11:01:14 OCA PAD AMENDMENT - PROJECT HEADER INFORMATION 09/12/96

Active

Project #: E-25-638 Cost share #: Rev #: 24
Center # : 10/24-6-R6300-0A0 Center shr #: OCA file #:
Work type : RES
Contract#: DE-FG05-87ER52141 Mod #: ADM. REVISION Document : GRANT
Prime #: Contract entity: GTRC

Subprojects ? : Y CFDA: 81.049
Main project #: PE #: N/A

Project unit: MECH ENGR Unit code: 02.010.126
Project director(s):
STACEY W M JR MECH ENGR (404)894-3714

Sponsor/division names: US DEPT OF ENERGY / DOE OAK RIDGE - TN
Sponsor/division codes: 141 / 017

Award period: 870401 to 960930 (performance) 961231 (reports)

Sponsor amount	New this change	Total to date
Contract value	0.00	570,000.00
Funded	0.00	570,000.00
Cost sharing amount		0.00

Does subcontracting plan apply ?: N

Title: FUSION STUDIES PROGRAM

PROJECT ADMINISTRATION DATA

OCA contact: Jacquelyn L. Bendall 894-4820

Sponsor technical contact	Sponsor issuing office
DR. ROBERT E. PRICE, ER-533 (301)903-3565	MAURICE DAVIS (615)576-0794
J-213/GTN U.S. DOE WASHINGTON, DC 20585	U.S. DOE, OAK RIDGE OPERATIONS PROCURMENT AND CONTRACTS DIVISION P.O. BOX 2001 OAK RIDGE, TN 37831-8757

Security class (U,C,S,TS) : U ONR resident rep. is ACO (Y/N): N
Defense priority rating : N/A N/A supplemental sheet
Equipment title vests with: Sponsor GIT X
HOWEVER, NONE PROPOSED.
Administrative comments -
ISSUED TO EXTEND THE PROJECT TO 30 SEP 96 WITH THE FINAL REPORT DUE 31 DEC 96

5857 U

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 01/07/97

Project No. E-25-638 Center No. 10/24-6-R6300-0A0

Project Director STACEY W M JR School/Lab MECH ENGR

Sponsor US DEPT OF ENERGY/DOE OAK RIDGE - TN

Contract/Grant No. DE-FG05-87ER52141 Contract Entity GTRC

Prime Contract No.

Title FUSION STUDIES PROGRAM

Effective Completion Date 960930 (Performance) 961231 (Reports)

Closeout Actions Required:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	Y	961210
Final Report of Inventions and/or Subcontracts	Y	
Government Property Inventory & Related Certificate	Y	
Classified Material Certificate	N	
Release and Assignment	N	
Other	N	

Comments

Subproject Under Main Project No.

Continues Project No. E-25-C01

Distribution Required:

Project Director	Y
Administrative Network Representative	Y
GTRI Accounting/Grants and Contracts	Y
Procurement/Supply Services	Y
Research Property Managment	Y
Research Security Services	N
Reports Coordinator (OCA)	Y
GTRC	Y
Project File	Y
Other	N
	N

NOTE: Final Patent Questionnaire sent to PDPI.

E-25-638

Georgia Tech

Office of Grants and Contracts Accounting

Georgia Institute of Technology
Hinman Building
Atlanta, Georgia 30332-0259
404•894•4624; 2629
Fax: 404•894•5519

February 7, 1990

Ms. Melissa Y. Johnson, Contract Specialist
U. S. Department of Energy-Oak Ridge Operations
Procurement and Contracts Division
P. O. Box 2001
Oak Ridge, TN 37831-8758

REFERENCE: Grant #DE-FG05-87ER52141

Dear Ms. Johnson,

Enclosed in triplicate is the Financial Status Report (SF-269) for Grant No. DE-FG05-87ER52141 covering the period October 1, 1988 through November 30, 1989.

If you should have questions or need additional information, please contact Geraldine Reese of this office or me at (404) 894-2629.

Sincerely,

David V. Welch
Director

DVW/GMR/djt

Enclosures

cc: Dr. W. O. Winer, Mech. Eng. 0405
Dr. W. M. Stacey, Mech. Eng. 0405
Ms. Mary Wolfe, OCA/CSD 0420
File E-25-638/R6300-0A0

FINANCIAL STATUS REPORT
(Short Form)
(Follow instructions on the back)

1. Federal Agency and Organizational Element to Which Report is Submitted	2. Federal Grant or Other Identifying Number Assigned By Federal Agency	OMB Approval No.	Page	of
U. S. Department of Energy	DE-FG05-87ER52141	0348-0039	1	1 pages

3. Recipient Organization (Name and complete address, including ZIP code)
Georgia Tech Research Corporation
P. O. Box 100117
Atlanta, GA 30384

4. Employer Identification Number	5. Recipient Account Number or Identifying Number	6. Final Report	7. Basis
58-0603146	E-25-638/R6300-0A0	☐ Yes ☒ No	☒ Cash ☐ Accrual

8. Funding/Grant Period *(See instructions)* From: (Month, Day, Year)	To: (Month, Day, Year)	9. Period Covered by this Report From: (Month, Day, Year)	To: (Month, Day, Year)
April 01, 1987	November 30, 1990	October 01, 1988	November 30, 1989

10. Transactions:	I Previously Reported	II This Period	III Cumulative
a. Total outlays	$ 114,250.95	$ 125,749.05	$240,000.00
b. Recipient share of outlays	-0-	-0-	-0-
c. Federal share of outlays	114,250.95	125,749.05	240,000.00
d. Total unliquidated obligations			-0-
e. Recipient share of unliquidated obligations			-0-
f. Federal share of unliquidated obligations			-0-
g. Total Federal share *(Sum of lines c and f)*			240,000.00
h. Total Federal funds authorized for this funding period			240,000.00
i. Unobligated balance of Federal funds *(Line h minus line g)*			-0-

11. Indirect Expense	a. Type of Rate *(Place "X" in appropriate box)* ☐ Provisional ☐ Predetermined ☐ Final ☒ Fixed			
	b. Rate: See Below	c. Base: MTDC	d. Total Amount	e. Federal Share

12. Remarks: *Attach any explanations deemed necessary or information required by Federal sponsoring agency in compliance with governing legislation.*

GEORGIA TECH'S FISCAL YEAR ENDS JUNE 30

Questions pertaining to this report should be directed to: Geraldine Reese (404) 894-2629

13. Certification: **I certify to the best of my knowledge and belief that this report is correct and complete and that all outlays and unliquidated obligations are for the purposes set forth in the award documents.**

Typed or Printed Name and Title	Telephone (Area code, number and extension)
David V. Welch, Director, Grants and Contracts Accounting	(404) 894-2629
Signature of Authorized Certifying Official	**Date Report Submitted**
	February 7, 1990

Previous Editions not Usable

Standard Form 269A (REV 4-88)
Prescribed by OMB Circulars A-102 and A-110

	Direct Costs	Indirect Costs
FY87 @ 63.5%	$ 7,894.15	$ 5,012.79
FY88 @ 60.0%	63,108.81	37,865.28
FY89 @ 60.0%	62,371.88	37,423.12
FY90 @ 62.5%	16,199.16	10,124.81

Report Period	Direct Costs	Indirect Costs
10/01/88-06/30/89	$62,140.68	$37,284.4
07/01/89-11/30/89	16,199.16	10,124.8

E-25638

Georgia Tech

Office of Grants and Contracts Accounting

Georgia Institute of Technology
Hinman Building
Atlanta, Georgia 30332-0259
404•894•4624: 2629
Fax: 404•894•5519

January 3, 1991

Ms. Melissa Y. Johnson, Contract Specialist
U. S. Department of Energy-Oak Ridge Operations
Procurement and Contracts Division
P. O. Box 2001
Oak Ridge, TN 37831-8758

REFERENCE: Grant # DE-FG05-87ER52141

Dear Ms. Johnson,

Enclosed in triplicate is the Financial Status Report (SF-269A) for Grant No. DE-FG05-87ER52141 covering the period December 01, 1989 through November 30, 1990.

If you should have questions or need additional information, please contact Geraldine Reese of this office at (404) 894-2629.

Sincerely,

David V. Welch
Director

DVW/GMR/djt

Enclosures

cc: Dr. W. O. Winer, Mech Eng 0405
Dr. W. M. Stacey, Mech Eng 0405
Ms. Mary Wolfe, OCA/CSD 0420
File E-25-638/R6300-0A0

FINANCIAL STATUS REPORT

(Short Form)

(Follow instructions on the back)

1. Federal Agency and Organizational Element to Which Report is Submitted	2. Federal Grant or Other Identifying Number Assigned By Federal Agency	OMB Approval No.	Page	of
U. S. DEPARTMENT OF ENERGY	DE-FG05-87ER52141	0348-0039	1	1 pages

3. Recipient Organization (Name and complete address, including ZIP code)

GEORGIA TECH RESEARCH CORPORATION
P. O. BOX 100117
ATLANTA, GA 30384

4. Employer Identification Number	5. Recipient Account Number or Identifying Number	6. Final Report	7. Basis
58-0603146	E-25-638/R6300-0A0	☐ Yes ☒ No	☒ Cash ☐ Accrual

8. Funding/Grant Period *(See instructions)* From: (Month, Day, Year)	To: (Month, Day, Year)	9. Period Covered by this Report From: (Month, Day, Year)	To: (Month, Day, Year)
April 01, 1987	November 30, 1990	December 01, 1989	November 30, 1990

10. Transactions:	I Previously Reported	II This Period	III Cumulative
a. Total outlays	240,000.00	48,420.91	288,420.91
b. Recipient share of outlays	N/A	N/A	N/A
c. Federal share of outlays	240,000.00	48,420.91	288,420.91
d. Total unliquidated obligations			-0-
e. Recipient share of unliquidated obligations			N/A
f. Federal share of unliquidated obligations			-0-
g. Total Federal share *(Sum of lines c and f)*			288,420.91
h. Total Federal funds authorized for this funding period			290,000.00
i. Unobligated balance of Federal funds *(Line h minus line g)*			1,579.09

11. Indirect Expense

a. Type of Rate *(Place "X" in appropriate box)* ☐ Provisional ☐ Predetermined ☐ Final ☒ Fixed

b. Rate	c. Base	d. Total Amount	e. Federal Share
SEE ATTACHED	MTDC	$18,623.23	$18,623.23

12. *Remarks: Attach any explanations deemed necessary or information required by Federal sponsoring agency in compliance with governing legislation.*

Questions pertaining to this report should be directed to: Ms. Geraldine Reese (404) 894-2629

GEORGIA TECH'S FISCAL YEAR ENDS JUNE 30

13. Certification: **I certify to the best of my knowledge and belief that this report is correct and complete and that all outlays and unliquidated obligations are for the purposes set forth in the award documents.**

Typed or Printed Name and Title	Telephone (Area code, number and extension)
David V. Welch, Director, Grants & Contracts Accounting	(404) 894-2629
Signature of Authorized Certifying Official	**Date Report Submitted**
	January 3, 1991

Attachment

01/03/91
Contract # DE-FG05-87ER52141
Financial Status Report
Period Covering: 12/01/89 - 11/30/90

	Direct Costs	Indirect Costs
FY'87 @ 63.5%	$ 7,894.15	$ 5,012.79
FY'88 @ 60.0%	63,108.81	37,865.28
FY'89 @ 60.0%	62,371.88	37,423.12
FY'90 @ 62.5%	42,397.62	26,498.52
FY'91 @ 62.5%	3,599.22	2,249.52

Report Period

	Direct Costs	Indirect Costs
12/01/89 - 06/30/90 @62.5%	$ 26,198.46	$ 16,373.71
07/01/90 - 11/14/90 @62.5%	3,599.22	2,249.52

Georgia Tech

Office of Grants and Contracts Accounting

Georgia Institute of Technology
190 Bobby Dodd Way
Atlanta, Georgia 30332-0259
USA
404•894•4624; 2629
Fax: 404•894•5519

July 22, 1993

Ms. Melissa Y. Johnson, Contract Specialist
Special Acquisitions Branch
U. S. Department of Energy
Procurement and Contracts Division
P. O. Box 2001
Oak Ridge, TN 37831-8757

REFERENCE: Grant #DE-FG05-87ER52141

Dear Ms. Johnson,

Enclosed in triplicate is the Financial Status Report Form (SF-269A) for Grant No. DE-FG05-87ER52141 covering the period December 01, 1992 through April 30, 1993.

Please note that a final Financial Status Report Form (SF-269A) was submitted on April 5, 1993. After the report was submitted, this office received notitification of an extension to April 30, 1993 and amendment #A014 extending the termination date to April 30, 1996. This report is being submitted to comply with the budget period through April 30, 1993.

If you should have questions or need additional information, please contact Geraldine Reese of this office at (404) 894-2629.

Sincerely,

David V. Welch
Director

DVW/GMR/djt

Enclosures

c: Dr. W. O. Winer, Mech eng 0405
Dr. W. M. Stacey, OIP 0130
Ms. Wanda Simon, OCA/CSD 0420
File E-25-638/R6300-0A0

FINANCIAL STATUS REPORT

(Short Form)

(Follow instructions on the back)

1. Federal Agency and Organizational Element to Which Report is Submitted	2. Federal Grant or Other Identifying Number Assigned By Federal Agency	OMB Approval No.	Page	of
U. S. DEPARTMENT OF ENERGY	DE-FG05-87ER52141	0348-0039	1	2 pages

3. Recipient Organization (Name and complete address, including ZIP code)

GEORGIA TECH RESEARCH CORPORATION
P. O. BOX 100117
ATLANTA, GA 30384

4. Employer Identification Number	5. Recipient Account Number or Identifying Number	6. Final Report	7. Basis
58-0603146	E-25-638/R6300-0A0	☐ Yes ☒ No	☒ Cash ☐ Accrual

8. Funding/Grant Period (See instructions) From: (Month, Day, Year)	To: (Month, Day, Year)	9. Period Covered by this Report From: (Month, Day, Year)	To: (Month, Day, Year)
April 01, 1987	April 30, 1996	December 01, 1992	April 30, 1993

10. Transactions:	I Previously Reported	II This Period	III Cumulative
a. Total outlays	349,165.96	367.82	349,533.78
b. Recipient share of outlays	-0-	-0-	-0-
c. Federal share of outlays	349,165.96	367.82	349,533.78
d. Total unliquidated obligations			24.70
e. Recipient share of unliquidated obligations			-0-
f. Federal share of unliquidated obligations			24.70
g. Total Federal share (Sum of lines c and f)			349,558.48
h. Total Federal funds authorized for this funding period			350,000.00
i. Unobligated balance of Federal funds (Line h minus line g)			441.52

11. Indirect Expense

a. Type of Rate (Place "X" in appropriate box) ☒ Provisional ☐ Predetermined ☐ Final ☒ Fixed

b. Rate	c. Base	d. Total Amount	e. Federal Share
SEE ATTACHED	MTDC	130.82	130.82

12. *Remarks: Attach any explanations deemed necessary or information required by Federal sponsoring agency in compliance with governing legislation.*

Questions pertaining to this report should be directed to: Geraldine Reese (404) 894-2629

GEORGIA TECH'S FISCAL YEAR ENDS JUNE 30

13. Certification: I certify to the best of my knowledge and belief that this report is correct and complete and that all outlays and unliquidated obligations are for the purposes set forth in the award documents.

Typed or Printed Name and Title	Telephone (Area code, number and extension)
David V. Welch, Director, Grants & Contracts Accounting	(404) 894-2629
Signature of Authorized Certifying Official	**Date Report Submitted**
	07/22/93

U. S. Department of Energy
Financial Status Report (07/22/93)
Grant No. DE-FG05-87ER52141 (E-25-638/R6300-0A0)
Period Covering: 12/01/92 - 04/30/93

	Direct Costs	Direct Costs
FY'87 @ 63.5%	$ 7,894.15	$ 5,012.79
FY'88 @ 60.0%	63,108.81	37,865.28
FY'89 @ 60.0%	62,371.88	37,423.12
FY'90 @ 62.5%	42,397.62	26,498.52
FY'91 @ 62.5%	20,112.40	12,570.26
FY'92 @ 61.5%	926.76	569.97
FY'93 @ 55.2%	21,122.57	11,659.65

REPORT PERIOD

	Direct Costs	Indirect Costs
12/01/92 - 04/30/93 @ 55.2%	$ 237.00	$ 130.82

E-25-638

DOE F538 (5-86)

OMB Control No. 1910-1400

1

1987-88

U. S. DEPARTMENT OF ENERGY

NOTICE OF ENERGY RD&D PROJECT

1. Descriptive TITLE of work (150 characters including spaces)

Fusion Studies Program

2. CONTRACT or grant number DE-FG05-87ER52141

2A. MASTER contract number (GOCO's) N/A

2B. Responsible PATENT office

3. Performing organization CONTROL number (internal) E-25-638 (R6300-0A0)

3A. Budget and Reporting code AT-15-03

3B. Funding YEAR for this award 1987 & 1988

4. Original contract start date April 1, 1987

4A. Current contract start date April 1, 1987

4B. Current contract close date March 31, 1989

4C. Anticipated project termination date Continuing

5. Work STATUS

- ☐ Proposed
- ☐ Renewal
- ☒ New
- ☐ Terminated

5A. Manpower (FTE)

5B. CONGRESSIONAL district 5th

5C. STATE or Country where work is being performed Georgia

5D. COUNTRY sponsoring research USA

6. Name of PERFORMING organization Georgia Tech Research Corporation

6A. DEPARTMENT or DIVISION	6B. Street Address	6C. City, State, Zip Code
Mechanical Eng./Nuclear Eng. & HP		Atlanta, GA 30332

7. Circle only one code for TYPE of Organization Performing R&D:

XX (CU) - College, university, or trade school
FF - Federally funded RD&D centers or laboratory operated for an agency of the U. S. Government
IN - Private industry
NP - Foundation or laboratory not operated for profit
ST - Regional, state or local government facility
TA - Trade or professional organization
US - Federal agency
XX - Other
EG - Electric or gas utility

8A. Contractor's PRINCIPAL INVESTIGATOR/s or project manager Name/s (Last, First, MI) Stacey, Weston M.

8B. PHONE/s (in order of PI names with commercial followed by FTS)

Comm. 404/894-3714 ; FTS ; Comm. ; FTS

8C. PI/s address (if different from that of Performing Organization)

Georgia Institute of Technology, Mechanical Eng./Nuclear Eng. & Health Physics Programs, Atlanta, GA 30332

12. PUBLICATIONS available to the public. List the five most descriptive publications that have resulted from this project in the last year that are available to the public. (Include author, title, where published, year of publication, and any other information you have to complete full bibliographic citation.) Use the back of this form or additional sheets if necessary.

1. W.M. Stacey, Jr. et al, "Rotation and Impurity Transport in a Tokamak Plasma with Directed Neutral Beam Injection", Nucl. Fusion, 25, 463 (1985); also Ga. Tech report GTFR-47.

2. W.M. Stacey, C.M. Ryu and M.A. Malik, "Analysis of the Unbalanced NBI Rotation Experiments In the ISX-B, PLT and PDX Tokamaks", Nucl. Fusion, 26, 293 (1986); also Ga. Tech report GTFR-59.

3. K.R. Davey, "3-D Transient Eddy Current Calculations for the Felix Cylinder Experiments", Ga. Tech report GTFR-64.

4. A. Krauss, D. Gruen, J. Brooks and B. DeWald, "Composite Materials for High Heat and Particle Flux Components in Fusion Devices", Ga. Tech report GTFR-66.

5. M.A. Malik, W.M. Stacey and C.E. Thomas, "Analysis of Neutral Beam Driven Impurity Flow Reversal In PLT", Ga. Tech report GTFR-67.

13. KEYWORDS (Listed five terms describing the technical aspects of the project. List specific chemicals and CAS number, if applicable.)

Impurity control, fusion, current drive

14. RESPONDENT. Name and address of person filling out the Form 538. Give telephone number, including extension (if you have FTS number, please include it) at which person can be reached. Record the date this form was completed or updated. The information in Item 14 will not be published.

Respondent's Name: Weston M. Stacey, Jr. Phone No.: 404/ 894-3758 Date: 4/29/87

Street: School of Nuclear Engineering and Health Physics
Georgia Institute of Technology

City: Atlanta State: GA Zip: 30332

DOE F538 (5-86)

OMB Control No. 1910-1400

U. S. DEPARTMENT OF ENERGY
NOTICE OF ENERGY RD&D PROJECT

E-25-638

3

1988-89

1. Descriptive TITLE of work (150 characters including spaces)

   Fusion Studies Program

2. CONTRACT or grant number DE-FG05-87ER52141

2A. MASTER contract number (GOCO's) N/A

2B. Responsible PATENT office

3. Performing organization CONTROL number (internal) E-25-638 (R6300-0A0)

3A. Budget and Reporting code AT-15-03

3B. Funding YEAR for this award 1988 & 1989

4. Original contract start date 1978

4A. Current contract start date April, 1987

4B. Current contract close date March, 1988

4C. Anticipated project termination date continuing

5. Work STATUS

   ☐ Proposed ☒ Renewal
   ☐ New ☐ Terminated

5A. Manpower (FTE)

5B. CONGRESSIONAL district 5th

5C. STATE or Country where work is being performed Georgia

5D. COUNTRY sponsoring research USA

6. Name of PERFORMING organization Georgia Tech Research Corporation

6A. DEPARTMENT or DIVISION Mechanical Eng./Nuclear Eng. & HP

6B. Street Address

6C. City, State, Zip Code Atlanta, GA 30332

7. Circle only one code for TYPE of Organization Performing R&D:

   XX (CU) - College, university, or trade school
   FF - Federally funded RD&D centers or laboratory operated for an agency of the U. S. Government
   IN - Private industry
   NP - Foundation or laboratory not operated for profit
   ST - Regional, state or local government facility
   TA - Trade or professional organization
   US - Federal agency
   XX - Other
   EG - Electric or gas utility

8A. Contractor's PRINCIPAL INVESTIGATOR/s or project manager Name/s (Last, First, MI) Stacey, Weston M.

8B. PHONE/s (in order of PI names with commercial followed by FTS)

   Comm. 404/894-3714 ; FTS ; Comm. ; FTS

8C. PI/s address (if different from that of Performing Organization)

   Georgia Institute of Technology, Mechanical Eng./Nuclear Eng. & Health Physics Programs, Atlanta, GA 30332

9. DOE SUPPORTING Organization (DOE Assistant Secretary and office sponsoring the work; technical monitor; and administrative monitor).

9A. PROGRAM division or office (full name) Office of Fusion Energy, Dept. of Energy — Program Office Code

9B. TECHNICAL monitor (Last, First, MI) Dowling, R.J. - D&T Division

9C. Address Office of Fusion Energy
Mail Stop 256,
Washington, D.C.

9D. Phone Comm. 301/353-4954
FTS

9E. ADMINISTRATIVE monitor (Last, First, MI) Mynatt, W.A. - Contract Management

10. FUNDING in thousands of dollars (K$). Funds represent budget obligations for operating and capital equipment (FY runs October 1 – September 30).

Funding organization(s)	Current FY 88	Next FY 90
A. DOE	$95,540	$95,540
B.		
C.		

10D. Does the current FUNDING cover more than one year's work? Yes ___ No X

E. If yes, provide dates (from when to when).

11. Descriptive SUMMARY of work. Enter a Project Summary using complete sentences limited to 200 words covering the following: Objective(s), state project objectives quantifying where possible (e.g., "The project objective is to demonstrate 95% recovery of sulphur from raw gas with molten salt recycling at a rate of one gallon per minute."); approach, describe the technical approach used (how the work is to be done); expected product/results, describe the final products or results expected from the project and their importance and relevance.

It is proposed to continue work on the development of innovative plasma engineering techniques that promise to reduce technology requirements for tokamak reactors and to apply those techniques to analyses in support of the ITER and Commercial Tokamak Studies.

12. PUBLICATIONS available to the public. List the five most descriptive publications that have resulted from this project in the last year that are available to the public. (Include author, title, where published, year of publication, and any other information you have to complete full bibliographic citation.) Use the back of this form or additional sheets if necessary.

1. "Analysis of the Unbalanced NBI Rotation Experiments in the ISX-B, PLT and PDX Tokamaks", Nucl. Fusion, 26, 293 (1986); with C.M. Ryu, M.A. Malik.

2. "Impurity Asymmetries and Radial Transport Produced by Asymmetric Impurity Sources", Nucl. Fusion, 27, 1213 (1987).

3. "Helium Flow Reversal with NBI and ECH in TIBER", Fusion Techn., to be published; with others.

4. M.A. Malik, W.M. Stacey, and C.E. Thomas, "Analysis of Neutral Beam Driven Impurity Flow Reversal in PLT", GTFR-67; October 1986.

5. M.A. Malik and W.M. Stacey, "Neutral Beam Driven Impurity Flow Reversal as an Impurity Control Scheme for INTOR", GTFR-68; October 1986.

6. M.A. Malik and W.M. Stacey, "Preliminary Analysis of the Neutral Beam Driven Impurity Flow Reversal in Tiber II", GTFR-72; April 1987.

7. M.A. Malik, J. Mandrekas, W.M. Stacey, and T.W. Ogden, "Impurity Flow Reversal in Tiber II", GTFR-74; July 1987.

8. W.M. Stacey, "Explanation of the Degradation of Energy Confinement in TFTR with Unbalanced Neutral Beam Injection", GTFR-76; October 1987.

9. W.M. Stacey, "Analysis of the Unbalanced Neutral Beam Power Scan Rotation Experiments in TFTR", GTFR-77; October 1987.

13. KEYWORDS (Listed five terms describing the technical aspects of the project. List specific chemicals and CAS number, if applicable.)

Fusion, Tokamak, Energy Confinement

14. RESPONDENT. Name and address of person filling out the Form 538. Give telephone number, including extension (if you have FTS number, please include it) at which person can be reached. Record the date this form was completed or updated. The information in Item 14 will not be published.

Respondent's Name: Weston M. Stacey, Jr. Phone No.: 404/894-3714 Date: 1/25/88

School of Nuclear Engineering and Health Physics

Street: Georgia Institute of Technology

City: Atlanta State: GA Zip: 30332

15. Additional space for furnishing information in items 1 to 14. (Indicate item numbers to which answers apply.)

Item No.	

NOTICE: Return this form to the office indicated in the reporting requirements for your award agreement covering this project. If you have completed a similar programmatic office project description during the current Fiscal Year, complete only the new data elements on this form and send it and a copy of the description completed earlier to Department of Energy, Office of Scientific Information, P. O. Box 62, Oak Ridge, TN 37831.

E-25-638
2
1988-89

A. RECENT ACCOMPLISHMENTS IN THE GEORGIA TECH FUSION STUDIES PROGRAM

The principal emphasis of work within the GIT Fusion Studies Program is on plasma engineering innovations that have the potential for reducing the technological requirements for near-term and commercial tokamak reactors. The secondary emphasis is on innovative solutions to technological problems for tokamaks.

1. NBI IMPURITY FLOW REVERSAL

In a series of papers [1-4], we have developed a self-consistent calculational model for the effect of unbalanced neutral beam injection on impurity transport. We were the first to predict [2] that co-injection would tend to drive impurities radially outward, while counter-injection would drive them inward, introducing thereby the possibility of using NBI for impurity control. Subsequent experiments in PLT [5-7], ISX-B [8,9] and TFTR [10] have all found that central impurity accumulation is several times greater with counter-injection than with co-injection, and there is evidence in ISX-B [9] that co-injection drives impurities out of the center of the plasma, in qualitative agreement with the prediction of our calculational model. The data from one set of PLT experiments [7] are particularly amenable to analysis. An analysis [11,12,13] based upon a preliminary version [2] of the calculational model and carried out as doctoral research, yielded relatively good agreement between predictions and experiment. A more recent analysis [14] of the same experiment, based upon a more complete version of the calculational model [4] and also carried out as doctoral research, yielded excellent agreement between prediction and experiment. Analysis of the other experiments is currently in progress as doctoral research. In a recently completed doctoral thesis [15], the fluid formulation and associated constitutive relations which are used in our calculations model were derived from kinetic theory.

Application of the calculational model to commercial (STARFIRE [12]) and near-term (FED [12], INTOR [16] and TIBER [17,18) tokamak reactor designs indicates that 25-75 MW of co-injected NB power should be sufficient to prevent edge-produced impurities from penetrating to the central plasma region. This introduces the possibility that co-injected NB could be used to produce a clean central plasma and a cool, radiating, edge plasma, thereby reducing the technological requirements upon the principal impurity control and plasma interface systems.

The combined usage of NBI for heating, current-drive and impurity control was one of the innovations identified at a recent IAEA specialists' meeting [19] as having substantial potential for improving the tokamak as a reactor concept. The input to this meeting on NBI impurity control was based upon the above-mentioned work.

2. MOMENTUM CONFINEMENT WITH UNBALANCED NBI

Because the self-consistent impurity transport model described in the previous section is based upon particle and momentum balance, the rate at which toroidal momentum input by the NBI is transported radially is an important parameter in the model. We have developed a calculational model for the radial transport of toroidal momentum [20], based upon gyroviscosity. We have derived [15] the gyroviscous stress tensor from kinetic theory. This model has been applied to calculate rotation velocities and momentum confinement times in ISX-B, PLT and PDX [21] and in TFTR [22], with good agreement being obtained between the predicted and measured values. This first-principle calculational model for the radial transport rate of toroidal momentum allows the NBI impurity flow reversal theory of the previous section to be extrapolated to future reactors, in addition to providing an explanation for measured rotation velocities and momentum confinement times in present experiments.

3. ENERGY CONFINEMENT DEGRADATION WITH UNBALANCED NBI

When the toroidal rotation velocity of the bulk plasma, which is driven by unbalanced NBI, is comparable to the thermal velocity, the work done by the rotating plasma against the pressure tensor becomes a significant contribution to the radial energy flux. This additional energy loss mechanism has been evaluated [23] using the gyroviscous stress tensor we had previously developed [20]. A calculational model for the degradation of energy confinement time with increasing toroidal rotation velocity was developed and shown to make predictions in good agreement with measurements made in one set of TFTR co-injected NBI experiments [23].

Thus, with NBI, our calculational model predicts that energy confinement is maximized when the beams are balanced (i.e. there is no net momentum input, hence no rotation). This prediction is in qualitative agreement with recent measurements in TFTR.

4. NBI CURRENT DRIVE

We have performed NBI current drive studies in support of the TIBER-II design and have carried out a sensitivity study for NBI current drive in TIBER-II, INTOR and the current US version of ITER [24], using the standard NBI current drive theory. The sensitivity of the current drive efficiency to variations in the design parameters was established for these three design points, which span the range that probably will be considered for ITER.

An improved calculational model for NBI current drive was developed [25]. This model includes the radial transport of momentum and the effect of the rotating background plasma ions. Preliminary model problem calculations for TFTR (which are still in progress) with this improved model predict current drive efficiencies as much as two times those predicted by the standard theory. This result potentially makes NBI an extremely attractive current drive option, subject to confirmation of the calculational model.

5. RF IMPURITY FLOW REVERSAL

When a tokamak plasma is heated with ECRH or ICRH the energy goes mainly into the perpendicular (to the magnetic field) component of the velocity. This enhancement of the perpendicular velocity relative to the parallel velocity increases the fraction of resonant particles (electrons for ECRH, ions for ICRH), thereby enhancing the number of resonant particles trapped in the magnetic well on the outboard of the torus, which produces a poloidal variation in the electrostatic potential, ϕ. It has been estimated that this poloidal variation in ϕ can be $O(\varepsilon)$.

We have shown [26] that an $O(\varepsilon)$ poloidal variation in ϕ drives a radial transport flux of impurities which is comparable to the radial flux driven by the pressure gradient (Pfirsh-Schlüter) flux in present experiments. When the plasma current and toroidal field are parallel, the predicted impurity transport flux driven by this poloidal variation in ϕ is radially outward for ECRH and inward for ICRH, and conversely when the plasma current and toroidal electric field are anti-parallel.

This result may in part explain the observation of enhanced central impurity accumulation in ICRH experiments. More importantly, it indicates that ECRH or ICRH can potentially be used to reverse the normally inward flow of impurities from the plasma edge, thus acting as an impurity control mechanism to reduce the technological requirements upon the divertor and first-wall systems. We have performed preliminary calculations for TIBER-II [17,18] which indicate that RF flow reversal could be a significant effect if $O(\varepsilon)$ variations in ϕ are produced.

6. LIMITER LOCATION

We have shown [27] that a poloidally localized impurity source alters impurity transport (relative to a poloidally uniform impurity source). Thus, it is possible to choose the poloidal location of limiters (the impurity source) in such a way as to minimize the inward transport of the limiter-sputtered impurity. We have identified [27] such locations for the different possible orientations of the plasma current and the toroidal field.

7. PLASMA-WALL INTERACTIONS

The concept of replenishing a low-Z surface by diffusion of the low-Z component of a binary alloy (e.g. Li in Cu-Li) has been developed and extensively analyzed [28-36]. These analyses, and supporting experiments at ANL, indicate that it would be possible to maintain a low-Z surface on a divertor plate or limiter, so that active impurity control requirements would be substantially reduced.

The magnitude of the sputtering yield of a surface material depends upon the energy and angle of incidence of the impinging particle from the plasma, which in turn depend upon the details of the acceleration of that particle across the sheath separating the plasma and the surface. We have developed [37] a sheath model which takes into account the angle of incidence of the magnetic field to the surface and have calculated sputtering yields for materials of interest in INTOR.

8. ELECTROMAGNETICS

We have carried out calculations [38-40] to investigate ways to design tokamak reactors with small toroidal field coil bores but which have acceptable field ripple at the plasma. We considered the use of novel ripple reduction poloidal field coils and of ferromagnetic inserts. We determined that a substantial reduction in TFC bore was possible with the use of either of these techniques.

A novel method for making eddy current calculations, which is much more computationally economical than the standard finite-element method, has been developed and successfully applied to analyze the ANL FELIX experiments [41] and benchmark problems [42].

9. SUMMARY

We have developed two innovative methods for impurity control-neutral beam impurity flow reversal and rf impurity flow reversal - which have the potential of reducing, or eliminating, the technological requirements on the principal impurity control system. We have partially verified the former method by comparison with experiment, and we have made preliminary evaluation of the use of both methods in future tokamak reactors.

We have developed a model for the gyroviscous stress in a rotating tokamak plasma. We have shown, by comparison with experiment, that this model can account for a large part of the momentum confinement time and the degradation of energy confinement time that is observed in rotating plasmas. This allows a first-principle extrapolation of the NB impurity flow reversal model to future tokamak reactors and allows a prediction of the degradation in energy confinement that would occur with unbalanced NBI.

The NBI current drive model has been extended to self-consistently take into account the radial transport of the deposited beam momentum and the background ion current contribution. Preliminary calculations indicate that the current drive efficiency may be as much as 2 times larger than heretofore predicted.

We have developed a model that allows the prediction of the poloidal location of a limiter which would minimize the inward transport of limiter-sputtered impurities.

We have developed the concept of a self-replenishing low-Z surface via diffusion of the low-Z component in a binary alloy and have performed substantial analysis in support of that concept. This could allow a divertor plate or limiter lifetime to be increased substantially.

We have developed concepts for reducing the toroidal field ripple, which would allow smaller toroidal field coils to be used in tokamak reactors. We also have developed a novel method for eddy current calculations.

B. PROPOSED CONTINUED WORK IN SUPPORT OF TOKAMAK REACTOR STUDIES BY THE GEORGIA TECH FUSION STUDIES PROGRAM

We propose to continue work in three areas -- NBI impurity flow reversal, NBI current drive and RF impurity flow reversal -- and to evaluate the relative merits of balanced vs. unbalanced NBI. The proposed work will support the ongoing ITER and Commercial Tokamak Reactor (CTR) studies in two ways. First, the development and validation of innovative impurity control schemes and improved current drive models which could reduce technological requirements generically support any study of a future tokamak reactor by providing options for improving the design performance. Second, the evaluation of NBI and RF impurity flow reversal, NBI current drive, and the energy confinement degradation with the unbalanced NBI that is necessary for flow reversal and current drive for the ITER and Commercial Tokamak reactors provides direct support to those design activities. We have an unique capability, in terms of familiarity with the theory in the calculational models and of availability of codes that contain the calculational models, to perform the proposed work.

1. NBI Impurity Flow Reversal (see A.1)

A one-dimensional, time-dependent impurity transport code, which is based upon the self-consistent model [4], has been under development during the past year. This code, which is operational, will be completed. A new atomic physics package will be created for scandium, to allow analysis of the most recent PLT experiments, and for such other impurities as may be needed in the analysis of ITER or CTR. The atomic physics package is needed to calculate impurity radiation. This time-dependent code will allow analysis of the evolution of the impurity density from an edge or volumetric impurity source.

Analyses of the PLT [6,7] and ISX-B [8,9] impurity accumulation experiments will be completed. This will serve to validate the model and provide the basis for confidence in the subsequent predictions that will be made for ITER and CTR.

The use of Co-injected NBI for alpha and wall-sputtered impurity control in ITER and CTR would be evaluated. The beam power required to maintain an acceptably clean central plasma would be calculated with the time-dependent code. The possibility of establishing and maintaining a cool, radiating plasma edge would be examined. Sensitivity studies would be performed to determine how to optimize the design parameters with respect to maximizing NBI impurity flow reversal. The results of this work would allow the ITER and CTR designers to evaluate the extent to which NBI impurity flow reversal could reduce the technological requirements on the main impurity control and first-wall systems in their designs and to evaluate the technological requirements for NBI impurity flow reversal.

2. <u>NBI Current Drive</u> (see A.4)

We would complete the development of the new model for NBI CD which incorporates effects due to the radial transfer of toroidal momentum and the current component due to the rotation of the background ions. We would check this model against NBI CD experiments in DITE and TFTR.

We would apply the newly developed model for NBI CD to ITER and CTR to establish current drive efficiencies. Sensitivity studies would be performed to learn how these designs could be optimized for NBI CD. The results are expected to be quite different than the results that have been obtained using the standard models for NBI CD, because the new model incorporates several new phenomena. The results of this work would allow the ITER and CTR designers to evaluate the technological requirements for using NBI CD and to understand how to optimize their designs for NBI CD.

3. Directed vs. Balanced NBI

If NBI is used in ITER or CTR, a choice must be made between balanced and directed (net CO or CTR) injection. Balanced injection optimizes energy confinement (see A.3.). On the other hand, CO or CTR injection is needed for current drive, and it is not yet known which direction would be optimal. Finally, CO aids and CTR degrades impurity control. Thus, there is a trade-off which must be made.

We would carry out comparative studies of balanced and directed NBI on ITER and CTR, taking into account energy confinement degradation, impurity flow reversal and current drive. The information which would be developed would provide the basis that would enable the ITER and CTR designers to take into account energy confinement degradation and impurity flow reversal considerations in evaluating NBI as a heating and current drive system, and to make a choice between balanced and directed NBI.

4. RF Impurity Flow Reversal (see A.5)

The present model for rf impurity flow reversal is restricted to plasmas in the collisional regime. We would extend the model to arbitrary collisional regimes, making use of the same type of transport formalism that is used in the NBI impurity flow reversal model. We would next include the extended model in the time-dependent impurity transport code that has been developed for NBI impurity flow reversal, which would allow calculation of the evolution of the impurity density distribution from a given edge or volumetric impurity source. We would develop a model to relate absorbed RF power to the magnitude of the resulting poloidal variation in electrostatic potential and incorporate this model in the time-dependent code, thus enabling the rf power required to achieve a given level of impurity flow reversal to be calculated. We would check the computational model against ECRH and ICRH experiments, to the extent that data on impurity accumulation are available.

We would apply the computational model to ITER and CTR to evaluate the efficacy of and technological requirements for rf impurity flow reversal in these designs. We would perform sensitivity studies to determine how these designs could be optimized for rf impurity flow reversal. The information provided by this work would enable the ITER and CTR designers to include impurity flow reversal considerations into their choice of rf heating and current drive systems and to evaluate the technological requirements for rf impurity flow reversal.

REFERENCES

1. W.M. Stacey, D.J. Sigmar, Phys. Fluids, 22, 2000 (1979).
2. W.M. Stacey, D.J. Sigmar, Nucl. Fusion, 19, 1665 (1979).
3. W.M. Stacey, D.J. Sigmar, Phys. Fluids, 27, 2076 (1984).
4. W.M. Stacey, A.W. Bailey, D.J. Sigmar, K.C. Shaing, Nucl. Fusion, 25, 463 (1985).
5. D.R. Eames, "Ultra-soft X-ray Emission from the Princeton Large Torus Tokamak", Ph.D. Thesis, Princeton University (1981).
6. S. Suckewer, et al., Nucl. Fusion, 21, 981 (1981).
7. S. Suckewer, et al., Nucl. Fusion, 24, 815 (1984).
8. C.E. Bush, et al., Nucl. Fusion, 23, 67 (1983).
9. R.C. Isler, et al., Nucl. Fusion, 23, 1017 (1983).
10. K.L. Wong, et al., "Impurity Penetration in a Rotating Plasma - Theory and Experiment", Proc. 14th European Conf. on Controlled Fusion and Plasma Physics, Madrid (1987).
11. W.M. Stacey, R.B. Bennett, D.J. Sigmar, J. Nucl. Mat. 121, 82 (1984).
12. R.B. Bennett, W.M. Stacey, Nucl. Sci & Eng., 88, 475 (1984).
13. R.B. Bennett, "Neutral Beam Driven Impurity Flow Reversal in Tokamaks", Ph.D. Thesis, Georgia Institute of Technology (1984).
14. M.A. Malik, W.M. Stacey, C.E. Thomas, "Analysis of Neutral Beam Driven Impurity Flow Reversal in PLT" Ga. Tech report GTFR-67 (1986).

15. G.W. Neeley, "Ion Transport Theory for a Strongly Rotating Beam - Injected Tokamak Plasma", Ph.D. Thesis, Georgia Institute of Technology (1987).

16. M.A. Malik, W.M. Stacey, "Neutral Beam Impurity Flow Reversal as an Impurity Control Scheme for INTOR", Georgia Tech report GTFR-68 (1986).

17. J. Mandrekas, et al., "Impurity Flow Reversal in TIBER-II", Georgia Tech report GTFR-74 (1987).

18. M.A. Malik, et al., "Helium Flow Reversal with Neutral Beam Injection and Electron Cyclotron Resonance Heating in TIBER", Fusion Techn., to be published (1988).

19. "Tokamak Concept Innovations" IAEA report IAEA-TECDOC-373, Vienna (1986).

20. W.M. Stacey, D.J. Sigmar, Phys. Fluids, 28, 2800 (1985).

21. W.M. Stacey, C.M. Ryu, M.A. Malik, Nucl. Fusion, 26, 293 (1986).

22. W.M. Stacey, "Analysis of the Unbalanced Neutral Beam Power Scan Rotation Experiments in TFTR", Georgia Tech report GTFR-77 (1987).

23. W.M. Stacey, "Explanation of the Degradation of Energy Confinement in TFTR with Unbalanced NBI", Georgia Tech report GTFR-76 (1987).

24. G. Pautasso, J. Mandrekas, W.M. Stacey, "NBI Current Drive Sensitivity Study for TIBER-II, ITER-US and INTOR", Georgia Tech report GTFR-78 (1988).

25. W.M. Stacey, J. Mandrekas, "An Improved Model for Neutral Beam Current Drive", Georgia Tech report GTFR-79 (1988).

26. W.M. Stacey, "The Effect of Poloidal Electric Fields on Impurity Asymmetries and Transport in Tokamaks", Georgia Tech report GTFR-63 (1986).

27. W.M. Stacey, Nucl. Fusion, 27, 1213 (1987).

28. A.B. DeWald, "A Study of Self-Sustaining Thin Films as a Means of Fusion Plasma Impurity and Wall Erosion Control", Ph.D. Thesis, Georgia Institute of Technology (1984).

29. A.B. DeWald, A.R. Krauss, D.M. Gruen, J. Nucl. Mat., 121, 398 (1984).

30. A.B. DeWald, et al., J. Nucl. Mat., 128, 570 (1984).

31. A.B. DeWald, et al., Fusion Techn., 8, 1269 (1985).

32. A.B. DeWald, et al., Radiation Effects, 89, 129 (1985).

33. A.B. DeWald, et al., Fusion Techn., 8, 1275 (1985).

34. A.B. DeWald, et al., J. Vac. Sci. Techn. A, 4, 1227 (1986).

35. A.B. DeWald, et al., J. Nucl. Mat., 145, 373 (1987).

36. A.B. DeWald, et al., J. Vac. Sci. Techn. A, 5, 2763 (1987).

37. A.B. DeWald, A.W. Bailey, J.N. Brooks, Phys. Fluids, 30, 267 (1987)

38. G.R. Bateman, "Ripple Reduction Poloidal Field Coils for Tokamak Reactors", Georgia Tech report GTFR-37 (1983).

39. G.R. Bateman, J.R. Fox, "Ripple Reduction Coils for Tokamak Reactors", Georgia Tech report GTFR-41 (1983).

40. G.R. Bateman, J.R. Fox, "Smaller Coil Systems for Tokamak Reactors", Georgia Tech report GTFR-45 (1983).

41. H.C. Han, K.R. Davey, L. Turner, "Calculations of Transient Fields in the FELIX Experiments at Argonne Using Null Field Integrated Techniques", Goergia Tech report GTFR-60 (1985).

42. K.R. Davey, "5th International Eddy Current Workshop", Georgia Tech report GTFR-71 (1987).

ER F 4620.1
(4-85)

U.S. Department of Energy

OER Grant Application Budget Summary

(See Reverse for Definitions and Instructions)

OMB Appr
No. 1910-

Please Print or Type

Organization:	Period Covering:	FOR ER USE ONLY
GEORGIA TECH RESEARCH CORPORATION	From: 4/1/88	Proposal No:
Principal Investigator (P.I.)/Project Director (P.D.):	To: 3/31/89	Award No.:

A. SENIOR PERSONNEL PI/PD Co PIs, Faculty and Other Senior Associates (List each separately with title, A.6 show number in brackets. Attach separate sheet, if required.)	DOE Funded Persons-Mos Cal.	Acad.	Sumr.	Funds Requested By Proposer $
1. W.M. Stacey, Principal Investigator	2.4			21,000
2. J. Mandrekas	10.0			26,821
3.				
4.				
5.				
6. (2) TOTAL SENIOR PERSONNEL (1-5)				47,821
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)				
1. ( ) POST DOCTORAL ASSOCIATES				
2. ( ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)				
3. (4) GRADUATE STUDENTS	48			40,000
4. ( ) UNDERGRADUATE STUDENTS				
5. (1) SECRETARIAL-CLERICAL (25% time)				5,000
6. ( ) OTHER				
TOTAL SALARIES AND WAGES (A + B)				92,821
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS) 27.6% of A1 & A2 and B.5				14,579
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				107,400
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM)				
TOTAL PERMANENT EQUIPMENT				
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				10,000
2. FOREIGN				•
F. OTHER DIRECT COSTS				
1. MATERIALS AND SUPPLIES				2,000
2. PUBLICATION COSTS/PAGE CHARGES				
3. CONSULTANT SERVICES				
4. COMPUTER (ADPE) SERVICES				
5. CONTRACTS AND SUBGRANTS				
6. OTHER				
TOTAL OTHER DIRECT COSTS				2,000
G. TOTAL DIRECT COSTS (A THROUGH F)				119,400
H. INDIRECT COSTS (SPECIFY RATE AND BASE)				
TOTAL INDIRECT COSTS (60% of G)				71,640
I. TOTAL DIRECT AND DIRECT COSTS (G & H)				191,040
J. PROPOSERS COST SHARING (IF ANY)				0
K. TOTAL AMOUNT OF THIS REQUEST (ITEM I LESS ITEM J)				191,040

PI/PD TYPED NAME & SIGNATURE	DATE
for Dr. W.M. Stacey	1/25/88
INST. REP. TYPED NAME & SIGNATURE	DATE
Jerry Goldbaugh	1/25/88

ER-F-4620.1A
(4-85)

U.S. Department of Energy

OER GRANT APPLICATION
TOTAL PROJECT PERIOD COSTS

OMB Approval
No. 1910-1400

(Must be completed for all new and renewal applications.)

Categories	01 Budget Period	02 Budget Period	03 Budget Period	04 Budget Period	05 Budget Period
A. Senior Personnel Totals	47,821				
B. Other Personnel Totals	45,000				
C. Fringe Benefit Totals	14,579				
Total of A, B & C	107,400				
D. Equipment					
E. Travel 1. Domestic	10,000				
2. Foreign					
F. Other Direct Costs	2,000				
G. Total Direct Costs	119,400				
H. Total Indirect Costs	71,640				
I. Total Direct & Indirect Costs	191,040				
J. Proposers Cost-Sharing (If any)					
K. Total Amount of Request	(1)* 191,040	(2)	(3)	(4)	(5)

*This should equal Item K on Budget Period Summary (ER-F-4620.1)

ESTIMATE

TOTAL COST OF PROJECT

$ 191,040

(add K1 thru 5)

E25-638

4 1989-90

DOE F 1332.16 (10-84)
(Formerly RA-427)

OMB Approval
No. 1910-1400

U. S. DEPARTMENT OF ENERGY

UNIVERSITY CONTRACTOR, GRANTEE, AND COOPERATIVE AGREEMENT RECOMMENDATIONS FOR ANNOUNCEMENT AND DISTRIBUTION OF DOCUMENTS

See Instructions on Reverse Side

1. DOE Report No.

2. DOE Contract No. DE-FG05-87ER52141

3. Title Annual Performance Report Fusion Studies Program

4. Type of Document ("x" one)
 - ☐ a. Scientific and technical report
 - ☐ b. Conference paper:
   - Title of conference ______
   - Date of conference ______
   - Exact location of conference ______
   - Sponsoring organization ______
 - ☒ c. Other (Specify) Progress Report

5. Recommended Announcement and Distribution ("x" one)
 - ☒ a. Unrestricted unlimited distribution.
 - ☐ b. Make available only within DOE and to DOE contractors and other U. S. Government agencies and their contractors.
 - ☐ c. Other (Specify) ______

6. Reason for Recommended Restrictions

7. Patent and Copyright Information:
 Does this information product disclose any new equipment, process, or material? ☒ No ☐ Yes If so, identify page nos. ______
 Has an invention disclosure been submitted to DOE covering any aspect of this information product? ☒ No ☐ Yes
 If so, identify the DOE (or other) disclosure number and to whom the disclosure was submitted.
 Are there any patent-related objections to the release of this information product? ☒ No ☐ Yes If so, state these objections.
 Does this information product contain copyrighted material? ☒ No ☐ Yes
 If so, identify the page numbers ______ and attach the license or other authority for the government to reproduce.

8. Submitted by Name and Position (Please print or type)
 W. M. Stacey, Jr., Professor
 Organization Georgia Tech, Atlanta, GA 30332
 School od Mechanical Engineering, Nuclear Engineering Program

Signature	Phone	Date
	404-894-3714	5/1/90

FOR DOE OR OTHER AUTHORIZED USE ONLY

9. Patent Clearance ("x" one)
 - ☐ a. DOE patent clearance has been granted by responsible DOE patent group.
 - ☐ b. Report has been sent to responsible DOE patent group for clearance.

MAY 1990

ANNUAL PERFORMANCE REPORT

FUSION STUDIES PROGRAM

DOE GRANT DE-FG05-87ER52141

(Georgia Tech Account E25-638)

Work under the Fusion Studies Program during this report period has been concentrated in two activities, participation in the ARIES project and development of methodology for assessing the feasibility of transport-enhanced fueling and impurity control using ECRH or ICRH.

1. PARTICIPATION IN ARIES

Since mid-1988, our group has been participating in the Advanced Reactor Innovation and Evaluation Study (ARIES). During the design of the first ARIES vision, the ARIES-I High Field tokamak reactor, our primary contribution was in the evaluation of neutral beam current drive as a possible scenario for the steady-state operation of the reactor.

We upgraded our computational tools to be able to calculate neutral beam deposition in 2-D flux surface geometry using the latest information about the beam stopping cross sections including multistep ionization effects. The calculation of the neutral beam driven current is self-consistent, including the bootstrap current contribution.

Our calculations indicated that the required seed current for the ARIES-I reactor can be driven using high energy negative-ion based neutral beams, with an acceptable current drive efficiency ($\simeq$ 0.05 A/W) [1,2]. The neutral beam system considered for the ARIES-I study was based on a design concept developed at ORNL and employing radio frequency quadrupole (RFQ) accelerators to produce the high energies (2-3 MeV) required. Based on our calculations, NB current drive has been selected as the backup current drive method for ARIES-I (fast wave current drive was selected as the primary current drive scenario because of the unavailability to the ARIES project of personnel experienced in designing the NB system).

As part of our NB current drive work we also developed a new theory for the calculation of NB driven currents in tokamaks, including for the first time the effects of plasma rotation and fast-ion bootstrap current [3]. While we found that these effects can be important in present-day devices, they would play a smaller role in reactors like ARIES-I due to the small momentum-per-ion deposited by the multi-MeV beams envisioned for use in these large devices.

The ARIES project is now in the beginning of the evaluation of the ARIES-II vision, which is a D-T tokamak reactor operating in the second stability regime. Current profile control is very important for reaching this regime and also for remaining there. Therefore, NB current drive may still have a role to play due to its excellent profile control capabilities, and we intend to continue our NB calculations for ARIES-II. At the same time, we are looking at passive current drive methods associated with the fusion products, which can be due either to the anisotropic distribution of the fusion products or due to their contribution to the bootstrap current.

A recently initiated contribution of our group in the ARIES-II design is in the area of Burn Control. Preliminary calculations by the MHD Stability group indicate that due to the high poloidal beta operation of the ARIES-II reactor, the resulting bootstrap current can be several times the required plasma current, requiring anti-current drive, i.e. driving a current in the opposite direction of the plasma current. Therefore, reducing the bootstrap fraction has been a major concern since the beginning of the ARIES-II design. One way to achieve this would be operate at low temperatures and high densities with peaked temperature profiles and flat density profiles. However, operating points in the high $\underline{n}$, low $\underline{T}$ regime are often thermally unstable, requiring active control. We intend to evaluate the thermal stability properties of proposed operating points of the ARIES-II reactor, and (if needed) to suggest methods for stabilizing them.

2. ECRH/ICRH TRANSPORT-ENHANCED FUELING AND IMPURITY CONTROL

There are experimental and theoretical indications that ECRH/ICRH alters the particle transport properties of tokamak plasmas, as well as heating them. This suggests the possibilities that ECRH/ICRH could be used to: 1) drive inward fuel ions that had been deposited off-center by pellet injection, thus reducing the technological requirements on pellet injectors needed for central fueling; and 2) drive outward edge-sputtered impurity ions, possibly leading to a cold, radiating edge that would reduce the technological requirements for handling high heat fluxes on the divertor plates.

We have collected and evaluated [4] the theoretical and experimental evidence that ECRH/ICRH alters particle transport in tokamaks. We conclude that this evidence is sufficiently compelling to motivate the development of a model that relates ECRH/ICRH power input to particle transport, which development we have initiated. One aspect of this model is the calculation of the electric fields. We have developed a model for calculating the radial electric field and checked it by comparison with heavy ion beam measurements of the electric field in ISX-B [5].

References:

1. T. K. Mau, D. A. Ehst, J. Mandrekas, and M. J. Schaffer, "Current Drive Analysis and System Design for the ARIES-I Tokamak Reactor", Proc. of 13th Symposium on Fusion Engineering, Knoxville, TN, 272 (1989).

2. J. Mandrekas, W. M. Stacey, Contributions to the ARIES-I Report, 1990.

3. W. M. Stacey, J. Mandrekas, "An Extension of the Theory for Neutral Beam Driven Currents in Tokamaks", Georgia Tech report GTFR-83, submitted to Fusion Technology, 1990.

4. K. Indireshkumar, "Particle Transport with ICRH and ECRH in Tokamaks", Georgia Tech report GTFR-93 (1990).

5. K. Indireshkumar, W. M. Stacey, "Analysis of Electric Potential Measurements in ISX-B", Georgia Tech report GTFR-90 (1989).

DOE F538 (5-86)

OMB Control No. 1910-1400

U. S. DEPARTMENT OF ENERGY
NOTICE OF ENERGY RD&D PROJECT

E-25-638

4

1. Descriptive TITLE of work (150 characters including spaces)

"Fusion Studies Program"

2. CONTRACT or grant number DE-FG05-87ER52141

2A. MASTER contract number (GOCO's)

2B. Responsible PATENT office

3. Performing organization CONTROL number (internal)

3A. Budget and Reporting code

3B. Funding YEAR for this award

4. Original contract start date

4A. Current contract start date

4B. Current contract close date

4C. Anticipated project termination date 4/14/90

5. Work STATUS

☐ Proposed ☐ Renewal

☒ New ☐ Terminated

5A. Manpower (FTE) 1

5B. CONGRESSIONAL district 5

5C. STATE or Country where work is being performed Georgia

5D. COUNTRY sponsoring research USA

6. Name of PERFORMING organization Georgia Institute of Technology

6A. DEPARTMENT or DIVISION

Nuclear Engineering Program

6B. Street Address

North Avenue

6C. City, State, Zip Code

Atlanta, GA 30332

7. Circle only one code for TYPE of Organization Performing R&D:

(CU) - College, university, or trade school
FF - Federally funded RD&D centers or laboratory operated for an agency of the U. S. Government
IN - Private industry
NP - Foundation or laboratory not operated for profit
ST - Regional, state or local government facility
TA - Trade or professional organization
US - Federal agency
XX - Other
EG - Electric or gas utility

8A. Contractor's PRINCIPAL INVESTIGATOR/s or project manager Name/s (Last, First, MI) Stacey, Weston M.

8B. PHONE/s (in order of PI names with commercial followed by FTS)

Comm. (404) 894-3714 ; FTS ; Comm. ; FTS

8C. PI/s address (if different from that of Performing Organization)

9. DOE SUPPORTING Organization (DOE Assistant Secretary and office sponsoring the work; technical monitor; and administrative monitor).

9A. PROGRAM division or office (full name) Office of Fusion Energy

Program Office Code ____

9B. TECHNICAL monitor (Last, First, MI) Dowling, R. J.

9C. Address Department of Energy

9D. Phone Comm. ____ FTS ____

9E. ADMINISTRATIVE monitor (Last, First, MI) ____

10. FUNDING in thousands of dollars (K$). Funds represent budget obligations for operating and capital equipment (FY runs October 1 – September 30).

Funding organization(s)	Current FY 89	Next FY 90
A. DOE	$53,000	$53,667
B.		
C.		

10D. Does the current FUNDING cover more than one year's work? Yes ____ No X

E. If yes, provide dates (from when to when). ____

11. Descriptive SUMMARY of work. Enter a Project Summary using complete sentences limited to 200 words covering the following: Objective(s), state project objectives quantifying where possible (e.g., "The project objective is to demonstrate 95% recovery of sulphur from raw gas with molten salt recycling at a rate of one gallon per minute."); approach, describe the technical approach used (how the work is to be done); expected product/results, describe the final products or results expected from the project and their importance and relevance.

ABSTRACT

A continuation of work under the Georgia Tech Fusion Studies grant is proposed. Specifically, it is proposed to study innovative techniques for plasma fueling and for impurity expulsion and to perform neutral beam current drive and other calculations in support of the ARIES project.

1. INTRODUCTION

The Fusion Studies Program at Georgia Tech has been supported by DOE since 1978. The emphasis in the Fusion Studies Program has been on the development and validation of innovative solutions to plasma physics problems that would have produced extremely demanding technological requirements in future tokamak devices.

Impurity flow reversal is a good example of the type of work that has been done in the Fusion Studies Program. In 1979, we predicted [1, 2] that CO (CTR) neutral beam injection would produce an outward (inward) impurity flux that would compensate (enhance) the inward flux driven by the pressure gradient. This raised the possibility that co-injection could be used to drive impurities from the center to the plasma edge where they might form a cool, radiating edge, thus reducing the heat load on the limiter or divertor plate and reducing the sputtering erosion, both of which are serious technological problems for fusion reactors.

Experiments which were subsequently performed in ISX-B and PLT found a reduced central impurity concentration with Co-injection and an increased central impurity concentration with CTR-injection, in qualitative agreement with experiment. A Ph.D. student analyzed [3, 4] these experiments, using the previously developed theory and using another theory based on inertial effects. The comparison was encouraging, but it was clear that neither theory was adequate to fully explain the experimental results. We also evaluated the technological requirements for achieving flow reversal in a tokamak reactor [4].

We then extended our original theory to self-consistently include inertial effects [5, 6]. A second Ph.D. student then analyzed the ISX-B and PLT experiments in great detail [7] and found excellent agreement between the extended theory and the experimental data.

One of the elements in the impurity transport model is rate of radial transfer of toroidal angular momentum. While this momentum transfer rate can be inferred from the measured rotation velocities in experiments, a theoretical model is required in order to make predictions for future devices. We found [8] that gyroviscosity could produce a radial momentum transfer rate of the magnitude needed to account for the observed rotation velocities. We subsequently found, as a result of detailed analyses, that gyroviscosity could account for the magnitude and scaling with plasma parameters of the measured rotation velocities and momentum confinement times in ISX-B and PLT [9] and in JET [10]. As an outgrowth of the success in predicting the ISX-B and PLT experiments, we are now collaborating with PPPL staff in analyzing the TFTR rotation experiments (supported by Confinement Systems). This work is being carried out as Ph.D. research by one of our students, who is finding [11] the same good agreement between theory and experiment. Another student (support by Georgia Power Co.) examined the kinetic theory basis for gyroviscosity as part of his Ph.D. thesis [12].

Calculations supporting the evaluation of neutral beam impurity flow reversal as an impurity control mechanism have been made in support of the INTOR [13] and TIBER [14, 15] reactor design activities.

In the meantime, impurity flow reversal was judged by an IAEA workshop [16] to be one of a limited number of innovations which were capable of improving the tokamak as a reactor concept.

We believe that the methodology that we have developed for impurity flow reversal could be extended to provide a useful tool for the analysis of impurity accumulation experiments in TFTR and other tokamaks, even in the presence of large, anomalous electron fluxes. We have proposed to OFE/DOE to undertake the necessary extensions of the theory under a separate grant.

A second example of the work carried out in the Georgia Tech Fusion Studies Program is in the area of neutral beam current drive. We were asked to support the TIBER reactor design activity in this area, which we did. We then extended the TIBER support work to perform a sensitivity study for three candidate next-step reactors--TIBER II, ITER-US and INTOR [17]. We are now providing the neutral beam current drive calculations for the ARIES project.

Because of our involvement in the analysis of the rotation experiments, it became apparent to us that the radial transfer of toroidal momentum that was being observed in the experiments would cause the neutral beam driven current profile to be different from the beam momentum deposition profile. This introduces the possibility that relatively lower energy neutral beams, which cannot penetrate to the center of the plasma, can be used to drive current in the center of the plasma, thereby reducing the neutral beam technology requirements. We also noted that the pressure associated with the population of fast beam ions would contribute to the bootstrap current, thereby reducing the volt-second requirement. We developed a preliminary theory [18] which incorporated these two effects and applied it to TFTR, where the effects are predicted to be quite substantial. As a result, we have submitted a proposal to OFE/DOE to develop an improved theory which removes some of the assumptions implicit in the standard kinetic theory results of standard NB current drive theory and that were carried forward into the extended theory.

These examples illustrate how the Georgia Tech Fusion Studies Program functions. Tasks are identified by seeking innovative solutions to plasma physics problems that are producing difficult technological requirements. In order to develop these solutions, some plasma theory is usually done. In order to validate these solutions, some analysis of experimental data is usually done. In order to evaluate these solutions, some reactor design analysis is usually done. Frequently, this work identifies promising areas for further development of theory or application to analysis of experiment, which are then proposed to OFE/DOE.

The Fusion Studies Program is the central focus of the faculty and student research in fusion at Georgia Tech. Weekly meetings to review progress are attended by those students funded by and working on the Program, by students funded by related programs and by students funded by themselves or by State funds and working on the Fusion Studies Program. Over the past 4 years, 2 students who were supported by the Fusion Studies Program and 3 students who were associated with the Program but funded otherwise have received their Ph.D.s. At present, there are 3 Ph.D. students partially supported by the Program and 3 Ph.D. students associated with the Program but funded otherwise.

Some of the proposed work would be completed within the one-year period of the proposal. Most of the work would take longer, and we would intend to submit a renewal proposal for continuation of the work. It is anticipated that much of the work would be done as part of Ph.D. dissertations.

2. INNOVATIVE METHODS FOR FUELING AND IMPURITY EXPULSION

Fueling the central regions of large, high-density plasmas of the type envisioned for ITER or for ARIES or other future devices is a formidable and unsolved problem. Credible extrapolation of pellet injection technology leads to the conclusion that achievable pellet velocities are likely to be too low to enable penetration to the plasma center. While plasmoid injection has been proposed, it is far from clear that this novel technique will be feasible or economical.

We propose to examine possible techniques for driving fuel which has been deposited off-center by pellet ablation into the center of the plasma. There is theoretical and experimental evidence that neutral beam injection (NBI), electron cyclotron heating (ECRH), ion cyclotron heating (ICRH), the radial electric field, and the conditions at the plasma boundary all affect particle transport within the plasma. Thus, there is the possibility that each of these could be used to drive fuel into the plasma center. We propose to investigate these possibilities. In general, there will be three phases of the investigation: 1) developing the appropriate model for particle transport in response to the specific driving mechanism; 2) checking the particle transport model by comparison with experiments in which the effect should be observable; and 3) evaluation of the technological requirements for producing central fueling and of any technological side effects (e.g. enhanced heat loads).

The fact that NBI, ECRH, etc. can affect particle transport suggests that they also might be used to drive unwanted impurities out of the center of the plasma or to prevent wall-sputtered impurities from penetrating to the center of the plasma. (It was, in fact, this possibility which first interested us.) We propose to investigate this possibility for the mechanisms mentioned above, proceeding through the same three phases of investigation.

2.1 Particle Transport Driven by Neutral Beam Injection

2.1.1 Background

There is a well-developed theory [1, 2, 5, 6, 19] for the effect of directed neutral beam injection and the resulting plasma rotation on the radial transport of the main (fuel) and impurity ions in a tokamak. This theory predicts that co-injection will drive impurities outward and will drive the main ion species inward. Thus, co-injected NB is a possible mechanism for driving fuel ions deposited in the outer region by pellet ablation into the center of the plasma and for driving impurity ions out of the center of the plasma or for preventing impurity ions from penetrating to the center of the plasma.

The predicted effect of NBI on impurities is well-established experimentally--the central accumulation of impurities is several times greater for counter-injection than for co-injection in ISX-B

[20-22] and PLT [23-25]. In ISX-B, there is evidence [20] that co-injection can reduce the central impurity accumulation. Detailed analysis [7] indicates that these ISX-B and PLT experiments can be explained quantitatively by the transport theory [6] that has been developed in the Georgia Tech Fusion Studies Program.

The earlier experiments in TFTR [26], with MW levels of NBI, exhibited the same impurity accumulation dependence upon beam direction, namely the central impurity accumulation was several times greater for counter-injection than for co-injection. More recent TFTR experiments [27], at the 10's of MW level of NBI, find the apparently contradictory result that central impurity confinement is less for counter-injection than for co-injection and longest for balanced injection. However, there is evidence [28] of large, anomalous outward electron fluxes in these high-power injection pulses. These anomalous electron fluxes would produce large anomalous impurity fluxes [29] which would overwhelm the impurity fluxes produced by momentum exchange and inertial effects [6]. Thus, the recent TFTR results [27] are not necessarily contradictory.

Thus, there is an established theory for the effect of NBI on main (fuel) ion and impurity ion transport, and the impurity ion transport portion is supported by experimental data. To our knowledge, there is no experimental evidence of the effect of NBI on main ion transport.

2.1.2 Proposed Work

We propose to evaluate the amount of co-injected NB power that is required to drive fuel deposited off-center by pellet ablation in the center of tokamak plasmas as a function of beam energy and orientation; pellet velocity and size; and plasma size, density and temperature (magnitude and profile), and impurity concentration. We would use models that we have developed for fuel ion transport, standard Fokker-Planck beam momentum deposition codes, and standard pellet ablation models.

We also propose to evaluate the amount of co-injected NB power that is required to drive He out of the center of tokamak plasmas and to prevent sputtered impurities from penetrating to the center as a function of beam energy and orientation and plasma size, density and temperature (magnitude and profile). The same transport model and beam deposition code as above would be used.

2.2 Particle Transport Driven by the Radial Electric Field

2.2.1 Background

We introduced [1, 2] a particle transport flux proportional to the radial electric field in our neoclassical treatment of rotating plasmas. Subsequent authors have produced a theory for fluctuation-driven transport fluxes [30], in which the radial electric field affects one of the thermodynamic forces that drive transport fluxes and for non-ambipolar transport [31] in which the radial electric field plays a major role in determining transport. We [5, 6] have also shown that the poloidal electric field could affect particle transport.

Experimental results from several tokamaks [32-35] indicate improved confinement when the radial electric field takes on a more negative value.

Thus, there seems to be a possibility that the electric field could be controlled so to drive externally deposited fuel ions to the plasma center and to prevent sputtered impurity ions from entering the plasma center.

2.2.2 Proposed Work

<u>We propose to investigate the possibility that control of the radial electric field can drive externally deposited fuel ions into the center of the plasma and can prevent sputtered impurity ions from penetrating to the center of the plasma.</u> The first stage of the work will be a literature review, followed by the development or adaptation of models for calculating the effect of the radial electric field on fuel ion and impurity ion transport and for controlling the radial electric field. These models will be checked by comparison with experimental results. Finally, the

technological requirements for central fueling and impurity control supplementation by the radial electric field will be evaluated as a function of plasma size and operating conditions.

2.3 Particle Transport Driven by ICRH and ECRH

2.3.1 Background

ICRH and ECRH are two of the main methods used for heating toroidal plasmas, in addition to NBI. High power ICRH (or ECRH) can significantly affect the transport of the main ion species as well as impurities. An understanding of transport introduces the possibility to control the flow of main ions and impurities. There have been limited theoretical studies of particle transport in the presence of ICRH and ECRH [36-40]. It has been shown [41] that the increased electron (ion) trapping associated with ECRH (or ICRH) can give rise to poloidal potential variations of the order ϵ. We have shown [39, 40] that an order ϵ variation in poloidal potential can give rise to an inward component of impurity flux in ICRH and an outward component in case of ECRH. It has been suggested [41] that an order ϵ potential variation and the resulting E X B drift could lead to a decrease of plasma density during ECRH and an increase in the density during ICRH. There is a considerable body of experimental data [42-45] indicating an enhanced inward flow of impurities with ICRH. There is also some evidence [42-44] that ICRH can also result in an inward flow of the main ion species. In ECRH, a rapid profile broadening and density reduction has been observed in most experiments [46, 47]. There is also evidence from TEXT experiments [48] that ECRH could produce an outward component of impurity flux. Thus, there would seem to exist the possibility that ECRH/ICRH could be exploited to drive externally deposited fuel ions inward and to prevent impurity ions from penetrating to the center.

2.3.2 Proposed Work

In our previous work [39, 40], we have assumed an order ϵ variation in poloidal potential in computing the impurity fluxes due to ECRH and ICRH. In order to assess the technological feasibility of particle flux control with ECRH (or ICRH), we need to know the exact magnitude of the potential variation as a function of power launched for the type of heating scheme under consideration. There are several heating schemes being used, such as, minority heating, second harmonic heating for ICRH and ordinary wave heating, extraordinary wave heating for ECRH. We propose to develop models to compute the magnitude of potential variation for several heating schemes, as a function of the relevant plasma parameters.

In a few experiments with ICRH and ECRH (with or without NBI), it has been observed that the plasma toroidal rotation velocity changes [49, 50]. This suggests the possibility of corresponding changes in radial electric fields. In fact, a change in potential during ECRH has been observed in TEXT [51]. Radial electric fields can have a significant effect on transport. We propose to investigate how radial electric fields may be created by ECRH and ICRH and the resulting effect on transport.

We intend to use the calculations in codes to compute particle fluxes. We have a code to calculate impurity fluxes during wave heating (ECRH or ICRH). Wave heating could change the particle distribution functions significantly, leading to a modification of transport properties. We propose to incorporate the results of our investigations into this code.

We propose to compare the results of our calculations against experimental data on density buildup and impurity accumulation.

We would then propose to apply our calculational model to establish the amount of ECRH/ICRH power that would be needed to drive externally deposited fuel ions into the center of the plasma and to prevent impurity ions from penetrating to the plasma center.

2.4 Particle Transport Driven by Plasma Boundary Control

2.4.1 Background

Theoretical investigations indicate that processes in the scrape-off region of a tokamak plasma can have an important effect on the transport in the interior of the plasma. Recent calculations [52] predict an inward contribution to the particle flux when the ion grad-B drift is toward the x-point in a single-null configuration, while the dependence of the power threshold for the H-mode transition on edge conditions (neutral particles, impurity accumulation) has been established [53]. Moreover, it has been shown [54] that poloidal asymmetries in the impurity sources (due to the location of the limiters, or to asymmetric recycling) give rise to poloidal asymmetries in the impurity density which in turn alter the radial impurity and main ion transport.

2.4.2 Proposed Work

We propose to examine the effect of scrapeoff conditions on particle transport, and to identify possible mechanisms that can lead to enhanced inward transport of fuel ions and outward transport of impurities, acting therefore as fueling and impurity control mechanisms.

3. PARTICIPATION IN ARIES

3.1 Neutral Beam Current Drive

3.1.1 Background

Since June 1988, Georgia Tech has been participating in the Advanced Reactor Innovation and Evaluation Study (ARIES). Our primary contribution has been in the neutral beam current drive calculations for the different ARIES versions.

The advantages of driving current with neutral beams (good experimental database, credible physics, seed current for the bootstrap current, good profile control) make NB current drive a serious candidate for any steady-state tokamak reactor design. This is definitely true for the first ARIES version, a high field reactor in the first stability regime, the design of which follows the philosophy of using relatively proven plasma physics.

During the scoping phase of this reactor design study, we presented detailed calculations for the current drive efficiency and other NB related parameters for the different design points of the reactor [55]. Based on our calculations, the Current Drive group recommended neutral beam current drive as the primary current drive technique for ARIES-I, at the last ARIES meeting.

3.1.2 Proposed Work

We propose to upgrade our computational tools in order to carry out a self-consistent NB current drive calculation for the design phase of ARIES-I.

Since a large fraction of the total current is expected to be provided by the bootstrap current, maximizing the latter is an important issue. Due to the inadequacy of present fueling methods to fuel near the magnetic axis, flat density profiles are expected in ARIES-I. It has been demonstrated [56] that, even with flat densities, it is possible to have large bootstrap current fractions in a high field reactor if the noninductive seed current is used to generate a high beta poloidal equilibrium with a high on-axis safety factor, and it has been shown that high frequency fast waves can provide the required seed current. Our calculations for the scoping phase of ARIES-I appear to be consistent with this operation. We wish to demonstrate this with a self-consistent MHD, neutral beam and bootstrap current calculation for the design phase of ARIES-I. For this, we propose to couple a full MHD free-boundary equilibrium code (as opposed to the approximate moments model presently used) with our neutral beam deposition and fast-ion slowing down module, while the bootstrap current will be calculated using the recent formalism by Hirshman [57], which is valid for arbitrary values of the aspect ratio and the effective charge. This way, our model will be valid not only for the ARIES-I calculations but also for the other more advanced ARIES versions that may have different aspect ratios and higher betas. We propose to perform the neutral beam current drive calculations for the ARIES-I design.

We are also proposing to continue our neutral beam current drive calculations for the other ARIES versions. Although other passive current drive techniques (e.g. synchrotron current drive) are being emphasized for the more advanced ARIES versions, we feel that NB current drive should be included at least as a back-up option.

Moreover, the high degree of profile control that is possible with NB current drive may be important for reactors in the second stability regime.

3.2 Innovative Fueling and Impurity Expulsion

3.2.1 Background

Peaked density profiles are desirable in tokamak designs in order to maximize the pressure gradient driven bootstrap current, and therefore minimize the external driver technology requirements.

However, early on in the ARIES collaboration it became apparent that reactor-sized plasmas are difficult to fuel near the magnetic axis [58]. Deep fueling with pellet injection requires pellet velocities outside the range of present and projected injection technologies, while other proposed methods such as fueling with accelerated compact toroids [59] may not be economically feasible [60]. Therefore, the development of novel techniques, capable of deep fueling at a reasonable cost was identified as a critical issue for ARIES.

It has been observed [61] in recent experiments, that density from pellets deposited in the outer regions of the plasma is transported inward by some unknown pinch mechanism. Moreover, theory predicts that neutral beam injection, electron cyclotron heating and ion cyclotron heating can modify the radial transport of the impurities and main ions in the plasma (see part 2 of this proposal).

3.2.2 Proposed Work

We propose to examine the feasibility of using the methods which will be developed under part 2 of this proposal to drive fuel deposited at the outer regions of the plasma into the center of the reactor for the different ARIES versions, and to estimate the power requirements of such a system. If such a system proves to be feasible, conventional fueling techniques (pellet fueling or gas puffing) could be used for fueling without requiring major technological extrapolations. Moreover, since the impurity transport will be affected as well, we propose to examine these mechanisms for possible impurity and ash control in ARIES.

3.3 Alternative Current Drive Methods for ARIES

3.3.1 Background

For the more advanced versions of ARIES (ARIES-II and ARIES-III), the emphasis is on innovative, preferably passive, current drive techniques such as bootstrap current with synchrotron radiation, etc. Moreover, some of these reactors are supposed to be in the second stability regime where the requirement for a hollow current profile makes the selection of an attractive current drive method even more challenging.

In addition, since passive mechanisms are inherently present during the operation of the reactor, it is important to assess their effect on the total current profile, specially in cases where precise profile control is very important.

It is well known that fusion products can generate toroidal currents in a tokamak reactor. This can be due either to the nonideal confinement of these fusion products which gives rise to an anisotropic distribution [62], or due to the alpha particle bootstrap current in the neighborhood of the magnetic axis which has been shown to be nonzero [63]. This has suggested the idea of a steady-state tokamak reactor with a toroidal current maintained by neoclassical processes connected with both the bulk plasma and the thermonuclear reaction products [64].

3.3.2 Proposed Work

We propose to study the feasibility of fusion-product driven bootstrap currents as a passive current drive technique for the advanced ARIES versions and to assess their impact on the net current profile. Some of the ARIES designs under consideration (a high field D-He^3 reactor, a low aspect ratio spherical torus etc.) provide us with a unique range of parameter to test these ideas.

DOE F538 (5-86)

E25-638

U. S. DEPARTMENT OF ENERGY
NOTICE OF ENERGY RD&D PROJECT

1990-91

1. Descriptive TITLE of work (150 characters including spaces)

"Fusion Studies Program"

2. CONTRACT or grant number: DE-FG05-87ER52141

2A. MASTER contract number (GOCO's): ______

2B. Responsible PATENT office: ______

3. Performing organization CONTROL number (internal)

3A. Budget and Reporting code

3B. Funding YEAR for this award

4. Original contract start date ______

4A. Current contract start date ______

4B. Current contract close date ______

4C. Anticipated project termination date ______

5. Work STATUS

☐ Proposed ☒ Renewal
☐ New ☐ Terminated

5A. Manpower (FTE) ______

5B. CONGRESSIONAL district: 5

5C. STATE or Country where work is being performed: ~~Georgia~~

5D. COUNTRY sponsoring research: USA

6. Name of PERFORMING organization: Georgia Institute of Technology

6A. DEPARTMENT or DIVISION	6B. Street Address	6C. City, State, Zip Code
Nuclear Engineering Program	620 Cherry St.	Atlanta, GA 30332

7. Circle only one code for TYPE of Organization Performing R&D:

(CU) - College, university, or trade school
FF - Federally funded RD&D centers or laboratory operated for an agency of the U. S. Government
IN - Private industry
NP - Foundation or laboratory not operated for profit
ST - Regional, state or local government facility
TA - Trade or professional organization
US - Federal agency
XX - Other
EG - Electric or gas utility

8A. Contractor's PRINCIPAL INVESTIGATOR/s or project manager
Name/s (Last, First, MI) ~~Stacey, Weston M.~~

8B. PHONE's (in order of PI names with commercial followed by FTS)
Comm. 404-894-3714 ; FTS ______ ; Comm. ______ ; FTS ______

8C. PI/s address (if different from that of Performing Organization)

9. DOE SUPPORTING Organization (DOE Assistant Secretary and office sponsoring the work; technical monitor; and administrative monitor).

9A. PROGRAM division or office (full name) Office of Fusion Energy

Program Office Code ______

9B. TECHNICAL monitor (Last, First, MI) S. Berk

9C. Address Department of Energy

9D. Phone Comm. 301-353-4171

FTS ______

9E. ADMINISTRATIVE monitor (Last, First, MI) ______

10. FUNDING in thousands of dollars (K$). Funds represent budget obligations for operating and capital equipment (FY runs October 1 – September 30).

Funding organization(s)	Current FY 91	Next FY 92
A. DOE	$30,000	$50,000
B.		
C.		

10D. Does the current FUNDING cover more than one year's work? Yes ____ No X

E. If yes, provide dates (from when to when). ______

11. Descriptive SUMMARY of work. Enter a Project Summary using complete sentences limited to 200 words covering the following: Objective(s), state project objectives quantifying where possible (e.g., "The project objective is to demonstrate 95% recovery of sulphur from raw gas with molten salt recycling at a rate of one gallon per minute."); approach, describe the technical approach used (how the work is to be done); expected product/results, describe the final products or results expected from the project and their importance and relevance.

ABSTRACT

A continuation of work under the Georgia Tech Fusion Studies Grant is proposed. The specific work proposed includes: 1) participation in ARIES and post-ARIES evaluation studies; and 2) participation in DEMO studies. Under a supplemental budget, it is proposed in addition to examine innovative techniques for fueling and better methods for modeling neutral beam current drive, both of which have promise of reducing technological requirements.

12. PUBLICATIONS available to the public. List the five most descriptive publications that have resulted from this project in the last year that are available to the public. (Include author, title, where published, year of publication, and any other information you have to complete full bibliographic citation.) Use the back of this form or additional sheets if necessary.

1. T.K. Mau, D.A. Ehst, J. Mandrekas, Chapter 4, and T.K. Mau, J. Mandrekas, Chapter 6 of ARIES-II report, 1991.

2. T.K. Mau, D.A. Ehst, J. Mandrekas, and M.J. Schaffer, "Current Drive Analysis and System Design for the ARIES-I Tokamak Reactor," Proc. of 13th Symposium on Fusion engineering, Knoxville, Tn, 272 (1989).

3. T.K. Mau, J. Mandrekas, D.A. Ehst, J.H. Whealton, "Current Drive and Profile Control for the ARIES-III Second Stability Advanced Fuel Tokamak Reactor," to be presented at the 14th IEEE Symposium on Fusion Engineering, October, 1991, San Diego, CA.

4. G.A. Emmert, C. Kessel, J. Mandrekas, T.K. Mau, "Plasma Startup of the ARIES-III Second Stability Advanced Fuel Tokamak," to be presented at the 14th IEEE Symposium on Fusion Engineering, October 1991, San Diego, CA.

13. KEYWORDS (Listed five terms describing the technical aspects of the project. List specific chemicals and CAS number, if applicable.)

Fusion reactor design
Fusion engineering

14. RESPONDENT. Name and address of person filling out the Form 538. Give telephone number, including extension (if you have FTS number, please include it) at which person can be reached. Record the date this form was completed or updated. The information in Item 14 will not be published.

Respondent's Name: ______ Phone No.: ______ Date: ______

Street: ______

City: ______ State: ______ Zip: ______

15. Additional space for furnishing information in items 1 to 14. (Indicate item numbers to which answers apply.)

Item No.	

NOTICE: Return this form to the office indicated in the reporting requirements for your award agreement covering this project. If you have completed a similar programmatic office project description during the current Fiscal Year, complete only the new data elements on this form and send it and a copy of the description completed earlier to Department of Energy, Office of Scientific Information, P. O. Box 62, Oak Ridge, TN 37831.

E-25-638

DOE F 1332.16 (10-84)
(Formerly RA-427)

OMB Approval
No. 1910-1400

U. S. DEPARTMENT OF ENERGY

UNIVERSITY CONTRACTOR, GRANTEE, AND COOPERATIVE AGREEMENT RECOMMENDATIONS FOR ANNOUNCEMENT AND DISTRIBUTION OF DOCUMENTS

See Instructions on Reverse Side

1. DOE Report No.

2. DOE Contract No.
DE-FG05-87ER-52141

3. Title
Annual Performance Report
Fusion Studies Program

4. Type of Document ("x" one)
☐ a. Scientific and technical report
☐ b. Conference paper:
Title of conference ______
Date of conference ______
Exact location of conference ______
Sponsoring organization ______
☒ c. Other (Specify) Progress Report

5. Recommended Announcement and Distribution ("x" one)
☒ a. Unrestricted unlimited distribution.
☐ b. Make available only within DOE and to DOE contractors and other U. S. Government agencies and their contractors.
☐ c. Other (Specify) ______

6. Reason for Recommended Restrictions

7. Patent and Copyright Information:
Does this information product disclose any new equipment, process, or material? ☒ No ☐ Yes If so, identify page nos. ______
Has an invention disclosure been submitted to DOE covering any aspect of this information product? ☒ No ☐ Yes
If so, identify the DOE (or other) disclosure number and to whom the disclosure was submitted.
Are there any patent-related objections to the release of this information product? ☒ No ☐ Yes If so, state these objections.
Does this information product contain copyrighted material? ☒ No ☐ Yes
If so, identify the page numbers ______ and attach the license or other authority for the government to reproduce.

8. Submitted by Name and Position (Please print or type)
W. M. Stacey, Jr., Professor

Organization Georgia Institute of Technology, Atlanta, GA 30332
School of Mechanical Engineering, Nuclear Engineering Programs

Signature	Phone	Date
	894-3714	5-31-91

FOR DOE OR OTHER AUTHORIZED USE ONLY

Patent Clearance ("x" one)
☐ a. DOE patent clearance has been granted by responsible DOE patent group.
☐ b. Report has been sent to responsible DOE patent group for clearance.

FUSION STUDIES PROGRAM

Fusion Research Center – Georgia Tech
Progress Report
May 31, 1990 – May 31, 1991

1. PARTICIPATION IN ARIES

During this period we participated in the ARIES–III design effort. The ARIES–III (the design of which was completed at the recent ARIES project meeting at Argonne National Laboratory), is an advanced fuel (D–^{3}He) reactor operating at the second region of MHD stability. The required high plasma β (24%) leads to a bootstrap current larger than the plasma equilibrium current necessitating anti–current drive, i.e. driving a current in the opposite direction of the main plasma current. Our studies showed that neutral beam current drive would be capable of providing the forward seed current as well as the reverse anti–current at a reasonable current drive efficiency.

Based on our calculations, the ARIES group selected NB current drive as the reference current drive method for the ARIES–III reactor. During the last part of 1990, and the first part of 1991 we have been doing calculations to determine the basic design parameters of the NB system (beam energies, geometry, beam optics, etc.), as well as the effects of the interaction of the beams with the rest of the plasma (β due to the fast beam ions, fusion power due to beam–plasma interactions, neutron production, etc.). During this work, we have been in close contact with the ARIES MHD and stability group (at PPPL) to ensure that the NB driven current profile is MHD stable.

We have also been involved in the startup calculations for ARIES–III. We determined the required parameters (energy and power) of the NB system in order to drive the required current during startup, and the power that the system can provide for heating the plasma to the final operating point.

Our contributions will appear in the upcoming ARIES–III report (chapters 6 and 8), and will be presented at the 14th IEEE Symposium on Fusion Engineering (September 30 – October 3, San Diego, CA).

2. INNOVATIVE METHODS FOR FUELING AND IMPURITY CONTROL

Much of the second half of 1990 was spent studying the direct and indirect effects of wave heating on particle transport in tokamaks. The study included a review of much of the relevant theoretical and experimental literature on particle transport during high power wave heating [1]. It was found that high power wave heating, in addition to its direct impact on transport, causes a significant enhancement of poloidal potential variation. Such a change in the potential can cause a significant enhancement of neoclassical transport coefficients. This could have implications for impurity transport, fueling and burn control in wave heated tokamaks. In addition to particle transport, we have also been interested in the production of large electric fields during high power wave heating. Electric fields could directly or indirectly cause changes in transport. We have studied the production of electric fields due to absorption of electromagnetic wave momentum using a simple model. The results of our work were presentedat the 32nd annual APS (Division of Plasma Physics) meeting [2]. This year, we have continued our work on particle transport. Considerable progress has already been made toward the calculation of particle transport coefficients in the presence of large poloidal potential variations in a multispecies plasma. We also plan to study the effect of large potential variations on the bootstrap current in a multispecies plasma.

References

1. K.Indireshkumar, W.M.Stacey, Jr.,"Particle Transport with ICRH and ECRHin Tokamaks", Georgia Tech Fusion Report, GTFR–93 (1990).

2. K.Indireshkumar, W.M.Stacey, Jr., "Electric Fields during Radio frequency Heating in Tokamaks", *Bull. Am. Phys. Soc.*, **1987** (1990).

E25-638

1991-92

FUSION STUDIES PROGRAM
Progress Report for the ARIES Participation
June 1, 1991 - May 31, 1992

During the second part of 1991, we were involved in the design of the ARIES-III second stability, advanced fuel (D - ^{3} He) reactor. Our contributions have been in the areas of neutral beam current drive, and startup operations. In particular, we performed calculations to determine the basic design parameters of the neutral beam (NB) system of the ARIES-III reactor, which had been selected as the reference current drive scenario.

Due to its high beta (23%), ARIES-III operates in a regime where the bootstrap current is larger than the desired equilibrium current for MHD stability. Thus, a portion of the bootstrap current must be canceled by the external current driver. This anti-current drive requirement made the ARIES-III NB reference design more challenging. It was found that two oppositely directed beam modules were needed: a co-injected one driving the central seed current, and a counter-injected module driving current in the outer parts of the plasma, to cancel the bootstrap overdrive. We determined the design characteristics of these systems (beam energies and geometry for optimum operation with enough flexibility for profile control, beam optics parameters, etc.) as well as the effects of the interaction of the beams with the rest of the plasma (beta due to fast beam ions, fusion power due to beam-target interactions, neutron production from these interactions, etc.)

We were also involved with the D-T startup scenario of ARIES-III. We did simulations to assess the performance of the NB system during start-up, and in particular its ability to drive the required external current for stable access to the second stability reference operating point (as determined by the MHD equilibrium and stability calculations), while at the same time being able to provide as much as possible of the required heating power along the start-up path. We found that in order to achieve these goals, the NB system should be capable of variable beam energy.

Our contributions in the ARIES-III design, were presented at the 14th IEEE/NPSS Symposium on Fusion Engineering (*San Diego, September 30 - October 3, 1991*) [1,2], and can also be found in Chapters 6 and 8 of the upcoming ARIES-III report.

During the last part of 1991 and the first part of 1992, we have been participating in the design of the ARIES-II/IV visions. As members of the Current Drive task group, we provided NB current drive calculations for the different proposed initial designs of the reactors, to help choose the most appropriate current drive concept. The current drive requirements of ARIES-II/IV are rather modest (about 1 MA) and therefore current drive efficiency was not a crucial factor. It was decided that ICRF fast waves would be the reference current drive scenario for ARIES-II/IV, mainly due to its better integrability to a reactor environment. However, neutral beams are still the primary backup option and they still may play an important role, since the latest results indicate that bootstrap overdrive may be a problem in ARIES-II/IV.

E25-638

1. INTRODUCTION

The Georgia Tech Fusion Studies Program has, since 1977, investigated innovative plasma engineering solutions which could reduce the technological requirements on tokamak systems and, more recently, participated in multi-institutional conceptual design studies.

We originated and validated by comparison with experiment the concept of using co-injected neutral beams to drive impurities outward, thereby reducing the requirements on the impurity control system. Recently, we have investigated the use of ECRH/ICRH to enhance the bootstrap current and to drive impurities outward and main ions inward, thereby reducing the requirements on both the impurity control and the current induction systems. We have also found that the radial diffusion of fast beam ion momentum may allow current to be driven in the center of the plasma by neutral beams which do not penetrate to the center, thereby reducing the neutral beam technology requirements.

Since the mid-1980's, we have participated in multi-institutional reactor design studies sponsored by DOE. We have performed neutral beam current drive calculations first for TIBER and extensively for ARIES. We have been involved in a number of fusion development strategy and DEMO requirements definition activities over the past decade.

It is proposed to continue our work on post-ARIES studies. It is further proposed to initiate research activities in the environment and safety area in order to make available our considerable experience in fusion reactor design to advance the achievement of DOE programmatic objectives in this area.

2. PARTICIPATION IN POST-ARIES & DEMO STUDIES

2.1 Progress Report

Since mid-1988, our group has been participating in the Advanced Reactor Innovation and Evaluation Study (ARIES). During the design of the first ARIES vision, the first stability ARIES-I high field tokamak reactor, our primary contribution was in the analysis and design of a high-energy neutral beam current drive (NBCD) system as an alternative current drive scenario for the steady-state operation of the reactor [1,2] (fast-wave current drive had been selected as the reference current drive option).

During the design of the ARIES-III second stability, advanced fuel (D - ^{3}He) reactor, we contributed in the areas of neutral beam current drive and startup operations [3-6]. In particular, we performed calculations to determine the basic design parameters of the neutral beam (NB) system of the ARIES-III reactor, which had been selected as the reference current drive scenario. Due to its high beta (23%), ARIES-III operated in a regime where the bootstrap current is larger than the desired equilibrium current for MHD stability. Thus, a portion of the bootstrap current must be canceled by the external current driver. This anti-current drive requirement made the ARIES-III NB reference design more challenging. It was found that two oppositely directed beam modules were needed: a co-injected one driving the central seed current, and a counter-injected module driving current in the outer parts of the plasma, to cancel the bootstrap overdrive. We determined the design characteristics of these systems (beam energies and geometry for optimum operation with enough flexibility for profile control, beam optics parameters, etc.) as well as the effects of the interaction of the beams with the rest of the plasma (beta due to fast beam ions, fusion power due to beam-target interactions, neutron production from these interactions, etc.)

We were also involved with the D-T startup scenario of ARIES-III. We did simulations to assess the performance of the NB system during start-up, and in particular its ability to drive the required external current for stable access to the second stability reference operating point (as determined by the MHD equilibrium and stability calculations), while at the same time being able to provide as much as possible of the required heating power along the start-up path. We found that in order to achieve these goals, the NB system should be capable of variable beam energy.

Finally, we participated in the design of the last of ARIES visions, the ARIES-II/IV reactor. As members of the Current Drive task group we provided NB current drive calculations for the different proposed initial designs of the reactors, to help choose the most appropriate current drive concept. The current drive requirements of ARIES-II/IV were rather modest (about 1 MA), and therefore current drive efficiency was not a crucial factor. It was decided that ICRF fast waves would be the reference current drive scenario for ARIES-II/IV, mainly due to its better integrability to a reactor environment. Neutral Beams remained the primary backup option.

Another activity under this project, has been the study of the effects of poloidal potential variations likely to be produced during ICRH and ECRH heating of tokamak plasmas. Calculations [7] indicate that a poloidal electric field of order ε can significantly enhance (by a factor of ~ 3) the neoclassical ion diffusion coefficients in an impure plasma. The magnitude of ion transport enhancement is found to depend upon the impurity content, impurity species, and the magnitude of the poloidal electric field. A poloidal electric field also causes a significant enhancement (a factor of ~ 2) of the bootstrap current coefficients. However, the nature of density and temperature profiles seem to be important in determining the change in the bootstrap current. A poloidal electric field leads to an increase in the bootstrap current when the potential on the outside is greater than that on the inside of the tokamak (as during ICRH), and the density profile is not too flat compared to the temperature profile.