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STUDY OF THE DEVELOPMENT OF
NEUTRON AND PLASMA RADIATION TEST FACILITIES
FOR THE
CTR MATERIALS PROGRAM

by

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TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	1
I. INTRODUCTION	1
II. NEUTRON AND PLASMA SOURCE REQUIREMENTS	2
A. SURFACE RADIATION EFFECTS.	3
B. BULK RADIATION EFFECTS	3
III. RADIATION TEST FACILITIES.	6
IV. TIMELINESS OF SOURCE DEVELOPMENT	6
V. GENERAL REMARKS.	13
REFERENCES	16

LIST OF TABLES

<u>No.</u>	<u>Title</u>	<u>Page</u>
I.	Surface Radiation Studies	4
II.	Materials Radiation Studies	5
III.	Classification of (D,T) Neutron and Plasma Source Facilities. .	7
IV.	Type of (D,T) Neutron and Plasma Facility - Group I	8
V.	Type of (D,T) Neutron and Plasma Facility - Group II.	9
VI.	Type of (D,T) Neutron and Plasma Facility - Group II-S.	9
VII.	Type of (D,T) Neutron and Plasma Facility - Group III	10
VIII.	Type of (D,T) Neutron and Plasma Facility - Group III-S	11
IX.	CTR Neutron and Plasma Source Concepts and Related Devices Development	14

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ABSTRACT

The Controlled Thermonuclear Research (CTR) program needs for high energy and high intensity neutron and plasma sources is investigated. The assessments include outlining source requirements, facilities available, and concepts for source development. The study of neutron and plasma radiation testing requirements for the CTR Materials Program indicates the need for developing several different types of testing facilities. An extensive R&D program is found necessary in order to scope the feasibility of translating various concepts into optimum radiation testing facilities. The development must be phased into a time scale consistent with the scheduled objectives of the overall CTR Technology Program.

I. INTRODUCTION

The design of fusion devices and power reactors will be based on developing and generating neutron and plasma surface and materials radiation design parameters. For systems based on any one of the more commonly considered fuel cycles, $D(T,n)^4\text{He}$, $D(D,n)^3\text{He}/D(D,p)T$ (branching ratio, 50%), and $D(^3\text{He},p)^4\text{He}$, the plasma energy is in the form of energetic neutrons, particles, and photons. The first two fuel cycles yield neutrons having kinetic energies of 14.1 and 2.45 MeV respectively. In the $D(^3\text{He},p)^4\text{He}$ cycle, the (D,D) reaction rate is of the magnitude comparable to the rate of the $(D,^3\text{He})$ reaction at plasma temperatures of 100 to 400 keV. Depending on the initial fuel composition, the secondary and subsequent ternary reactions in the $(D,^3\text{He})$ cycle also result in an intense source of 2.45 and 14.1 MeV neutrons via the (D,D) and (D,T) chains respectively. An appreciable fraction of the fusion energy is therefore always in the form of energetic neutrons for any of the fuel systems used.

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Another component of the plasma energy is represented in the kinetic energy of the fusion reactant particles and of the unreacted primary ions from the plasma preparation phase of the fueling cycle. The charged and neutral particles are emitted from the plasma and impact on the adjacent surfaces or surface components with varying degrees of intensities via diffusion, charge exchange, recombination, and attachment processes, and from magnetic field singularities that may exist as in the case of the open-ended mirror systems.

The photon radiation field is comprised of plasma bremsstrahlung, synchrotron, and X-ray radiations incident on the containment surface and surface components; and gamma radiation generated via secondary reaction processes throughout the blanket, shield, magnet systems and other components of a power facility.

The technology of converting plasma energy into electrical energy will, therefore, be based on understanding the fundamentals of the radiation field interactions with matter in the areas such as: (1) the neutron, particle, and photon interaction effects on the vacuum wall and surface components which will influence the physics of plasma confinement, heating, and wall erosion; (2) the neutron radiation damage of materials in the form of dimensional instability (swelling), and changes in the mechanical and physical properties; and (3) the transport and transformation of the neutron and photon energy.

The existing neutron and plasma sources fall several orders of magnitude short of simulating these radiation effects as they would occur in the planned fusion devices and power systems.

The purpose of this study^(1,2) is to anticipate the needs and the necessary development for neutron and plasma source testing facilities in the CTR Technology program. The study includes surveying, technically assessing and evaluating the surface and materials programmatic needs and the capabilities of existing and proposed source facilities to satisfy these needs.

II. NEUTRON AND PLASMA SOURCE REQUIREMENTS

The energy and intensity requirements of the source are varied and involve generally seven areas of experimental study. These are listed below in an approximate order of increasing source intensity.

CTR NEUTRON AND PLASMA SOURCE REQUIREMENTS

1. Cross Section and Related Nuclear Data
2. Superconducting System Materials Studies
3. Radiolysis in Materials
4. Engineering Design-related Neutronics Experiments (Integral Experiments)
5. Surface Radiation Studies
6. Materials Radiation Studies
7. Engineering Radiation Experiments

The first four areas do not appear to impose severe demands on source energy spectra and/or intensity and therefore can probably be satisfied by available or modified systems within current technology.

The experimental program needs for the latter three areas require from modest to extensive research and development efforts in scaling concepts into more intense testing facilities.

In assessing the technical justification and requirements for Radiation testing facilities, it is necessary to delineate between two major areas; the (A) Surface Radiation Effects, and (B) Bulk Radiation Effects.

(A) Surface Radiation Effects

The surface effects involves the study of the primary and secondary plasma radiation (MeV neutrons, energetic particles and ions, X-rays, bremsstrahlung, soft X-rays and synchrotron radiation) interaction effects on the immediately adjacent vacuum-wall surface components. The resulting blistering, sputtering, and particulate emission lead to wall erosion and plasma contamination, which in turn influences the physics of plasma confinement and heating. A most important aspect of the overall surface area problem is that the incident radiation field is a spectrum of reaction mechanisms. The surface problem relates directly to the plasma physics and confinement experiments such as the Fusion Test Reactors being planned in the major CTR laboratories. The importance of these experiments places a priority of efforts in this phase of CTR program.

The more long range consequences of plasma-wall interactions will include the effects on the physical and structural integrity of surface components including electrical properties of insulators relating to the conditions in fusion power reactors.

A summary of the measurements description for surface effects experiments and facility requirements are presented in Table I.

(B) Bulk Radiation Effects

The bulk radiation effects involves the study of fusion spectra (eV to 14 MeV) neutrons with the structural component materials of higher power fusion reactors. The volume integrated (bulk) neutron fluence effects on the physical and mechanical properties, creep strength, ductility and dimensional instability (swelling) relate to the design problems of prototype and/or demonstration fusion power reactors. The high performance conditions associated with the power reactors necessitates initiating basic materials studies, neutron and ion-bombardment correlation experiments, void formation, defect formation, etc.

The bulk radiation measurement descriptions with neutron source strength requirements are outlined in Table II. The test conditions for the bulk studies require neutron fluxes and fluences of one or two orders of magnitude greater than the needs specified in the surface science program. The minimum fluence needed to obtain observable measurements for surface effects ($\sim 10^{17}$ to 10^{18} n/cm²) is lower than the minimum fluence requirements for measuring observable bulk effects ($> 10^{20}$ n/cm²).

Neutron source facilities in the energy range and intensities of long term interest to the CTR program, are presently not available.

Table I

Surface Radiation Studies

A. Measurement Description

(1) Vacuum wall, surface components, and insulators erosion

- (a) Sputtering
- (b) Radiation blistering by photons, particles, neutron and reaction products: (n, α), (n,p), etc.
- (c) Particle desorption by direct plasma radiation, neutron and reaction product interactions.
- (d) Photo-decomposition of surface compounds by plasma and by neutron-induced energetic photons and reaction products.
- (e) Radiation damage in surface layers.

(2) Plasma contamination

- (a) Multiple backscattering.
- (b) Secondary particle emission (see 1.(a)-1.(d) above).
- (c) Secondary electron emission (electron sheath formation).

B. Source Description

Plasma Density:	10^{16} p/cm ³
Neutron Energy Range:	keV-14 MeV
Intensity (at sample surface):	$>10^{12}$ n/cm ² -sec
Fluence (yield 0.1 monolayer):	3×10^{17} n/cm ²
High Fluence Effects:	10^{20} - 10^{21} n/cm ²
Geometry:	point source, beam flux

Table II

Material Radiation Studies

A. Measurement Description

- (1) Neutron fluence effects on physical and mechanical properties: creep strength, and loss of ductility in vacuum wall and structural material at temperatures in range of 500-1000°C.
- (2) Synergetic effect of high gas generation and point defect production rates in a high flux of high energy neutrons on void formation at temperatures in the range of 500-1000°C.
- (3) Establish correlation between heavy-ion bombardment effects and neutron radiation effects at several energies (discrete or integral) in the range of 2-14 MeV.
- (4) Transmutation effects on physical and mechanical properties of structural materials.

B. Source Description

Energy Range:	keV-14 MeV
Intensity (long term):	$>10^{15}$ n/cm ² -sec
High Fluence:	10^{23} - 10^{24} n/cm ²
Intensity (correlation experiments):	10^{13} - 10^{14} n/cm ²
Minimum Fluence:	
(irradiation period 4 mo., 2 wk.)	10^{20} n/cm ²
Geometry:	point source, beam flux in-core irradiation

III. RADIATION TEST FACILITIES

Many devices such as solid and liquid targets, tritium drive-in targets, gas-targets, dense plasma focus devices, laser-plasma, e-beam plasma devices as well as magnetic field confinement devices have been considered as potential candidates for developing into intense neutron and plasma generators. The variety of these concepts and the variety of the CTR programmatic needs necessitated introducing some order of classification.

A preliminary classification involves five groups as outlined in Table III. The three main groupings are based, in part, on the type of systems and the level of source intensity actually achieved or anticipated. The supplementary Group II-S and III-S are defined to indicate that the concept may be utilized as an auxiliary heating technique for other systems as well as a source device itself. Group I and part of Group II are neutron sources whereas the remaining concepts are neutron and/or plasma sources.

The general design features and problems and the anticipated contribution to the surface, materials and engineering program for each of the categories have been reviewed and involve: the level of intensity; source geometry; a statement on the effort required for the successful development of the concept; the relationship between the activities involved in developing the source and the activities involved in the CTR program; and an estimate of the scale of the necessary research and development for each of the categories. A summary of these considerations are included in Tables IV-VIII.

IV. TIMELINESS OF SOURCE DEVELOPMENT

There has recently been an increasing emphasis among plasma physicists to understand and control impurities resulting from plasma radiation and wall-surface interaction.⁽³⁻⁹⁾ The impurities have the effect of increasing the radiation losses of the plasma and of introducing instabilities which enhances the diffusion of the impurities into the plasma and compromises the confinement. These impurity effects are found to be strongly species dependent. It is therefore important to correlate the mechanisms, energy spectra, and types of surface impurities with the type of radiation fields in both energy and intensity. This dependence on the quality of the impurity as a function of the incident complex radiation field of a plasma, introduces a need for developing test facilities based on a plasma source concept. The plasma problem will be of central interest in the near-term (5-8 years) plasma physics and confinement program. The completion of the goals and objectives in the CTR Program will depend on the understanding of the plasma-wall interaction. The program of experiments outlined by the surface investigators is central to the investigation of these problems. In addition to the experiments

Table III

Classification of (D,T) Neutron and Plasma Source Facilities

Group I - Accelerator and Target Systems

1. Rotating target system
 - a. Solid TiT_2 target
 - b. Sputtering-electrode TiT_2 thick target
2. Drive-in target system
 - a. Mixed (D,T) ion beam on solid Cr target
3. Self-replenishing target system
 - a. Tritium gas flow in solid TiT_2 target
4. Liquid-jet LiT/Li mixture target

Group II

1. Dense plasma focus device
2. Supersonic gas-jet target
3. Liquid-jet target (LiT)

Group II-S

1. Laser-plasma interaction device
 - a. Auxiliary heating for Group III type concepts
 - b. Laser-plasma solenoid as neutron and plasma source
2. Relativistic-electron-beam plasma interaction device
 - a. Auxiliary heating for Group III type concepts
 - b. Relativistic-electron-beam plasma as neutron and plasma source
3. Drift Orbit Cyclotron Heating (DOCH)
 - a. Auxiliary heating for Group III type concepts

Group III

1. Theta-Pinch Machine
2. Mirror-Machine
3. Others

Group III-S

1. Laser-pellet interaction
2. Relativistic-electron-beam-pellet interaction

Table IV

Type of (D,T) Neutron and Plasma Facility

Group I

Design-related Considerations

1. Low intensity $>10^{13}$ n/sec	6. State of art technology
2. Point geometry source	7. Technology for source development not related to the main CTR development program in the SFX
3. Limited experimental access	
4. Low calculated risk in performance expectation	8. Moderate investment in R&D (millions)
5. Modest scaling for accelerator and target development	

Anticipated Contribution to Materials Program

1. Initiate scoping experiments on effects of fusion-energy neutrons on surface and materials.
2. Observation of threshold or onset of damage phenomena.
3. Assess significance of damage phenomena.
4. Guidance in planning a surface and materials development program directly relevant to fusion reactor systems.
5. Contribute to establishing and planning specific output feature of the CTR Radiation Testing Facility.

Table V

Group II

Design-related Considerations

1. Medium to high intensity
>10 ¹⁴ n/sec	6. Major R & D effort for development
2. Point source geometry	7. Extending current technology
3. Limited experimental access	8. Technology for development peripherally related to main CTR program for SFX
4. Higher calculated risk in performance expectations than in Group I	9. Major investment in R & D (tens of millions)
5. Moderate to substantial scaling	

Anticipated Contribution to Materials Program

1. Surface Radiation effects at higher fluence.
2. Significant radiation fluence allowing study of materials damage over extended time periods.
3. Improved assessment of damage phenomena (dimensional instability) for preliminary design studies.
4. Neutron fluence effects on mechanical and physical properties for structural materials.

Table VI

Group II-S

Design-related Considerations

1. Medium intensity as a neutron source	5. Substantial scaling required
2. Point, line, or extended source geometry	6. Major R & D effort for development
3. Alternate function to use as auxiliary heating in Group III and III-S	7. Extending current technology
4. Higher calculated risk in performance expectation than Group I type	8. Technology for development marginally related to the main CTR program
	9. Major investment in R & D

Anticipated Contribution to Materials Program

1. Indirectly as an auxiliary heating subsystem of a neutron and plasma source.
2. As a source same as Group II systems.

Table VII

Group III

Design-related Considerations

1. Medium to high flux
 $>10^{14}$ n/cm²-sec
2. Extended geometry
3. Extended accessibility to
accommodate a range of ex-
perimental program
4. Lower calculated risk than
"break-even" thermonuclear
machine
5. Substantial scaling required
6. Major R&D effort for development
can be obtained from the main
CTR SFX program
7. Extending current technology
8. Technology for development of a
thermonuclear machine as a neutron
source is related directly with
the main CTR program
9. Major extensive investment in R & D
(Facility level effort) Added
note: The current SFX R&D program
forms the basis for development of
the fusion radiation test facility

Anticipated Contribution to Materials Program

1. Surface and Materials radiation effects and Engineering Testing Program
in environment characteristic of a fusion power reactor.
2. Engineering testing program in this environment includes:
 - a. materials damage
 - b. blanket designs
 - c. superconducting systems
design
 - d. instrumentation for
reactor control
 - e. isotopic concentrations
 - f. liquid-metal coolant chemistry
 - g. heat transport mechanisms
 - h. mechanical designs
 - i. etc.

Table VIII

Group III-S

Design-related Considerations

1. Medium to high flux
>10 ¹⁴ n/cm ² -sec	6. Major R&D effort for development
2. Extended geometry	7. Long-range technology and
development
3. Extended accessibility to
accommodate a range of ex-
perimental programs	8. Technology for development
related directly with laser-
induced fusion CTR program
4. Lower calculated risk than
"break-even" thermonuclear
machine	9. Major extensive investment in
R&D
5. Substantial scaling required	

Anticipated Contribution to Materials Program

1. Surface and Materials and Engineering Testing Program in environment characteristic of a laser-induced fusion power reactor.

utilizing currently available or planned test facilities, the surface program identifies the need for experiments with total radiation fields more characteristic of a thermonuclear plasma. The purpose being to study the synergetic effects of MeV neutrons, particles, bremsstrahlung, soft X-rays and synchrotron radiation.

The plasma source has the potential of simulating a thermonuclear plasma radiation environment and as such would be a major advance in the level of surface and bulk radiation research which can be performed. The simulation relates to the condition that in thermonuclear plasma reactions the relative intensity ratios of the neutron and alpha particles, and the bremsstrahlung radiation are constant and independent of the type of confinement device. The relative ratio with respect to synchrotron radiation is somewhat device dependent and will rely on estimating the opacity of the plasma to this radiation. A further correlation between the plasma test source and thermonuclear confinement machines may also be established from the presence of a plasma and magnetic field interface region in both systems.

The timeliness of neutron and plasma source requirements introduces a new emphasis in considering the general area of Surface Radiation Effects. The near-term needs emphasize the plasma radiation and wall surface interaction as it relates to the plasma confinement program. The long-term needs relate to the plasma-wall interaction effects on the physical and structural integrity of the surface components under Fusion Power Reactor conditions. This is summarized as follows:

Surface Radiation Effects

A. Near-Term Needs

- A.1 Plasma Radiation and Wall Surface Interaction
- A.2 Plasma Physics Confinement Program
- A.3 Understanding Separate and Combined Radiation Component Mechanisms
- A.4 Controlling Plasma Contamination

B. Long-Term Needs

- B.1 Plasma-Wall Interaction Effects on Physical and Structural Integrity on Surface Components under Fusion Power Reactor Conditions

The bulk radiation problem will become significant for the longer-term high-performance fusion power reactor systems. The fluxes and fluences of MeV neutrons required by this program are more severe than the intensity requirements of the surface studies at this time. The neutron source concepts that have been suggested would partially satisfy the bulk materials program. The limitation as to type of experiments and/or significance of the results of these experiments to the CTR program are a consequence of the fluence capabilities of these machines, and just as important the limitations resulting from the small-size sample access capability and the position of peak flux.

The time-phase in neutron source development associated with the Bulk Radiation Effects may be outlined as follows:

Bulk Radiation Effects

A. Near-Term Needs

A.1 Low Fluence for Basic Materials Studies and Analytical Modeling Correlations with Ion-Bombardment Techniques

B. Long-Term Needs

B.1 High Fluence Radiation Damage for Structural Integrity in Fusion Power Reactor Conditions

Engineering-Type Experiments

For Engineering-Type Radiation Experiments, the time-emphasis is long-term for large-scale experiments of the many subsystems in a Fusion Power Reactor. Eventually the study of surface and bulk radiation effects as well as large-scale engineering tests relating to the high-performance conditions of fusion power systems, will require testing facilities on the level of a Fusion Engineering Research Facility, FERF. Preliminary feasibility design studies on FERF type systems are presently being pursued by several CTR laboratories.

The time-emphasis of source development and the main CTR Program can be assessed by the schedules outlined in Table IX. Neutron sources may be developed in time to influence either the experimental program or the design of several near-term confinement experiments. The intermediate plasma source in addition to its utility as a neutron source may contribute importantly to the FTR-1 and 2, and EPR design programs, if developed in time.

V. GENERAL REMARKS

The selection of neutron and plasma source concepts for developing into radiation test facilities must be based on the following considerations:

- (a) The level of source intensity actually available to the investigator;
- (b) The capability and flexibility of the source concept to accommodate a range of experimental needs;
- (c) The number of experiments which can be performed simultaneously in order to provide a broad base of support for the total facility;
- (d) The experimental data output from the facility is of the quality output needed to make significant advances in understanding radiation interaction with materials; and
- (e) The economics of the research and development necessary to establish the feasibility of a concept, the capital costs to build the facility, and the operating costs per experiment.

An important phase in the logistics of developing Radiation Test Facilities is the formulation of an overall CTR-Technology experimental program.

Table IX

CTR Neutron and Plasma Source Concepts and Related Devices Development

	<u>1974</u>	<u>1975</u>	<u>1976</u>	<u>1977</u>	<u>1978</u>	<u>1979</u>
<u>Neutron Source</u>						
Rotating Target R.T. (LLL)						
RT Ia	<u>Development</u>					
RT II	<u>Proposed R&D</u>					
Super Sonic Jet-Target (LASL)	<u>Proposed Conceptual Design</u>					
<u>Plasma Source</u>						
Plasma Focus DPF (EURATOM)	<u>Development</u>					
Laser-Beam-Plasma Interaction						
E-Beam-Plasma Interaction						
Other Plasma Concepts						
<u>Plasma Device (Fusion Engineering Radiation Facility)</u>						
Mirror				Conceptual Design		
θ-Pinch				Conceptual Design		

CTR Plasma Confinement Program

Princeton PLT	<u>Development</u>	<u>Experimental Program</u>
Princeton PDX	<u>Planned</u>	<u>Experimental Program</u>
LASL SYLLAC	<u>Experimental Program</u>	
LLL Small Mirror - 2X-IIB (Pulsed)	<u>Experimental Program</u>	
LLL Mirror Baseball II, MX I, 2X-II Advanced	<u>Development</u>	<u>Experimental Program</u>
GA Doublet III	<u>Development</u>	<u>Experimental Program</u>
Fusion Test Reactor (FTR) FTR-1 (Tokamak D-T Burner)	<u>Design</u>	<u>Construction</u>
FTR-2 (Mirror or θ-Pinch D-T Burner)	Decision Point	Decision Point
EPR (Experimental Power Reactor)	Decision Point (1980)	Decision Point (1985)

The identification and delineation of the specific needs of this broad surface and bulk materials radiation program and engineering test program will be the major factor in influencing the selection and design features of the optimum test facilities. The coordination of designer's efforts with users' needs would require that a Designers-Users Group include the following responsibilities:

- (a) Identifying, evaluating and coordinating the interface problem areas of various disciplines involved in the design and the users' needs into a studied effort toward the goal of developing a radiation facility,
- (b) Scoping the experimental program which will influence the design features,
- (c) Initiating and developing new areas of effort necessary to resolve problems within each of the disciplines as well as across the disciplines,
- (d) Evaluating the technical significance of developments and progress in other CTR programs and translating these into the design of the facility,
- (e) Maintaining an overview of the total program in order to put into better perspective the balance between the magnitude of effort and the quality of the output for programs and sub-projects,
- (f) Utilizing experience or knowledge in the fields of research reactor design, accelerator design, magnet systems, energy storage and transfer systems, etc.

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