional twist about the vertical machine centerline, two types of external torque structures were considered.

The first is a demountable space frame which attaches to the upper and lower precompression rings. This concept is shown in Fig. C-1. It consists of horizontal antitorque members which form an equilateral triangle at the top and bottom of the machine. The triangles are pinned at three equally spaced locations on the upper and lower compression rings. The corners of the top triangle are rotated 60° from the bottom triangle. Diagonal struts connect the corners of the top triangle to the bottom triangle at corner fittings.

The second concept is a demountable torque cylinder installed on the outer periphery of the machine, as shown in Fig. C-7. In this concept, the top and bottom shear plates are bolted to machined, cylindrical

TRW

Fig. C-6. Vacuum vessel/first-wall/limiter system.

Fig. C-7. MIT LITE alternate torque structure.

sections. The cylindrical sections have machined, mating, shear-teeth surfaces. Bolted plates are used to secure the mated, cylindrical sections. A disadvantage of this concept is that access at eight ports is lost due to structural requirements. It does have the advantage of being a smaller overall size, allowing a smaller test cell size.

C-2.5 Liquid Nitrogen-Cooled Concept

A variation of the LITE concept features coils cooled with liquid nitrogen (LN_2). This concept is identical to the water-cooled concept in both physical size and major parameters.

The design approach suggested by MIT is to provide coils which could be either water-cooled or LN_2 -cooled. Initial operation would be done with LN_2 -cooled coils, allowing the project to be funded at a significantly lower cost. This configuration would require that the device be installed in a dewar vessel or thermal barrier to maintain the initial operating temperature of approximately 80 K.

The TF and PF coils would be cooled by flowing LN_2 through the coolant passages until the entire system reaches thermal equilibrium at approximately 80 K. The operating scenario is then initiated, and each of the coils is pulsed through a predetermined operating cycle. Heat dissipation due to electrical resistance and nuclear response causes a rapid temperature rise within the limiter tiles, first wall, vacuum vessel, and coils. The temperature in the throat region of the TF coils at the end of the 5-s pulse is approximately 300 K. At the end of each burn pulse, a cooldown period is required to recool the coils.

A future upgrade could be provided at a later date to convert the system to an actively water-cooled concept. This would allow a significantly longer burn pulse length.

APPENDIX D
RECOMMENDATIONS OF THE PHYSICS IGNITION PANEL
(March 1985)
H. Furth, PPPL

D-1. OBJECTIVES

The prime objective of a near-term tokamak ignition experiment should be to establish the physics of ignition and quasi-steady-state burn as definitively as possible. Other objectives should have secondary status.

D-2. PLASMA CONFIGURATION

The selection of plasma shape should be constrained to fall within the range for which there is currently a significant experimental data base:

- Elongation $\kappa = b/a$ should be limited to $\kappa \leq 1.8$.
- Aspect ratio $A = R/a$ should be limited to $A \geq 2.4$.
- Use of strong triangularity or bean-shaping is permissible--but only in the first stability regime context.
- Magnetic and mechanical limiter configurations should be studied with roughly equal emphasis.

D-3. MHD CONSTRAINTS

To avoid frequent disruptions, the "real" MHD q value should be kept greater than 2.6, and preferably greater than 3. The average beta value should be constrained by

$$\beta \leq 3 \frac{I}{aB} .$$

The following units will be used throughout: beta values in percentages, linear dimensions in meters, currents in megamperes, fields in tesla, powers in megawatts, densities in units of 10^{20} m^{-3} , and times in seconds.

D-4. ENERGY CONFINEMENT

In the ohmically heated regime, there is general agreement on the scaling of the particular formulation for τ_E where temperature does not appear explicitly. The scaling laws in plasmas with auxiliary heating

are still subject to a wide divergence of opinion and are likely to become well established only on the basis of the TFTR generation of large tokamak experiments. Transport in alpha-heated plasmas will begin to be addressed during the late 1980s.

Recognizing these uncertainties, the Physics Ignition Panel does not propose to establish an "official" nonohmic confinement scaling law. Instead, we offer two pieces of cautionary advice.

D-4.1 Minimum Toroidal Field Strength and Machine Size

The $n(0)\tau_E$ value calculated for an ignition device on the basis of its ohmic heating performance--with the density limited to a "good" Murakami value--should exceed the minimum value required for ignition by a factor of at least 1.5. In terms of conventionally used empirical formulas, we have

$$\tau_{NA} \sim 0.07 \bar{n} a R^2 q, \quad (1)$$

$$\bar{n}_{MU} \sim 1.7 B / R q, \quad (2)$$

so that the ohmic heating limit is

$$\tau_{OH} \leq 0.12 B a R. \quad (3)$$

Taking $n(0) \sim 1.5 \bar{n}$, we have

$$n(0)\tau_{OH} \sim 0.3 B^2 a / q. \quad (4)$$

For a desired minimum margin of 1.5 relative to ignition at $n(0)\tau_{Ign} \sim 3$, the requirement is

$$B^2 a / q >_{15}. \quad (5)$$

[Some Panel members felt that the "safe" target for the ohmic heating $n(0)\tau_E$ should be $6 \times 10^{14} \text{ cm}^{-3} \text{ s}$ rather than $4.5 \times 10^{14} \text{ cm}^{-3} \text{ s}$. Others

felt that the coefficient in Eq. (2) should be 2.5 instead of 1.7. To first approximation, these two changes would leave Eq. (5) invariant.]

The Panel's advice is based on the observation that tokamak $n\tau_E$ values to date have generally been found to decrease with the addition of nonohmic heating power. In some experiments, the ohmic $n\tau_E$ value has been maintained by compensating for a drop in τ_E by a rise in n --but there are no quasi-steady-state experiments thus far where the $n\tau_E$ value has actually improved significantly in the nonohmic regime. Future experimental developments in regard to this point will be easy to note and should serve to relax (or tighten) the present guideline.

Holding the $n\tau_E$ value to the ohmic level may indeed turn out to be insufficiently pessimistic. For some heating methods, the effective τ_E value during auxiliary heating (i.e., the plasma energy content divided by the auxiliary power input P_{aux}) would naturally be expected to be shorter than in the case of the more centrally deposited ohmic heating power; in addition, the profile changes and other irregularities associated with particular heating methods can easily cause a real deterioration of tokamak transport coefficients. As a minimal precaution, the Panel therefore recommends that auxiliary heating power requirements should be calculated on the basis of a τ_E value that is reduced by some appropriate factor ϵ_{aux} relative to τ_{OH} in Eq. (3):

$$\tau_{aux} \leq 0.12 \epsilon_{aux} \text{ BaR} . \quad (6)$$

The magnitude of ϵ_{aux} will depend on the specifics of the heating method, as well as on the H-mode/L-mode issue, and should be based on contemporary experimental performance. For purposes of ignition, the critical unknown issue is, of course, whether "internal heating" by alpha particles will turn out to resemble ohmic heating. If $\epsilon_\alpha < 2/3$, then the advice of Eq. (5) may be insufficiently restrictive.

The main ambiguity in the Panel's proposed confinement guideline arises from Eq. (3): the Murakami limit is known to be sensitive to special techniques, fuel injection, and edge plasma control. In order

to avoid excessive severity, the Panel has allowed a "good" Murakami limit--like that observed in ASDEX--rather than the sort of density limit observed in the initial experiments on TFTR or JET.

D-4.2 Minimum Plasma Current

In the auxiliary heating regime, the dependence of confinement on plasma current is found to be more favorable than in the ohmic heating regime. The experimental τ_E values tend not to follow Eq. (3), but rather to increase with I , as in the familiar "Mirnov" (or "MGS") scaling:

$$\tau_{MI} = 0.45 I a \kappa^{1/2} . \quad (7)$$

To contrast τ_{MI} with τ_{OH} , we can use $I \geq 5 a^2 \kappa^{3/2} B/qR$ (where the equals sign holds for large values of A) and obtain

$$\tau_{MI} \geq 2.2 a^3 \kappa^2 B/qR \geq \tau_{OH} (18 \kappa^2 / q A^2) . \quad (8)$$

While the configurational restrictions given in Sects. 2 and 3 serve to limit the dimensionless factor in Eq. (8), the best auxiliary heating confinement results are likely to be obtained near the upper limit of the permitted range, that is, for

$$1 < 18 \kappa^2 / q A^2 \leq 4 . \quad (9)$$

Since the density limit given by Eq. (2) is usually somewhat more restrictive than the density limit derived from the MHD beta limit, the present rules tend to ensure that the conventionally used "Mirnov ignition margin" is quite substantial, and that even pessimistic ignition margins, such as "Kaye-Goldston," come close to unity. The apprehension that poor confinement may result when $A \beta_p$ exceeds $\sim 1/2$ is also automatically put to rest for q values close to the limit allowed in Sect. 3 and beta-values not exceeding the specified limit. Finally, the present guidelines tend to ensure that classical transport is

relatively unimportant; however, we should like to add an explicit caution against detailed transport models that allow less than a factor of 3 margin relative to the Hazelton-Hinton χ_1 or that come close to violating the neoclassical ripple-trapping limit.

D-5. IMPURITY CONTROL

Since the $n\tau_E$ value required for ignition is sensitive to impurity admixture, realistic assumptions should be made about Z_{eff} and ionic composition. After allowing for the increase of Z_{eff} due to the accumulation of helium ash, one should assume an additional $\Delta Z_{eff} \geq 0.5$ due to impurities.

D-6. PULSE LENGTH

In order to begin to obtain meaningful information concerning the alpha-heated equilibrium state, the absolute lower limits on the burn time should be

$$\tau_{burn} \geq 3\tau_E \geq 3\tau_{\alpha \text{ slow-down}}$$

The requirement $\tau_{burn} > 3\tau_{\text{sawtooth}}$ should also be kept in mind as highly desirable, though it is more difficult to quantify as a design guideline. Successful operation under these conditions will not provide a complete data base sufficient to predict the performance of a long-pulse fusion reactor core. To help meet this more extensive requirement, the accumulation and transport of helium and impurity ions could be studied under lower-power, longer-pulse conditions. If there are any critical phenomena associated with the full skin-relaxation time scale, they will be difficult to address in a compact ignition experiment.

D-7. PLASMA FUELING, HEATING, AND CURRENT DRIVE

Pellet injection is clearly preferable to gas feed. Of the nonohmic heating options, ion cyclotron resonant frequency (ICRF) heating appears to have the best combination of engineering desirability and physics

feasibility. Current drive is not essential to achieve the fairly short pulse lengths envisaged in Sect. 6 in tokamak geometries conforming with the constraints of Sect. 2.

(The possibility of using rf current drive and/or rf heating to feedback-stabilize resistive kink modes is still experimentally unproven, but it should be kept in mind in order to maximize plasma performance consistent with engineering constraints relating to Sect. 8.)

D-8. DISRUPTION SCENARIOS

Both mechanical and thermal effects of disruptions are potentially dangerous to the machine lifetime. Realistic engineering constraints should be derived by scaling from worst-case disruptions and loss of vertical stability in TFTR and JET.

D-9. TOTAL NUMBER OF PULSES

Considering that operation at less than the full-power level is usually sufficient to meet most of the experimental pulse requirements, the Panel recommends a minimum of 3000 full-power ignited pulses. There should be a capability to run 10^5 pulses at the half-stress level.

D-10. BURN CONTROL

When operating near the MHD beta limit, a strong adverse dependence of transport on beta is likely to ensure global thermal stability. Local excursions, such as alpha-driven sawtooth modes, are more likely to be seen and may turn out to lend themselves to control by rf feedback techniques. The Panel believes that specific provisions for burn control should await the actual observation of alpha-driven temperature excursions.

D-11. PORT SIZE

The access requirements for rf heating may impose substantial constraints on the machine design. In addition, the Panel believes that essential diagnostic requirements should be allowed to impact the design

to whatever extent may prove to be necessary. Advice on specifics should be sought from rf and diagnostic teams on the large operating tokamaks.

D-12. MACHINE PARAMETERS

The Panel believes that it should not try to specify a set of machine parameters. While the illustrative numbers in the charge letter appear to fall into a reasonable range, the choice of optimal parameters will have to be made by the design groups themselves, on the basis of the general physics guidelines.

INTERNAL DISTRIBUTION

1. R. J. Barrett	27. J. Sheffield
2-3. T. G. Brown	28. P. T. Spampinato
4. B. A. Carreras	29. D. A. Spong
5. R. E. Clausing	30. P. N. Stevens
6. A. E. Dabiri	31. D. J. Strickler
7-11. C. A. Flanagan	32. D. W. Swain
12. G. E. Gorker	33. N. A. Uckan
13-14. J. R. Haines	34. T. Uckan
15-16. W. R. Hamilton	35. F. W. Wiffen
17. J. T. Hogan	36. R. A. Zuhr
18. S. S. Kalsi	37-38. Laboratory Records Department
19. E. A. Lazarus	39. Laboratory Records, ORNL-RC
20-21. V. D. Lee	40. Document Reference Section
22. Y-K. M. Peng	41. Central Research Library
23. R. L. Reid	42. Fusion Energy Division Library
24. J. A. Rome	43. Fusion Energy Division Publications Office
25. M. J. Saltmarsh	44. ORNL Patent Office
26. T. E. Shannon	

EXTERNAL DISTRIBUTION

45. M. A. Abdou, Boelter Hall, University of California, Los Angeles, CA 90024
46. J. L. Anderson, CMB-3, Mail Stop 348, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545
47. C. C. Baker, FPP/208, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439
48. D. S. Beard, Office of Fusion Energy, Office of Energy Research, ER-531, Germantown, U.S. Department of Energy, Washington, DC 20545
49. K. L. Black, Department E452, McDonnell Douglas Astronautics Company, P.O. Box 516, St. Louis, MO 63166
50. R. Botwin, C47-05, Grumman Aerospace Corporation, P.O. Box 31, Bethpage, NY 11714
51. J. N. Brooks, FPP/207, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439
52. J. D. Callen, Department of Nuclear Engineering, University of Wisconsin, Madison, WI 53706
53. D. R. Cohn, MIT Plasma Fusion Center, 167 Albany Street, Cambridge, MA 02139
54. R. W. Conn, Department of Chemical, Nuclear, and Thermal Engineering, Boelter Hall, University of California, Los Angeles, CA 90024
55. J. G. Crocker, EG&G Idaho, P.O. Box 1625, Idaho Falls, ID 83401
56. G. R. Dalton, Department of Nuclear Engineering Science, Nuclear Science Center, University of Florida, Gainesville, FL 32611
57. R. C. Davidson, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139

58. N. A. Davies, Office of Fusion Energy, Office of Energy Research, ER-51, Germantown, U.S. Department of Energy, Washington, DC 20545
59. S. O. Dean, Director, Fusion Energy Development, Science Applications International Corporation, 2 Professional Drive, Suite 249, Gaithersburg, MD 20760
60. D. DeFreece, E451, Building 81/1/B7, McDonnell Douglas Astronautics Company, P.O. Box 516, St. Louis, MO 63166
61. J. N. Doggett, L-441, Lawrence Livermore National Laboratory, P.O. Box 5511, Livermore, CA 94550
62. H. Dreicer, Division Leader, CRT, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545
63. D. Ehst, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439
64. F. Farfaletti-Casali, Engineering Division, Joint Research Center, Ispra Establishment, 21020 Ispra (Varese), Italy
65. P. A. Finn, Fusion Program, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439
66. H. K. Forsen, Bechtel Group, Inc., Research & Engineering, P.O. Box 3965, San Francisco, CA 94119
67. J. S. Foster, Jr., Building R4-2004, TRW Defense and Space Systems, 1 Space Park, Redondo Beach, CA 90278
68. T. K. Fowler, Associate Director for Magnetic Fusion Energy, L-436, Lawrence Livermore National Laboratory, P.O. Box 5511, Livermore, CA 94550
- 69-70. H. P. Furth, Director, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
71. J. G. Gavin, Jr., President, A01-11, Grumman Aerospace Corporation, P.O. Box 31, Bethpage, NY 11714
72. G. Gibson, Westinghouse Electric Corporation, R&D Center, Churchill Site, 1310 Beulah Road, Pittsburgh, PA 15235
73. J. R. Gilleland, Fusion and Advanced Technology, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92138
74. M. Y. Gohar, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439
75. R. W. Gould, Department of Applied Physics, California Institute of Technology, Pasadena, CA 91109
76. M. W. Griffin, Department E236, McDonnell Douglas Astronautics Company, P.O. Box 516, St. Louis, MO 63166
77. R. A. Gross, Plasma Research Laboratory, Columbia University, New York, NY 10027
78. C. D. Henning, Lawrence Livermore National Laboratory, P.O. Box 5511, Livermore, CA 94550
79. J. J. Holmes, Westinghouse-Hanford Engineering Development Laboratory, P.O. Box 1970, Richland, WA 99352
80. J. B. Joyce, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
81. R. A. Krakowski, CTR-12, Mail Stop 641, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545
82. G. L. Kulcinski, University of Wisconsin, Department of Nuclear Engineering, Engineering Research Building, Room 439, 1500 Johnson Drive, Madison, WI 53706
83. W. Marton, Office of Fusion Energy, Office of Energy Research, ER-55, Germantown, U.S. Department of Energy, Washington, DC 20545
84. L. G. Masson, EG&G Idaho, Idaho National Engineering Laboratory, P.O. Box 1625, Idaho Falls, ID 83401
85. D. M. Meade, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
86. R. W. Moir, Lawrence Livermore National Laboratory, P.O. Box 5511, Livermore, CA 94550

- 87-88. D. B. Montgomery, MIT Plasma Fusion Center, 167 Albany Street, Cambridge, MA 02139
89. T. Ohkawa, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92138
90. J. A. O'Toole, Plasma Physics Laboratory, Building I-P, Room 8A, James Forrestal Campus, P.O. Box 451, Princeton, NJ 08544
91. R. R. Parker, Francis Bitter National Magnet Laboratory, 170 Albany Street, Cambridge, MA 02139
92. B. Pease, Culham Laboratory, Abingdon, Oxfordshire OX14 3DB, United Kingdom
93. M. Pelovitz, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
94. F. W. Perkins, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
95. M. Porkolab, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139
96. D. E. Post, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
97. R. E. Price, Office of Fusion Energy, Office of Energy Research, ER-55, Germantown, U.S. Department of Energy, Washington, DC 20545
- 98-99. F. A. Puhn, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92138
100. R. V. Pyle, University of California, Lawrence Berkeley Laboratory, Berkeley, CA 94720
101. J. M. Rawls, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92138
102. P. J. Reardon, Brookhaven National Laboratory, Upton, NY 11973
103. M. Roberts, International Programs, Office of Fusion Energy, Office of Energy Research, ER-52, Germantown, U.S. Department of Energy, Washington, DC 20545
104. J. D. Rogers, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545
105. M. N. Rosenbluth, RLM 11.218, Institute for Fusion Studies, University of Texas, Austin, TX 78712
106. P. H. Rutherford, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
107. J. A. Schmidt, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
108. J. Schultz, MIT Plasma Fusion Center, 167 Albany Street, Cambridge, MA 02139
109. D. Smith, Materials Science Division, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439
110. W. M. Stacey, Jr., Georgia Institute of Technology, School of Nuclear Engineering and Health Physics, Atlanta, GA 30332
111. D. Steiner, Nuclear Engineering Department, NES Building, Rensselaer Polytechnic Institute, Troy, NY 12181
112. P. M. Stone, Fusion Systems Design Branch, Division of Development and Technology, Office of Fusion Energy, Office of Energy Research, ER-532, Germantown, U.S. Department of Energy, Washington, DC 20545
113. I. N. Sviatoslavsky, Room 33, Engineering Research Building, 1500 Johnson Drive, University of Wisconsin, Madison, WI 53706
114. F. Thomas, B-20-5, Grumman Aerospace Corporation, Bethpage, NY 11714
115. K. I. Thomassen, Lawrence Livermore National Laboratory, P.O. Box 5511, Livermore, CA 94550
116. R. J. Thome, Francis Bitter National Magnet Laboratory, 170 Albany Street, Cambridge, MA 02139
- 117-118. C. Trachsel, McDonnell Douglas Astronautics Company, P.O. Box 516, St. Louis, MO 63166
119. A. W. Trivelpiece, Office of Energy Research, U.S. Department of Energy, Washington, DC 20545
120. L. R. Turner, Fusion Power Program, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439
121. E. H. Valeo, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
122. R. Varma, Physical Research Laboratory, Navrangpura, Ahmedabad 380009, India

123. J. E. C. Williams, Francis Bitter National Magnet Laboratory, 170 Albany Street, Cambridge, MA 02139
124. H. H. Yoshikawa, W/A-62, Hanford Engineering Development Laboratory, P.O. Box 1970, Richland, WA 99352
125. K. M. Young, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
126. N. E. Young, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
127. Bibliothek, Max-Planck Institut für Plasmaphysik, D-8046 Garching bei München, Federal Republic of Germany
128. Bibliothek, Institut für Plasmaphysik, KFA, Postfach 1913, D-5170 Jülich, Federal Republic of Germany
129. Bibliothèque, CEN/Cadarache, Département de Recherches sur la Fusion Contrôlée, 13108 Saint-Paul-lez-Durance, France
130. Documentation S.I.G.N., Département de la Physique du Plasma et de la Fusion Contrôlée, Association EURATOM-CEA, Centre d'Etudes Nucleaires, B.P. 85, Centre du Tri, 38041 Grenoble, France
131. Library, Centre de Recherches en Physique des Plasmas, 21 Avenue des Bains, 1007 Lausanne, Switzerland
132. Library, Culham Laboratory, UKAEA, Abingdon, Oxfordshire OX14 3DB, England
133. Library, FOM Instituut voor Plasma-Fysica, Rijnhuizen, Edisonbaan 14, NL-3430 Nieuwegein, the Netherlands
134. Library, Institute of Physics, Academia Sinica, Beijing, People's Republic of China
135. Library, Institute for Plasma Physics, Nagoya University, Nagoya 464, Japan
136. Library, International Centre for Theoretical Physics, Trieste, Italy
137. Library, JET Joint Undertaking, Abingdon, Oxfordshire OX14 3DB, England
138. Library, Laboratorio Gas Ionizzati, C.P. 56, I-00044 Frascati, Italy
139. Plasma Research Laboratory, Australian National Laboratory, P.O. Box 4, Canberra, ACT 2000, Australia
140. Thermonuclear Library, Japan Atomic Energy Research Institute, Tokai, Naka, Ibaraki, Japan
141. Library, Plasma Physics Laboratory, Kyoto University, Gokasho, Uji, Kyoto, Japan
142. Office of the Assistant Manager for Energy Research and Development, U.S. Department of Energy, Oak Ridge Operations, P.O. Box E, Oak Ridge, TN 37831
143. E. Selpietro, The NET Team, Max-Planck Institut für Plasmaphysik, Boltzmannstrasse 2, D-8046, Garching, Federal Republic of Germany
144. L. E. Strawbridge, Westinghouse Advanced Energy Systems, P.O. Box 158, Waltzmill Site, Madison, PA 15663
145. R. Andreani, Dipartimento Fusione e Applicazioni Laser, Associazioni Euratom-ENEA Fusione, P.O. Box 65, I-0004 Frascati, Rome, Italy
- 146-322. Given distribution as shown in TID-4500, Magnetic Fusion Energy (Category UC-20 c,d: Reactor Materials and Fusion Systems)