

UCLA-PPG-1323

Volume I

# THE ARIES-I TOKAMAK REACTOR STUDY

## FINAL REPORT

### 1991

University of California, Los Angeles  
Institute of Plasma and Fusion Research  
Los Angeles, CA

General Atomics  
San Diego, CA

Argonne National Laboratory  
Argonne, IL

Los Alamos National Laboratory  
Los Alamos, NM

Massachusetts Institute of Technology  
Cambridge, MA

Princeton Plasma Physics Laboratory  
Princeton, NJ

Oak Ridge National Laboratory  
Oak Ridge, TN

Rensselaer Polytechnic Institute  
Department of Nuclear Engineering  
Troy, NY

Idaho Engineering National Laboratory  
Idaho Falls, ID

University of Wisconsin  
Madison, WI

#### **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 on 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.

**CONTRIBUTING AUTHORS****University of California, Los Angeles**

Patrick I. H. Cooke<sup>1</sup>  
 Erfan Ibrahim  
 Rodger C. Martin

Farrokh Najmabadi, Robert W. Conn  
 Steven P. Grotz  
 Tomoaki Kunugi<sup>2</sup>  
 Shahram Sharafat

Mohammad Z. Hasan  
 Tak-Kuen Mau  
 Erik L. Vold

**Argonne National Laboratory**

Charles C. Baker<sup>3</sup>  
 Kenneth Evans, Jr.

David A. Ehst, Dai-Kai Sze

Michael Billone  
 Shiu-Wing Tam

**General Atomics**

Edward T. Cheng  
 Barry W. McQuillan

Kenneth R. Schultz, Clement P. C. Wong  
 Richard L. Creedon  
 Elmer E. Reis, Jr.

James A. Leuer  
 Michael J. Schaffer

**Idaho National Engineering Laboratory**

J. Stephen Herring

**Los Alamos National Laboratory**

John R. Bartlit<sup>4</sup>  
 Girogio L. Varsamis<sup>5</sup>

Robert A. Krakowski  
 Charles G. Bathke

Ronald L. Miller  
 Ken A. Werley

**Massachusetts Institute of Technology**

Justin Schwartz  
 Peter Titus

Daniel R. Cohn, Leslie Bromberg

Joel Schultz  
 John E. C. Williams

**Oak Ridge National Laboratory**

Michael J. Gouge  
 Dennis J. Strickler

Y-K. Martin Peng

John T. Hogan  
 John C. Whitson

**Princeton Plasma Physics Laboratory**

Stephen C. Jardin

Charles E. Kessel

David J. Ward

**Rensselaer Polytechnic Institute**

Marc L. Klasky

Don Steiner  
 Lance Snead

Mark E. Valenti

**Georgia Institute of Technology**

John Mandrekas

**University of California, Berkeley**

Shu-Kay Ho

<sup>1</sup>On assignment from Culham Laboratory, Abingdon, Oxfordshire, United Kingdom.

<sup>2</sup>Permanent Address: Japan Atomic Energy Research Institute, Tokai-Mura, Naka-gun, Japan.

<sup>3</sup>Present Address: Oak Ridge National Laboratory, Oak Ridge, TN.

<sup>4</sup>TSTA program.

<sup>5</sup>U.S. DOE Fusion Energy Postdoctoral Research Program.

Present Address: Atlas Wireline Company, Houston, TX.

## Contents

### Volume I

	EXECUTIVE SUMMARY . . . . .	1
1.	OVERVIEW OF THE ARIES-I TOKAMAK REACTOR STUDY . . . . .	1-1
1.1.	DESIGN DESCRIPTION . . . . .	1-1
1.2.	SYSTEMS STUDIES AND ECONOMICS . . . . .	1-8
1.3.	REACTOR PLASMA PHYSICS . . . . .	1-12
1.4.	MAGNET ENGINEERING . . . . .	1-37
1.5.	FUSION-POWER-CORE ENGINEERING . . . . .	1-49
1.6.	ENVIRONMENTAL AND SAFETY FEATURES . . . . .	1-82
	REFERENCES . . . . .	1-88

### Volume II

2.	SYSTEMS STUDIES . . . . .	2-1
2.1.	INTRODUCTION . . . . .	2-1
2.2.	MODELS AND METHODS . . . . .	2-3
2.3.	COSTING AND ECONOMICS . . . . .	2-19
2.4.	DESIGN POINT DETERMINATION . . . . .	2-33
2.5.	CRITICAL ISSUES . . . . .	2-57
2.6.	SUMMARY AND CONCLUSIONS . . . . .	2-57
	REFERENCES . . . . .	2-59
3.	EQUILIBRIUM, STABILITY, AND TRANSPORT . . . . .	3-1
3.1.	INTRODUCTION . . . . .	3-1
3.2.	MHD EQUILIBRIUM . . . . .	3-3
3.3.	MHD-STABILITY BETA LIMIT . . . . .	3-12
3.4.	VERTICAL STABILITY . . . . .	3-16
3.5.	TRANSPORT ANALYSIS . . . . .	3-26

3.6.	SUMMARY AND CONCLUSIONS . . . . .	3-36
	REFERENCES . . . . .	3-38
4.	CURRENT DRIVE . . . . .	4-1
4.1.	INTRODUCTION . . . . .	4-1
4.2.	CURRENT-DRIVER SELECTION . . . . .	4-3
4.3.	BOOTSTRAP CURRENT . . . . .	4-11
4.4.	PHYSICS OF FAST-WAVE CURRENT DRIVE . . . . .	4-18
4.5.	FAST-WAVE CURRENT-DRIVE SYSTEM . . . . .	4-36
4.6.	NEUTRAL-BEAM CURRENT DRIVE . . . . .	4-57
4.7.	SUMMARY . . . . .	4-62
	REFERENCES . . . . .	4-64
5.	IMPURITY CONTROL SYSTEM . . . . .	5-1
5.1.	INTRODUCTION . . . . .	5-1
5.2.	EDGE-PLASMA SIMULATIONS . . . . .	5-3
5.3.	EROSION . . . . .	5-15
5.4.	DIVERTOR DESIGN AND ENGINEERING . . . . .	5-19
5.5.	THERMAL RESPONSE TO PLASMA DISRUPTION . . . . .	5-27
5.6.	PELLET FUELING SYSTEM . . . . .	5-36
5.7.	SUMMARY AND R&D DIRECTIONS . . . . .	5-65
	REFERENCES . . . . .	5-68
6.	TRITIUM SYSTEMS . . . . .	6-1
6.1.	INTRODUCTION . . . . .	6-1
6.2.	DIVERTOR . . . . .	6-2
6.3.	BLANKET . . . . .	6-6
6.4.	PLASMA EXHAUST SYSTEM . . . . .	6-12
6.5.	SUMMARY . . . . .	6-13
	REFERENCES . . . . .	6-17

7.	MAGNET ENGINEERING . . . . .	7-1
7.1.	INTRODUCTION . . . . .	7-1
7.2.	MATERIALS OPTIONS . . . . .	7-2
7.3.	FLUX JUMP STABILITY . . . . .	7-17
7.4.	TOROIDAL-FIELD COIL DESIGNS . . . . .	7-18
7.5.	POLOIDAL-FIELD SYSTEM DESIGN . . . . .	7-49
7.6.	POLOIDAL- AND TOROIDAL-FIELD PULSED LOSSES . . . . .	7-58
7.7.	COSTING . . . . .	7-70
7.8.	SUMMARY AND CONCLUSIONS . . . . .	7-74
	REFERENCES . . . . .	7-77
8.	FUSION-POWER-CORE ENGINEERING . . . . .	8-1
8.1.	INTRODUCTION . . . . .	8-1
8.2.	MATERIALS . . . . .	8-9
8.3.	MECHANICAL DESIGN . . . . .	8-58
8.4.	NEUTRONICS AND ACTIVATION . . . . .	8-64
8.5.	THERMAL ANALYSIS . . . . .	8-74
8.6.	TRITIUM PURGE-FLOW DESIGN . . . . .	8-88
8.7.	HEAT TRANSFER IN PLASMA-FACING COMPONENTS . . . . .	8-89
8.8.	SUMMARY AND CONCLUSIONS . . . . .	8-98
	REFERENCES . . . . .	8-101
9.	POWER CONVERSION . . . . .	9-1
9.1.	INTRODUCTION . . . . .	9-1
9.2.	CANDIDATE POWER CYCLES . . . . .	9-2
9.3.	STATUS OF ADVANCED RANKINE STEAM CYCLE . . . . .	9-6
9.4.	ANALYSIS OF THE REFERENCE POWER CYCLE . . . . .	9-11
9.5.	CONCLUSIONS . . . . .	9-15
	REFERENCES . . . . .	9-16

10.	ARIES-I SAFETY DESIGN AND ANALYSIS . . . . .	10-1
10.1.	INTRODUCTION . . . . .	10-1
10.2.	SAFETY GOALS IN THE ARIES-I DESIGN . . . . .	10-1
10.3.	ACCIDENT ANALYSES . . . . .	10-2
10.4.	RELEASABLE INVENTORIES AND PUBLIC DOSE . . . . .	10-8
10.5.	WASTE DISPOSAL RATINGS . . . . .	10-22
10.6.	ECONOMIC IMPACT OF SAFETY ISSUES . . . . .	10-22
10.7.	SUMMARY AND CONCLUSIONS . . . . .	10-29
	REFERENCES . . . . .	10-31
11.	DESIGN LAYOUT AND MAINTENANCE . . . . .	11-1
11.1.	INTRODUCTION . . . . .	11-1
11.2.	MAINTENANCE PHILOSOPHY . . . . .	11-1
11.3.	DESIGN DESCRIPTION/INTEGRATION . . . . .	11-4
11.4.	ARIES-I MAINTENANCE PROCEDURE . . . . .	11-11
11.5.	CONCLUSIONS . . . . .	11-17
	REFERENCES . . . . .	11-19
12.	START-UP AND OPERATIONS . . . . .	12-1
12.1.	INTRODUCTION . . . . .	12-1
12.2.	PLASMA START-UP . . . . .	12-2
12.3.	PLANT START-UP . . . . .	12-26
12.4.	SUMMARY AND CONCLUSIONS . . . . .	12-31
	REFERENCES . . . . .	12-32
A.	APPENDIX . . . . .	A-1
A.1.	TABLE OF ARIES-I REACTOR PARAMETERS . . . . .	A-1
A.2.	SYSTEMS-CODE PARAMETERS OF ARIES-I . . . . .	A-24
A.3.	COST SUMMARY OF ARIES-I REACTOR . . . . .	A-32
A.4.	COST DATA BASE FOR ARIES-I REACTOR . . . . .	A-41
	REFERENCES . . . . .	A-47

## ACKNOWLEDGMENTS

The ARIES team wishes to acknowledge the consultations and advice given by the ARIES Review Committee. Useful discussions with the following individuals on silicon-carbide-composite R&D efforts are also acknowledged: William E. Bustamante, Manager of Engineering, Amercom, Chatsworth, CA; D. P. H. Hasselman, Whittemore Professor of Materials Engineering, Virginia Polytechnic Institute and Virginia State University, Blacksburg, VA; James A. DiCarlo, Deputy Chief, Ceramics Branch, National Aeronautics and Space Administration Lewis Research Center, Cleveland, OH; John E. Garnier and William A. Graham, Lanxide/Du Pont Inc., Newark, DE; George R. Hopkins, President, Composite Engineering Company, La Jolla, CA; and John Davis, High Energy Systems Division, McDonnell Douglas Missile Systems Company, Saint Louis, MO. The authors also wish to express their appreciation to Ms. Joan George for her effort in editing and to Ms. Haya Leiner for typing this report.

The ARIES program is supported by the U.S. Department of Energy, Office of Fusion Energy, at the University of California, Los Angeles under grant DE-FG03-86ER52126; at Argonne National Laboratory under contract W-31-109-ENG-38; at General Atomics under contract DE-AC03-89ER52153; at Idaho National Engineering Laboratory under contract DE-AC07-76ID01570; at Los Alamos National Laboratory, which is operated by the University of California for the U.S. DOE under contract W-7405-ENG-36; at Massachusetts Institute of Technology under grant DE-FG02-91ER54110; at Princeton Plasma Physics Laboratory under grant DE-AC02-76CH03073; at Rensselaer Polytechnic Institute under grant DE-FG05-85ER52118; at the Georgia Institute of Technology under grant DE-FG05-87ER52141; and at the University of California, Berkeley under grant DE-FG03-89ER52154.

## ARIES-I REVIEW COMMITTEE

Charles C. Baker	Oak Ridge National Laboratory
John W. Davis	McDonnell Douglas Astronautics Company
Stephen O. Dean	Fusion Power Associates
Glenn Ducat	Southern California Edison
Douglas F. Holland	Idaho National Engineering Laboratory
Carl Johnson	Argonne National Laboratory
B. Grant Logan	Lawrence Livermore National Laboratory
Dale M. Meade	Princeton Plasma Physics Laboratory
D. Bruce Montgomery	Massachusetts Institute of Technology
John B. Whitley	Sandia National Laboratory