Projected Thermodynamic Efficiencies of Fusion Power Plants

by
M. A. McKinnon

September 1976

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OF FUSION POWER PLANTS

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M. A. McKinnon

September 1976

Battelle
Pacific Northwest Laboratories
Richland, Washington 99352

PREFACE

Fusion reactor technology has developed far enough to expect laboratory demonstration of practical levels of fusion employing the D-T reaction to occur in the early 1980s. Following that demonstration, and depending upon the national priorities for energy from D-T fusion, construction and operation of experimental reactors and demonstration power reactors could occur before the end of this century. Operation of the first commercial power plants could then follow, starting about 2010.

Development and adoption of a new power system eventually will require a description of the environmental effects in an environmental statement providing a comparison to the effects of competitive systems. In anticipation of that statement, an environmental analysis (BNWL-2010) has been prepared for the ERDA Division of Magnetic Fusion Energy. That analysis estimates the environmental effects of constructing and operating D-T fusion reactors as an economically competitive source of electricity in the 21st century.

The analysis has four primary purposes:

1. To describe the general nature of the environmental effects,
2. To determine current ability to estimate the effects,
3. To determine methods for reducing the effects, and
4. To determine research necessary for increasing capability to define and reduce the effects.

Timely identification of needed research and methods for reducing effects will permit the performance of that research and the revision of conceptual fusion power plant designs before preparation of the program environmental statement. This would improve the quality of the environmental statements and could reduce the estimated adverse environmental effects due to fusion power plants.

The environmental analysis (BNWL-2010) concludes that the following assumed characteristics are the best set for the first operating fusion power plants:

- The D-T fusion reaction
- Large quantities of activation products
- Kilogram quantities of tritium in the plant systems
- Massive reactor structures
- Large lithium inventories
- Large inventories of liquid metals and salts
- Standard electricity generation
- Standard radioactive waste systems
- Large magnetic fields
- A self-contained fuel cycle
- Rural siting

Using these characteristics a reference reactor was analyzed to determine the environmental effects by using available concepts of plant subsystems designs that control interactions with the environment or by assumption that best current technology would be used in subsystems design.

Because this analysis does not take into account advances in both fusion and waste control technology during the next thirty years, the estimated effects probably are significantly higher than the actual effects will be for the first fusion power plants. The estimated environmental effects should be interpreted only as being the probable upper limit for the actual effects.

Preparation of the fusion power plant environmental analysis required development and use of specially developed data and analysis methods not used in the preparation of current environmental statements for fossil and fission power plants. These data and analysis requirements are documented in a series of reference topical reports to make this information publicly available and to assure understanding of the basis for the conclusions made in the environmental analysis.

These reference topical reports summarize the state-of-the-art as applicable to preparation of environmental statements for fusion power plants. They present the data and analytical techniques used in the environmental analysis to estimate the interactions with the environment and the resultant environmental effects. This information then was analyzed for adequacy and the need was determined for additional research to assure satisfactory ability to prepare environmental statements for the fusion development program and experimental facilities in the early 1980s. Estimated environmental effects are presented in these reference documents only as necessary to illustrate use of the data and analytical techniques.

This report is one of those reference documents for the environmental analysis. The other documents in this series contain more details of the power plant concepts and the probable environmental effects of fusion power plants with the assumed characteristics listed above. These documents are available through the National Technical Information Service:

An Environmental Analysis of Fusion Power to Determine Related R&D Needs, BNWL-2010
Review of Fusion Research Program: Historical Summary and Program Projections, BNWL-2011
Fuel Procurement for First Generation Fusion Power Plants, BNWL-2012
Current Fusion Power Plant Design Concepts, BNWL-2013
Reference Commercial Fusion Power Plants, BNWL-2014
Siting Commercial Fusion Power Plants, BNWL-2015
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SUMMARY

Estimated thermal efficiencies of proposed fusion power plant concepts are compared in this report to the efficiencies of nonfusion power plants. Present trends in electrical power generation are also discussed. The fusion reactor system designs will have about the same thermal efficiencies as present day power plants using steam if these designs require the collection of thermal energy at the blanket and the transfer of that energy to a heat exchanger or boiler using the current technology.

Ample ability to estimate the thermal efficiency of fusion power plants currently is available. The thermodynamics of power conversion systems are well enough known that it is possible to estimate the thermal efficiency of any system for which the operating temperatures are known.

Two general methods should be pursued for increasing the thermal efficiencies of fusion power plants and thereby reducing the amount of waste heat. Methods should be developed for increasing the temperatures of the reactor coolants since the maximum attainable thermal efficiency of systems using coolants can be increased only by increasing the coolant temperatures. Second, advanced power recovery systems such as potassium topping turbines, MHD, and direct conversion should be developed since such systems avoid the limits on steam systems due to excessive operating pressures at high temperatures. Direct conversion is particularly attractive because it avoids the theoretical Carnot limit on thermal efficiency when heat is converted to electrical energy.

RESEARCH REQUIREMENTS

Energy conversion technology is well enough defined that no additional research on thermal conversion is needed to assure adequate preparation of environmental statements on the thermal effects of experimental or commercial fusion reactors. If thermal conversion systems are improved for fusion reactors, the information needed for defining the thermal efficiencies will be available with the system designs.

BACKGROUND

The rapid depletion of our natural resources has focused additional attention on fusion power plant as a future energy source. Over the last 25 years, controlled thermonuclear research has emphasized the containment of fusion plasma to demonstrate the scientific feasibility of obtaining more energy from fusion reactions than is supplied to the plasma. Recent successes in plasma containment have caused scientists to look beyond plasma confinement problems and identify fusion reactor engineering problems which need solutions before useful power can be produced. The ultimate success of fusion reactors as a contributor to the U.S. power economy will depend on their performance in comparison to competing systems. This report compares the thermal efficiencies of current conceptual fusion reactors to the competing power systems to determine if there are any significant differences and to determine if additional research is needed to assure adequate estimates of fusion reactor thermal efficiencies.

Data from fusion power plant concepts being developed at various Energy Research and Development (ERDA) laboratories are used in this report.

The concepts and their originators are:

- Tokamak University of Wisconsin (UWMAK)
 Brookhaven National Laboratory (BNL)
 Princeton Plasma Physics Laboratory (PPPL)
 Oak Ridge National Laboratory (ORNL)
- Theta Pinch Los Alamos Scientific Laboratory (LASL)
- Mirror Lawrence Livermore Laboratory (LLL)
- Blascon ORNL
- Wetted Wall LASL
- Suppressed
 Ablation LLL

ENERGY CONVERSION

The energy released in a fusion reaction comes from a conversion of mass to energy that is carried off as the kinetic energy of the reaction product particles. The collection and conversion of this energy is the function of the energy conversion device of the fusion power plant.

Both charged particles (atomic nuclei) and uncharged particles (neutrons) can be produced in fusion reactions. The proportion of charged to uncharged particles and the amount of energy associated with each particle depends on the fuel cycle used.^(1,2) The energy of the neutrons is converted to heat as the neutrons collide with the reactor blanket. The heat can be converted to electricity by a thermal power plant. The energy associated with the charged particles can be collected as heat by allowing the particles to collide with the reactor blanket. Electric and magnetic fields could direct the motion of the charged particles while extracting energy from them. This would be a direct conversion of the energy to electricity.

The only currently proposed fusion power plant concept in which the energy of the charged particle is converted directly to electricity is the Mirror concept of Lawrence Livermore Laboratory (LLL). Charged particle energy conversion efficiencies of 85 percent for a 22-stage electrostatic collector were obtained in a laboratory setting. However, the economics of such a device would limit the electrostatic collector to one or two stages with efficiencies of 50 to 60 percent.⁽³⁾ The energy required to run the reactor would further limit the overall efficiency of the concept to about 27 percent.

In other proposed fusion reactor concepts the energy of the charged particles is converted to heat and collected by the blanket. The conversion of the thermal energy thus generated to electricity requires a heat engine operating in a thermodynamic cycle. The energy not extracted as electricity by the direct conversion process or the heat engine is rejected as waste heat to the environment. The efficiency of a conversion

system relates the energy converted, Q_e (electrical), to the energy rejected, Q_r , by the following relationship; $Q_r = Q_e [(1-\eta)/\eta]$ where η is the thermal efficiency. The thermal efficiency of a heat engine is limited by the second law of thermodynamics to be less than or equal to the Carnot efficiency

$$\eta_{\text{Carnot}} = \frac{T_{\text{high}} - T_{\text{low}}}{T_{\text{high}}}$$

where the temperatures used are absolute temperatures. The maximum temperature is normally limited by containment methods. The low temperature is limited to the temperature of the environment.

Containment of high temperatures is limited by the properties and availability of materials. Boom et al., reports that typical stress levels of 10,000 to 20,000 lb/in.² limit the useful operating temperatures to less than 1202°F (650°C) for 316 stainless steel, 1472°F (800°C) for vanadium and its alloys, 1832°F (1000°C) for niobium and its alloys, and 2192°F (1200°C) for molybdenum and its alloys.⁽⁴⁾ As these temperatures are approached the incidence of failure by creep, rupture, and fatigue are expected to rapidly increase. The materials with the best high-temperature strength cost more and are more difficult to fabricate than common materials.

PROJECTED EFFICIENCIES OF FUSION POWER PLANTS

Table 1 reviews the estimated design efficiencies of the proposed fusion reactor concepts. Even though the temperature of the reaction is of the order of millions of degrees, the high temperature strength of materials limits the temperature within the power conversion systems to 1832°F (1000°C) or less.

TABLE 1. Projected Efficiencies of Fusion Power Plants

<u>Parameters</u>	<u>Magnetic Power Plant</u>						
	<u>UWMAK-I</u>	<u>BNL Blanket</u>	<u>UWMAK-II</u>	<u>PPPL</u>	<u>ORNL</u>	<u>Ø PINCH</u>	<u>MIRROR</u>
Net Plant Efficiency	33	32	36	38	52	34	27
Gross Thermal Efficiency	36	34	-	45	56	40	45/ 70*
Maximum Working Fluid Temperature (°C)	489	727	650	638	1052	540	627
Working Fluids	Li/Na/ Steam	He/Steam	He/Steam	Li/K/ Steam	Li/Na/ Steam	Li/Na/ Steam	Li/Na/ Steam

<u>Parameters</u>	<u>Laser Power Plant</u>		
	<u>WET WALL</u>	<u>BLASCON</u>	<u>SUPPRESSED ABLATION</u>
Net Plant Efficiency	27	-	36
Gross Thermal Efficiency	40	40	44
Maximum Working Fluid Temperature (°C)	750	500	977
Working Fluids	Li/Na/ Steam	Li/NaK/ Steam	Li/ Steam

*Direct conversion of charged particles.

In this table the net plant efficiency represents that portion of the energy generated in the reactor that is available as input to the electrical power grid. The gross efficiency represents the thermal efficiency of the energy conversion system. The difference between the two efficiencies is the amount of power required to heat and inject fuel into the reaction zone and to furnish power to auxiliary systems.

Most of the fusion energy concepts operate in a pulsed manner. The cycle associated with their operation can be of the order of a tenth of a second to over an hour depending on the device. The designs have assumed that where needed, energy storage devices and thermal accumulators can be designed to smooth out the cyclic nature of the power output. The possible loss of efficiency due to the devices needed to smooth out the temperature and power transients has not been considered and research may be needed in design and development of economic thermal damping devices to assure availability of a satisfactory system for operation.

Also, the stresses caused by the inherent thermal and pressure cycling of fusion reactor devices may require that their operating temperatures be limited to values less than for fission or nonnuclear power plants. This could also cause a decrease in their thermal efficiency. Although research may be needed to determine the best designs for the energy storage and heat transfer systems, that research is not needed to assure satisfactory estimation of thermal efficiencies.

PRESENT AND PROJECTED EFFICIENCIES OF NONFUSION POWER PLANTS

The present day and projected thermal efficiencies of other types of power plants are shown in Table 2. The table was compiled from data in several reports.^(2,4-14) Detailed descriptions of these systems are presented in another document in this series.⁽¹⁵⁾

Steam turbines presently constitute about 78 percent of the electricity generating capacity in the U.S. with average heat input to electric output conversion efficiencies of 33 percent. Maximum efficiencies are as high as 45 percent. With present materials, more efficient power plants can be built, but the costs are prohibitive. To increase the maximum operating temperature, the materials that must be used are an order of magnitude more expensive to obtain and much more costly to fabricate. A point is reached where the plant's increased efficiency cannot compensate for the increased cost of the improved plant. Factors which have a bearing on the efficiency of thermal power plants are the

TABLE 2. Efficiencies in Power Generation

	Typical Present Efficiency (Percent)	Present Operating Temperature (°C)	Projected ^(a) Efficiency Year 2000 (Percent)	Projected Operating Temperature (°C)
Steam Turbine	39	540	40 - 54	
Gas Turbine	30	980	31 - 42	1400
Combined Cycle (Gas & Steam)	40	980	40 - 59	1400
Nuclear				
Steam	33 - 35	540	33 - 43	
Gas Cooled	39	540	40 - 42	
Fast Breeder		540	37 - 43	
Feher Cycle			45	730
Binary Cycle			55	
Potassium Topping ^(b)		815	20	980
Thermionic Topping ^(b)	15		25 - 30	
Bottoming Cycle ^(b)	12	315	14	315
MHD - Steam			50 - 60	1500+

(a) The two numbers in this area represent the difference in opinion between those developing the system and those operating present systems.

(b) When a topping of bottoming cycle is applied to a power cycle, the binary efficiency can be calculated as follows:

$$\eta_b = \eta_t + (1 - \eta_t)\eta_s$$

η_b = Binary efficiency (fractions)

η_t = Topping or bottoming efficiency (fractions)

η_s = Power cycle efficiency (fractions)

type and design of the heat sink, and the cost of the energy source as well as the system design and materials. The economic and cycle considerations⁽⁵⁾ limit steam turbines to an efficiency of 41 percent.

As steam turbine designs have become more refined and as materials have been developed to withstand high temperatures, the attainable efficiency of generating electricity using a thermal source has increased. However, a decrease in the efficiency of energy generation has occurred in the power industry during the past decade. This decrease is due to the more stringent controls set on emissions and to the increased use of less costly, less efficient energy conversion systems.

Interest in gas turbines increased over the last two decades because of the reduced capital expense for such a system to supplement peak electrical network power demands and because higher temperature applications are possible. Gas turbines can still expect modest increases in system efficiencies.

A system using the principle of magnetohydrodynamics (MHD) for energy conversion is not as temperature limited as steam or gas turbine systems because there are no turbine blades. The MHD surfaces in contact with the hot fluid stream can be easily cooled; therefore higher temperatures can be tolerated. Since major development of MHD did not begin until about 1960, the efficiency of present day systems does not appear to be representative of the MHD potential. The efficiency of a first generation MHD device is projected to reach 50 percent with further development work extending the efficiency to over 60 percent. Some reports optimistically predict efficiencies reaching 75 to 80 percent.^(12,13)

Another scheme that has been used to increase system efficiency is using combined systems where two or more cycles are operated in tandem. This allows one system to be designed for optimum performance at a high temperature with lower pressures and the other system designed to operate at low temperatures with high pressures. Several working fluids are

available which allow a wide range of temperature and pressure operation. The combined gas and steam, MHD steam, gas Feher, potassium topping cycles are examples of this approach. However, the operational complexities of combining cycles offer problems to be solved. Heat and mass flows between systems have to be carefully controlled to insure efficient operation. The economics of the design would determine the plant efficiency that is most cost effective.

The environmental pollution of a system must be considered. For a fossil fuel plant, if the emissions of particulate matter or noxious gases are expected to be controlled, energy would be used to process the combustion products and/or further refine the fuel. This could consume as much as 20 percent of the energy output. If the goal is thermal pollution control, then the thermal efficiency of the system must be highly developed. Comparisons are shown in Table 3.

TABLE 3. Waste Heat Emission

<u>Assumed Efficiency (Percent)</u>	<u>Possible System</u>	<u>Waste Heat to Environment/ Electric Energy Generated</u>
60	Fossil Fueled - MHD	0.67
55	Binary System	0.82
50	Proposed ORNL-Fusion Concept Gas - Steam Cycle	1.0
40-45	Feher Cycle Steam turbines Gas turbines	1.5 - 1.22
35-40	Proposed Fusion Reactor Concepts	1.9 - 1.5

CONCLUSIONS

The currently proposed fusion reactor concepts have estimated thermal efficiencies which are generally less than 40 percent or about the same efficiencies as the best current thermal power plant systems. Fossil-fueled MHD systems offer potential efficiencies of about 60 percent for the same time period which may also have application to fusion reactors. The lower efficiencies projected for the fusion concepts are due primarily to material property limitations. As long as fusion reactor system designs require the collection of thermal energy at the reactor blanket and the transfer of that energy to a heat exchanger or boiler, the fusion system would appear to have the same efficiency restrictions as present day steam power plants.

Energy conversion technology is well understood. Ample information is available for accurate estimation of the thermal efficiency of a developed energy conversion system. No research appears necessary to assure adequate ability to estimate thermal efficiencies for an environmental statement for either experimental or commercial fusion reactors.

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OFFSITE

A. A. Churm
ERDA Chicago Patent
Group
9800 S. Cass Avenue
Argonne, IL 60439

J. W. Beal
ERDA Div. of Magnetic
Fusion Energy
Washington, DC 20545

S. O. Dean
ERDA Div. of Magnetic
Fusion Energy
Washington, DC 20545

E. E. Kintner
ERDA Div. of Magnetic
Fusion Energy
Washington, DC 20545

J. M. Williams
ERDA Div. of Magnetic
Fusion Energy
Washington, DC 20545

J. N. Grace
ERDA Div. of Magnetic
Fusion Energy
Washington, DC 20545

J. Baublitz
ERDA Div. of Magnetic
Fusion Energy
Washington, DC 20545

3 F. E. Coffman
ERDA Div. of Magnetic
Fusion Energy
Washington, DC 20545

J. F. Decker
ERDA Div. of Magnetic
Fusion Energy
Washington, DC 20545

3 K. M. Zwilsky
ERDA Div. of Magnetic
Fusion Energy
Washington, DC 20545

Dr. Philip M. Stone
ERDA Applied Plasma Physics
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G. W. Kuswa
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Application
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M. A. Bell
ERDA Div. of Safety
Standards and Compliance
Washington, DC 20545

27 ERDA Technical Information
Center

M. S. Kaminsky
Argonne National Laboratory
9700 S. Cass Avenue
Argonne, IL 60439

V. A. Maroni
Argonne National Laboratory
9700 S. Cass Avenue
Argonne, IL 60439

P. M. Persiani
Argonne National Laboratory
9700 S. Cass Avenue
Argonne, IL 60439

M. Petrick
Engineering and Technology
Division
Argonne National Laboratory
9700 S. Cass Avenue
Argonne, IL 60439

W. E. Parkins, Manager
Atomics International
Component Engineering and
Technology Division
North American Rockwell
P.O. Box 309
Canoga Park, CA 91304

D. Gurinsky
Brookhaven National Laboratory
ERDA Brookhaven Area Office
Upton, NY 11973

H. J. Kouts
Brookhaven National Laboratory
ERDA Brookhaven Area Office
Upton, NY 11973

S. Pearlstein
Brookhaven National Laboratory
ERDA Brookhaven Area Office
Upton, NY 11973

OFFSITE

J. R. Powell
Brookhaven National Laboratory
ERDA Brookhaven Area Office
Upton, NY 11973

A. J. Impink, Jr.
Carnegie Mellon University
Pittsburgh, PA 15213

R. A. Gross
Plasma Research Laboratory
236 SW Mudd Bldg.
Columbia University
New York, NY 10027

W. C. Gough
Electric Power Research Inst.
3412 Hillview Ave.
Palo Alto, CA 94304

G. R. Hopkins
Gulf General Atomic
P.O. Box 1111
San Diego, CA 92112

Zeinab Sabri
Iowa State University
261 Sweeney Hall
Nuclear Engineering Department
Ames, IA 50010

R. Borg
Lawrence Livermore Laboratory
P.O. Box 808
Livermore, CA 94550

T. K. Fowler
Lawrence Livermore Laboratory
P.O. Box 808
Livermore, CA 94550

R. Moir
Lawrence Livermore Laboratory
P.O. Box 808
Livermore, CA 94550

A. Carl Haussmann
Lawrence Livermore Laboratory
P.O. Box 808
Livermore, CA 94550

J. Hovingh
Lawrence Livermore Laboratory
P.O. Box 808
Livermore, CA 94550

R. F. Post
Lawrence Livermore Laboratory
P.O. Box 808
Livermore, CA 94550

C. J. Taylor
Lawrence Livermore Laboratory
P.O. Box 808
Livermore, CA 94550

OFFSITE

R. Werner
Lawrence Livermore
Laboratory
P.O. Box 808
Livermore, CA 94550

L. L. Wood
Lawrence Livermore
Laboratory
P.O. Box 808
Livermore, CA 94550

W. Bauer
Division Supervisor
of Physical Research
Sandia Labs Livermore
Livermore, CA 94550

L. Booth
Los Alamos Scientific
Laboratory
CTN Research
P.O. Box 1663
Los Alamos, NM 87544

D. J. Dudziak
Los Alamos Scientific
Laboratory
CTN Research
P.O. Box 1663
Los Alamos, NM 87544

D. B. Henderson
Los Alamos Scientific
Laboratory
CTN Research
P.O. Box 1663
Los Alamos, NM 87544

E. L. Kemp
Los Alamos Scientific
Laboratory
CTN Research
P.O. Box 1663
Los Alamos, NM 87544

F. L. Ribe
Los Alamos Scientific
Laboratory
CTN Research
P.O. Box 1663
Los Alamos, NM 87544

L. Stewart
Los Alamos Scientific
Laboratory
CTN Research
P.O. Box 1663
Los Alamos, NM 87544

K. Thomassen
Los Alamos Scientific
Laboratory
CTN Research
P.O. Box 1663
Los Alamos, NM 87544

OFFSITE

O. K. Harling
Massachusetts Institute of
Technology
Cambridge, MA 02139

Bruno Coppi
Department of Physics
Massachusetts Institute of
Technology
Cambridge, MA 02139

L. Lidsky
Dept. of Nuclear Engineering
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Technology
Cambridge, MA 02139

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Cambridge, MA 02139

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Massachusetts Institute of
Technology
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Mechanical Engineering
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Technology
Cambridge, MA 02139

J. J. Reinmann
NASA - Lewis Research Center
2100 Bookpark Rd.
Cleveland, OH 44135

Vincent Arp
National Bureau of Standards
Cryogenics Division
Boulder, CO 80302

J. F. Clarke
Oak Ridge National
Laboratory
P.O. Box Y
Oak Ridge, TN 37830

A. P. Fraas
Oak Ridge National
Laboratory
P.O. Box Y
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Laboratory
P.O. Box Y
Oak Ridge, TN 37830

D. Steiner
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P.O. Box Y
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OFFSITE

J. Scott
Oak Ridge National Laboratory
P. O. Box X
Oak Ridge, TN 37830

J. Banford
Physics International
2700 Merced St.
San Leandro, CA 94577

R. A. Huse
Public Service Electric
and Gas Co.
80 Park Place
Newark, NJ 07101

M. Gottlieb
Princeton University, PPPL
P.O. Box 451
Princeton, NJ 08540

R. G. Mills
Princeton University
P.O. Box 451
Princeton, NJ 08540

E. C. Tanner
Princeton University
P.O. Box 451
Princeton, NJ 08540

H. Perkins
Dept. of Chemistry
Princeton University
Princeton, NJ 06540

R. E. Gold
303 Sayre Hall
Forrestal Campus
P.O. Box 451
Princeton, NJ 06540

M. Kristiansen
Texas Tech. University
Lubbock, TX 79409

A. F. Haught
United Aircraft Research Lab.
United Aircraft Corporation
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L. Levine
U.S. Naval Research Laboratory
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C. Z. Serpan, Jr.
U.S. Naval Research Laboratory
Washington, DC 20390

Francis Chen
University of California
Electronics Research
Laboratory
College of Engineering
Berkeley, CA 94720

OFFSITE

A. J. Lichtenberg
University of California
Electronics Research
Laboratory
College of Engineering
Berkeley, CA 94720

Dave Okrent
U.C.L.A.
Los Angeles, CA 90024

C. D. Hendricks
University of Illinois
Nuclear Engineering
Laboratory
Urbana, IL 61801

G. H. Miley
University of Illinois
Nuclear Engineering
Laboratory
Urbana, IL 61801

Terry Kammash
University of Michigan
Nuclear Engineering
Department
Ann Arbor, MI 48105

Dean Abrahamson
University of Minnesota
School of Public
Affairs
Social Science
Building/309
Minneapolis, MN 55455

W. G. Davey
University of Texas
Department of Physics
Austin, TX 78712

E. Linn Draper, Jr.
University of Texas
Department of Physics
Austin, TX 78712

W. E. Drummond
University of Texas
Department of Physics
Austin, TX 78712

Abraham Hertzberg
University of Washington
Aerospace Research
Laboratory
316 Guggenheim
Seattle, WA 98105

A. L. Babb
University of Washington
Nuclear Engineering
Department
Seattle, WA 98105

OFFSITE

R. Conn
University of Wisconsin
Nuclear Engineering
Department
Madison, WI 53706

G. L. Kulcinski
University of Wisconsin
Nuclear Engineering
Department
Madison, WI 53706

C. W. Maynard
University of Wisconsin
Nuclear Engineering
Department
Madison, WI 53706

D. Lichtman
Department of Physics
University of Wisconsin
Milwaukee, WI 53201

E. E. Donaldson
Washington State University
Department of Physics
Pullman, WA 99163

D. D. Mahlum
Division of Biomedical
and Environmental Research
Washington, DC 20545

J. V. Vanston
Engineering Science
Building
University of Texas
Austin, TX 78712

Leslie S. Ramsey
450 North 5th Street
Indiana, PA 15701

ONSITE

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