

CONTRIBUTING AUTHORS

UNIVERSITY OF CALIFORNIA, LOS ANGELES

Farrokh Najmabadi, Robert W. Conn, Nasr Ghoniem

James P. Blanchard

Yuh-Yi Chu

Patrick I. H. Cooke⁽¹⁾

Steven P. Grotz

Mohammad Z. Hasan

Charles E. Kessel

Rodger C. Martin

Anil K. Prinja⁽²⁾

George E. Orient

Shahram Sharafat

Erik L. Vold

GENERAL ATOMICS

Kenneth R. Schultz

Edward T. Cheng

Richard L. Creedon

Charles G. Hoot

Clement P. C. Wong

LOS ALAMOS NATIONAL LABORATORY

Robert A. Krakowski

John R. Bartlit⁽³⁾

Charles G. Bathke

Ronald L. Miller

Ken A. Werley

RENSSELAER POLYTECHNIC INSTITUTE

Don Steiner

William P. Duggan

William P. Kelleher

ARGONNE NATIONAL LABORATORY

Dai-Kai Sze

CANADIAN FUSION FUELS TECHNOLOGY PROJECT

Paul J. Gierszewski

Otto K. Kevton

(1) Permanent address: Culham Laboratory, Abington, Oxfordshire, United Kingdom.

(2) Present address: University of New Mexico, Albuquerque, New Mexico.

(3) TSTA Program.

Contents

Volume I: EXECUTIVE SUMMARY

1.	EXECUTIVE SUMMARY	1-1
1.1.	SYNOPSIS	1-1
1.2.	OVERVIEW OF TITAN PLASMA ENGINEERING	1-18
1.3.	OVERVIEW OF TITAN-I FUSION POWER CORE	1-86
1.4.	OVERVIEW OF TITAN-II FUSION POWER CORE	1-133
	REFERENCES	1-176

Volume II: TITAN PLASMA ENGINEERING

2.	REVERSED-FIELD PINCH AS A FUSION REACTOR	2-1
2.1.	INTRODUCTION	2-1
2.2.	RFP THEORY	2-5
2.3.	RFP EXPERIMENTS	2-24
2.4.	SUMMARY	2-70
	REFERENCES	2-71
3.	PARAMETRIC SYSTEMS STUDIES...	3-1
3.1.	INTRODUCTION	3-1
3.2.	MODELS	3-6
3.3.	COSTING	3-23
3.4.	TITAN-I DESIGN POINT	3-32
3.5.	TITAN-II DESIGN POINT	3-53
3.6.	SUMMARY AND CONCLUSIONS	3-57
	REFERENCES	3-64
4.	MAGNETICS	4-1
4.1.	INTRODUCTION	4-1
4.2.	INTEGRATED-BLANKET-COIL (IBC) CONCEPT	4-3
4.3.	TOROIDAL-FIELD (TF) COILS	4-4
4.4.	DIVERTOR-FIELD (DF) COILS	4-20
4.5.	OHMIC-HEATING (OH) COILS	4-32
4.6.	EQUILIBRIUM-FIELD (EF) COILS	4-59
4.7.	SUMMARY AND CONCLUSIONS	4-60
	REFERENCES	4-63

5.	BURNING-PLASMA SIMULATIONS	5-1
5.1.	INTRODUCTION	5-1
5.2.	EQUILIBRIUM AND STABILITY	5-2
5.3.	CORE-PLASMA SIMULATIONS	5-16
5.4.	EDGE-PLASMA SIMULATIONS	5-27
5.5.	NEUTRAL TRANSPORT AND EROSION	5-36
5.6.	FUELING	5-44
5.7.	SUMMARY AND CONCLUSIONS	5-52
	REFERENCES	5-55
6	PLASMA TRANSIENT OPERATIONS	6-1
6.1.	INTRODUCTION	6-1
6.2.	RFP START-UP DATA BASE	6-3
6.3.	FORMATION OF THE TITAN PLASMA	6-14
6.4.	IGNITION REQUIREMENTS	6-19
6.5.	CURRENT RAMP-UP TO IGNITION AND BURN	6-29
6.6.	SHUTDOWN & TERMINATION OF TITAN PLASMA	6-55
6.7.	SUMMARY AND CONCLUSIONS	6-62
	REFERENCES	6-65
7.	CURRENT DRIVE	7-1
7.1.	INTRODUCTION	7-1
7.2.	CURRENT-DRIVE OPTIONS	7-2
7.3.	OSCILLATING-FIELD CURRENT-DRIVE MODEL	7-12
7.4.	CURRENT-DRIVE PARAMETERS	7-26
7.5.	SUMMARY AND CONCLUSIONS	7-35
	REFERENCES	7-40

8.	PHYSICS ISSUES FOR COMPACT RFP REACTORS	8-1
8.1.	INTRODUCTION	8-1
8.2.	CONFINEMENT	8-8
8.3.	CURRENT DRIVE	8-21
8.4.	IMPURITY CONTROL	8-28
8.5.	FORMATION AND START-UP	8-36
8.6.	SUMMARY AND RECOMMENDATIONS	8-51
	REFERENCES	8-53

Volume III: TITAN-I FUSION POWER CORE

9.	OVERVIEW OF TITAN-I DESIGN	9-1
9.1.	INTRODUCTION	9-1
9.2.	CONFIGURATION	9-7
9.3.	MATERIALS	9-15
9.4.	NEUTRONICS	9-19
9.5.	THERMAL AND STRUCTURAL DESIGN	9-23
9.6.	MAGNET ENGINEERING	9-28
9.7.	POWER CYCLE	9-32
9.8.	DIVERTOR ENGINEERING	9-33
9.9.	TRITIUM SYSTEMS	9-40
9.10.	SAFETY DESIGN	9-43
9.11.	WASTE DISPOSAL	9-46
9.12.	MAINTENANCE	9-48
9.13.	SUMMARY AND KEY TECHNICAL ISSUES	9-53
	REFERENCES	9-61
10.	TITAN-I FUSION-POWER-CORE ENGINEERING	10-1
10.1.	INTRODUCTION	10-1
10.2.	MATERIAL SELECTION	10-1
10.3.	NEUTRONICS	10-54
10.4.	THERMAL AND STRUCTURAL DESIGN	10-66
10.5.	MAGNET ENGINEERING	10-110
10.6.	POWER-CYCLE ANALYSIS	10-133
10.7.	SUMMARY AND CONCLUSIONS	10-142
	REFERENCES	10-144

11.	TITAN-I DIVERTOR ENGINEERING	11-1
11.1.	INTRODUCTION	11-1
11.2.	MATERIALS	11-3
11.3.	TARGET FABRICATION	11-11
11.4.	TARGET DESIGN	11-15
11.5.	THERMAL AND STRUCTURAL ANALYSIS	11-27
11.6.	DIVERTOR COIL ENGINEERING	11-34
11.7.	NEUTRONICS	11-38
11.8.	VACUUM SYSTEMS	11-39
11.9.	SUMMARY AND CONCLUSIONS	11-42
	REFERENCES	11-44
12.	TITAN-I TRITIUM SYSTEMS	12-1
12.1.	INTRODUCTION	12-1
12.2.	BLANKET TRITIUM SYSTEM	12-2
12.3.	FUEL-PROCESSING AND SAFETY SYSTEMS	12-10
12.4.	SUMMARY AND CONCLUSIONS	12-25
	REFERENCES	12-29
13.	TITAN-I SAFETY DESIGN AND RADIOACTIVE-WASTE DISPOSAL .	13-1
13.1.	INTRODUCTION	13-1
13.2.	SAFETY-DESIGN GOALS	13-1
13.3.	SAFETY-DESIGN FEATURES	13-5
13.4.	LOSS-OF-FLOW & LOSS-OF-COOLANT ACCIDENTS	13-14
13.5.	LITHIUM-FIRE ACCIDENTS	13-32
13.6.	PLASMA ACCIDENTS	13-37
13.7.	RADIOACTIVE-WASTE DISPOSAL	13-40

13.8.	SUMMARY AND CONCLUSIONS	13-45
	REFERENCES	13-48
14.	TITAN-I MAINTENANCE PROCEDURES	14-1
14.1.	INTRODUCTION	14-1
14.2.	TITAN-I PLANT LAYOUT	14-2
14.3.	MAINTENANCE PROCEDURES	14-6
14.4.	FUSION POWER CORE PRETESTING	14-12
14.5.	SUMMARY	14-14
	REFERENCES	14-16
A.	APPENDIX A	A-1
A.1.	TABLE OF TITAN-I REACTOR PARAMETERS	A-1
A.2.	SYSTEMS CODE PARAMETERS OF TITAN-I	A-24
A.3.	COST SUMMARY OF TITAN-I REACTOR	A-27
A.4.	COST DATA BASE FOR TITAN-I REACTOR	A-35
	REFERENCES	A-43

Volume IV: TITAN-II FUSION POWER CORE

15.	OVERVIEW OF TITAN-II DESIGN	15-1
15.1.	INTRODUCTION	15-1
15.2.	CONFIGURATION	15-7
15.3.	MATERIALS	15-16
15.4.	NEUTRONICS	15-23
15.5.	THERMAL AND STRUCTURAL DESIGN	15-25
15.6.	MAGNET ENGINEERING	15-29
15.7.	POWER CYCLE	15-29
15.8.	DIVERTOR ENGINEERING	15-30
15.9.	TRITIUM SYSTEMS	15-37
15.10.	SAFETY DESIGN	15-41
15.11.	WASTE DISPOSAL	15-45
15.12.	MAINTENANCE	15-48
15.13.	SUMMARY AND KEY TECHNICAL ISSUES	15-51
	REFERENCES	15-57
16.	TITAN-II FUSION-POWER-CORE ENGINEERING	16-1
16.1.	INTRODUCTION	16-1
16.2.	MATERIAL SELECTION	16-7
16.3.	NEUTRONICS	16-95
16.4.	THERMAL AND STRUCTURAL DESIGN	16-104
16.5.	POWER-CYCLE ANALYSIS	16-127
16.6.	SUMMARY AND CONCLUSIONS	16-129
	REFERENCES	16-133

17.	TITAN-II DIVERTOR ENGINEERING	17-1
17.1.	INTRODUCTION	17-1
17.2.	MATERIALS	17-4
17.3.	TARGET FABRICATION	17-6
17.4.	TARGET DESIGN	17-10
17.5.	THERMAL AND STRUCTURAL ANALYSES	17-17
17.6.	DIVERTOR-COIL ENGINEERING	17-25
17.7.	VACUUM SYSTEMS	17-27
17.8.	SUMMARY AND CONCLUSIONS	17-27
	REFERENCES	17-29
18.	TITAN-II TRITIUM SYSTEMS	18-1
18.1.	INTRODUCTION	18-1
18.2.	PERMEATION	18-2
18.3.	TRITIUM CONTROL	18-4
18.4.	BLANKET TRITIUM-RECOVERY SYSTEM	18-10
18.5.	PLASMA-EXHAUST-PURIFICATION SYSTEM	18-23
18.6.	ROOM-AIR-CLEANUP SYSTEM	18-24
18.7.	SUMMARY	18-24
	REFERENCES	18-28
19.	TITAN-II SAFETY DESIGN AND RADIOACTIVE-WASTE DISPOSAL	19-1
19.1.	INTRODUCTION	19-1
19.2.	SAFETY-DESIGN GOALS	19-1
19.3.	SAFETY-DESIGN FEATURES	19-3
19.4.	LOSS-OF-FLOW & LOSS-OF-COOLANT ACCIDENTS	19-11
19.5.	RADIOACTIVE-WASTE DISPOSAL	19-22

19.6.	SUMMARY AND CONCLUSIONS	19-29
	REFERENCES	19-30
20.	TITAN-II MAINTENANCE PROCEDURES	20-1
20.1.	INTRODUCTION	20-1
20.2.	TITAN-II PLANT LAYOUT	20-2
20.3.	MAINTENANCE PROCEDURES	20-8
20.4.	SUMMARY	20-12
	REFERENCES	20-14
B.	APPENDIX B	B-1
B.1.	TABLE OF TITAN-II REACTOR PARAMETERS	B-1
B.2.	SYSTEMS CODE PARAMETERS OF TITAN-II	B-22
B.3.	COST SUMMARY OF TITAN-II REACTOR	B-25
B.4.	COST DATA BASE FOR TITAN-II REACTOR	B-33
	REFERENCES	B-41

ACKNOWLEDGEMENTS

The TITAN design team wishes to acknowledge the consultations and advice given by the TITAN Physics Advisory Committee on reversed-field-pinch physics issues and by the TITAN Engineering Review Committee on engineering design and analysis. Useful discussions with Frank Clinard of Los Alamos National Laboratory on properties of ceramic insulators, with John Davis of McDonnell Douglas on refractory metals, with John Haines of McDonnell Douglas on vacuum pumping issues, with Steve Piet of Idaho National Engineering Laboratory on safety aspects of the design, with Mark Tillack of University of California, Los Angeles on liquid-metal MHD issues, and with scientists of Fusion Engineering Design Center at Oak Ridge National Laboratory on design maintenance and integration are also acknowledged. The authors also wish to express their appreciation to Ms. Joan George for her effort in preparing this report.

The TITAN research program is supported by the U. S. Department of Energy, Office of Fusion Energy, at University of California, Los Angeles under grant DE-FG03-86ER52126, at General Atomics under contract DE-AC03-84ER53158, at Rensselaer Polytechnic Institute under grant DE-FG02-85ER52118, and at Los Alamos National Laboratory which is operated by the University of California for the U. S. DOE under contract W-7405-ENG-36.

TITAN PHYSICS ADVISORY COMMITTEE

Richard A. Nebel

Allan Newton

Stewart C. Prager

Michael J. Schaffer

Kurt F. Schoenberg

Teruo Tamano

Starnes Walker

Los Alamos National Laboratory

Culham Laboratory

University of Wisconsin, Madison

General Atomics

Los Alamos National Laboratory

General Atomics

Phillips Petroleum Company

TITAN ENGINEERING REVIEW COMMITTEE

Mohamed A. Abdou

Charles C. Baker

Daniel Cohn

James D. Gordon

Carl D. Henning

Michael J. Schaffer

University Of California, Los Angeles

Argonne National Laboratory

Massachusetts Institute Of Technology

TRW

Lawrence Livermore National Laboratory

General Atomics

ABSTRACT

The TITAN Reversed-Field-Pinch (RFP) fusion-reactor study is a multi-institutional research effort to determine the technical feasibility and key developmental issues for an RFP fusion reactor operating at high power density, and to determine the potential economic (cost of electricity), operational (maintenance and availability), safety and environmental features of high mass-power-density fusion systems. Mass power density (MPD) is defined as the ratio of net electric output to the mass of the fusion power core (FPC). The fusion power core includes the plasma chamber, first wall, blanket, shield, magnets, and related structure.

Two different detailed designs, TITAN-I and TITAN-II, have been produced to demonstrate the possibility of multiple engineering-design approaches to high-MPD reactors. TITAN-I is a self-cooled lithium design with a vanadium-alloy structure. TITAN-II is a self-cooled aqueous loop-in-pool design with 9C ferritic steel as the structural material. Both designs would use RFP plasmas operating with essentially the same parameters. Both conceptual reactors are based on the DT fuel cycle, have a net electric output of about 1000 MWe, are compact, and have a high MPD of 800 kWe per tonne of FPC. The inherent physical characteristics of the RFP confinement concept make possible compact fusion reactors with such a high mass power density. The TITAN designs would meet the U. S. criteria for the near-surface disposal of radioactive waste (Class C, 10CFR61) and would achieve a high Level of Safety Assurance with respect to FPC damage by decay afterheat and radioactivity release caused by accidents. Very importantly, a "single-piece" FPC maintenance procedure has been worked out and appears feasible for both designs.

Parametric system studies have been used to find cost-optimized designs, to determine the parametric design window associated with each approach, and to assess the sensitivity of the designs to a wide range of physics and engineering requirements and assumptions. The design window for such compact RFP reactors would include machines with neutron wall loadings in the range of 10 – 20 MW/m² with a shallow minimum-COE at about 18 MW/m². Even though operation at the lower end of the this range of wall loading (10 – 12 MW/m²) is possible, and may be preferable, the TITAN study adopted the design point at the upper end (18 MW/m²) in order to quantify and assess the technical feasibility and physics limits for such high-MPD reactors. From this work, key physics and engineering issues central to achieving reactors with the features of TITAN-I and TITAN-II have emerged.