ORNL FACE PAGE

A PROLIFERATION-RESISTANT REACTOR AND FUEL CYCLE WITHOUT SIGNIFICANT QUANTITIES OF CHEMICALLY SEPARABLE WEAPONS-USABLE FISSILE MATERIALS

Submitted in Response to
Program Announcement LAB NE-2001-1
Nuclear Energy Research Initiative (NERI)

Oak Ridge National Laboratory

Principal Investigator

C. W. Forsberg

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Laboratory Official

Gordon E. Michaels
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P.O. Box 2009
Oak Ridge TN, 37831-8063

Requested Funding

Institution	Funding by year ($1000)			
	Year 1	Year 2	Year 3	Total
Oak Ridge National Laboratory	350	300	195	845
Massachusetts Institute of Technology	100	100	105	305
U. of California–Berkeley	100	100	100	300
Burns and Roe	50	100	200	350
Total	600	600	600	1800

C. W. Forsberg (Principal Investigator) Date

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U.S. DEPARTMENT OF ENERGY
OAK RIDGE OPERATIONS
FIELD WORK PROPOSAL

PROGRAM: AF Nuclear Energy Research and Development

1. WORK PROPOSAL NO.	2. REVISION NO.	3. DATE PREPARED	
NEAF908	0	01-19-2001	03

4. WORK PROPOSAL TITLE:	5. BUDGET AND REPORTING CODE
Proliferation-Resistant Reactor and Fuel Cycle Without....	AF 35 00 00 0

6. WORK PROPOSAL TERM	PATENT STATUS	7. Is This Work Proposal Included in the Institutional Plan?
BEGIN: 06-01-2001 END: OPEN	This proposal is being transmitted in advance of patent review for evaluation purposes only. No further dissemination or publication shall be made without prior approval of the Assistant General Counsel for Patents, DOE.	☐Yes ☒No

NAME: (Last, First, MI) (Phone Number)

8. HEADQUARTERS/OPERATIONS OFFICE PROGRAM MANAGER: Ross, Frank A. (301)903-4416	11. HEADQUARTERS ORGANIZATIONS: **Nuclear Energy**	14. DOE ORGANIZATION CODE: **NE**
9. OPERATIONS OFFICE WORK PROPOSAL REVIEWER: Clark, H. W. (865)576-0823	12. FIELD OFFICE: **Oak Ridge Operations**	15. DOE ORGANIZATION CODE: **ON**
10. CONTRACTOR WORK PROPOSAL PRINCIPAL INVESTIGATOR(S)/MANAGER: Forsberg, Charles W (865)574-6783	13. CONTRACTOR NAME: **Oak Ridge National Laboratory** **Managed by UT-Battelle, LLC** **For the U.S. Department of Energy** **Post Office Box 2008** **Oak Ridge, TN 37831**	16. DOE CONTRACTOR CODE: **41**

17. WORK PROPOSAL DESCRIPTION (Approach, anticipated benefits in 200 words or less)

Full Title: Proliferation Resistant Reactor and Fuel Cycle Without Significant Quantities of Chemically Separable Weapons-Usable Fissile Materials

A major concern with nuclear power is nuclear proliferation. Over the lifetime of an LWR, sufficient plutonium is produced such as to build several hundred nuclear weapons. An alternative approach is proposed to address nuclear power related proliferation issues-develop a reactor and fuel cycle with no significant inventory of weapons-usable materials-a proliferation resistant molten salt reactor (PR-MSR). It may be possible to reduce the total inventory of weapons-usable plutonium in the reactor and fuel cycle to less than the quantity of plutonium identified by the IAEA as sufficient such as to build one nuclear weapon. The proposed work will determine (1) if it is possible to design such a reactor, (2) if such a design could be practical, and (3) the potential viability of such a reactor for a Generation IV reactor (passive safety, better waste management, and lower costs).

ORNL will lead the program and conduct the research on chemical processing and fuel cycles. The Massachusetts Institute of Technology will extend methodologies to assess proliferation resistance of this reactor. The University of California at Berkeley will conduct the neutronic analysis. Burns and Roe will conduct the economic analysis.

18. CONTRACTOR WORK PROPOSAL MANAGER: (Name and Phone No.)	19. OPERATIONS OFFICE REVIEW OFFICIAL
Gordon Elliot Michaels (865)574-4187 Signature: Date: 01-19-2001	(Signature) (Date)

20. DETAIL ATTACHMENTS: (See instructions for page 3)

☐ a. Facility Requirements	☐ e. Approach	☐ i. NEPA Requirements	☐ m. ES&H Considerations
☐ b. Publications	☐ f. Technical Progress	☐ j. Milestones	☐ n. Human/Animal Subjects
☐ c. Purpose	☐ g. Future Accomplishments	☐ k. Deliverables	☒ o. Other (Specify)
☐ d. Background	☐ h. Relationships To Other Projects	☐ l. Perform Measures/Expectations	

DOE Form 5120.2 (Page 2)
(1-96)

WORK PROPOSAL REQUIREMENTS FOR OPERATING/EQUIPMENT OBLIGATIONS AND COSTS

PROGRAM: AF Nuclear Energy Research and Development

CONTRACTOR NAME:	WORK PROPOSAL TITLE:		
UT-BATTELLE, LLC	Proliferation-Resistant Reactor and Fuel Cycle Without....		
	WORK PROPOSAL NO. NEAF908	REVISION NO. 0	DATE PREPARED 01-19-2001

21. STAFFING (in staff years)	PRIOR YEARS	FY 2002	FY 2003 REQUEST	FY 2003 AUTHOR.	FY 2004	FY 2005	TOTAL TO COMPLETE
a. SCIENTIFIC	1.2	0.9	0.6				
b. OTHER DIRECT-ORNL							
c. OTHER DIRECT-OTHER SITES							
d. TOTAL DIRECT	1.2	0.9	0.6				
22. OPERATING EXPENSE (in Thousands)							
a. TOTAL OBLIGATIONS	695	600	600				
COSTS:							
1) WAGE POOL AND ORG. BURDEN	227	194	122				
2) MATERIALS AND SERVICES	24	20	15				
3) SUBCONTRACTS AND CONSULTANTS	250	300	405				
4) INDIRECT COSTS	99	86	58				
b. TOTAL COSTS	600	600	600				
23. EQUIPMENT (in Thousands)							
a. EQUIPMENT OBLIGATIONS							
b. EQUIPMENT COSTS							

24. MILESTONE SCHEDULE (TASKS:)	DOLLARS (in Thousands) PROPOSED	DOLLARS (in Thousands) AUTHORIZED	SCHEDULE (DATE) PROPOSED	SCHEDULE (DATE) AUTHORIZED
Baseline PR-MSR pre-conceptual design			Year 1	
Equivalence of plutonium and uranium isotopes			Year 1	
Requirements for salt processing			Year 1	
Reactor core design			Year 2	
Non-proliferation methodology			Year 2	
Salt processing options			Year 2	
Reactor analysis			Year 3	
Proliferation resistance analysis			Year 3	
TRU-burning			Year 3	
Economic analysis			Year 3	

25. REPORTING REQUIREMENTS (DESCRIPTION:)

Annual report plus technical reports

DOE Form 5120.2 (Page 3)
(1-96)

WORK PROPOSAL REQUIREMENTS FOR OPERATING/EQUIPMENT OBLIGATIONS AND COSTS

PROGRAM: AF Nuclear Energy Research and Development

CONTRACTOR NAME:	WORK PROPOSAL TITLE:		
UT-BATTELLE, LLC	Proliferation-Resistant Reactor and Fuel Cycle Without....		
	WORK PROPOSAL NO. NEAF908	REVISION NO. 0	DATE PREPARED 01-19-2001

20. DETAIL ATTACHMENT CONTINUED:

o. Other

(1) OBLIGATIONS FOR OPERATING EXPENSES-Budget Authority (B/A)

	Obligation Estimates		
	FY 2001	FY 2002	FY 2003
Cost (B/O) Estimates	600	600	600
Less: Uncosted Balance (--) at 10/01		95	95
Plus: Commitments for Continued Operations	11	11	11
Outstanding Commitment Balance 10/08	84	84	84
TOTAL OBLIGATIONS--CHANGE	695	600	600

(2) CAPITAL EQUIPMENT OBLIGATIONS AND COSTS - None

OMB Approval No. 0348-0043

APPLICATION FOR FEDERAL ASSISTANCE

2. DATE SUBMITTED January 19, 2001

Applicant Identifier

1. TYPE OF SUBMISSION:

Application
- [ ] **Construction**
- [x] **Non-Construction**

Preapplication
- [ ] **Construction**
- [x] **Non-Construction**

3. DATE RECEIVED BY STATE

State Application Identifier

4. DATE RECEIVED BY FEDERAL AGENCY

Federal Identifier

5. APPLICANT INFORMATION

Legal Name: ORNL, managed by UT-Battelle, LLC

Organizational Unit: Oak Ridge National Laboratory

Address *(give city, county, State, and zip code):* P.O. Box 2008 Oak Ridge, TN 37831

Name and telephone number of person to be contacted on matters involving this application *(give area code)* Charles W. Forsberg (865) 574-6783

6. EMPLOYER IDENTIFICATION NUMBER *(EIN):* 52-1946236

7. TYPE OF APPLICANT: *(enter appropriate letter in box)* N

A. State	H. Independent School Dist.
B. County	I. State Controlled Institution of Higher Learning
C. Municipal	J. Private University
D. Township	K. Indian Tribe
E. Interstate	L. Individual
F. Intermunicipal	M. Profit Organization
G. Special District	N. Other (Specify) DOE National Laboratory

8. TYPE OF APPLICATION:

- [x] **New**
- [ ] **Continuation**
- [ ] **Revision**

If Revision, enter appropriate letter(s) in box(es)

A. Increase Award B. Decrease Award C. Increase Duration
D. Decrease Duration Other*(specify):*

9. NAME OF FEDERAL AGENCY: Department of Energy

10. CATALOG OF FEDERAL DOMESTIC ASSISTANCE NUMBER: 81-121

TITLE: Nuclear Energy Research Initiative

11. DESCRIPTIVE TITLE OF APPLICANT'S PROJECT: A Proliferation-Resistant Reactor and Fuel Cycle Without Significant Quantities of Chemically-Separable Weapons-Usable Fissile Material

12. AREAS AFFECTED BY PROJECT *(Cities, Counties, States, etc.):* Oak Ridge, Anderson County, Knoxville, Knox County

13. PROPOSED PROJECT

Start Date: 6-1-2001 Ending Date: open

14. CONGRESSIONAL DISTRICTS OF:

a. Applicant: Districts 2 and 3 b. Project: Districts 2 and 3

15. ESTIMATED FUNDING:

a. Federal	$ 1,800,000 .00
b. Applicant	$ .00
c. State	$ .00
d. Local	$ .00
e. Other	$ .00
f. Program Income	$ .00
g. TOTAL	$ 1,800,000 .00

16. IS APPLICATION SUBJECT TO REVIEW BY STATE EXECUTIVE ORDER 12372 PROCESS?

a. YES. THIS PREAPPLICATION/APPLICATION WAS MADE AVAILABLE TO THE STATE EXECUTIVE ORDER 12372 PROCESS FOR REVIEW ON:

DATE ____________________

b. No.
- [x] PROGRAM IS NOT COVERED BY E. O. 12372
- [ ] OR PROGRAM HAS NOT BEEN SELECTED BY STATE FOR REVIEW

17. IS THE APPLICANT DELINQUENT ON ANY FEDERAL DEBT?

- [ ] **Yes** **If "Yes," attach an explanation.**
- [x] **No**

18. TO THE BEST OF MY KNOWLEDGE AND BELIEF, ALL DATA IN THIS APPLICATION/PREAPPLICATION ARE TRUE AND CORRECT, THE DOCUMENT HAS BEEN DULY AUTHORIZED BY THE GOVERNING BODY OF THE APPLICANT AND THE APPLICANT WILL COMPLY WITH THE ATTACHED ASSURANCES IF THE ASSISTANCE IS AWARDED.

a. Type Name of Authorized Representative	b. Title	c. Telephone Number
Gordon E. Michaels	Program Manager	(865) 574-4187

d. Signature of Authorized Representative

e. Date Signed

OMB Approval No. 0348-0043

APPLICATION FOR FEDERAL ASSISTANCE

2. DATE SUBMITTED	1/18/2001
Applicant Identifier	ESRC-6581
3. DATE RECEIVED BY STATE	
State Application Identifier	
4. DATE RECEIVED BY FEDERAL AGENCY	
Federal Identifier	

1. TYPE OF SUBMISSION:

Application
- [ ] Construction
- [x] Non-Construction

Preapplication
- [ ] Construction
- [ ] Non-Construction

5 APPLICANT INFORMATION

Legal Name: The Regents of The University of California

Organizational Unit: Sponsored Projects Office

Address *(give city, county, state, and zip code)*

University of California
Sponsored Projects Office
336 Sproul Hall
Berkeley, CA 94720-5940

Name and telephone number and E-mail number of the person to be contacted on matters involving this application *(give area code)*

PI: Ehud Greenspan (510) 643-9983
gehud@nuc.berkeley.edu
ADMINISTRATIVE CONTACT: Patricia Gates 510/642-8109
pgates@uclink.berkeley.edu

6 EMPLOYER IDENTIFICATION NUMBER (EIN): 94-6002123

7. TYPE OF APPLICANT: *(enter appropriate letter in box)* I

A.	State	H.	Independent School Dist.
B.	County	I.	State Controlled Institution of Higher Learning
C.	Municipal	J.	Private University
D.	Township	K.	Indian Tribe
E.	Interstate	L.	Individual
F.	Intermunicipal	M.	Profit Organization
G.	Special District	N.	Other (Specify):

8 TYPE OF APPLICATION:

- [x] New
- [ ] Continuation
- [ ] Revision

If Revision enter appropriate letter(s) in box(es):

A. Increase Award B. Decrease Award C. Increase Duration
D. Decrease Duration Other (specify):

9. NAME OF FEDERAL AGENCY:

U.S. Department of Energy

10. CATALOG OF FEDERAL DOMESTIC ASSISTANCE NUMBER: 81-121

TITLE: LAB NE-2001-1
Nuclear Energy Research Initiative

11. DESCRIPTIVE TITLE OF APPLICANT'S PROJECT:

Proliferation-Resistant Reactor and Fuel Cycle Without Significant Quantities of Chemically Separable Weapons-Usable Fissile Materials

12. AREAS AFFECTED BY PROJECT *(cities, counties, states, etc.)*:

City of Berkeley, County of Alameda, California

13. PROPOSED PROJECT:

Start Date	Ending Date
7/1/2001	6/30/2004

14. CONGRESSIONAL DISTRICTS OF:

a. Applicant	b. Project
Ninth	Ninth

15 ESTIMATED FUNDING:

a.	Federal	$299,998
b.	Applicant	
c.	State	
d.	Local	
e.	Other	
f.	Program Income	
g.	TOTAL	$299,998

16. IS APPLICATION SUBJECT TO REVIEW BY STATE EXECUTIVE ORDER 12372 PROCESS?

a. THIS PREAPPLICATION/APPLICATION WAS MADE AVAILABLE TO THE STATE EXECUTIVE ORDER 12372 PROCESS FOR REVIEW ON

DATE

b. [ ] NO PROGRAM IS NOT COVERED BY E.O. 12372

[x] OR PROGRAM HAS NOT BEEN SELECTED BY STATE FOR REVIEW

17. IS THE APPLICANT DELINQUENT ON ANY FEDERAL DEBT?

Yes [ ] If "Yes," attach an explanation [x] No

18 TO THE BEST OF MY KNOWLEDGE AND BELIEF, ALL DATA IN THIS APPLICATION/PREAPPLICATION ARE TRUE AND CORRECT. THE DOCUMENT HAS BEEN DULY AUTHORIZED BY THE GOVERNING BODY OF THE APPLICANT AND THE APPLICANT WILL COMPLY WITH THE ATTACHED ASSURANCES IF THE ASSISTANCE IS AWARDED

a. Typed Name of Authorized Representative	b. Title	c. Telephone number
Patricia A. Gates	Senior Research Administrator	510-642-8109
d. Signature of Authorized Representative		e. Date Signed

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Prescribed by OMB Circular A-102

APPLICATION FOR FEDERAL ASSISTANCE

OMB Approval No. 0348-0043

1. TYPE OF SUBMISSION: *Application* [ ] Construction [X] Non-Construction; *Preapplication* [ ] Construction [ ] Non-Construction	2. DATE SUBMITTED 1/19/01	Applicant Identifier
	3. DATE RECEIVED BY STATE	State Application Identifier
	4. DATE RECEIVED BY FEDERAL AGENCY	Federal Identifier

5. APPLICANT INFORMATION

Legal Name: **MASSACHUSETTS INSTITUTE OF TECHNOLOGY**	Organizational Unit: **NUCLEAR ENGINEERING DEPARTMENT**
Address *(give city, county, state, and zip code)* : **Office of Sponsored Programs, 77 Massachusetts Avenue, E19-750, Cambridge, MA 02139-4307**	Name and telephone number of the person to be contacted on matters involving this application *(give area code):* **Mary A. McGonagle Phone: (617) 258-8017**

6. EMPLOYER IDENTIFICATION NUMBER (EIN): 04 - 2103594

7. TYPE OF APPLICANT: *(enter appropriate letter in box)* : J

A. State H. Independent School Dist.
B. County I. State Controlled Institution of
C. Municipal J. Private University
D. Township K. Indian Tribe
E. Interstate L. Individual
F. Intermunicipal M. Profit Organization
G. Special District N. Other (Specify):

8. TYPE OF APPLICATION

[X] New [ ] Continuation [ ] Revision

If Revision, enter appropriate letter(s) in box(es): [ ] [ ]

A. Increase Award B. Decrease Award C. Increase Duration
D. Decrease Duration Other (specify)

9. NAME OF FEDERAL AGENCY: **United States Department of Energy, Office of Nuclear Energy, Science and Technology**

10. CATALOG OF FEDERAL DOMESTIC ASSISTANCE NUMBER: **81-121**

TITLE: **Energy & Water Development Appropriations Act of 2001**

11. DESCRIPTIVE TITLE OF APPLICANT'S PROJECT:

PROLIFERATION-RESISTANT REACTOR AND FUEL CYCLE WITHOUT SIGNIFICANT QUANTITITES OF CHEMICALLY-SEPARABLE WEAPONS-USABLE FISSILE MATERIALS

12. AREAS AFFECTED BY PROJECT (cities, counties, states, etc.):

13. PROPOSED PROJECT: Start Date	Ending Date	14 CONGRESSIONAL DISTRICTS OF: a. Applicant	b. Project
10/1/01	**9/30/04**	**Eighth**	**Eighth**

15. ESTIMATED FUNDING:	
a. Federal	$ **304,661**
b. Applicant	$
c. State	$ 0
d. Local	$ 0
e. Other	$ 0
f. Program Income	$ 0
g. TOTAL	$ **304,661**

16. IS APPLICATION SUBJECT TO REVIEW BY STATE EXECUTIVE ORDER 12372 PROCE

a. YES. THIS PREAPPLICATION/APPLICATION WAS MADE AVAILABLE TO THE STATE EXECUTIVE ORDER 12372 PROCESS FOR REVIEW ON:

DATE ____________

b. NO. [X] PROGRAM IS NOT COVERED BY E.O. 12372

[ ] OR PROGRAM HAS NOT BEEN SELECTED BY STATE FOR REVIEW

17. IS THE APPLICANT DELINQUENT ON ANY FEDERAL DEBT?

[ ] Yes If "Yes," attach an explanation [X] No

18. TO THE BEST OF MY KNOWLEDGE AND BELIEF, ALL DATA IN THIS APPLICATION/PREAPPLICATION ARE TRUE AND CORRECT. THE DOCUMENT H AUTHORIZED BY THE GOVERNING BODY OF THE APPLICANT AND THE APPLICANT WILL COMPLY WITH THE ATTACHED ASSURANCES IF THE ASSIS

a. Typed Name of Authorized Representative	b. Title	c. Telephone Number
Paul C. Powell	**Assistant Director**	**(617) 253-3856**
d. Signature of Authorized Representative		e. Date Signed

APPLICATION FOR FEDERAL ASSISTANCE

OMB Approval No. 0348-0043

2. DATE SUBMITTED 1/19/01	Applicant Identifier
3. DATE RECEIVED BY STATE	State Application Identifier
4. DATE RECEIVED BY FEDERAL AGENCY	Federal Identifier

1. TYPE OF SUBMISSION:

Application
- ☐ **Construction**
- ☒ **Non-Construction**

Preapplication
- ☐ **Construction**
- ☐ **Non-Construction**

5. APPLICANT INFORMATION

Legal Name: Burns and Roe Enterprises, Inc.	Organizational Unit: Advanced Technology Services
Address *(give city, county, State, and zip code):* 800 Kinderkamack Road, Oradell, NJ 07649 - Bergen County	Name and telephone number of person to be contacted on matters involving this application *(give area code)* John M. Tuohy 201-986-4838

6. EMPLOYER IDENTIFICATION NUMBER *(EIN):* 13 — 4978230

7. TYPE OF APPLICANT: *(enter appropriate letter in box)* M

A. State	H. Independent School Dist.
B. County	I. State Controlled Institution of Higher Learning
C. Municipal	J. Private University
D. Township	K. Indian Tribe
E. Interstate	L. Individual
F. Intermunicipal	M. Profit Organization
G. Special District	N. Other (Specify) ____________________

8. TYPE OF APPLICATION:

☒ **New** ☐ **Continuation** ☐ **Revision**

If Revision, enter appropriate letter(s) in box(es) ☐ ☐

A. Increase Award B. Decrease Award C. Increase Duration
D. Decrease Duration Other*(specify):*

____

9. NAME OF FEDERAL AGENCY: Department of Energy

10. CATALOG OF FEDERAL DOMESTIC ASSISTANCE NUMBER: 81 — 121

TITLE: Nuclear Energy Research

11. DESCRIPTIVE TITLE OF APPLICANT'S PROJECT:

Proliferation - Resistant Reactor and Fuel Cycle without Significant Quantities of Chemically - Separable Weapons - Usable Fissle Materials

12. AREAS AFFECTED BY PROJECT *(Cities, Counties, States, etc.):* Oradell, Bergen County, New Jersey

13. PROPOSED PROJECT

Start Date	Ending Date
6/1/01	

14. CONGRESSIONAL DISTRICTS OF:

a. Applicant	b. Project
Marge Roukema - 5th NJ	Marge Roukema - 5th NJ

15. ESTIMATED FUNDING:

a. Federal	$ 350,000 .00
b. Applicant	$ .00
c. State	$ .00
d. Local	$ .00
e. Other	$ .00
f. Program Income	$ .00
g. TOTAL	$ 350,000 .00

16. IS APPLICATION SUBJECT TO REVIEW BY STATE EXECUTIVE ORDER 12372 PROCESS?

a. YES. THIS PREAPPLICATION/APPLICATION WAS MADE AVAILABLE TO THE STATE EXECUTIVE ORDER 12372 PROCESS FOR REVIEW ON:

DATE ____________________

b. No. ☒ PROGRAM IS NOT COVERED BY E. O. 12372
☐ OR PROGRAM HAS NOT BEEN SELECTED BY STATE FOR REVIEW

17. IS THE APPLICANT DELINQUENT ON ANY FEDERAL DEBT?

☐ **Yes If "Yes," attach an explanation.** ☒ **No**

18. TO THE BEST OF MY KNOWLEDGE AND BELIEF, ALL DATA IN THIS APPLICATION/PREAPPLICATION ARE TRUE AND CORRECT, THE DOCUMENT HAS BEEN DULY AUTHORIZED BY THE GOVERNING BODY OF THE APPLICANT AND THE APPLICANT WILL COMPLY WITH THE ATTACHED ASSURANCES IF THE ASSISTANCE IS AWARDED.

a. Type Name of Authorized Representative John M. Tuohy	b. Title Director - Advanced Technology Services	c. Telephone Number 201-986-4838
d. Signature of Authorized Representative		e. Date Signed

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Standard Form 424 (Rev. 7-97)
Prescribed by OMB Circular A-102

TABLE OF CONTENTS

PROJECT ABSTRACT

Title:	**A Proliferation-Resistant Reactor And Fuel Cycle Without Significant Quantities of Chemically Separable, Weapons-Usable Fissile Materials**
Program:	**Nuclear Energy Research Initiate Program Announcement LAB NE 2001-1**
Principal Investigators:	**Charles W. Forsberg (Oak Ridge National Laboratory)** **Dave F. Williams (Oak Ridge National Laboratory)** **Michael W. Golay (Massachusetts Institute of Technology)** **Ehud Greenspan (University of California–Berkeley)** **Michael Crane (Burns and Roe)**
Scope of Work:	**Proliferation Resistant Reactors and Fuel Technology (primary)** **Generation IV Nuclear Energy Systems**
Field of Proposed Work:	**Nuclear Engineering** **F1 Reactors, reactor systems, components, structures, and reactor and power conversion cycles/concepts** **F3 Nuclear fuel systems /fuel cycles**

ABSTRACT

A major concern with nuclear power is nuclear proliferation. Over the lifetime of a large light-water reactor, sufficient plutonium is produced such as to fabricate several hundred weapons. The world inventory of commercial plutonium is estimated at 1270 tonnes (t) [195 t of separated plutonium and 1065 t of plutonium in spent nuclear fuel (SNF)]. A combination of institutional and technical barriers are used today to prevent the use of power reactors as a source of plutonium for weapons.

This proposal suggests an alternative approach—a reactor and fuel cycle with (1) no significant inventory of chemically separable, weapons-usable materials and (2) ultimately no requirement for fuel cycle (enrichment) facilities, which could rapidly produce significant quantities of weapons-usable materials. The characteristics of such a system include (a) very small accumulated inventories of chemically separable, weapons-usable fissile material in the reactor; (b) a chemically separable, weapons-usable fissile material inventory in the reactor and fuel cycle that is an order of magnitude or more smaller than in other power reactors and fuel cycles; and (c) an asymptotic mix of plutonium isotopes significantly less attractive for weapons applications than plutonium from other reactors.

An initial assessment indicates that a ^{233}U–thorium-fueled, thermal-neutron, high-conversion, molten-salt reactor (MSR)—with added ^{238}U to isotopically dilute the ^{233}U to non-weapon-usable fissile material—would have the lowest inventory of weapons-usable fissile materials of any type of power reactor. The fuel is a liquid mixture of fluoride salts. This reactor herein is called a proliferation-resistant (PR) MSR. There is the potential that the total quantity of weapons-usable plutonium per reactor [1000 MW(e)] and the associate fuel cycle could be reduced to less than the quantity of plutonium identified by the International Atomic Energy Agency as necessary to build one nuclear weapon.

The objective of the proposal is to determine the feasibility of a nuclear power reactor and fuel cycle that minimizes nuclear proliferation issues by minimizing the existence of and capabilities to produce weapons-usable fissile materials. To meet the objective, there are two activities.

- *Reactor and fuel cycle with ultralow chemically separable, weapons-usable inventory*. The proposed work will determine (1) if it is possible to design a PR-MSR with the desired PR characteristics, (2) if such a design could be practicable, and (3) if the reactor would be potentially viable as a Generation IV reactor (passive safety, better waste management, and lower costs).

- *Destroying existing inventories of chemically separable, weapons-usable materials*. The proposed work will examine the use of a PR-MSR to dispose of transuranic (TRU) elements from SNF, which is discharged by other types of reactors, and thus to reduce the world-wide inventory of weapons-usable material. The proposed approach avoids the separation of actinides from fission products and thus the traditional proliferation concerns associated with processing SNF. There are several other potential longer-term impacts: The approach (1) may ultimately eliminate the need for uranium enrichment facilities (a proliferation hazard) and (2) destroy all, except trace quantities, of TRU elements in waste streams and thus minimize the quantity of actinides going to the repository. This, in turn, addresses safeguards, criticality, and some public acceptance issues associated with the repository.

While the primary objectives are to examine the feasibility of building a practical power reactor that minimizes proliferation concerns by minimizing the inventory of weapons-usable materials, the PR-MSR may have other unique capabilities that help meet Generation IV reactor goals.

- *Generation IV safety and economics*. The PR-MSR is the only proposed large [>1000 MW(e)] reactor with passive safety. Historically, proposed passively safe reactors have been small reactors to provide the conditions necessary to provide passive decay heat removal from the reactor core. Because of questions about the economics of small reactors, so far these small reactors have remained unused despite their very attractive features. The MSR has the potential to overcome this obstacle to commercial introduction and create a reactor with both economics of scale and passive safety. The PR-MSR is a fluid-fuel reactor, which, when overheated, dumps its fuel to passively cooled storage tanks. The fuel is then transferred from a system, which is designed for power production, to a system which is designed for safe storage and passive cooling. Passive decay heat removal is ensured independent of reactor size.

- *Waste transmutation*. The PR-MSR removes fission products, not actinides, from the fuel. The actinides remain in the reactor until they fission. A secondary consequence of the nonproliferation goals is a waste stream that does not contain significant quantities of actinides. This offers potential advantages to the repository: major reductions in the quantities of certain actinides (neptunium) that potentially control long-term repository performance, avoidance of repository criticality issues, avoidance of repository safeguards requirements, and potentially improved public acceptance.

There has been a significant renewal of interest in MSRs in Europe and Japan as a method to burn actinides to improve repository performance and acceptance. In the United States, there has been a growing interest accelerator transmutation of waste where the target is a molten salt.

Oak Ridge National Laboratory will lead the program and conduct work associated with the fuel cycle and engineering. The Massachusetts Institute of Technology will extend current methodologies to evaluate PR to allow comparison of this reactor and fuel cycle concept with other reactors and fuel cycles. The University of California (Berkeley) will be responsible for the neutronic analysis of the reactor. Burns and Roe will undertake the economic analysis.

PROJECT DESCRIPTION

1. INTRODUCTION

The goal of this research is to determine the feasibility of a proliferation-resistant (PR) power-reactor and fuel-cycle concept for which the inventory of chemically separable, weapons-usable materials is very small.

The primary objective is to develop a preconceptual design of a large power reactor [$1000 Mw(e)] and associated fuel cycle where the total quantity of chemically separable, weapons-usable material will be less than that quantity of material as defined by the International Atomic Energy Agency (IAEA) as sufficient such as to build one nuclear weapon. This objective is important from two perspectives.

- Demonstration that such a concept is possible will encourage further thinking and research on reactors that do not contain large inventories of chemically separable, weapons-usable materials.

- If a practical concept can be developed (competitive costs with other methods of power generation, better safety, and reduced waste generation), a radically different type of nuclear power option would be provided to the United States and the world—a Generation IV reactor, which would also advance national nonproliferation goals.

The secondary objective is to determine the feasibility of using the above reactor to burn the transuranics (TRUs) in spent-nuclear-fuel (SNF) from other reactors—without an increase in proliferation risks. This would address the long-term proliferation risks from the growing inventory of chemically separable, weapons-usable materials in SNF.

The historical "belief" has been that any large nuclear power reactor and the associated fuel cycle will contain large quantities of chemically separable, weapons-usable materials (i.e., production of weapons-usable material is an intrinsic characteristic of the production of nuclear power). The chemically separable inventory of weapons-usable materials in SNF from several decades of operating a large light-water reactor (LWR) is sufficient such as to construct several hundred nuclear weapons. The alternative approach, which is proposed herein, if successful, would fundamentally alter this characteristic of nuclear power.

The investigation will proceed along two pathways. The first pathway involves examination of a reactor and fuel cycle, which are chosen to minimize the inventory of chemically separable weapons-usable fissile materials. As will be described, initial analysis (Forsberg 2001) indicates that a molten-salt, liquid-fueled, high-conversion, thermal-neutron reactor with a ^{233}U-thorium fuel cycle will most likely meet the goals. The conversion ratio (CR)—breeding ratio—is equal to or slightly exceeds 1. We call this reactor a PR molten salt reactor (MSR). The PR-MSR is similar to other MSR concepts except (1) sufficient ^{238}U is in the fuel such as to isotopically dilute the ^{233}U to non-weapons-usable ^{233}U [<12 wt % ^{233}U in ^{238}U] and (2) the reactor is designed to minimize plutonium inventories produced from the ^{238}U. The plutonium is the major chemically separable, weapons-usable material in the reactor. The objective of minimizing the inventory of weapons-usable material must be met within the constraints of potentially meeting Generation IV reactor goals: improved (1) safety [passive and inherent safety to prevent large accidents], (2) waste management [reduced actinides to repository], and (3) economics.

The second pathway is to investigate the feasibility of using the PR-MSR to burn (TRUs—primarily plutonium) in SNF from other reactors. Because of the different feed requirements for an MSR as compared to those for solid-fuel reactors, there are potential SNF processing methods that are more PR than processing methods used to recycle TRU elements into solid-fuel reactors.

Many studies (e.g., *Nuclear Technology* February 1970, Bettis and Robinson February 1970, and MacPherson 1985) were conducted in the 1950s and 1960s on MSRs. These led in the late 1960s to the Molten Salt Reactor Experiment (MSRE), an 8-MW(th) reactor, which demonstrated the technology using first a fuel with ^{235}U fluorides, which were dissolved in molten salts, and later a fuel with ^{233}U fluorides, which were dissolved in molten salts. The MSRE operated for 13,000 equivalent full-power hours. A conceptual design (Robertson, June 1971) of a Molten Salt Breeder Reactor (MSBR) was developed and became the primary backup for the liquid-metal fast breeder reactor (LMFBR). The program was canceled in the early 1970s for nontechnical reasons. There have been two major changes in the three decades since the concept was last seriously examined.

- *Goals*. The goals have changed. When the MSBR was being originally developed, the goal was to create a breeder reactor with a CR (breeding ratio) significantly above 1. It was thought at that time that uranium resources were very limited and, thus, that the economic viability of nuclear power depended upon rapidly creating fissile material to start up new reactors. The LMFBR has a significantly higher CR than does the MSRE. It is now recognized that there are sufficient uranium resources such as to start up reactors. Any advanced reactor with a CR of 1 or higher can meet long-term energy needs. Nonproliferation, safety, and waste management were not then considered major issues. Each of these is now a major issue. When the goals change, the preferred technology often changes.

- *Technology.* The original MSR program was a large-scale program. The technology was workable, but many of the solutions to identified problems were complex and difficult to implement. Elegant scientific solutions to significantly improve the reactor were identified, but they were not adopted because the technology did not exist to effectively implement them. "New technologies" (developed in the last 3 decades) imply major changes and improvements over the original reactor concept. Most of these technologies were developed for other programs (LWRs: reactor analysis codes; fusion energy: tritium control; waste management: cold-wall melters; high-temperature gas-cooled reactors (HTGRs): better graphites; salt processing: materials; etc.) but now can be applied to MSRs.

  An example of this are the construction materials for an MSR. In the initial development of the MSBR, the construction materials were a major concern. It was discovered that the fission product tellurium caused intergranular metal corrosion. A metallurgical science development program continued after the main program ended. The longer-term metallurgical program (DeVan 1995) ultimately developed a modified Hastelloy-N, a metal alloy that meets the long-term requirements for an MSR.

In recent years, there has been a renewed worldwide interest in MSRs. This reflects (1) the understanding that many of the barriers to MSRs have disappeared because of technical developments and (2) different goals. Most of the work has been to develop the reactor concept for waste partitioning and transmutation. Significant efforts are underway in Japan and France. The French AMSTER concept (Vergnes December 2000) is being supported by both the French government and the French national utility, EdF. There has also been work on using molten salts as targets for the accelerator transmutation of waste (ATW). However, there has not been significant work on (1) analysis of the PR potential of an MSR or (2) how to improve the PR characteristics of an MSR. There are other related areas important to a Generation IV reactor that have also not been addressed. The proposal addresses these subjects.

The proposed research on the PR-MSR would start with the MSBR and modify it (add ^{238}U to convert weapons-usable ^{233}U into non-weapons-usable ^{233}U, suppress plutonium inventory, and update the technology to meet the goals of the proposal). This proposal is organized into six sections. Section 2 defines the nonproliferation objectives. Section 3 describes the PR-MSR and fuel cycle. Section 4 describes the fuel cycle to destroy SNF TRUs. Section 5 describes the proposed work. Section 6 describes other programmatic interactions.

2. PR CRITERIA

The primary objective of this proposal is to develop a preconceptual design of a PR-MSR and fuel cycle with high resistance to proliferation. To achieve that goal, one must first define *PR*. Three criteria are used to define the characteristics of a reactor and associated fuel cycle, which is designed to minimize the potential connection between nuclear weapons and nuclear power.

- Criterion I: *The waste shall not contain significant quantities of chemically separable, weapons-usable fissile materials.* The primary waste from existing power reactors is SNF, which contains large quantities of chemically separable, weapons-usable plutonium. If PR is to be maximized, this inventory of weapons-usable fissile materials must be eliminated.

- Criterion II: *The reactor shall not contain significant quantities of chemically separable, weapons-usable fissile materials*. The goal for a 1000-MW(e) plant is to reduce the quantity of chemically separable, weapons-usable material to less than that defined by the IAEA as sufficient such as to construct one nuclear weapon (equivalent to 8 kg ^{239}Pu, 8 kg ^{233}U, or 25 kg ^{235}U). If the reactor contains large quantities of chemically separable, weapons-usable materials, it may become a potential source of weapons-usable materials by a nation-state.

- Criterion III: *The reactor and fuel cycle shall strongly inhibit conversion of the facilities and organizations for the production of weapons-usable fissile materials.* This criterion ensures that if a nation-state chooses to develop nuclear weapons, it will choose to build special-purpose production facilities rather than to convert or otherwise use civilian power-reactor or fuel-cycle facilities as sources of weapons-usable fissile materials. A corollary is the need to avoid uranium enrichment facilities for *long-term* production of fuel. Enrichment facilities can be used to produce (1) fuel or (2) weapons-usable, high-enriched uranium (HEU). Many nations have the legitimate desire to use nuclear power to ensure energy independence. For such nations, it would be acceptable to import enriched uranium from existing facilities one time to start a reactor. However, many nations would be concerned if continued importation of enriched uranium was required *to maintain reactor operations*.

3. DESCRIPTION OF A PR-MSR

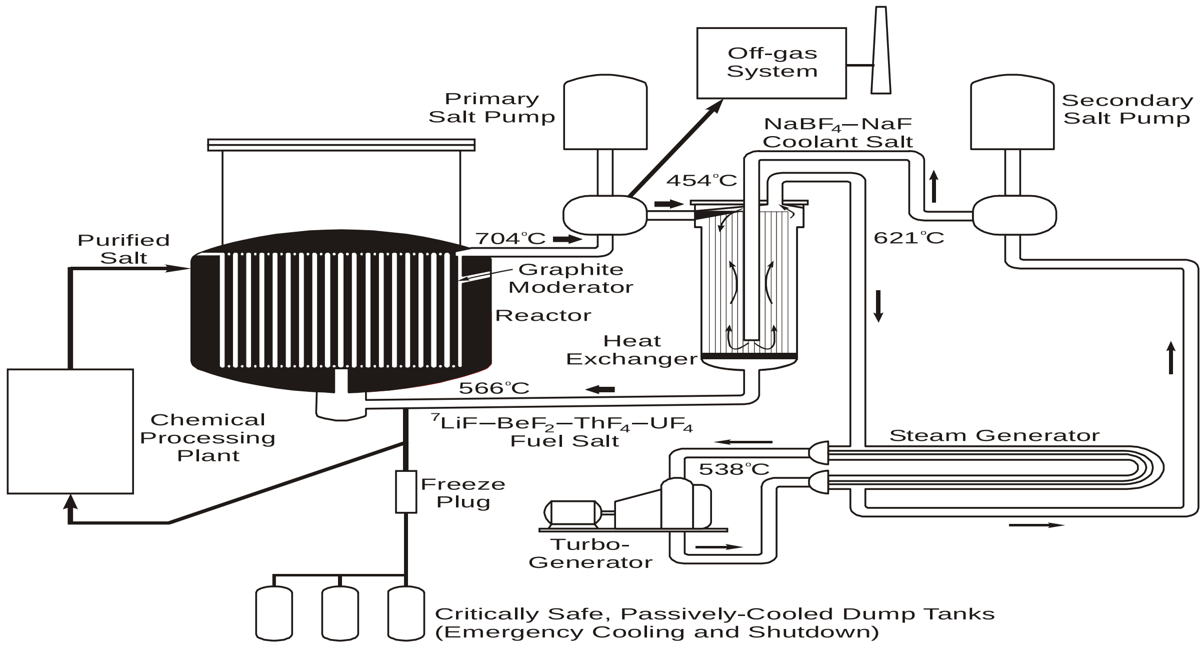
In the late 1960s, a conceptual design of a 1000-MW(e) MSBR was developed (Robertson et al. 1971). The design characteristics are shown in Table 1, and a schematic of the reactor is shown in Fig 1. The proposed PR-MSR concept is similar to that reactor *except for changes in reactor core design and the associated fuel-salt processing system to change the PR, safety, and waste-generation characteristics of the reactor*. The fuel-salt composition, general plant layout, heat-transfer systems, and power-generation systems for the proposed PR-MSR are similar. The major changes in design are:

- *Uranium-233*. The MSBR fuel used weapons-usable ^{233}U. The PR-MSR fuel will be a mixture of non-weapons-usable ^{233}U, ^{238}U, and other uranium isotopes.

- *Plutonium*. The PR-MSR core design and salt-processing systems will be modified to suppress plutonium production and inventories.

- *Other sources of weapons-usable materials*. The PR-MSR design will be modified to minimize the potential for the reactor to be used to produce other weapons-usable materials.

- *Safety and waste management*. The MSR design will be modified to address modern safety and waste-management concerns.



Proliferation-Resistant Molten-Salt Reactor

Table 1. Characteristics of a large MSR

Net electric generation	1000 MW		Maximum core flow velocity	2.6 m/s
Thermal efficiency	44.4 %		Total fuel salt	48.7 m^3
Core height	3.96 m		^{233}U	1,500 kg
Vessel design pressure	5.2 10^5 N/m^2 (75 psi)		Thorium	68,100 kg
Graphite mass	304,000 kg		Salt components	^7LiF-BeF_2-ThF_4-UF_4
Average power density	22.2 kW/L		Salt composition (see line above)	71.7-16-12-0.3 mol %

3.1 SYSTEM DESCRIPTION

The proposed design of the PR-MSR will be similar to that of the MSBR. The fuel is a liquid mixture of lithium-7 fluoride, beryllium fluoride, thorium fluoride, and uranium fluorides. During operation, various fission products and actinides also form fluorides in the liquid. Nuclear criticality occurs in the reactor vessel, which contains unclad graphite. The liquid-fuel salt flows upward through vertical channels in the graphite. The graphite slows down fast-fission neutrons and creates a thermal neutron flux. The heat is primarily generated in the liquid fuel. The molten fuel has a high boiling point; thus, the reactor operates at atmospheric pressure. The liquid-fuel salt enters the reactor vessel at 565EC (1050EF) and exits at 705EC (1300EF). The reactor and primary system are constructed of modified Hastelloy for corrosion resistance to the molten salt. An inert cover gas is used to prevent unwanted chemical reactions.

The fuel flows to a primary heat exchanger, where the heat is transferred to a heat-transfer fluid. The liquid fuel flows back to the reactor core. The heat-transfer coolant ($NaBF_4$-NaF) provides isolation between the molten fuel and the steam cycle. The heat-transfer fluid flows to a steam generator to produce steam and back to the primary heat exchanger. A conventional steam cycle converts the heat to electricity. The electrical efficiency of the plant is ~44%. The high efficiency, as compared to that of LWRs, is a consequence of the high reactor operating temperatures. The temperatures are determined by the need to ensure low salt viscosity and a significant margin between the salt melting point and the system operating temperature. It is a consequence of the selection of the salt composition. In the molten fuel salt, xenon and other fission-product gases are stripped from the salt in the primary-system circulation pumps. The reactor has control rods for rapid shutdown; however, during normal operation, the control rods are in the fully withdrawn position.

In the 1970s, several limited studies (Bauman 1997; Engel 1978) were undertaken to identify methods to improve the PR of the MSBR. One study (Engel 1978) examined the possibility of an MSBR that operates with isotopically diluted ^{233}U. The study indicated that isotopic dilution of ^{233}U (<12 wt % ^{233}U in ^{238}U) to a non-weapons-usable material is feasible, but *it did not examine how to reduce the resultant plutonium inventory or the implications of the plutonium isotopics*. Feasibility was defined in terms of maintaining a CR >1.

The reactor starts up on low-enriched uranium (LEU). After startup, thorium and depleted uranium (DU) are added as needed. The thorium is the fertile fuel to make ^{233}U. The ^{238}U in the DU is used to maintain the ^{233}U as non-weapons usable ^{233}U. With a CR of slightly >1, there is no need for adding fissile fuel after startup. A small side stream of molten salt is processed to (1) remove fission products [minimize parasitic capture of neutrons by fission produces and avoid exceeding solubility limits for fission produces in the salt] and (2) manage protactinium in the reactor (optional–see below). If the fission product solubilities are exceeded, they can precipitate out and block flow channels. The fuel is never removed from the plant during its lifetime. Lower-cost, inefficient fission-product separations are used because this molten salt (after processing) is immediately mixed back with the molten salt in the reactor. Unlike solid fuels, there are no cost or technical reasons for good separations.

The fuel cycle has major impacts on the isotopics of the fissile materials in the PR-MSR. Actinides never leave the reactor. Each actinide is either fissioned or absorbs a neutron to become a higher actinide. Ultimately, all actinides are fissioned. A direct consequence of this fuel cycle is the destruction of all actinides with minimal actinides to the wastes. In terms of waste management, the reactor is a partitioning-transmutation machine, which destroys long-lived actinides; thus, this has major implications for the repository in that repository criticality and safeguards are eliminated by eliminating the actinides in the wastes.

There is a second effect. The infinite recycle results in unusual plutonium isotopics. Plutonium-242 becomes the dominant plutonium isotope, and ^{239}Pu becomes a minor plutonium isotope in a PR-MSR. Not all ^{239}Pu fissions. After neutron absorption, a small fraction of the ^{239}Pu is converted to ^{240}Pu. Further neutron irradiation converts the ^{240}Pu to ^{241}Pu. With neutron irradiation, most of the ^{241}Pu is fissioned, but a small fraction is converted to ^{242}Pu. Plutonium-242 has a low neutron absorption cross section and therefore builds up in the reactor.

Table 2 shows the expected equilibrium plutonium isotopics for weapons-grade plutonium and plutonium from various reactors. The column *PR-MSR* refers to the calculated equilibrium plutonium isotopics, as determined by Engel (1978), for an MSR, which contains ^{233}U and sufficient ^{238}U such as to convert the ^{233}U to non-weapons-usable ^{233}U. That study had as a goal to modify the MSR to make the ^{233}U non-weapons usable. The reactor core design was not modified to minimize plutonium inventories; whereas, this proposal would modify the core design to minimize plutonium inventories. The last column, *LWR Actinide Recycle in MSR*, is the equilibrium plutonium isotopics for an MSR designed as a partitioning-transmutation machine to burn plutonium and higher actinides from LWR SNF. These calculations were done by E. Greenspan (2001)—a principle investigator of this proposal. For the PR-MSR, the expected plutonium isotopics are expected to be between those in the last 2 columns. Plutonium-239, the plutonium isotope preferred for weapons, is a minor plutonium isotope in a PR-MSR.

Table 2. Plutonium isotopics

Isotope	Weapons-grade	Reactor-grade[a] [pressurized-water reactor (PWR)]	PR-MSR (Engel 1978)	LWR actinide recycle in MSR[b]
^{239}Pu	93.	56.6	30	4.5
^{240}Pu	6.5	23.2	18	17.9
^{241}Pu	0.5	13.9	14	5.0
^{242}Pu	0.0	4.7	38	70.2

[a]PWR SNF also has 1.3% ^{238}Pu; [b]Includes 2.3% ^{238}Pu.

3.2 REACTOR PHYSICS

A simplified description of the reactor physics is provided herein to indicate how it is proposed to create a PR-MSR.

3.2.1 Inventory of Fissile Fuel and Weapons-Usable Materials

Four nuclear reactions are important in the PR-MSR: production of ^{233}U from ^{232}Th, fissioning of ^{233}U, production of ^{239}Pu from ^{238}U, and the fissioning of ^{239}Pu. To explain the PR characteristics of the reactor, the following simplified assumptions are used: (1) all neutrons are at thermal energies, (2) all fissile materials fission with one neutron, (3) all fertile materials are converted to fissile materials with one neutron, and (4) the absorption cross sections of structural materials, moderators, and, fission products are small and can be ignored. Using these simplifying assumptions, the following logic provides an explanation of the basis for the reactor's nonproliferation characteristics. The actual neutronics calculations are very complex.

- *CR*. In this system, the CR equals - 1 (^{233}U production = ^{233}U destruction). For every fission of ^{233}U, another ^{233}U will be generated in the PR-MSR by absorption of neutrons by ^{232}Th. *The CR must be near 1 to meet nonproliferation goals*. If the ratio is significantly <1, more fissile fuel must be added to compensate for fuel burnup. In a liquid-fuel reactor, if LEU is added, more ^{238}U is added. The buildup of ^{238}U over time increases the viscosity of the salt until the salt solidifies at high temperature and the reactor shuts down. There is no way to get excess ^{238}U mixed with ^{233}U or ^{235}U out of the reactor. *This is a fundamental difference between a liquid-fuel and solid-fuel reactor. In a solid-fuel reactor, the ^{235}U in a fuel element is burned, and the ^{238}U is* *mechanically removed as SNF*. If plutonium or HEU are used to maintain reactor operations, the reactor does not meet the stated PR goals. The CR must be near or >1 if nonproliferation goals are to be met. With a CR of 1, the following equality exists:

$$^{233}\text{U production} = {}^{233}\text{U destruction} \quad \text{or}$$

$$N_{232Th} \times \sigma_{232Th} = N_{233U} \times \sigma_{233U} \quad \text{(With constant thermal neutron flux)}$$

where σ = Nuclear absorption cross section of each nuclide
N = The number density of atoms of each radionuclide

- *Production ratio*. The relative production ratio of ^{239}Pu to ^{233}U is:

$$\text{Production ratio } ^{239}\text{Pu}:{}^{233}\text{U} = (\text{production of } ^{239}\text{Pu})/(\text{production of } ^{233}\text{U})$$

$$\text{Production ratio } ^{239}\text{Pu}:{}^{233}\text{U} = (N_{238U} \times \sigma_{238U})/(N_{232Th} \times \sigma_{232Th})$$

To ensure that the ^{233}U is nonweapons usable, there need to be 7.3 times as many ^{238}U atoms as ^{233}U atoms—this equals 12% ^{233}U in ^{238}U—the dividing line between weapons-usable and non-weapons-usable ^{233}U (Forsberg 1998). Consequently, $N_{238U} = 7.3 \times N_{233U}$, thus,

$$\text{Production ratio } ^{239}\text{Pu}:{}^{233}\text{U} = (7.3 \times N_{233U} \times \sigma_{238U})/(N_{232Th} \times \sigma_{232Th})$$

From the requirement above that the reactor have a CR of - 1, $N_{232Th} = N_{233U} \times \sigma_{233U} / \sigma_{232Th}$. Substituting this into the production ratio yields:

$$\text{Production ratio } ^{239}\text{Pu}:{}^{233}\text{U} = (7.3 \times \sigma_{238U})/(\sigma_{233U})$$

The thermal cross section of ^{238}U is 2.7 barns. The thermal cross section of ^{233}U is 578.8 barns. Consequently, the production ratio is:

$$\text{Production ratio } ^{239}\text{Pu}:{}^{233}\text{U} = (7.3 \times 2.7)/(578.8) = 0.03$$

- *Inventory ratio*. The inventory of ^{239}Pu to ^{233}U is the production ratio times the relative rate of destruction of the two isotopes. The thermal cross section of ^{239}Pu (σ_{239Pu} = 1011.3) is much larger than the thermal cross section of ^{233}U (σ_{233U} = 578.8 barns), so the ^{239}Pu is preferentially destroyed

$$\text{Inventory ratio } {}^{239}\text{Pu}:{}^{233}\text{U} = (578.8 \times 0.03/1011.3) = 0.017$$

- *Allowable inventory*. The IAEA definition of the quantity of plutonium required for building one nuclear weapon is 8 kg. If the quantity of ^{239}Pu allowed in the reactor is that needed for one weapon (8 kg), the allowable ^{233}U in the reactor is 470 kg (8kg/0.017).

  The actual neutronic calculations are complex. As discussed earlier, one limited study (Engel 1978) examined the possibility of an MSR, which operates with isotopically diluted ^{233}U. The study indicated that isotopic dilution of ^{233}U is feasible, but it did not examine how to reduce the resultant plutonium inventory from irradiation of ^{238}U. However, this study recognized that the next step to improve PR would be to minimize the inventory of plutonium in the reactor and indicated the directions to achieve such goals: a more thermalized neutron flux and modification of the geometry to minimize resonance neutron absorption in ^{238}U. Engel (1978) also noted the difficulties and limitations that would be encountered in such a study based on the then existing nuclear analysis codes and the uncertainties in actinide nuclear cross sections. In the several decades since this study, there have been major advances in methods for neutronic analysis of reactor cores and major improvements in the accuracy of actinide nuclear cross sections. The proposal herein will develop reactor core designs to minimize the weapons-usable fissile inventories with modern tools and nuclear cross sections.

3.2.2 Fuel Isotopics

The previous ^{233}U allowable reactor inventory calculation to meet nonproliferation goals does not account for fuel isotopics—this has a major impact on the allowable ^{233}U inventory in the reactor. An MSR does not remove uranium or plutonium from the reactor—they remain until fissioned or transmuted. The fissile inventory per megawatt is significantly lower than that in an LWR and more than an order of magnitude lower than in a fast-breeder reactor. The total fissile inventory (Robertson et al. 1971; Bettis February 1970) in a 1000-MW(e) MSBR system (reactor core, heat exchangers, processing systems, etc.) is only 1500 kg. The fissile fuel sees a higher effective neutron flux. After one year in a PR-MSR, the uranium and plutonium isotopics of the fuel will begin to resemble LWR fuel that has been irradiated for several years. After five years of operation, the PR-MSR isotopes will be different from anything previously seen in any other type of power reactor.

Under these conditions, the concentrations of ^{234}U and ^{236}U in the fuel approach that of ^{233}U. These isotopes, like ^{238}U, isotopically dilute the ^{233}U and convert it to non-weapons-usable ^{233}U. This isotopic dilution by other uranium isotopes (1) reduces the quantity of ^{238}U required in the reactor to convert ^{233}U to non-weapons-usable ^{233}U,and thus (2) reduces the quantities of plutonium that are produced. With less plutonium, the allowable inventory of non-weapons-usable ^{233}U increases. The quantities of ^{238}U required to convert ^{233}U to non-weapons-usable ^{233}U in the presence of these other isotopes are currently undefined.

Similarly, as discussed previously and shown in Table 2, the reactor has unusual plutonium isotopics. Plutonium-242 is the primary plutonium isotope. The critical mass of ^{242}Pu is about an order of magnitude greater than that for ^{239}Pu—the plutonium isotope preferred for weapons. If 8 kg of ^{239}Pu is required to build a weapon, a significantly larger—but currently undefined—quantity of this plutonium is required.

The practical implication of these considerations is that the allowable quantity of ^{233}U for a 1000-MW(e) PR-MSR will be some multiple of 470 kg because more than (a) 8 kg of plutonium and (b) >12% ^{233}U in ^{238}U in some mixture of other uranium isotopes are allowable while still meeting nonproliferation goals. Without modifications, earlier designs of MSRs had a ^{233}U inventory of ~1500 kg. *It appears that it may be possible to build a large reactor where (1) the total weapons-usable inventory is less than that required for a single nuclear weapon using the standards of the IAEA and (2) there is no SNF with its inventory of weapons-usable materials.*

Because no existing reactor has such unusual plutonium and uranium isotopics, there is no methodology to define (1) non-weapons-usable uranium with complex uranium isotopics or (2) the equivalence of 8 kg of ^{239}Pu in a plutonium mixture with only a few percent of ^{239}Pu. The proposed activity includes development of such a methodology to define equivalence of different isotopic mixtures in terms of PR.

3.2.3 Protactinium Management

When ^{232}Th absorbs a neutron, it is converted to ^{233}Pa, which then decays to ^{233}U. Protactinium-233 has a 27-d half-life. If the ^{233}Pa absorbs a neutron, it will no longer decay to fissile ^{233}U. If ^{233}Pa losses are too high, the reactor will no longer have a CR -1 and thus will not meet non-proliferation goals. This must be avoided. There are two options for such an avoidance:

- *Limit reactor-core power density*. As the reactor-core power density is lowered, neutron absorption by ^{233}Pa is reduced, and ^{233}U is produced. However, this reduction in power density implies a larger reactor core; a larger ^{233}U inventory in the reactor; and, consequently, a larger plutonium inventory in the reactor. This requires careful trade-offs in core design to ensure a reactor with a CR >1 that meets nonproliferation goals.

- *Separate ^{233}Pa*. The ^{233}Pa can be separated from the fuel salt and allowed to decay to ^{233}U outside the reactor. The resultant ^{233}U can then be added back to the reactor. This process minimizes loss of ^{233}Pa by neutron absorption in the reactor core and maximizes ^{233}U production. It improves fuel economy and breeder performance. However, if the ^{233}Pa were completely separated from the isotopically diluted ^{233}U, its decay would produce ^{233}U, which would not be isotopically diluted with ^{238}U—a proliferation risk.

However, several enabling characteristics of this system may make ^{233}Pa separation from the fuel salt feasible while maintaining high PR.

- *Limited possible ^{233}U production*. For the reactor to operate, the ^{233}U from decay of ^{233}Pa must be recycled. It is the fuel. Only limited amounts of ^{233}U (from ^{233}Pa) can be removed before the reactor shuts down because of a lack of fuel, and ^{233}Pa production is stopped. For the nation-state, the choice is electric power or a small inventory of ^{233}U.

- *Hot ^{233}U*. Any chemical separation process for protactinium separates all protactinium isotopes equally—including ^{232}Pa, which decays to ^{232}U. Uranium-232 has a decay product that emits a 2.6- MeV gamma-ray. The choice of uranium-thorium feeds and reactor design determines the ^{232}Pa and subsequent ^{232}U concentrations. It may be feasible to modify the system so that the radiation levels from the ^{232}U and decay products assure that the separated uranium radiation fields would quickly exceed the IAEA definition of SNF—100 R/h at 1 m.

- *Limited ^{233}Pa separation from isotopically diluted ^{233}U*. The quantity of ^{233}Pa in the reactor is very small compared to the quantity of ^{238}U in the reactor. If weapons-usable ^{233}U is to be produced by separation of the ^{233}Pa from the uranium in the fuel salt, the separation process to separate the ^{233}Pa from the uranium in the fuel salt must be efficient. If a small fraction of a percent of the ^{233}U-^{238}U inventory is not separated from the ^{233}Pa, that ^{233}U-^{238}U mixture will isotopically dilute the new ^{233}U from decay of ^{233}Pa to non-weapons-usable ^{233}U. The separation must also be done quickly or the ^{233}Pa decays to ^{233}U in the presence of ^{238}U in the fuel salt.

  A PR system that allows separation of ^{233}Pa from the fuel salt is any technology that, because of thermodynamic equilibrium limits or other mechanisms, does not allow full separation of all of the ^{233}U/^{238}U from the ^{233}Pa. If some ^{233}U/^{238}U remains with the ^{233}Pa, the ^{233}U from its decay will be isotopically diluted to non-weapons usable ^{233}U outside the reactor. There are several possible technologies with these characteristics.

Protactinium management is secondary to reducing plutonium inventories. The total ^{233}Pa inventory is a several tens of kilograms dissolved in >100,000 kg of highly radioactive molten salt. Because the ^{233}Pa decays rapidly to ^{233}U, any nation that wants to separate the ^{233}Pa has to build a chemical separations plant next to the reactor because of the short half-life. Uranium-233 output will be limited before reactor shutdown because of insufficient fuel and the separation facility can't be hidden since it must be close to the reactor. Any international on-line monitoring of the fuel-salt composition would indicate significant removal of ^{233}Pa from the reactor salt. In contrast, plutonium remains weapons usable for tens of thousands of years, and thus the just-in-time separations requirements for ^{233}Pa do not exist for plutonium. Offsite processing of feeds for plutonium recovery is viable with the option to build a plutonium separations plant and test it before diverting feed materials and making the facility's existence known.

For a PR-MSR, an evaluation of protactinium processing options (with and without) in the context of PR is a required activity and part of this proposal.

3.2.4 Chemical Separations

Fission products accumulate in the fuel salt and must be removed to avoid (1) excessive parasitic neutron capture, that will ultimately shut down the reactor and (2) exceeding the radionuclide solubility limits in salt and thus precipitating solids in the molten salt. Protactinium may or may not be partly separated from the fuel salt. The uranium and actinides must remain with the molten salt until fissioned. Actinide loses must be minimized to maintain a CR \$1. The online salt-purification systems are necessary to (1) maintain operations and (2) meet the goals of a PR reactor.

The choice of what radionuclides to remove and of the rate of removal (hours, days, or years) directly determines the nuclear performance of the reactor. Consequently, the design of the fission product separations operations must be done simultaneously with the reactor core. Reactor physics and chemical separations are tightly coupled in this system.

The most important fission product removal step is removal of noble gases. At operating temperatures, volatile gases (Xe, Kr, I) are stripped from the salt into the off-gas system. The gases removed from the reactor are trapped and decay to non-radioactive isotopes. Special fluid-fuel circulating pumps ensure the rapid removal of volatile fission products from the molten salt. The noble gases, particularly certain xenon isotopes, are strong neutron absorbers. Without the quick removal of the gases, the neutrons absorbed by these gases would prevent the reactor from having a CR \$1. These gases must be efficiently removed. The most important fission-product separation process—removal of noble gases—was demonstrated in the MSRE. Many alternative flowsheets were identified, and some were partly developed.

The concept of the PR-MSR will alter chemical separation requirements. A more thermal neutron flux in the reactor core (Sect. 3.2.1) increases parasitic neutron capture by fission products. This, in turn, may change the required removal rates of certain fission products from the salt. There have also been major advances in certain technologies that may significantly improve and simplify the flowsheets. The original MSR program identified many fuel-salt-processing options. These included options that were highly attractive from a theoretical perspective (including PR) but for which the practical engineering technology did not exist at the time. These options were not further examined.

In the 30 years since these studies, many of the technical barriers have fallen. A specific example of one such technology is the use of cold-wall, induction-heated melters to (1) distill salts and other liquid streams and (2) use as a chemical reactor for separations. Earlier MSBR studies (Bauman et al. February 1977; Engel et al. 1978) noted that pot distillation processes for the fuel salt might (1) greatly simplify processing, (2) improve separation of troublesome fission products from the fuel salt (aid suppression of plutonium production), and (3) allow ^{233}Pa partial separation from the fuel salt (improve economics and aid suppression of plutonium production) but with sufficient $^{233}U/^{238}U$ such as to avoid proliferation concerns. In addition to distillation, if process temperatures can be increased, this (1) changes the chemical distribution coefficients between the different liquids historically used in

MSR chemical processes for separation purposes and (2) alters phase relationships. This in turn creates new separations options. Such options were noted but not examined because the reliable high-temperature-melter technology did not exist at the time to make such options feasible. In the last decade, such melters have been developed in France and elsewhere to produce high-level waste (HLW) glass (at -1200+EC) and glass fiber-optic cables (at -1700EC). In France, some of these melters have operated in hot cells under industrial conditions for over 5 years.

Examination of these newer technologies may significantly alter the viability of a PR-MSR and are a component of the proposed research activities.

3.3 RESISTANCE TO SUBNATIONAL MATERIALS THEFT

The concept of a PR-MSR is designed to make it unattractive for a nation-state to consider using commercial power reactors for production of weapons-usable materials. The proposed approach makes theft of nuclear materials by subnational groups not credible. The initial fuel for the PR-MSBR is non-weapons-usable LEU or non-weapons-usable ^{233}U mixed with ^{238}U. The fuel salt contains only small concentrations of weapons-usable materials mixed with >100,000 kg of molten salts. There is no SNF. To recover any weapons-usable materials, a separations plant must be built at the reactor. Building, testing, and operating a separations plant at an operating reactor are not credible for a subnational group.

3.4 SAFETY

The characteristics of MSRs compared to solid fueled reactors may offer significant safety advantages with respect to large accidents. The approach may also eliminated potential conflicts between improving safety and improving PR.

3.4.1 Accident Source Term Control

The greatest danger in a nuclear reactor accident is the catastrophic release of radionuclides to the environment. In solid-fueled reactors, the accident source term—the quantity of radioactivity in the reactor core—is a given. In an MSR, radionuclides are continuously removed from the molten fuel salt, solidified, packaged, and placed in passively cooled storage vaults. The reactor radionuclide inventory is a design variable, which depends upon the fission product removal capabilities of the molten salt cleanup system. The inventory of fission products in an MSR is less than that in a conventional reactor and thus the maximum accident consequences are less.

In the PR-MSR, the need for the CR near 1 dictates what fission products must be removed and the rate of removal. The safety advantages of removing additional fission products from the reactor and solidifying them into a stable waste form were recognized in earlier work on MSRs but have never been seriously investigated. In the design of proposed PR-MSR, consideration will be given to removing radionuclides that are significant contributors to accident risk but whose removal is not dictated by reactor physics considerations.

Historically, there has been an implicit trade-off between nonproliferation and safety. Most proposed PR fuel cycles use higher-burnup fuels with higher inventories of fission products in the reactor core to increase PR by increasing radiation levels. The implicit goal is to maximize the radioactivity in the fuel per the quantity of fissile material needed to construct a weapon (curies per weapon). Unfortunately this increases the accident source term and implies greater consequences if an accident occurs. *The PR-MSR breaks this historical trade-off between PR and safety*. The PR-MSR has a very low weapons-usable fissile inventory and unusual plutonium isotopics. Although the radioactivity in the reactor core is reduced, the inventory of weapons-usable fissile materials (as measured in the number of weapons that could be constructed) is reduced further. There is a much larger inventory of radioactivity per potential weapon (curies/weapon) but less radioactivity in the reactor. Similarly, the mass of the fuel per potential weapon is much higher than in other fuel cycles. A large PR-MSR will have 100,000 kg of fuel salt.

3.4.2 Emergency Core Cooling

MSRs use passive emergency core cooling systems. If the molten reactor fuel salt overheats, the molten reactor fuel salt is dumped by gravity to multiple, critically safe storage tanks with passive, decay-heat, cooling systems. Freeze valves, which open upon overheating of the salt, or parallel mechanical valves can be used to initiate core dump of fuel. Drains under the primary system also dump fuel salt to the storage tanks if there is primary system leak. This was a design feature of the MSRE and is also a plant requirement to do maintenance on the primary system.

This approach to reactor decay-heat removal is unique to liquid-fuel reactors and allows reactors of any size to be built with passive decay-heat cooling. There have been many proposals for passively safe reactors—the modular high-temperature gas-cooled reactor (MHTGR), the integral fast reactor, and others. A common characteristic of these reactors is their small size as compared to large LWRs. This allows for passive decay cooling. The economic assumption is that the benefits of passive safety and potentially lower cost safety systems will exceed the economics of scale. It is not yet known if this assumption is correct. An MSR operates with different ground rules: Very large power reactors with the economics of scale can be built with passive safety.

The operation of such a safety system over long periods of time may require limits on the plate-out of some metallic fission products on the primary-system metal surfaces. Excess plate-out can create a decay-heat source, which would not be dumped with the primary salt in an emergency and could damage equipment. The operation of this passive safety system requires control of the concentrations of certain metallic fission products in the fuel salt to limit plate-out to acceptable levels. In the proposed work, the requirements to ensure passive safety will be examined carefully since passive safety was not a major consideration in the original design of the MSBR.

3.5 WASTE MANAGEMENT

The wastes from the ^{233}U-Th fuel cycle have very low actinide concentrations as compared to those of (1) SNF or (2) conventional reprocessing HLW streams. The primary fuel is ^{233}U. Most ^{233}U fissions with only small quantities of ^{234}U produced. The ^{234}U eventually absorbs neutrons and is converted to ^{235}U. Most of the ^{235}U is fissioned. It takes many more neutron absorptions to create an actinide in this fuel cycle than it does during a ^{235}U or ^{239}Pu fuel cycle. The addition of ^{238}U for isotopic dilution of ^{233}U will generate some actinides. However, suppressing plutonium production to meet nonproliferation goals aids waste management by minimizing actinides in the waste. The actinides that are produced are burned out.

There is no SNF, and the concentration of weapons-usable materials in the waste is very low. The different waste characteristics have important institutional and repository performance implications. The waste has (1) no significant fissile content and thus no repository nuclear criticality or safeguards issues and (2) a low actinide content and thus limited concerns about long-lived actinides in the repository—a particular concern to part of the public. The long-term (but small) health risks from the proposed Yucca Mountain (YM) Repository [U.S. Department of Energy (DOE) November 13, 1999] and many other proposed repositories [Nuclear Energy Agency (NEA) 1999] are from a limited number of isotopes. Typically, one of the major isotopes in terms of potential releases to the environment from the repository is neptunium, which is generated from ^{235}U by multiple neutron capture. A ^{233}U fuel cycle minimizes neptunium production, and a PR-MSR destroys much of the neptunium, which is produced.

3.6 ECONOMICS

The early studies indicated that the economics were slightly better than those of LWRs. *These studies were performed before the Three Mile Island (TMI) accident and the ensuing changes in safety requirements*. No post TMI cost studies have been done. Several factors strongly suggest that a MSR may have significantly lower costs than an advanced LWR:

- *Low fuel-cycle cost.* There are no fuel-fabrication or -enrichment (after initial core) costs. Since the CR $1, there is no long-term concern about uranium prices.

- *Reduced safety-system costs*. The growth in nuclear power plant costs since the TMI accident has been driven by safety requirements: more backup equipment and higher assurance of proper operation. MSRs dump the fuel to passively cooled tanks for (1) primary system maintenance, (2) emergency core cooling, and (3) any other major accident initiator. This approach to safety avoids the need for large emergency power systems and various emergency core-cooling systems. The areas of large cost growth in nuclear power reactors after TMI would be expected to impact a modern MSR less than other reactor types because most of the required safety systems do not exist in an MSR.

- The costs of safety systems are potentially lower through several effects: reduced reactor source term with potentially reduced evacuation zone, smaller reactor containment system because the reactor operates at low pressure with less stored energy, and passive (no moving parts) emergency core- cooling systems (passively cooled fuel storage tanks).

An economic evaluation of a large PR-MSR is included as part of this proposal. This must be preceded by updating the MSR design basis to (1) meet current regulatory requirements and (2) reflect current technology. There have been major regulatory and technical changes in the three decades since the last MSR economic evaluation was completed.

The economics may also be improved by increasing the operating temperature of the MSR and thus (1) increase power plant efficiency and (2) thus reduce plant costs. The French program is currently investigating an MSR exit temperature of 800EC (Vernges 2000). If the temperature can be further increased, the reactor can be coupled to a helium-gas turbine or combined cycle. The MSR was an outgrowth of the Aircraft Nuclear Propulsion Program, which was attempting to produce a nuclear-powered jet engine. As a consequence, there has been serious investigations of very-high-temperature operations and coupling of the reactor to a gas-turbine cycle.

The technical issue is the material of construction for the primary system. After an extended research program, a modified Hastelloy was successfully developed and tested for the particular environment of the MSBR. However, this Hastelloy would not be suitable at significantly higher temperatures. Two classes of metals have been identified (rhenium-molybdenum; MA956), which would potentially allow higher operating temperatures. One of the options, a rhenium-molybdenum alloy, is in the same class of alloys being proposed as a potential material of construction for lead-cooled reactors. Significant research and development (R&D) would be required to develop these materials. For the PR-MSR, a limited economic analysis is proposed to (1) estimate the potential gains and thus (2) determine if these gains would be sufficient such as to seriously consider a metallurgical research program to develop higher temperature reactor materials.

4. DESTRUCTION OF TRU MATERIALS IN SNF

It is estimated that world inventory of commercial plutonium is 1270 tons (t) (Albright 2000). About 205 t is in unirradiated form, and the remaining 1065 t are in SNF. The inventory will ultimately grow to many thousands of tons. As the SNF ages and the radiation levels decline, recovery of the plutonium from the SNF becomes easier. If global PR is to be improved by reducing inventories of weapons-usable materials, a method to destroy this plutonium is required.

It is proposed that the PR-MSR would be the preferred reactor to destroy the TRUs in SNF [plutonium and minor actinides (MA)] by converting them to a non-weapons-usable mixture of ^{233}U and ^{238}U. The same technical characteristics that result in very low weapons-usable fissile inventories in the PR-MSR imply that the same reactor would be the most efficient reactor to convert weapons-usable fissile materials into non-weapons-usable fissile materials. The feed to the reactor would be a fluorinated plutonium–MA–fission product mixture. SNF would be separated into the low-enriched, non-weapons-usable uranium and a plutonium–MA–fission product mixture, which would be directly fed to the PR-MSR. No separated plutonium stream would be created, and the inventory of weapons-usable plutonium in LWR SNF would be destroyed. There are several important characteristics of this system.

- *PR separations*. The degree of SNF chemical processing necessary to allow the recycle of TRU elements depends upon the reactor. An MSR has two requirements: (1) converting the elements to fluoride form and (2) removing most of the uranium. A solid-fuel reactor has many more requirements to produce a fuel assembly. The chemical composition of the recycle fissile material must be controlled to ensure integrity of the fuel assembly. The feed composition to an MSR can vary widely. If the solid fuel is to be manually fabricated, all the fission products must be removed. The ratio of fissile-to-fertile isotopes must be controlled so that no fuel element has too much or too little fissile material. In an MSR, the fuel can be added incrementally. The differences in reactor fuel requirements imply that much better SNF separations processes are required to recycle TRU elements to a solid-fuel reactor as compared to an MSR. *This difference in requirements implies that the potential exists for much more PR processing of SNF to feed a PR-MSR than to feed any other solid-fuel reactor.*

  There are several candidate processes to convert SNF into a form acceptable for an MSR. In the 1950s and 1960s, major development programs were undertaken to develop direct fluorination methods to recover plutonium and uranium from SNF. Most of the processes were able to successfully separate the uranium, but none of the processes was shown to be effective and reliable at separating the plutonium from the fission products. Similarly, there are several Pyrochemical salt processes, which can remove excess uranium but for which separating plutonium from fission products is extremely difficult. The important characteristics of these processes are that (1) evaluations indicated the processes were potentially economic if they can be made to work and (2) the processes failed to produce clean plutonium.

- *Rapid burn*. The PR-MSR is potentially the most efficient machine for converting plutonium to non-weapons-usable materials as measured in grams converted per unit energy produced. Plutonium fissioning generates heat. In a PR-MSR, the reactor can be designed for almost all the heat to be generated by plutonium destruction with the excess neutrons being used to convert ^{232}Th to a non-weapons-usable ^{233}U. The ^{233}U-^{238}U mixture would be removed frequently to avoid the burning of the ^{233}U. A single large reactor could convert -700 kg of plutonium to non-weapons-usable ^{233}U each year. At one time, the MSRs were proposed as a weapons-production reactors. The feed was to be HEU. The product was to be plutonium, which was to be removed continuously before the buildup of higher plutonium isotopes. This is conceptually similar to the Savannah River Site production reactors, which used HEU driver fuel to irradiate DU targets and produce weapons-grade plutonium. HEU was required as the fissile fuel. If LEU was the fuel, the need to continuously add LEU to replace the ^{235}U would continuously add ^{238}U in the reactor until the fuel salt solidified because of the excess uranium concentration in the salt. The plutonium separations technologies were never developed, but the capability to convert a weapons-usable material to another fissile material was clearly evident.

- *Isotopic dilution*. The PR-MSR would be fed with the plutonium–MA–fission-product mixture. The mixing of SNF plutonium and PR-MSR plutonium in the fuel salt immediately degrades the SNF plutonium isotopics to those similar to the last column in Table 2. The SNF plutonium, after its addition to the PR-MSR, would be the least desirable reactor-grade plutonium in the world.

This type of operation provides a basis for the destruction of SNF and plutonium from existing LWRs or future reactors such as HTGRs. The non-weapons-usable ^{233}U could be recycled back to these reactors. This system allows the burning of the plutonium without creating chemically separated, weapons-usable materials.

5. TASKS

The proposed research is divided into five tasks with the objective of determining the viability of a PR-MSR as a practical PR reactor and fuel cycle. The responsible organizations for the work are shown in parentheses.

5.1 TASK 1: QUANTIFICATION OF PR [MASSACHUSETTS INSTITUTE OF TECHNOLOGY (MIT)]

5.1.1 Isotopic Equivalence

There are two requirements to make fissile materials from a power plant unavailable for nuclear weapons. First, the quantities of plutonium and MA must be less than that required to build one weapon. Second, the ^{233}U must be isotopically diluted with other uranium isotopes to become non-weapons-usable ^{233}U. The PR-MSR has unusual fissile and fertile isotopics. Plutonium-242, not ^{239}Pu, is the primary plutonium isotope. The uranium will contain ^{233}U, ^{238}U, and large quantities of other uranium isotopes (^{234}U and ^{236}U). A methodology will be developed to (1) determine the equivalence of complex mixtures of plutonium isotopics to the IAEA definition of the quantity of plutonium required to build a nuclear weapon and (2) define non-weapons-usable ^{233}U in the presence of complex mixtures of other uranium isotopes (^{234}U, ^{235}U, ^{236}U, and ^{238}U).

5.1.2 Measurement of Total PR

Existing methodologies will be extended to create a probabilistic methodology to evaluate the relative PR of different reactors and fuel cycles—including the PR-MSR. The PR-MSR has unique features (fluid fuels, unusual isotopics, etc.) as compared to those of existing reactors. These unique features require the development of a broader methodology than has been traditionally used A fault tree-based theoretical framework for this approach has been developed (Golay June 3 1999, Golay 2001). The framework takes into account all stages of proliferation—from creating fissile material to deploying weapon. PR is measured by the reactor–fuel cycle-dependent marginal change in the proliferation failure probability as one compares alternative technological concepts. In the proposed work, the MSR versions of interest will be compared to the PWR as a reference concept. These comparisons will be used to quantify PR and to guide improvement of the PR-MSR within the project.

5.2 TASK 2: REACTOR CORE DESIGN [UNIVERSITY OF CALIFORNIA–BERKELEY (UCB)]

This task involves modifying the MSR core design to create a PR-MSR by using non-weapons-usable ^{233}U and suppressing plutonium production. The starting point for this design will be the existing conceptual design of the 1000-MW(e) MSBR, which was developed about 1970. The task includes the following major activities.

- *Reactor core model.* Upgraded neutronics models for the analysis of MSRs will be developed and benchmarked using SCALE 4.4 and MOCUP. MSR neutronic models must address several factors that most neutronic codes do not need to address: continuous removal of selected radionuclides, loss of some fraction of delayed neutrons by flow of fuel out of the reactor, et cetera.

- *Reactor core design*. Using the neutronics model, alternative reactor core designs (graphite-to-salt ratio, dimensions, graphite geometry, etc.) will be developed and evaluated in terms of their capability to reduce the inventory of chemically separable, weapons-usable fissile material in the reactor. The investigation will consider reactor core designs with a more thermal neutron flux and geometric changes that are designed to minimize ^{238}U resonance absorption, which produces plutonium. This effort will include (1) analysis of steady-state conditions and (2) reactor core behavior under multiple accident initiators (void coefficients, temperature coefficients, etc.). The preferred core design will be selected based on PR criteria, which are to be developed in Task 1 and appropriate safety criteria.

- *Reactor behavior as a plutonium burner*. The behavior of the reactor when burning plutonium–MA–fission-product mixtures from SNF will be analyzed.

UCB, in support of the DOE ATW Program, has been investigating the use of molten-salt target systems to burn actinides and has developed neutronic code systems to assist in this investigation. It has also conducted several studies on waste partitioning and transmutation using MSRs (Greenspan and Lowenthal September 2001). This previous work will be used as the basis for creating the PR-MSR models.

5.3 TASK 3: PR-MSR FUEL PROCESSING [OAK RIDGE NATIONAL LABORATORY (ORNL)]

The viability of the PR-MSR depends upon the process facilities to remove fission products from the molten salt. This task investigates the requirements and technology that is required.

5.3.1 Requirements

This task is to develop a methodology and use that methodology to determine (1) what fission products and what fission-product removal rates are required for the reactor to meet different goals and (2) what is the allowable leakage of actinides to the wastes. Several factors potentially determine the required separations efficiencies.

- *Non-proliferation goals*. The non-proliferation goals place three requirements on salt processing: (1) some fission products [defined by reactor neutronic analysis] must be removed to allow continued operation of the reactor while maintaining a low inventory of plutonium, (2) protactinium levels in the reactor must be managed, and (3) actinides to the wastes must be limited. The IAEA has defined waste thresholds below which recovery of weapons-usable fissile materials from wastes is not considered practicable. Such wastes do not require safeguards. The IAEA waste thresholds do not cover the types of waste produced from a PR-MSR (Forsberg July 1998). Consequently, the IAEA methodology will be extended to determine the allowable fissile content in PR-MSR wastes.

- *Safety*. The operation of passive cooling systems depends upon avoiding the long-term buildup of noble-metal fission products on surfaces in the primary system. Buildup of fission products on surfaces depends upon the concentrations of specific fission products in the salt. The maximum consequences of an accident depend upon the reactor source term—primarily the inventory of the fission products in the reactor core that are the most dispersable and bio-accumulate in the environment (iodine, cesium, etc.). An examination will be conducted to determine allowable fission product inventory by element to (1) at a minimum ensure passive safety-system operations over the reactor lifetime and (2) at a maximum materially reduce the accident source term. If the source term is sufficiently limited, safety requirements, such as emergency evacuation plans, may be avoided.

- *Waste management.* The performance of PR-MSR wastes in the proposed YM Repository, as a function of what radionuclides are sent to waste, will be evaluated by extrapolation from the published performance of other wastes in the repository (DOE November 13, 1998). It is known that a very small number of radionuclides, such as ^{237}Np, control long-term performance of the repository. The evaluation will determine if sufficient incentives exist to ensure destruction of one or two of these radionuclides by avoiding their inclusion in the waste streams.

5.3.2 Flowsheet Development

Alternative options for the fuel-salt processing system will be identified and characterized. Options will be selected that include (1) multiple methods to manage ^{233}Pa in the reactor (decay and no decay outside the reactor core) and (2) “new” technologies, such as high-temperature, cold-wall melters, which were not previously considered. The original MSR program identified many fuel-salt processing options—including options that were highly attractive from a theoretical perspective (including PR) but for which the practical engineering technology did not exist at the time. It was noted that these options existed (distillation, changing distribution coefficients by changing temperatures, etc.), but they were not examined because they were not technologically feasible in the 1960s. The options will be examined with a consideration of current industrial technical capabilities.

This task may include limited experimental work. Various analytical methodologies will be used to estimate physical and chemical properties needed to develop chemical flowsheets. Depending upon the confidence in the physical and chemical properties and their importance, decisions will be made concerning what properties need to be measured.

5.3.3 Assessment of Flowsheets

The alternative salt-processing options will be evaluated using two criteria.

- *Proliferation assessment*. Using the methodology, which is to be developed in Task 1, the flowsheets will be examined in terms of proliferation risks.

- *Separations assessment*. Using the requirements developed in Sect.5.3.1, the flowsheets will be evaluated in terms of (1) viability and (2) capability to meet specific goals.

5.4 TASK 4: TRU-BURNING FUEL CYCLE (ORNL)

The option of burning the TRU components from SNF will be examined. This option includes three activities.

- *Separations flowsheet*. An assessment of direct fluorination and pyrochemical processes will be made to identify a flowsheet to convert SNF to a plutonium–MA–fission-product mixture. Economics and PR will be used as the criteria to identify a baseline flowsheet for further analysis.

- *PR-MSR*. The behavior of the PR-MSR will be examined when fed a plutonium–MA–fission-product fluoride mixture as defined by the selected flowsheet or flowsheets as defined above.

- *Fuel-cycle analysis*. Fuel cycles containing LWRs and PR-MSRs will be analyzed to determine the characteristics of a combined system, which burns the actinides from the LWR SNF.

5.5 TASK 5: ECONOMICS (BURNS AND ROE)

An economic evaluation will be conducted. It will consist of two components:

- *Standard plant costs*. A cost estimate of PR-MSR will be developed. The starting point will be the design of the MSBR, which was done in 1970. The design basis will be modified to meet current regulatory requirements (safety systems, quality assurance, etc.) and updated to include current technology. The new cost estimate will reflect these changes.

- *High-temperature PR-MSR*. A limited economic study of a higher temperature PR-MSR will be conducted to determine the economic incentives for higher temperature operation. These benefits must be significant to justify a serious development program in this direction.

5.6 LEVEL OF EFFORT

The budget breakdown by task and organization is shown in Table 3, which provides an indicator of the relative level of effort associated with each task.

6. INTERFACES

The DOE ATW Program is exploring the partitioning and transmutation of actinides in SNF using an accelerator for transmutation. There are several activities in common. In these cases, activities will be coordinated to avoid overlap.

- *Repository analysis*. Both ATW and the PR-MSR destroy actinides, which otherwise would go to the repository. ATW activities in this area will provide input into the activity.

Table 3. Cost breakdown by year and organization[a] (thousands of dollars)

Task	Institution	Year 1	Year 2	Year 3	Total
Quantification of PR	MIT	100	100	105	305
Reactor core design	UCB	100	100	100	300
PR-MSR processing	ORNL	300	225	100	625
TRU-burning fuel cycle	ORNL	50	75	95	220
Economics	Burns and Roe	50	100	200	350
Total		600	600	600	1,800

- *Molten-salt*. The ATW Program is investigating many target options. One of the backup target options is to use a molten salt target. No work is currently being done in this area; but, some earlier analysis is applicable. Future work may occur in this area.

There are significant MSR research activities in France and Japan. Most of these investigations are associated with (1) fuel recycle or (2) waste partitioning and transmutation (NEA 1999) programs. Because there are many common issues, an effort will be made to develop a joint program to extend resources. DOE has recently signed a cooperative agreement with the French government; this agreement provides a potential vehicle for such cooperative work with France. The French AMSTER program (Vergnes 2000) has recently received support of the French national utility (EdF).

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PROJECT SCHEDULE AND MILESTONES

This is a three-year study. The progress each year of the study will be reported on in research reports and an annual report. When appropriate, a research report may be in the form of a journal article, conference paper, or a thesis. The schedule below shows the completion dates for research reports. Actual publication date may depend upon the journal or article.

Year 1

- *Baseline PR-MSR preconceptual design*. This report will describe the basis for the PR-MSR, the trade-off options, the preconceptual design, and the results of initial analysis.

- *Equivalence of plutonium and uranium isotopics*. This report will describe the methodology and results in determining the equivalence of different fissile mixtures in terms of PR.

- *Requirements for salt processing*. This report will define the levels of molten-salt purification which are required to achieve PR-MSR goals (nonproliferation, safety, and waste management).

Year 2

- *Reactor-core design*. This report will define a conceptual reactor-core design and its performance based on analysis.

- *Nonproliferation methodology*. This report will define the probabilistic nonproliferation methodology that has been developed.

- *Salt-processing alternatives*. This report will define and compare flowsheets for salt processing. A preferred flowsheet will be defined based on design goals.

Year 3

- *Reactor analysis*. The reactor-core analysis of the PR-MSR will be completed—including behavior when used as a method to burn plutonium and MAs from SNF.

- *PR analysis*. Using the new methodology, the relative PR of the PR-MSR will be compared to other reactors and fuel cycles.

- *SNF burning*. The report will describe the fuel cycle analysis when using a PR-MSR to burn SNF TRUs.

- *Economic analysis*. The report will describe the preliminary economic assessment of the PR-MSR.

COLLABORATIVE R&D

This is a cooperative program between ORNL, UCB, MIT, and Burns and Row. Each organization will investigate specific areas associated with this concept, as described in Sect. 5 of the project description.

ORNL

ORNL will lead the program and integrate results. It will undertake Task 3 (PR-MSR processing) and Task 4 (TRU-burning fuel cycle).

MIT

MIT will be responsible for development and use of an extended nonproliferation methodology suitable for reactors with unique characteristics (Task 1).

UCB

UCB will conduct and be responsible for PR-MSR neutronics analysis and reactor core design (Task 2).

Burns and Roe

Burns and Roe will conduct and be responsible for all economic analysis and related tasks (Task 5).

ORGANIZATIONS AND QUALIFICATIONS

ORNL, MIT, UCB, and Burns and Roe are internationally recognized for R&D. Each has unique qualifications to contribute to this effort.

ORNL will lead the program (see Collaborative R&D above), address separations and fuel cycle issues, and integrate results. It will undertake Task 3 (PR-MSR processing) and Task 4 (TRU-burning fuel cycle). The program manager is Charles Forsberg. ORNL conducted the original research on MSBRs and continues to work with ^{233}U. As a result, many staff members have a detailed knowledge about ^{233}U and MSR concepts. Furthermore, the ORNL library and central records contain both published and unpublished reports—including documentation about alternative design concepts that were abandoned in the 1960s because of technical limitations at that time that may no longer exist. ORNL is the national repository for the long-term storage of ^{233}U. ORNL currently (1) processes ^{233}U to recover the medical isotope ^{213}Bi, (2) is developing molten salt chemistry to recover ^{233}U from the MSRE salt and convert to an oxide for long-term storage, and (3) is conducting several other ongoing research programs on molten-salt chemistry and properties for other applications. To support these and other programs, ORNL has the facilities and technical staff with unique expertise in ^{233}U, molten salt chemistry, and reactor design.

MIT will lead proliferation risk assessment activities (Task 1). Professor Michael W. Golay is responsible for the proliferation risk studies. He has been a member of the NERAC TOPS subcommittee, which has been concerned with PR within the DOE reactor innovation program. Within his recent activities he has been conducting research in better methods to assess PR. A method for PR quantification that he has developed will be the foundation for such evaluations within the proposed project.

The Department of Nuclear Engineering at MIT, established in 1958, is the largest university program in this area in the U.S., with 17 professors, 120 graduate students, and 30 undergraduates. Therefore, its teaching and research activities cover a wide range of disciplines involved in the engineering of reactors including: reactor physics and fuel management, reactor thermal hydraulics, nuclear materials and structural engineering, reliability and risk assessment, chemical and waste technology, and economics and policy analysis. It has consistently been ranked number one in the field by the U.S. News and World report. It was the first department to introduce a formal course on nuclear fuel management in 1972, on nuclear waste management in 1977, and on proliferation and nuclear technology in 1980.

UCB will lead all reactor core neutronic studies (Task 2). Professor Ehud Greenspan is responsible for these studies. Established in 1958, the Department of Nuclear Engineering at UCB is now the only department that offers degrees in nuclear engineering in California. The department offers undergraduate programs in nuclear energy, nuclear waste management, and bionuclear engineering, as well as graduate programs in reactor analysis and theory, reactor engineering (including thermal hydraulics and safety), nuclear materials, radiation physics and dosimetry, nuclear waste management, risk assessment, bio-medical applications and fusion energy. Current student enrollment is about 50 graduate students and 30 undergraduate students. The department has 8 full-time faculty members, 3 part-time faculty members, and 3 active emeritus faculty members. The department has close research ties with 3 national laboratories: Lawrence Livermore National Laboratory, Los Alamos National Laboratory (LANL), and Lawrence Berkely National Laboratory.

UCB qualifies for the leading role in the neutronic analysis of this project as it is the only Nuclear Engineering department in the USA that has been involved during the last decade in the neutronics analysis of a couple of MSRs. In addition, UCB been involved in the neutronics analysis of a number of other types of advanced nuclear reactors and their fuel cycle. These includes advanced liquid metal cooled reactors, advanced LWRs, and the ATW.

UCB has extensive research experience also in the nuclear fuel cycle. We have developed tools for quantifying the waste streams from the fuel-cycle and for evaluating the impact of the nuclear waste on proliferation, radiological, and other hazards. Berkeley is also home for the Center for Risk Analysis, which is comprised of scholars working on both the risks of technological systems and natural hazards.

Burns and Roe will lead economic assessments including modification of the design to meet current requirements. Michael Crane will be responsible for these studies. Burns and Roe has significant experience in developing requirements and estimating costs for advanced energy systems.

Established in 1932, Burns and Roe is an independent consulting engineering organization devoted to the practice of engineering and design construction and related supporting services for major utility, industrial, chemical, and research projects. The company's activities cover the entire spectrum of technical and project management services from the inception of a project through its start-up and operation. Burns and Roe has been deeply involved in the development of new technologies. In addition to our "First-of-a-Kind" nuclear projects, we are also provide independent cost estimating services to support DOE capital projects.

This broad experience includes planning, project financing, technical and economic studies, cost estimating, site selection, engineering, design, scale modeling, procurement, scheduling, logistic support, construction, quality assurance, start-up and test, operator recruitment and training, technical manual preparation, and plant maintenance and operation.

CURRICULUM VITAE

CHARLES FORSBERG
OAK RIDGE NATIONAL LABORATORY

Education

University of Minnesota, Minneapolis	B.S.—1969, Chemical Engineering
Massachusetts Institute of Technology, Cambridge	M.S.—1971, Nuclear Engineering
Massachusetts Institute of Technology, Cambridge	Sc.D —1974, Nuclear Engineering

Professional Activities and Affiliations

Fellow, American Nuclear Society
Member, American Association for the Advancement of Science
Member, American Institute of Chemical Engineers
Member, Materials Research Society
Member, U.S. Department of Energy ^{233}U Team
Member, U.S. Department of Energy High-level Waste Technical Advisory Panel
Registered Professional Engineer (State of Tennessee)
Principal holder of eight U.S. patents

Highlights

Dr. Charles Forsberg is a senior staff member of ORNL. His research areas are advanced reactors and fuel cycles. His doctorate thesis was on uranium enrichment technologies, and he has done subsequent research on reprocessing, fuel fabrication, and other fuel-cycle technologies. He has been the program manager for several programs, including the developmental LWR program, which examined inherently and passively safe LWRs. He holds eight patents in the areas of passive safety systems for power reactors, reprocessing, and waste treatment.

At ORNL, he is a member of the DOE ^{233}U multi-site team addressing ^{233}U safety and storage issues. He directed the technical studies on disposition options for excess ^{233}U. He participated in the DOE TOPS workshops to examine how to improve PR in the nuclear fuel, is the U.S. MSR contact for the DOE/Russian Proliferation-Resistant Nuclear Technology program, and is a member of the non-classical reactor team for the Generation IV road map activity. Dr. Forsberg led the team that developed the technical basis for defining weapons-usable ^{233}U (>12 wt % ^{233}U in ^{238}U), which is based on isotopic composition. He also developed the methodology to define waste thresholds for ^{233}U, that is, the concentration of ^{233}U in waste at which safeguards may be terminated because the ^{233}U is practicably unrecoverable. He is currently conducting studies on the future uses of ^{233}U for reactors and other applications. Consequently, reviews of worldwide activities in these areas are being completed.

Selected Publications (Total list is >150 articles and reports)

C. W. Forsberg, “Are Chemically Separable Weapons-Usable Fissile Materials a Characteristic of Nuclear Power Systems”, *Science and Global Security*, (submitted).

C. W. Forsberg, “What is Non-Weapons-Usable Material?,” p. 62 in *Trans. 1999 Winter American Nuclear Society Meeting, Long Beach, California, November 14–18, 1999*, Vol. 81.

C. W. Forsberg and L. C. Lewis, *Uses For Uranium-233: What Should Be Kept for Future Needs?*, ORNL/TM-6952, Oak Ridge National Laboratory, Oak Ridge, Tennessee, September 24, 1999.

C. W. Forsberg, E. C. Beahm, L. R. Dole, A. S. Icenhour, S. N. Storch, L. C. Lewis, and E. L. Youngblood, *Disposition Options for Uranium-233*, ORNL/TM-13553, Oak Ridge National Laboratory, June 1, 1999.

C. W. Forsberg, "Fissile-Waste Management Constraints: Safeguards and Criticality," pp. 91–91 in *Trans. 1998 Winter American Nuclear Society Meeting, Washington, D.C., November 15–19, 1998*, Am. Nuc. Soc., La Grange Park, Illinois.

C. W. Forsberg, "Recovery of Fissile Materials From Wastes and Conversion of the Wastes To Glass," *Nucl. Techno.*, **123**, 341–349, September 1998.

C. W. Forsberg, "Plutonium Futures," *MIT Nuclear Systems Safety Course*, Department of Nuclear Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, July 23, 1998.

C. W. Forsberg, S. N. Storch, and L. Lewis, *Uranium-233 Waste Definition: Disposal Options, Safeguards, Criticality Control, and Arms Control*, ORNL/TM-13591, Oak Ridge National Laboratory, Oak Ridge, Tennessee, July 7, 1998.

C. W. Forsberg, C. M. Hopper, J. L. Richter, and H.C. Vantine, *Definition of Weapons-Usable Uranium-233*, ORNL/TM-13517, Oak Ridge National Laboratory, Oak Ridge, Tennessee, March 1998.

C. W. Forsberg and J. C. Conklin, "Passive Cooling System with Temperature Control for Reactor Containments," *Nucl. Technol.* **116**, 55–65, October 1996.

C. W. Forsberg, "Passive and Inherent Safety Technologies Applicable to Light-Water Reactors," *Proc. 3rd Annual Former Soviet Union Nuclear Society Meeting*, *St. Petersburg, Russia, September 14–18, 1992.*

C. W. Forsberg, "A Water-Level Initiated Decay Energy Cooling System," *Nucl. Technol*. **96**, 229–235 (November 1991).

C. W. Forsberg and A. M. Weinberg, "Advanced Reactors, Passive Safety, and the Acceptance of Nuclear Energy," *Annual Rev. of Energy*, **15**, 133–152, 1990.

C. W. Forsberg, et al., *Proposed and Existing Passive and Inherent Safety-Related Structures, Systems, and Components (Building Blocks) for Advanced Light-Water Reactors*, ORNL-6554, Oak Ridge National Laboratory, Oak Ridge, Tennessee, December 1989.

C. W. Forsberg, "Passive Emergency Cooling Systems for Boiling Water Reactors (PECOS-BWR)," *Nucl. Technol.* **76**, 185, January 1987.

C. W. Forsberg, "A Process-Inherent Ultimate Safety Boiling Water Reactor," *Nucl. Technol.* **72**, 121–134, February 1986.

CURRICULUM VITAE

DAVE F. WILLIAMS
OAK RIDGE NATIONAL LABORATORY

Education

Virginia Institute of Technology	B.S. 1978	Chemical and Nuclear Engineering
University of Tennessee	M.S. 1985	Chemical Engineering
University of Washington	Ph.D. 1991	Chemical Engineering

David F. Williams has 15 years of professional experience in radiochemical R&D. His experience has ranged from design work in support of production of sol-gel particulate nuclear fuel, to development of flowsheet and equipment for the radiochemical recovery of special isotopes, to more basic chemical research. For the past three years he has led the basic research studies that established the salt chemistry necessary for the remediation of the MSRE at ORNL. He is the present Group Leader of the Chemistry Research Group in the Chemical Technology Division.

Selected Publications

D. F. Williams, A. S. Icenhour, L. D. Trowbridge, G. D. Del Cul, and L. M. Toth, "Radiolysis Studies in Support of the Remediation of the Molten Salt Reactor Experiment," Transactions of the American Nuclear Society (invited paper published in 1999 Winter Meeting Proceedings, November 14–18, 1999, Long Beach, California).

D. F. Williams, G. D. Del Cul, and L. M. Toth, "Molten Salt Fuel Cycle Requirements for ADTT Applications," *3rd International Conference on Accelerator Driven Transmutation Technologies and Applications (ADDTA '99), Prague, Czech Republic, June 7–11, 1999, (paper* We-I-17) in http//www.fjfi.cvut.cz/con_adtt99/).

D. F. Williams, J. Brynestad, "Evaluation of Fluorine-Trapping Agents for Use During Storage of the MSRE Fuel Salt," ORNL/TM-13770, Oak Ridge National Laboratory, Oak Ridge, Tennessee, May 1999.

D. F. Williams, L. M. Toth, and G. D. Del Cul, *Chemical Interactions During Melting of the MSRE Fuel Salt*, ORNL/M-5506, Oak Ridge National Laboratory, Oak Ridge, Tennessee, November 1996.

D. F. Williams and F. J. Peretz, "Characterization of the Molten Salt Reactor Experiment Fuel and Flush Salts," American Nuclear Society Meeting Proceedings (Conference on DOE Spent Nuclear Fuel and Fissile Material Management June 18, 1996, Reno, Nevada).

D. F. Williams, G. D. Del Cul, and L. M. Toth, *A Descriptive Model of the MSRE after Shutdown Review of FY 95 Progress*, ORNL/TM-13142, Oak Ridge National Laboratory, Oak Ridge, Tennessee, January 1996.

CURRICULUM VITAE

EHUD GREENSPAN
UNIVERSITY OF CALIFORNIA AT BERKELEY

Department of Nuclear Engineering; University of California
Berkeley, CA 94720-1730
Work phone: (510) 643-9983; Fax: (510) 643-9685; E-mail: gehud@nuc.berkeley.edu

Areas of Expertise:

Advanced nuclear reactors and nuclear fuel-cycle conception and analysis. Reactor physics. Optimization of nuclear systems. Advanced energy conversion systems conception and analysis.

Education:

1957-1961	B.Sc in Mechanical Eng. + Nuclear Option (Cum Laude), Technion - Israel Institute of Technology.
1961-1963	M.Sc in Nuclear Science & Eng., Technion, Israel. "Optimization of the Nuclear Design of a 125 MWe Heavy-Water Natural Uranium Power Reactor."
1963-1966	Ph.D in Nuclear Science & Eng., Cornell University, Ithaca, N.Y., USA. "Theory and Measurement of Neutron Importance in Nuclear Reactors."

Present position (since 1992):

Professor-in-Residence, Nuclear Engineering Dept., University of California, Berkeley.

Relevant Experience:

Ehud Greenspan is a full-time faculty member of the Department of Nuclear Engineering of the University of California at Berkeley. He teaches reactor theory and reactor design & analysis courses. Prior to joining UCB he was an Associate Director for Research and Development at the Nuclear Engineering and Applications Division of the Israeli Atomic Energy Commission. He has extensive and broad research experience and was the PI on dozens of advanced nuclear systems conception and analysis. Among these are a couple of studies of MSRs: (1) A Neutronic Scooping Study of a MSR for the Transmutation of Actinides and Fission Products from LWRs (see publications No. 8, 9 and 20), (2) A Once-Through, Graphite-Moderated Molten Salt Transmutation Reactor. He has more than 350 publications a sample of which follows.

Publications sample:

Ehud Greenspan, "Optimization of the Nuclear Design of a 125 MWe Heavy-Water Natural Uranium Power Reactor," M.Sc. Thesis, Israel Institute of Technology, 1963.

E. Greenspan, K. B. Cady, and J. P. Howe, "Economic Potential of Variable Enrichment Fuel Elements for Power Reactors," *Trans. American Nuclear Society*, **9**, 295–296 (1966).

E. Greenspan, "Energy Dependent Fine Structure Effects on the Reactivity Worth of Resonances," *Proc. Advanced Reactors; Physics, Design and Economics*, (J. E. Kallfeltz and R. A. Karam, eds.) Pergamon Press, 196–205, 1975.

E. Greenspan, A. Schneider, D. Gilai, and P. Levin, "Natural-Uranium Light-Water Breeding Hybrid Reactors," *Proc. 2nd Topical Meeting on the Technology of Controlled Nuclear Fusion*, CONF-760935-P3, 1061–1072 (1976).

E. Greenspan, A. Schneider, and A. Misolovin, "On the Feasibility of Plutonium Separation-Free Nuclear Power Economy with LWHRs," *Trans. American Nucl. Society*, **26**, 305–306, (1977).

E. Greenspan, A. Schneider, and A. Misolovin, "The Physics and Applications of Subcritical Light Water U-Pu Lattices," *Proc. Topical Meeting on Advances in Reactor Physics*, Gatlinburg, Tennessee, CONF 780401, 411–422 (1978).

E. Greenspan and Y. Karni, "Spectral Fine Structure Effects on Material and Doppler Reactivity Worth," *Nuclear Sci. and Eng.*, **69**, 169–190 (1979).

J. Hughes, I. Soares, E. Greenspan, W. F. Miller, and Z. Shayer, "Molten Salt Critical Reactors for the Transmutation of Transuranics and Fission Products," *Proc. of the GLOBAL '93 International Conference*, Seattle, Washington, September 12–17, 644–651 (1993).

Z. Shayer, J. Hughes, I. Soares, E. Greenspan, and W. Miller, "Modifying SCALE-4.1 for Transmutation Calculations," *Trans. Israeli Nuc. Soc.*, **18**, VII 27–VII 30 (1994).

E. Greenspan, "BWR Fuel Assembly Having Oxide and Hydride Fuel," U.S. Patent No. 5,349,618, September 20, 1994.

J. Vujic, E. Greenspan, S. Slater, T. Postam, L. Leal, Greg Casher, and I. Soares, "Development of Coupled SCALE 4.2/GTRAN2 Computational Capability for Advanced MOX Fueled Assembly Designs," *Proc. International Conference on Math & Computations Reactor Physics and Environmental Analysis*, Portland, Oregon, April 30–May 4, 1995, pp. 1001–1010.

N. E. Brown, J. Hassberger, E. Greenspan, and E. Elias, "Proliferation Resistant Fission Energy Systems," *Proc. Global '97: International Conference on Future Nuclear Systems*, Yokohama, Japan, October 5–10, 1997. pp. 879–884.

T. H. Kim, N. Z. Cho, and E. Greenspan, "Fuel-Self-Sufficient Heavy-Water Lattices for Proliferation Resistant Multiple Fuel Recycling," *Trans. Am. Nucl. Soc.*, **77**, 108–110 (1997).

E. Greenspan, E. Elias, W. E. Kastenberg, and N. W. Brown, "Compact Long Fuel-Life Reactors for Developing Countries," *Proc. 9th International Conference on Emerging Nuclear Energy Systems, ICENES '98*, Herzlia, Israel, June 28–July 2, 1998, pp. 74–83.

E. Greenspan, W. E. Kastenberg, N. Z. Cho, T. H. Kim, and S. G. Hong, "Multi-Recycling of Spent Fuel with Low Proliferation Risk" *Proc. 9th International Conference on Emerging Nuclear Energy Systems, ICENES '98*, Herzlia, Israel, June 28–July 2, 1998, pp. 455–464.

N. Z. Cho, S. G. Hong, T. H. Kim, E. Greenspan, and W. E. Kastenberg, "Fuel Self-Sufficient and Low Proliferation Risk Multi-Recycling of Spent Fuel," *Proc. 13th KAIF/KNS Annual Conf.*, Seoul, Korea, April 1998, pp. 417–425.

A. S. Boloori, M. Frank, E. Greenspan, E. Hill, D. M. Hutchinson, S. Jones, X. Mahini, M. Nichol, B. H. Park, H. Shimada, N. Stone, and S. Wang, "Once-for-Life Fueled, Highly-Modular, Simple, Super-Safe, Pb-Cooled Reactors," *Proc. GLOBAL '99: International Conf. on Future Nuclear Systems*, Jackson Hole, Wyoming, August 30–September 2, 1999.

E. Greenspan, H. Shimada, D. C. Wade, M. D. Carelli, L. Conway, N. W. Brown, and Q. Hossain, "The Encapsulated Nuclear Heat Source Reactor Concept," *Proc. 8th International Conf. On Nuclear Engineering*, Paper ICONE-8750, Baltimore, Maryland, April 2–6, 2000.

E. Greenspan, H. Shimada, and K. Wang, "Long-Life Cores with Small Burnup Reactivity Swing," *Proc. of the 2000 International Topical Mtg. on Advances in Reactor Physics and Math and Computation into the Next Millennium*, PHYSOR2000, Pittsburgh, Pennsylvania, May 7–11, 2000.

M. D. Lowenthal and E. Greenspan, "Parametric Studies For Optimization Of A Graphite-Moderated Molten Salt Transmuter," submitted to Global '01, Paris, France, September 2001.

CURRICULUM VITAE

MICHAEL WARREN GOLAY

Department of Nuclear Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139

TITLE Professor of Nuclear Engineering, Fission Faculty Chairman
Registered Professional Engineer (Massachusetts #28539)

Principal Fields of Interest

Risk and Reliability, Decision Analysis, Nuclear Technology Performance Improvement Methods

Education

Georgia Institute of Technology/ University of Florida	B	Mech. Eng.
Cornell University	Ph.D.	Nuclear Eng.

Consulting, Governmental and Industrial Advisory Record (last 10 years):

Sandia National Laboratories, Albuquerque, NM Proliferation Resistance	2000-present
Eaton Corporation, Bethel, CT I&C Strategy	2000-present
Korea Electric Power Research Institute, Taejeon, Korea Organizational modeling of nuclear power plant operations	2000-present
TOPS (Proliferation Resistance) Subcommittee of Nuclear Energy Research Advisory Committee to DOE	2000-present
Mtechnology, Inc., Framingham, MA Reliability analysis	2000-present 1998
Institute for Nuclear Power Operations, Atlanta, GA Advisory Council Member	1998-present
Duke Hanford Corp., Handford, WA Nuclear fuel stabilization	1998
GPU Nuclear Corp., Parsippany, NJ Safety Review Committee Member	1996-1997
U.S. Nuclear Regulatory Commission, Washington, D.C. Nuclear Safety Research Review Committee	1994-1997
Stone & Webster Engineering Corp., Boston, MA	1983-1994
Congressional Office of Technology Assessment, Washington, D.C. Panel on aging nuclear power plants: Managing plant life and decommissioning	1992-1993
Los Alamos National Laboratory, Los Alamos, NM Non-prescriptive nuclear safety regulations	1991-1992
Westinghouse Hanford Co., Richland, WA High-level nuclear waste remediation	1991-1992
International Atomic Energy Agency, Vienna, Austria Working group on advanced reactors for an international conference on the future of reactor safety	1991

MIT Sponsored Research Projects (last 10 years):

Comparison of Public Risks from Severe External Events* Direct vs nuclear power plant-related risks	Tokyo Electric Power Corp.	1999-2002
Risk-Informed Assessment of Regulatory and Design Requirements for Future Nuclear Power Plants Development of a scientific, risk-informed approach for simplifying new nuclear plant designs, by using risk analysis tools to identify (and, then, eliminate or modify) deterministic regulatory requirements and industry standards that are not significantly contributing to reliability and safety	NERI (with ABB-Combustion Eng.)	1999-present
"Smart" Equipment and Systems to Improve Reliability and Safety in Future Nuclear Power Plant Operations Integration of plant maintenance information and real-time sensor data utilizing self-monitoring and self-diagnostic characteristics built into plant equipment	NERI (with Sandia National Lab.)	1999-present
Development of Advanced Technologies to Reduce Design, Fabrication, and Construction Costs for Future Nuclear Plants Development of analytic methods for change management and modularization with factory fabrication of new nuclear power plants	NERI (with Duke Eng. and Services)	1999-present
Development of a Method for Quantifying the Reliability of Nuclear Safety-Related Software* Assessment of digital technology reliability in nuclear power plant safety-related software applications hopefully yielding substantial improvements in both nuclear power safety and economics	NEER (DOE)	1999-present
Risk-Informed, Performance-Based Regulator of DOE Facilities* Investigation of how risk-informed, performance-based safety regulation can be applied to DOE facilities	INEEL/DOE (Univ. Research Consortium)	1998-present
Factors of Nuclear Power Success in China Collaboration with Chinese organizations to increase nuclear safety	MIT Fund for Energy and En-vironment (est. by Kann-Rasmussen Foundation	1998-present
Integrated Models, Data Bases, and Practices Needed for Performance-Based Safety Regulation* Investigation of practical barriers to successful reform of the U.S. nuclear safety regulation system	INEEL/DOE (Univ. Research Consortium)	1996-1998
On-Line Monitoring and Expert Advice for Improved LWR Operation Availability* Monitoring for incipient failures of plant components which have been important in causing forced outages	Korea Electric Power Research Institute	1996-1998

Publications

Over 100 papers and articles, including invited articles in leading professional journals.

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*Principal Investigator.

CURRICULUM VITAE

DR. MICHAEL CRANE, P.E.
Nuclear Safety Manager

Education

Ph.D. in Chemical Engineering, New York University. Master of Science in Nuclear Engineering, New York University. Bachelor of Science in Chemical Engineering, Brooklyn Polytechnic Institute. Special Course in Nuclear Power Reactor Safety, MIT, Accelerator fundamentals course, LANL.

Licenses

Registered Professional Engineer: States of New York and New Jersey.

Experience

Dr. Crane is a senior engineering manager with extensive experience in advanced technology projects including fused salt, liquid metal, plutonium processing, and process systems design.

Burns and Roe (1964-Present)

As nuclear safety manager for the accelerator production of tritium (APT) project, Dr. Crane is responsible for performing safety reviews of project design documents and for chairing weekly safety meetings for the APT plant project office. He was responsible for coordinating the preparation of the Preliminary Safety Analysis report (PSAR), the Safety Implementation Plan, the Integrated Safety Management system description, and responses to DOE/Defense Nuclear Facility Safety Board comments on the APT PSAR

As Chief Nuclear Engineer, Dr. Crane directed and was responsible for all nuclear engineering, design, and licensing activities on nuclear power projects. At various times he has had additional responsibilities in chemical and environmental engineering. Major assignments have included the following representative projects:

As Project Manager, Dr. Crane was responsible for studies and analyses relating to the manufacture and use of mixed oxide nuclear fuel for the disposition of weapons grade plutonium. These studies include facility layout, equipment arrangements, automation assessments, capital cost estimates and financial analysis.

As Environmental/Safety Group Leader for the North Korean Nuclear Project, Dr. Crane was responsible for studies and analyses relating to the Sinpo Area Site Study. This project was performed under the auspices of the U.S. Department of State for KEDO, the Korean Peninsula Energy Development Organization. It involved the siting for installation of two large PWR power plants.

As Project Director for the Synthetic Fuels support contract for the Oak Ridge Operations office of DOE, Oak Ridge, Tennessee, Dr. Crane's technical duties included management of engineering reviews of R&D Task Summary Reports, R&D Final Reports, Subcontractor Engineering and Support, Quarterly Technical Reports, SRC-1 Area Contractor Engineering, R&T Subcontract Reports, Environmental R&D Tasks Summary Reports, Simulation Model Reports, and Topical Reports.

As Project Director, Dr. Crane was responsible for the administration and management of the Support Contract for DOE, Headquarters Operations, Germantown, Maryland. His duties included coordination of process engineering, engineering analysis, project controls and administrative activities. He was responsible for client liaison and for fulfillment of contractual obligations.

Major prior assignments have been as Technical Evaluation Supervisor, responsible for conducting independent design reviews of safety related systems of PWR type nuclear power projects and for conducting special design reviews on boiling-water reactor and other nuclear power projects as assigned.

Process Design, 460 ton/year Heavy-Water Production Plant for Canada.

United Nuclear Corporation, Development Division (1961-1964)

Responsible for design study including design and equipment specifications for all fluid system components for Argonne Advanced Research Reactor. Also responsible for equipment specifications, for the liquid-metal system components for the Military Compact Reactor sodium-cooled nuclear power plant.

Societies

Member: American Institute of Chemical Engineers; American Nuclear Society, Past Vice Chairman, Northern New Jersey Chapter. National Society of Professional Engineers, American Glovebox Society.

Papers

"Burnout Behavior of Europium" (presented at second winter meeting of American Nuclear Society, October, 1975); “Find Sieve Tray Weepage Ratesz' (Hydrocarbon Processing, December, 1967); “Nuclear Reactor Licensing and Radwaste” (Newark College of Engineering Seminar Series, October, 1970); “Packaging and Shipment of Solid Radioactive Wastes from Nuclear Power Plants” (American Nuclear Society Conference, June, 1971); “Design Verification for Nuclear Power Plants” (American Power Conference, April, 1982).

Instructor

Professional Engineers Refresher Course, Rockland Community College

“Nuclear Power Engineering - Part 1" (American Society of Mechanical Engineers - North Jersey Section, October 16 to December 11, 1975).

FACILITIES AND RESOURCES

ORNL, MIT, UCB, and Burns and Roe have the facilities and resources to complete all necessary work associated with this proposal (see ORGANIZATION AND QUALIFICATIONS).

ORNL is the national repository for the long-term storage of ^{233}U. ORNL currently (1) processes ^{233}U to recover the medical isotope ^{213}Bi, (2) is responsible for the DOE ^{233}U disposition program, (3) is developing molten salt chemistry to recover ^{233}U from the MSRE salt and convert to an oxide for long-term storage, and (4) is conducting several other ongoing research programs on molten-salt chemistry and properties for other applications. Consequently, the facilities and knowledgeable staff are available. From an historical perspective, ORNL conducted the original research on MSRs. As a consequence, the central files contain most of the nation's published and unpublished reports on this type of reactor. This is a unique resource for the proposed activity.

UCB's part of this project will involve primarily computational work and will be carried-out at our Advanced Nuclear Engineering Computer Laboratory (ANECL). The ANECL is continually growing and updating its hardware and software. Presently the ANECL has a workstation cluster consisting of about 30 Sun Ultra Sparcs, Sparc 20s, Sun Sparc 10s, and Sparc 2s. The cluster server is one of the Sparc 10 machines with 128 MB RAM. Most of the workstations have 128 MB RAM or more. A Mass Storage of over 16 GB is also available. P4, MPI and PVM Parallel Programming Language library routines are installed in the ANECL cluster, and allow a spread of the workload over multiple workstations. This feature is particularly useful for running the MOCUP code we are planning to use for this project.

Also available to us is the College of Engineering computing facility, DECF that is developing the "Millennium" cluster. This new cluster will consist of hundreds of Intel Pentium parallel processing clusters running SolarisX86 (UNIX). This is an evolving project made possible by grants from Intel, IBM, Microsoft, and Sun Microsystems, and is expected to soon become one of the top 100 of the most powerful computing resources in the world. Professor Jasmina Vujic, Co-PI for this project, is the Director of both the ANECL and of the DCEF-JAVA Center.

MIT is conducting multiple reactor and proliferation studies and has the facilities and resources to examine a PR-MSR. In the seventies, the department was involved in the ERDA/DOE programs evaluating the utilization of uranium and thorium in LWRs which were part of the NASAP and INFCE activities. Currently, the department is involved in multiple non-proliferation studies associated with different thorium fuel cycles. This includes work on fuel cycles including: (1) ultra long fuel cycle, (2) the dry recycling of LWR fuel, (3) several thorium-uranium fuel cycle and (4) transmutation by reactors. Professor Golay is currently leading the non-proliferation studies. The department has produced multiple theses in this area.

Burns and Roe has over 1,700 employees located in several offices. Our international headquarters is located in Oradell, New Jersey. We also have engineering offices in Los Alamos, NM; Aiken, SC; and Mt. Laurel, NJ. Regional Offices are also located in Washington, D.C. and Sydney, Australia. All locations are connected via a WAN with stand alone LANs at each location.

Burns and Roe has a full-time nuclear engineering and design staff who are integrated together with our full-time cost estimating specialists. We have been involved in the nuclear industry from the very beginning of the commercial nuclear power industry. Our involvement and commitment to nuclear energy stem from the very first commercial reactor, Shippingport, to the first privately financed reactor, Oyster Creek, to the detailed design of the U.S.'s demonstration LMFBR, Clinch River. Burns and Roe's involvement in advanced nuclear projects includes such projects as the DOE/EPRI Advanced Light Water Study (AP-600), the DOE/EPRI Advanced Liquid Metal Reactor Program, the Princeton University Tokamak Fusion Facility, the DOE MHTGR - New Production Reactor Project, and the APT.

Burns and Roe is currently the prime Independent Cost Estimating contractor for DOE OECM. In this capacity, we have the latest understanding of the cost estimating philosophy of DOE and we have performed ICE's of the Spallation Neutron Source, the National Ignition Facility, and YM. We utilize the cost estimating software success and we are trained in the risk-based estimating software Crystal Ball to perform necessary analyses of cost estimate risks.

BUDGET

The budget summary by institution and year is shown below with the detailed tables on the following pages. The total work will require 3 years from the time the monies are initially received.

Cost breakdown by year and organization ($1000)

Institution	Year 1	Year 2	Year 3	Total
ORNL	350	300	195	845
UCB	100	100	100	300
MIT	100	100	105	305
Burns and Roe	50	100	200	350
Total	600	600	600	1800

The budgets for (1) ORNL, (2) MIT, (3) UCB, and (4) Burns and Roe are shown on the following DOE F.4620.1 forms. For each institution, the costs for each year (three sheets) and the total costs (one sheet) are shown. Additional explanation of the numbers in the cost sheets is also provided.

As required in the Request for Proposal (RFP), the funds would be sent to ORNL and ORNL would then subcontract to MIT, UCB, and Burns and Roe. ORNL cost sheets therefor include these subcontract costs. Consequently, ORNL costs and total program costs are identical.

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Year 1

ORGANIZATION Oak Ridge National Laboratory				**Budget Page No:** 1 of 4	
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR Charles Forsberg				Requested Duration: 12 (Months)	
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)	DOE Funded Person-mos. CAL	ACAD	SUMR	Funds Requested by Applpicant	Funds Granted by DOE
Charles Forsberg	7.00			$57,260	
David Williams	8.00			$59,132	
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. (1.20) TOTAL SENIOR PERSONNEL (1-6)	15.00			$116,392	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. ( ) POST DOCTORAL ASSOCIATES					
2. ( ) OTHER PROFESSIONAL (TECHNICIAN, PROGRAMMER, ETC.)					
3. ( ) GRADUATE STUDENTS					
4. ( ) UNDERGRADUATE STUDENTS					
5. (0.2) SECRETARIAL - CLERICAL				$10,000	
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A+B)				$126,392	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				$54,238	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				$180,630	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM.)					
TOTAL PERMANENT EQUIPMENT					
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				$6,700	
2. FOREIGN				$5,000	
TOTAL TRAVEL				$11,700	
F. TRAINEE/PARTICIPANT COSTS					
1. STIPENDS (Itemize levels, types + totals on budget justification page)					
2. TUITION & FEES					
3. TRAINEE TRAVEL					
4. OTHER (fully explain on justification page)					
TOTAL PARTICIPANTS ( ) TOTAL COST					
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				$10,000	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				$2,000	
3. CONSULTANT SERVICES					
4. COMPUTER (ADPE) SERVICES					
5. SUBCONTRACTS				$250,000	
6. OTHER				$46,670	
TOTAL OTHER DIRECT COSTS				$308,670	
H. TOTAL DIRECT COSTS (A THROUGH G)				$501,000	
I. INDIRECT COSTS (SPECIFY RATE AND BASE)					
TOTAL INDIRECT COSTS				$99,000	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				$600,000	
K. AMOUNT OF ANY REQUIRED COST SHARING FROM NON-FEDERAL SOURCES					
L. TOTAL COST OF PROJECT (J+K)				$600,000	

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Year 2

ORGANIZATION Oak Ridge National Laboratory				Budget Page No:	2 of 4
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR Charles Forsberg				Requested Duration:	12 (Months)
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)	DOE Funded Person-mos. CAL	ACAD	SUMR	Funds Requested by Applpicant	Funds Granted by DOE
Charles Forsberg	5.50			$56,279	
David Williams	5.00			$37,442	
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. (0.90) TOTAL SENIOR PERSONNEL (1-6)	10.50			$93,721	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. ( ) POST DOCTORAL ASSOCIATES					
2. ( ) OTHER PROFESSIONAL (TECHNICIAN, PROGRAMMER, ETC.)					
3. ( ) GRADUATE STUDENTS					
4. ( ) UNDERGRADUATE STUDENTS					
5. (0.2) SECRETARIAL - CLERICAL				$10,000	
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A+B)				$103,721	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				$43,673	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				$147,394	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM.)					
TOTAL PERMANENT EQUIPMENT					
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				$6,700	
2. FOREIGN				$5,000	
TOTAL TRAVEL				$11,700	
F. TRAINEE/PARTICIPANT COSTS					
1. STIPENDS (Itemize levels, types + totals on budget justification page)					
2. TUITION & FEES					
3. TRAINEE TRAVEL					
4. OTHER (fully explain on justification page)					
TOTAL PARTICIPANTS ( ) TOTAL COST					
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				$5,000	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				$2,000	
3. CONSULTANT SERVICES					
4. COMPUTER (ADPE) SERVICES					
5. SUBCONTRACTS				$300,000	
6. OTHER				$47,906	
TOTAL OTHER DIRECT COSTS				$354,906	
H. TOTAL DIRECT COSTS (A THROUGH G)				$514,000	
I. INDIRECT COSTS (SPECIFY RATE AND BASE)					
TOTAL INDIRECT COSTS				$86,000	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				$600,000	
K. AMOUNT OF ANY REQUIRED COST SHARING FROM NON-FEDERAL SOURCES					
L. TOTAL COST OF PROJECT (J+K)				$600,000	

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Year 3

ORGANIZATION Oak Ridge National Laboratory				**Budget Page No:**	3 of 4
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR Charles Forsberg				Requested Duration:	12 (Months)
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)	DOE Funded Person-mos. CAL	ACAD	SUMR	Funds Requested by Applpicant	Funds Granted by DOE
Charles Forsberg	4.00			$44,019	
David Williams	3.00			$24,016	
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. (0.60) TOTAL SENIOR PERSONNEL (1-6)	7.00			$68,035	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. ( ) POST DOCTORAL ASSOCIATES					
2. ( ) OTHER PROFESSIONAL (TECHNICIAN, PROGRAMMER, ETC.)					
3. ( ) GRADUATE STUDENTS					
4. ( ) UNDERGRADUATE STUDENTS					
5. (0.2) SECRETARIAL - CLERICAL				$10,000	
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A+B)				$78,035	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				$31,704	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				$109,739	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM.)					
TOTAL PERMANENT EQUIPMENT					
E. TRAVEL — 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				$6,700	
2. FOREIGN				$5,000	
TOTAL TRAVEL				$11,700	
F. TRAINEE/PARTICIPANT COSTS					
1. STIPENDS (Itemize levels, types + totals on budget justification page)					
2. TUITION & FEES					
3. TRAINEE TRAVEL					
4. OTHER (fully explain on justification page)					
TOTAL PARTICIPANTS ( ) TOTAL COST					
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES					
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				$3,000	
3. CONSULTANT SERVICES					
4. COMPUTER (ADPE) SERVICES					
5. SUBCONTRACTS				$405,000	
6. OTHER				$12,561	
TOTAL OTHER DIRECT COSTS				$420,561	
H. TOTAL DIRECT COSTS (A THROUGH G)				$542,000	
I. INDIRECT COSTS (SPECIFY RATE AND BASE)					
TOTAL INDIRECT COSTS				$58,000	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				$600,000	
K. AMOUNT OF ANY REQUIRED COST SHARING FROM NON-FEDERAL SOURCES					
L. TOTAL COST OF PROJECT (J+K)				$600,000	

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Summary Page

ORGANIZATION: Oak Ridge National Laboratory				**Budget Page No:** 4 of 4	
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR: Charles Forsberg				Requested Duration: 36 (Months)	
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)	DOE Funded Person-mos. CAL	ACAD	SUMR	Funds Requested by Applpicant	Funds Granted by DOE
Charles Forsberg	16.50			$157,558	
David Williams	16.00			$120,590	
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. (2.70) TOTAL SENIOR PERSONNEL (1-6)	32.50			$278,148	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. ( ) POST DOCTORAL ASSOCIATES					
2. ( ) OTHER PROFESSIONAL (TECHNICIAN, PROGRAMMER, ETC.)					
3. ( ) GRADUATE STUDENTS					
4. ( ) UNDERGRADUATE STUDENTS					
5. (0.6) SECRETARIAL - CLERICAL				$30,000	
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A+B)				$308,148	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				$129,615	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				$437,763	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM.)					
TOTAL PERMANENT EQUIPMENT					
E. TRAVEL — 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				$20,100	
2. FOREIGN				$15,000	
TOTAL TRAVEL				$35,100	
F. TRAINEE/PARTICIPANT COSTS					
1. STIPENDS (Itemize levels, types + totals on budget justification page)					
2. TUITION & FEES					
3. TRAINEE TRAVEL					
4. OTHER (fully explain on justification page)					
TOTAL PARTICIPANTS ( ) TOTAL COST					
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				$15,000	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				$7,000	
3. CONSULTANT SERVICES					
4. COMPUTER (ADPE) SERVICES					
5. SUBCONTRACTS				$955,000	
6. OTHER				$107,137	
TOTAL OTHER DIRECT COSTS				$1,084,137	
H. TOTAL DIRECT COSTS (A THROUGH G)				$1,557,000	
I. INDIRECT COSTS (SPECIFY RATE AND BASE)					
TOTAL INDIRECT COSTS				$243,000	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				$1,800,000	
K. AMOUNT OF ANY REQUIRED COST SHARING FROM NON-FEDERAL SOURCES					
L. TOTAL COST OF PROJECT (J+K)				$1,800,000	

Justification and Explanation for ORNL Budget

Cost estimates presented in this proposal have been reclassified in order to be comparable to other research institution's proposals. At ORNL, actual costs will be collected and reported in accordance with the DOE-approved cost accounting system. Total costs presented in this proposal and actual cost totals will be equivalent as will the subtotal of direct and indirect costs.

A. Senior Personnel

Charles W. Forsberg will lead the project. C. W. Forsberg and D. Williams will undertake Tasks 2 and 3.

C. Fringe Benefits

Fringe benefits of 46.60% for Year 1, 30.75 % for Year 2, and 32.25% for year 3 is applied on labor cost in Years 1–3.

E. Travel

Domestic travel includes one conference ($2,500), two coordination and information exchange meeting with partners ($1,900 each), and one meeting with the sponsor ($600) per year.

Foreign travel includes one person-trip per year to France or Japan if a cooperative agreement is developed with either of these countries.

G. Other Direct Costs

- (1) Materials and Supplies. Miscellaneous materials. Several small proof-of-principle experiments on flowsheets may be required. The materials are for these experiments. The materials and supplies cost includes a material handling fee of 10.7% for all three years.

- (5) Subcontracts. The RFP requires that NERI funds be sent to ORNL and ORNL distribute the funds to the proposal partners. The subcontracts are to MIT, UCB, and Burns and Roe for work as defined in this proposal.

  - Year 1
    - MIT (100K)
    - UCB (100K)
    - Burns and Roe (50K)
  - Year 2
    - MIT (100K)
    - UCB (100K)
    - Burns and Roe (100K)
  - Year 3
    - MIT (105K)
    - UCB (100K)
    - Burns and Roe (200K)

In addition to the base cost, all subcontract cost has an ORNL subcontract administration fee of 0.70% for all three years.

- (6) Other. Use of cost collection centers in ORNL R&D divisions is the approved method for collection and distribution of costs related to direct effort. These accounts are established to collect costs associated with personnel engaged in a single operation or several closely related operations. The objective is to establish uniformity and compatibility in recording, distribution, and reporting direct effort for all ORNL R&D divisions. The types of cost which can be charged to cost collection centers are division administration, and general materials/services costs, including but not limited to, telecommunications, word processing, and copying, which are not directly attributable or chargeable to R&D projects. Division administration costs include managerial, technical, and administrative oversight and support activities provided for the general benefit of a division.

  The labor and fringe components have been estimated and reported in items A–C. The organization and administrative burden components have been estimated and are being reported in item G.6. Inclusion of these costs is necessary to provide a full accounting of estimated cost for the proposed project period. All costs will be collected and reported in ORNL's cost accounting system, as approved by DOE.

  In addition, the forward-financing and commitment requirements are also reported in item G.6.

I. Indirect Costs

Indirect costs include ORNL Common Site Support and General and Administrative Support and is applied on a value-added base.

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ESRC-6581 **Period:** 7/1/2001- 6/30/2004 **Year 1**

ORGANIZATION: The Regents of the University of California
c/o Sponsored Projects Office
Berkeley, CA 94720-5940

Budget Page No: 1

PRINCIPAL INVESTIGATOR (PI)/PROJECT DIRECTOR (PD)
Ehud Greenspan

Requested Duration: 36 (Months)

A. SENIOR PERSONNEL: PI/PD, Co-PIs, Faculty, and Other Senior Associates (list each separately with title: A7, show number in brackets.	DOE Funded Person-Mos. CAL	ACAD	SUMR	Funds Requested By Applicant	Funds Granted by DOE
1. Ehud Greenspan, Professor			1.5	17,384	
2. Jasmina Vujic, Associate Professor			0.5	4,722	
3.					
4.					
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. (2) TOTAL SENIOR PERSONNEL (1-6)			2	22,106	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. ( ) POSTDOCTORAL ASSOCIATES					
2. ( ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
3. (1) GRADUATE STUDENTS		9	3	19,865	
4. ( ) UNDERGRADUATE STUDENTS					
5. ( ) SECRETARIAL - CLERICAL					
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A + B)				41,971	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				18,196	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				60,167	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM)					
TOTAL PERMANENT EQUIPMENT					
E. TRAVEL: 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				2,476	
2. FOREIGN					
TOTAL TRAVEL				2,476	
F. TRAINEE/PARTICIPANT COSTS					
1. STIPENDS (itemize levels, types + totals on budget justification page)					
2. TUITION & FEES					
3. TRAINEE TRAVEL					
4. OTHER (fully explain on justification page)					
TOTAL PARTICIPANTS ( ) TOTAL COST					
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				8,871	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION					
3. CONSULTANT SERVICES					
4. COMPUTER (ADP) SERVICES					
5. SUBCONTRACTS					
6. OTHER : Photocopying					
TOTAL OTHER DIRECT COSTS				8,871	
H. TOTAL DIRECT COSTS (A THROUGH G)				71,514	
I. INDIRECT COSTS (SPECIFY RATE AND BASE) Indirect Costs @ 50.4% of Modified Total Direct Costs: $56,518					
TOTAL INDIRECT COSTS				28,485	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				99,999	
K. AMOUNT OF ANY REQUIRED COST-SHARING FROM NON-FEDERAL SOURCES					
L. TOTAL COST OF PROJECT (J+K)				**$99,999**	

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ESRC-6581	***Period:*** 7/1/2001- 6/30/2004 **Year 2**	

ORGANIZATION: The Regents of the University of California c/o Sponsored Projects Office Berkeley, CA 94720-5940				Budget Page No: 2	
PRINCIPAL INVESTIGATOR (PI)/PROJECT DIRECTOR (PD) Ehud Greenspan				Requested Duration: 36 (Months)	
A. SENIOR PERSONNEL: PI/PD, Co-PIs, Faculty, and Other Senior Associates (list each separately with title: A7, show number in brackets.	DOE Funded Person-Mos. CAL	ACAD	SUMR	Funds Requested By Applicant	Funds Granted by DOE
1. Ehud Greenspan, Professor			1.5	17,732	
2. Jasmina Vujic, Associate Professor			0.5	4,816	
3.					
4.					
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. (2) TOTAL SENIOR PERSONNEL (1-6)			2	22,548	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. ( ) POSTDOCTORAL ASSOCIATES					
2. ( ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
3. (1) GRADUATE STUDENTS		9	3	20,262	
4. ( ) UNDERGRADUATE STUDENTS					
5. ( ) SECRETARIAL - CLERICAL					
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A + B)				42,810	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				18,559	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				61,369	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM)					
TOTAL PERMANENT EQUIPMENT					
E. TRAVEL: 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				2,476	
2. FOREIGN					
TOTAL TRAVEL				2,476	
F. TRAINEE/PARTICIPANT COSTS					
1. STIPENDS (itemize levels, types + totals on budget justification page)					
2. TUITION & FEES					
3. TRAINEE TRAVEL					
4. OTHER (fully explain on justification page)					
TOTAL PARTICIPANTS ( ) TOTAL COST					
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				7,769	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION					
3. CONSULTANT SERVICES					
4. COMPUTER (ADP) SERVICES					
5. SUBCONTRACTS					
6. OTHER : Photocopying					
TOTAL OTHER DIRECT COSTS				7,769	
H. TOTAL DIRECT COSTS (A THROUGH G)				71,614	
I. INDIRECT COSTS (SPECIFY RATE AND BASE) Indirect Costs @ 50.4% of Modified Total Direct Costs: $56,320 TOTAL INDIRECT COSTS				28,385	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				99,999	
K. AMOUNT OF ANY REQUIRED COST-SHARING FROM NON-FEDERAL SOURCES					
L. TOTAL COST OF PROJECT (J+K)				**$99,999**	

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ESRC-6581 ***Period:*** 7/1/2001- 6/30/2004 **Year 3**

ORGANIZATION: The Regents of the University of California
c/o Sponsored Projects Office
Berkeley, CA 94720-5940

Budget Page No: 3

PRINCIPAL INVESTIGATOR (PI)/PROJECT DIRECTOR (PD)
Ehud Greenspan

Requested Duration: 36 (Months)

	CAL	ACAD	SUMR	Funds Requested By Applicant	Funds Granted by DOE
A. SENIOR PERSONNEL: PI/PD, Co-PIs, Faculty, and Other Senior Associates (list each separately with title: A7, show number in brackets.) — DOE Funded Person-Mos.					
1. Ehud Greenspan, Professor			1.5	18,087	
2. Jasmina Vujic, Associate Professor			0.5	4,912	
3.					
4.					
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. (2) TOTAL SENIOR PERSONNEL (1-6)			2	22,999	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. ( ) POSTDOCTORAL ASSOCIATES					
2. ( ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
3. (1) GRADUATE STUDENTS		9	3	20,668	
4. ( ) UNDERGRADUATE STUDENTS					
5. ( ) SECRETARIAL - CLERICAL					
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A + B)				43,667	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				18,929	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				62,596	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM)					
TOTAL PERMANENT EQUIPMENT					
E. TRAVEL: 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				2,476	
2. FOREIGN					
TOTAL TRAVEL				2,476	
F. TRAINEE/PARTICIPANT COSTS					
1. STIPENDS (itemize levels, types + totals on budget justification page)					
2. TUITION & FEES					
3. TRAINEE TRAVEL					
4. OTHER (fully explain on justification page)					
TOTAL PARTICIPANTS ( ) TOTAL COST					
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				6,645	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION					
3. CONSULTANT SERVICES					
4. COMPUTER (ADP) SERVICES					
5. SUBCONTRACTS					
6. OTHER : Photocopying					
TOTAL OTHER DIRECT COSTS				6,645	
H. TOTAL DIRECT COSTS (A THROUGH G)				71,717	
I. INDIRECT COSTS (SPECIFY RATE AND BASE) Indirect Costs @ 50.4% of Modified Total Direct Costs: $56,117					
TOTAL INDIRECT COSTS				28,283	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				100,000	
K. AMOUNT OF ANY REQUIRED COST-SHARING FROM NON-FEDERAL SOURCES					
L. TOTAL COST OF PROJECT (J+K)				**$100,000**	

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ESRC-6581 ***Period:*** 7/1/2001- 6/30/2004 **TOTAL**

ORGANIZATION: The Regents of the University of California c/o Sponsored Projects Office Berkeley, CA 94720-5940				Budget Page No: 4	
PRINCIPAL INVESTIGATOR (PI)/PROJECT DIRECTOR (PD) Ehud Greenspan				Requested Duration: 36 (Months)	
A. SENIOR PERSONNEL: PI/PD, Co-PIs, Faculty, and Other Senior Associates (list each separately with title: A7, show number in brackets.	DOE Funded Person-Mos.			Funds Requested	Funds Granted
	CAL	ACAD	SUMR	By Applicant	by DOE
1. Ehud Greenspan, Professor			1.5	53,203	
2. Jasmina Vujic, Associate Professor			0.5	14,450	
3.					
4.					
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. (2) TOTAL SENIOR PERSONNEL (1-6)			2	67,653	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. ( ) POSTDOCTORAL ASSOCIATES					
2. ( ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
3. (1) GRADUATE STUDENTS		9	12	60,795	
4. ( ) UNDERGRADUATE STUDENTS					
5. ( ) SECRETARIAL - CLERICAL					
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A + B)				128,448	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				55,684	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				184,132	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM)					
TOTAL PERMANENT EQUIPMENT					
E. TRAVEL: 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				7,428	
2. FOREIGN					
TOTAL TRAVEL				7,428	
F. TRAINEE/PARTICIPANT COSTS					
1. STIPENDS (itemize levels, types + totals on budget justification page)					
2. TUITION & FEES					
3. TRAINEE TRAVEL					
4. OTHER (fully explain on justification page)					
TOTAL PARTICIPANTS ( ) TOTAL COST					
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				23,285	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION					
3. CONSULTANT SERVICES					
4. COMPUTER (ADP) SERVICES					
5. SUBCONTRACTS					
6. OTHER : Photocopying					
TOTAL OTHER DIRECT COSTS				23,285	
H. TOTAL DIRECT COSTS (A THROUGH G)				214,845	
I. INDIRECT COSTS (SPECIFY RATE AND BASE) Indirect Costs @ 50.4% of Modified Total Direct Costs: $168,955					
TOTAL INDIRECT COSTS				85,153	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				299,998	
K. AMOUNT OF ANY REQUIRED COST-SHARING FROM NON-FEDERAL SOURCES					
L. TOTAL COST OF PROJECT (J+K)				**$299,998**	

ESRC-6581
ORU - ESRC

Budget
(July 1, 2001 - June 30, 2004)

	Monthly Rate	No. of Months	%	7/1/2001-6/30/2002	7/1/2002-6/30/2003	7/1/2003-6/30/2004		
Personnel Costs-Direct Labor								
Prof. Ehud Greenspan, PI Prof. in Residence, step 5	$11,589	1.5 summer	100%	$17,384	$17,732	$18,087	1	$53,203
Prof. J. Vujic, Co-PI Assoc. Professor, step 5	$9,444	0.5 summer	100%	$4,722	$4,816	$4,912		$14,450
1 Graduate Student Researcher II	$2,614	1 ac. yr.	50%	$1,307	$1,333	$1,360	1	
	$2,666	8 ac. yr.	50%	$10,664	$10,877	$11,095	1	
	$2,614	2 summer	100%	$5,228	$5,333	$5,440	2	
	$2,666	1 summer	100%	$2,666	$2,719	$2,773	2	
TOTAL PERSONNEL				**$41,971**	**$42,810**	**$43,667**		$128,448

	Rates Per Period							
Fringe Benefits								
Principal Investigator, summer	12.70%	12.70%	12.70%	$2,807	$2,864	$2,921		$55,684
Graduate Student Researcher, ac. yr	1.30%	1.30%	1.30%	$156	$159	$162		
Graduate Student Researcher, smr.	3.00%	3.00%	3.00%	$237	$242	$246		
Full Fee Remission/per sem.	$2,274	$2,319	$2,365	$4,548	$4,638	$4,730	*	
Nonresident Tuition Remission/per sem.	$5,224	$5,328	$5,435	$10,448	$10,656	$10,870	*	
TOTAL EMPLOYEE BENEFITS				**$18,196**	**$18,559**	**$18,929**		$55,684
TOTAL PERSONNEL & BENEFITS				**$60,167**	**$61,369**	**$62,596**		$184,132
Travel								
2 RTs to conference on East Coast to present results of research ($725 RT airfare, 3 days per diem @ $46/day, lodging @ $125/day)				$2,476	$2,476	$2,476		
TOTAL TRAVEL				**$2,476**	**$2,476**	**$2,476**		$7,428
Supplies/Materials Costs								
Miscellaneous research supplies				$7,871	$6,769	$5,645		
Publications				$1,000	$1,000	$1,000		$23,285
TOTAL OTHER DIRECT COSTS				**$8,871**	**$7,769**	**$6,645**		
TOTAL DIRECT COSTS				**$71,514**	**$71,614**	**$71,717**		$214,845
Indirect Costs	MTDC							
50.4% of Modified Total Direct Costs	$56,518	$56,320	$56,117	$28,485	$28,385	$28,283		$85,153
TOTAL AMOUNT REQUESTED PER YEAR				**$99,999**	**$99,999**	**$100,000**		$299,998
TOTAL AMOUNT REQUESTED						**$299,998**		

[1] Current salary rate as of 10/1/00. Annual totals include a projected 2% COLA effective each October 1.
[2] Projected salary rate as of 10/1/01. Annual totals include a projected 2% COLA effective each October 1.
* These items are not subject to indirect costs.

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ORGANIZATION **MASSACHUSETTS INSTITUTE OF TECHNOLOGY**					**Budget Page No:**	YEAR 1
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR **PROFESSOR MICHAEL W. GOLAY**					Requested Duration:	12 MONTHS 10/01/01-09/30/02
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)	DOE Funded Person-mos.				Funds Requested by Applicant	Funds Granted by DOE
	CAL	ACAD	SUMR			
1. (1) PROFESSOR MICHAEL W. GOLAY			1.00		$13,763	
2. ( )						
3. ( )						
4. ( )						
5. ( )						
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)						
7. (1) TOTAL SENIOR PERSONNEL (1-6)			1.00		$13,763	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)						
1. ( ) POST DOCTORAL ASSOCIATES						
2. ( ) OTHER PROFESSIONAL (TECHNICIAN, PROGRAMMER, ETC.)						
3. (1) GRADUATE STUDENTS					$21,393	
4. ( ) UNDERGRADUATE STUDENTS						
5. (1) SECRETARIAL - CLERICAL					$4,918	
6. ( ) OTHER						
TOTAL SALARIES AND WAGES (A+B)					$40,074	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS) **@ 21% non-stdt s&w and @ 10%**					$4,415	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C) **vacation accrual non-fac & non-stdt s&w**					$44,489	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM.) COMPUTER						
TOTAL PERMANENT EQUIPMENT					$3,000	
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)					$6,500	
2. FOREIGN						
TOTAL TRAVEL					$6,500	
F. TRAINEE/PARTICIPANT COSTS						
1. STIPENDS (Itemize levels, types + totals on budget justification page)						
2. TUITION & FEES						
3. TRAINEE TRAVEL						
4. OTHER (fully explain on justification page)						
TOTAL PARTICIPANTS ( ) TOTAL COST						
G. OTHER DIRECT COSTS						
1. MATERIALS AND SUPPLIES					$1,500	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION						
3. CONSULTANT SERVICES						
4. COMPUTER (ADPE) SERVICES						
5. SUBCONTRACTS						
6. OTHER: **GRADUATE STUDENT STAFF TUITION @ 35% MIT SUBSIDY 65%**					$9,627	
TOTAL OTHER DIRECT COSTS					$11,127	
H. TOTAL DIRECT COSTS (A THROUGH G)					$65,116	
I. INDIRECT COSTS (SPECIFY RATE AND BASE) **65.5% MTDC excluding RA Tuition and Equipment $3K+, maximum $25K per subcontract**						
TOTAL INDIRECT COSTS					$33,858	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)					$98,973	
K. AMOUNT OF ANY REQUIRED COST SHARING FROM NON-FEDERAL SOURCES						
L. TOTAL COST OF PROJECT (J+K)					$98,973	

MIT fully supports the academic year salaries of professors, associate professors, and assistant professors but makes no specific commitment of time or salary to this particular research project.

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ORGANIZATION **MASSACHUSETTS INSTITUTE OF TECHNOLOGY**				**Budget Page No:**	YEAR 2
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR **PROFESSOR MICHAEL W. GOLAY**				Requested Duration:	12 MONTHS 10/01/02-09/30/03
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)	DOE Funded Person-mos.			Funds Requested	Funds Granted
	CAL	ACAD	SUMR	by Applicant	by DOE
1. (1) PROFESSOR MICHAEL W. GOLAY			1.00	$14,451	
2. ( )					
3. ( )					
4. ( )					
5. ( )					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. (1) TOTAL SENIOR PERSONNEL (1-6)			1.00	$14,451	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. ( ) POST DOCTORAL ASSOCIATES					
2. ( ) OTHER PROFESSIONAL (TECHNICIAN, PROGRAMMER, ETC.)					
3. (1) GRADUATE STUDENTS				$22,462	
4. ( ) UNDERGRADUATE STUDENTS					
5. (1) SECRETARIAL - CLERICAL				$5,164	
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A+B)				$42,078	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS) **@ 21% non-stdt s&w and @ 10%**				$4,636	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C) **vacation accrual non-fac & non-stdt s&w**				$46,713	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM.)					
TOTAL PERMANENT EQUIPMENT					
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				$6,500	
2. FOREIGN					
TOTAL TRAVEL				$6,500	
F. TRAINEE/PARTICIPANT COSTS					
1. STIPENDS (Itemize levels, types + totals on budget justification page)					
2. TUITION & FEES					
3. TRAINEE TRAVEL					
4. OTHER (fully explain on justification page)					
TOTAL PARTICIPANTS ( ) TOTAL COST					
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				$1,500	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION					
3. CONSULTANT SERVICES					
4. COMPUTER (ADPE) SERVICES					
5. SUBCONTRACTS					
6. OTHER: **GRADUATE STUDENT STAFF TUITION @ 35% MIT SUBSIDY 65%**				$10,108	
TOTAL OTHER DIRECT COSTS				$11,608	
H. TOTAL DIRECT COSTS (A THROUGH G)				$64,821	
I. INDIRECT COSTS (SPECIFY RATE AND BASE) **65.5% MTDC excluding RA Tuition and Equipment $3K+, maximum $25K per subcontract**					
TOTAL INDIRECT COSTS				$35,837	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				$100,659	
K. AMOUNT OF ANY REQUIRED COST SHARING FROM NON-FEDERAL SOURCES					
L. TOTAL COST OF PROJECT (J+K)				$100,659	

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Budget Page

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ORGANIZATION **MASSACHUSETTS INSTITUTE OF TECHNOLOGY**				**Budget Page No:**	YEAR 3	
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR				Requested Duration:	12 MONTHS 10/01/03-09/30/04	
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)	DOE Funded Person-mos.			Funds Requested	Funds Granted	
	CAL	ACAD	SUMR	by Applicant	by DOE	
1. (1) PROFESSOR MICHAEL W. GOLAY			1.00	$15,174		
2. ( )						
3. ( )						
4. ( )						
5. ( )						
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)						
7. (1) TOTAL SENIOR PERSONNEL (1-6)			1.00	$15,174		
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)						
1. ( ) POST DOCTORAL ASSOCIATES						
2. ( ) OTHER PROFESSIONAL (TECHNICIAN, PROGRAMMER, ETC.)						
3. (1) GRADUATE STUDENTS				$23,585		
4. ( ) UNDERGRADUATE STUDENTS						
5. (1) SECRETARIAL - CLERICAL				$5,423		
6. ( ) OTHER						
TOTAL SALARIES AND WAGES (A+B)				$44,182		
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS) **@ 21% non-stdt s&w and @ 10%**				$4,867		
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C) **vacation accrual non-fac & non-stdt s&w**				$49,049		
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM.)						
TOTAL PERMANENT EQUIPMENT						
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				$6,500		
2. FOREIGN						
TOTAL TRAVEL				$6,500		
F. TRAINEE/PARTICIPANT COSTS						
1. STIPENDS (Itemize levels, types + totals on budget justification page)						
2. TUITION & FEES						
3. TRAINEE TRAVEL						
4. OTHER (fully explain on justification page)						
TOTAL PARTICIPANTS ( ) TOTAL COST						
G. OTHER DIRECT COSTS						
1. MATERIALS AND SUPPLIES				$1,500		
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION						
3. CONSULTANT SERVICES						
4. COMPUTER (ADPE) SERVICES						
5. SUBCONTRACTS						
6. OTHER: Grad Stdt Stf Tuition **GRADUATE STUDENT STAFF TUITION @ 35% MIT SUBSIDY 65%**				$10,613		
TOTAL OTHER DIRECT COSTS				$12,113		
H. TOTAL DIRECT COSTS (A THROUGH G)				$67,662		
I. INDIRECT COSTS (SPECIFY RATE AND BASE) **65.5% MTDC excluding RA Tuition and Equipment $3K+, maximum $25K per subcontract**						
TOTAL INDIRECT COSTS				$37,367		
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				$105,030		
K. AMOUNT OF ANY REQUIRED COST SHARING FROM NON-FEDERAL SOURCES						
L. TOTAL COST OF PROJECT (J+K)				$105,030		

MIT fully supports the academic year salaries of professors, associate professors, and assistant professors but makes no specific commitment of time or salary to this particular research project.

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ORGANIZATION **MASSACHUSETTS INSTITUTE OF TECHNOLOGY**				**Budget Page No:**	YEARS 1-3
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR **PROFESSOR MICHAEL W. GOLAY**				Requested Duration:	36 MONTHS 10/01/01-09/30/04
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)	DOE Funded Person-mos. CAL	ACAD	SUMR	Funds Requested by Applicant	Funds Granted by DOE
1. (1) PROFESSOR MICHAEL W. GOLAY			3.00	$43,387	
2. ( )					
3. ( )					
4. ( )					
5. ( )					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. (1) TOTAL SENIOR PERSONNEL (1-6)			3.00	$43,387	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. ( ) POST DOCTORAL ASSOCIATES					
2. ( ) OTHER PROFESSIONAL (TECHNICIAN, PROGRAMMER, ETC.)					
3. (1) GRADUATE STUDENTS				$67,440	
4. ( ) UNDERGRADUATE STUDENTS					
5. (1) SECRETARIAL - CLERICAL				$15,505	
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A+B)				$126,333	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS) **@ 21% non-stdt s&w and @ 10%**				$13,918	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C) **vacation accrual non-fac & non-stdt s&w**				$140,251	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM.)					
TOTAL PERMANENT EQUIPMENT				$3,000	
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				$19,500	
2. FOREIGN					
TOTAL TRAVEL				$19,500	
F. TRAINEE/PARTICIPANT COSTS					
1. STIPENDS (Itemize levels, types + totals on budget justification page)					
2. TUITION & FEES					
3. TRAINEE TRAVEL					
4. OTHER (fully explain on justification page)					
TOTAL PARTICIPANTS ( ) TOTAL COST					
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				$4,500	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION					
3. CONSULTANT SERVICES					
4. COMPUTER (ADPE) SERVICES					
5. SUBCONTRACTS					
6. OTHER: Grad Stdt Stf Tuition **GRADUATE STUDENT STAFF TUITION @ 35% MIT SUBSIDY 65%**				$30,348	
TOTAL OTHER DIRECT COSTS				$34,848	
H. TOTAL DIRECT COSTS (A THROUGH G)				$197,599	
I. INDIRECT COSTS (SPECIFY RATE AND BASE) **65.5% MTDC excluding RA Tuition and Equipment $3K+, maximum $25K per subcontract**					
TOTAL INDIRECT COSTS				$107,062	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				$304,661	
K. AMOUNT OF ANY REQUIRED COST SHARING FROM NON-FEDERAL SOURCES					
L. TOTAL COST OF PROJECT (J+K)				$304,661	

MIT fully supports the academic year salaries of professors, associate professors, and assistant professors but makes no specific commitment of time or salary to this particular research project.

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Budget Page
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ORGANIZATION
Burns and Roe Enterprises, Inc.

Budget Page No: 1

PRINCIPAL INVESTIGATOR (PI)/PROJECT DIRECTOR (PD)
Michael Crane

Requested Duration: 12 (Months)

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in bracket(s))	DOE Funded Person - mos CAL	ACAD	SUMR	Funds Requested by Applicant	Funds Granted by DOE
1. Michael Crane	1.4			$ 12,000	
2. Robert Nicholas	0.8			$ 5,100	
3. Walter Krzatek	0.1			$ 590	
4. Scott Foster	0.2			$ 1,000	
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. ( ) TOTAL SENIOR PERSONNEL (1-6)				$ 18,890	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. ( ) POST DOCTORAL ASSOCIATES					
2. (2) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.1			$ 660	
3. ( ) GRADUATE STUDENTS					
4. ( ) UNDERGRADUATE STUDENTS					
5. (1) SECRETARIAL - CLERICAL				$ 1,350	
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A + B)				$20,900	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				$24,500	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				$45,400	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM)					
TOTAL PERMANENT EQUIPMENT				-0-	
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				$ 3,200	
2. FOREIGN					
TOTAL TRAVEL				$ 3,200	
F. TRAINEE/PARTICIPANT COSTS					
1. STIPENDS (itemize levels, types + totals on budget justification page)					
2. TUITION & FEES					
3. TRAINEE TRAVEL					
4. OTHER (fully explain on justification page)					
TOTAL PARTICIPANTS ( ) TOTAL COST				-0-	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				$ 1,400	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION					
3. CONSULTANT SERVICES					
4. COMPUTER (ADP) SERVICES					
5. SUBCONTRACTS					
6. OTHER					
TOTAL OTHER DIRECT COSTS				$ 1,400	
H. TOTAL DIRECT COSTS (A THROUGH G)				$ 50,000	
I. INDIRECT COSTS (SPECIFY RATE AND BASE) TOTAL INDIRECT COSTS					
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				$ 50,000	
K. AMOUNT OF ANY REQUIRED COST-SHARING FROM NON-FEDERAL SOURCES					
L. TOTAL COST OF PROJECT (J + K)				$ 50,000	

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Budget Page

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OMB Control No.
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Statement on Reverse

ORGANIZATION Burns and Roe Enterprises, Inc.				Budget Page No: 2	
PRINCIPAL INVESTIGATOR (PI)/PROJECT DIRECTOR (PD) Michael Crane				Requested Duration: 12 (Months)	
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in bracket(s))	DOE Funded Person - mos			Funds Requested by Applicant	Funds Granted by DOE
	CAL	ACAD	SUMR		
1. Michael Crane	2.2			$ 19,500	
2. Robert Nicholas	1.2			$ 8,200	
3. Walter Krzatek	0.3			$ 2,000	
4. Scott Foster	0.5			$ 2,800	
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. (4) TOTAL SENIOR PERSONNEL (1-6)				$ 32,500	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. ( ) POST DOCTORAL ASSOCIATES					
2. (4) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	1.0			$ 5,900	
3. ( ) GRADUATE STUDENTS					
4. ( ) UNDERGRADUATE STUDENTS					
5. (1) SECRETARIAL - CLERICAL				$ 3,080	
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A + B)				$ 41,480	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				$ 48,620	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				$ 90,100	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM)					
TOTAL PERMANENT EQUIPMENT				-0-	
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				$ 5,600	
2. FOREIGN					
TOTAL TRAVEL				$ 5,600	
F. TRAINEE/PARTICIPANT COSTS					
1. STIPENDS (itemize levels, types + totals on budget justification page)					
2. TUITION & FEES					
3. TRAINEE TRAVEL					
4. OTHER (fully explain on justification page)					
TOTAL PARTICIPANTS ( ) TOTAL COST				-0-	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				$ 2,900	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION					
3. CONSULTANT SERVICES					
4. COMPUTER (ADP) SERVICES				$ 1,400	
5. SUBCONTRACTS					
6. OTHER					
TOTAL OTHER DIRECT COSTS				$ 4,300	
H. TOTAL DIRECT COSTS (A THROUGH G)				$100,000	
I. INDIRECT COSTS (SPECIFY RATE AND BASE) TOTAL INDIRECT COSTS					
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				$100,000	
K. AMOUNT OF ANY REQUIRED COST-SHARING FROM NON-FEDERAL SOURCES					
L. TOTAL COST OF PROJECT (J + K)				$100,000	

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U.S. Department of Energy
Budget Page
(See reverse for Instructions)

OMB Control No.
1910-1400
OMB Burden Disclosure
Statement on Reverse

ORGANIZATION Burns and Roe Enterprises, Inc.				Budget Page No: 3	
PRINCIPAL INVESTIGATOR (PI)/PROJECT DIRECTOR (PD) Michael Crane				Requested Duration: 12 (Months)	
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in bracket(s))	DOE Funded Person - mos			Funds Requested	Funds Granted
	CAL	ACAD	SUMR	by Applicant	by DOE
1. Michael Crane	4.1			$ 37,300	
2. Robert Nicholas	2.1			$ 13,800	
3. Walter Krzatek	0.3			$ 2,700	
4. Scott Foster	1.5			$ 10,000	
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. ( ) TOTAL SENIOR PERSONNEL (1-6)				$ 63,800	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. ( ) POST DOCTORAL ASSOCIATES					
2. (4) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	2.6			$ 14,600	
3. ( ) GRADUATE STUDENTS					
4. ( ) UNDERGRADUATE STUDENTS					
5. (1) SECRETARIAL - CLERICAL				$ 6,500	
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A + B)				$ 84,900	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				$ 99,600	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				$184,500	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM)					
TOTAL PERMANENT EQUIPMENT				-0-	
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)					
2. FOREIGN					
TOTAL TRAVEL				$ 5,500	
F. TRAINEE/PARTICIPANT COSTS					
1. STIPENDS (itemize levels, types + totals on budget justification page)					
2. TUITION & FEES					
3. TRAINEE TRAVEL					
4. OTHER (fully explain on justification page)					
TOTAL PARTICIPANTS ( ) TOTAL COST				-0-	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				$ 6,000	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION					
3. CONSULTANT SERVICES					
4. COMPUTER (ADP) SERVICES				$ 4,000	
5. SUBCONTRACTS					
6. OTHER				$ 10,000	
TOTAL OTHER DIRECT COSTS					
H. TOTAL DIRECT COSTS (A THROUGH G)				$200,000	
I. INDIRECT COSTS (SPECIFY RATE AND BASE)					
TOTAL INDIRECT COSTS					
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				$200,000	
K. AMOUNT OF ANY REQUIRED COST-SHARING FROM NON-FEDERAL SOURCES					
L. TOTAL COST OF PROJECT (J + K)				$200,000	

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U.S. Department of Energy
Budget Page
(See reverse for Instructions)

OMB Control No.
1910-1400
OMB Burden Disclosure
Statement on Reverse

ORGANIZATION Burns and Roe Enterprises, Inc.				Budget Page No: 4		
PRINCIPAL INVESTIGATOR (PI)/PROJECT DIRECTOR (PD) Michael Crane				Requested Duration: 36 (Months)		
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in bracket(s))	DOE Funded Person - mos			Funds Requested	Funds Granted	
	CAL	ACAD	SUMR	by Applicant	by DOE	
1. Michael Crane	7.7			$ 69,000		
2. Robert Nicholas	4.1			$ 27,100		
3. Walter Krzatek	0.7			$ 5,290		
4. Scott Foster	2.2			$ 13,800		
5.						
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)						
7. ( ) TOTAL SENIOR PERSONNEL (1-6)				$115,190		
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)						
1. ( ) POST DOCTORAL ASSOCIATES						
2. (4) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	3.7			$ 21,160		
3. ( ) GRADUATE STUDENTS						
4. ( ) UNDERGRADUATE STUDENTS						
5. (1) SECRETARIAL - CLERICAL				$ 10,930		
6. ( ) OTHER						
TOTAL SALARIES AND WAGES (A + B)				$147,280		
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				$172,720		
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				$320,000		
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM)						
TOTAL PERMANENT EQUIPMENT						
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				$ 14,300		
2. FOREIGN						
TOTAL TRAVEL				$ 14,300		
F. TRAINEE/PARTICIPANT COSTS 1. STIPENDS (itemize levels, types + totals on budget justification page) 2. TUITION & FEES 3. TRAINEE TRAVEL 4. OTHER (fully explain on justification page)						
TOTAL PARTICIPANTS ( ) TOTAL COST				-0-		
G. OTHER DIRECT COSTS						
1. MATERIALS AND SUPPLIES				$ 10,300		
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION						
3. CONSULTANT SERVICES						
4. COMPUTER (ADP) SERVICES				$ 5,400		
5. SUBCONTRACTS						
6. OTHER						
TOTAL OTHER DIRECT COSTS				$ 15,700		
H. TOTAL DIRECT COSTS (A THROUGH G)				$350,000		
I. INDIRECT COSTS (SPECIFY RATE AND BASE) TOTAL INDIRECT COSTS				-0-		
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				$350,000		
K. AMOUNT OF ANY REQUIRED COST-SHARING FROM NON-FEDERAL SOURCES						
L. TOTAL COST OF PROJECT (J + K)				$350,000		