PROGRAM PLAN

OFFICE OF FUSION ENERGY TASK GROUP ON

DAMAGE ANALYSIS AND FUNDAMENTAL STUDIES (DAFS)

PROGRAM PLAN

OFE TASK GROUP ON DAFS

FOREWORD

The research and development activities of the Reactor Materials Program of the Office of Fusion Energy, DOE, consist of four major elements or task areas - *Alloy Development for Irradiation Performance (ADIP), Damage Analysis and Fundamental Studies (DAFS), Plasma Materials Interaction (PMI),* and *Special Purpose Materials (SPM).* Program Plans for each element have been prepared by technical Task Groups composed of personnel from the various laboratories and contractors which contribute to the magnetic fusion program. Each Task Group of 6-10 principal investigators and/or consultants worked under the guidance of a Chairman drawn from a National Laboratory and his Counterpart, a staff member of the Materials and Radiation Effects Branch of the Office of Fusion Energy. For preparation of the Program Plans, these have been:

Task Group	Chairman	Counterpart
ADIP	J. O. Stiegler, ORNL	T. C. Reuther
DAFS	D. G. Doran, HEDL	T. C. Reuther
PMI	W. Bauer, Sandia	C. R. Finfgeld
SPM	J. L. Scott, ORNL	M. M. Cohen

The distribution of the Task Group members from among national laboratories, universities, industrial concerns and other Government organizations is given in the following table:

Type of Laboratory	Number of Laboratories	Individual Participants
National	8	19
Industrial	6	7
University	2	3
Other Government	2	2
TOTALS	18	31
Office of Fusion Energy Staff		3
		34

Each group operated through a number of Subtask Groups which were *ad hoc* groups charged with problem definition and program planning in specific technical areas. Including membership on Subtask Groups, a total of over 100 individuals were involved in various stages of preparation of the Plans.

The assumptions inherent in the planning process were the construction of an experimental power producing reactor about 1990 and a Demonstration Plant by the end of the century. Beyond those assumptions, the Plans deal with the generic materials work that needs to be done, irrespective of magnetic confinement system. To the extent that such generic problems apply to hybrid reactors and laser fusion reactors, the Plans are applicable to them as well. However, they do not include tasks that are specific to hybrids (fuels, for example) or laser fusion (optical materials and ultra high frequency pulsing or ramp rates, for example).

The emphasis in the planning process was to examine the potential problems and to create a summary of materials-related work that needs to be undertaken for the successful development of fusion reactors. The wide representation of national laboratories, universities, and industry was encouraged to remove institutional bias to the greatest extent possible.

Each Task Group adopted a common format so that each Plan contains the same type of information. The format includes the following chapters:

Chapter 1, *"Executive Summary"*

Chapter 2, *"Introduction"*

In addition to introducing the subject matter, the Introduction contains a complete listing of Task Group members, Subtask Group members, and consultants.

Chapter 3, *"Problem Definition and Analysis"*

A discussion of materials-related problems and an analysis of such problems is given for each major topical area.

Chapter 4, *"Program Strategy and Major Milestones"*

This chapter is the most important one in each of the Plans. It describes the strategy that will be used to solve the materials problems described in Chapter 3. As part of this program strategy, a series of major milestones (Level 1) is identified that extends over the next 20 years. Chapter 4 is meant to be a *stand alone* section which succinctly summarizes the strategy to be employed in solving problems. It is generally quite brief and is recommended to the reader who would like to get an overview of the approach that has been developed for solving the problems.

Chapter 5, *"Task Definition"*

This chapter contains detailed task descriptions for the next five years leading to the achievement of the major milestones listed in Chapter 4. Each task is described on a separate page (or task sheet) which includes the task number, task title, objective, scope, and the major milestones addressed by the task. Secondary milestones (Level 2) within a given task or subtask are defined, together with a priority assignment and an estimate of man-years to accomplish the work. Each Plan is organized along major topics which parallel the Subtask organization of the Task Group responsible for the Plan. In outline form, these major topics are given a letter designation, as follows:

Plan I: *Alloy Development for Irradiation Performance*

A. Analysis and Evaluation

B. Mechanical Behavior

C. In-Reactor Deformation

Plan II: *Damage Analysis and Fundamental Studies*

A. Environment Characterization

B. Damage Production

C. Damage Microstructure Evolution and Mechanical Behavior

Plan III: *Plasma-Materials Interaction*

A. Plasma Device Characterization: Wall Interaction

B. H, D, and T Recycling

C. Impurity Introduction

D. Near-Surface Wall Modification

Plan IV: *Special Purpose Materials*

A. Breeding Materials

B. Coolants

C. Materials for Tritium Service

D. Graphite and Silicon Carbide

E. Ceramics

F. Heat Sink Materials

G. Magnet Materials

Major milestones are designated by Roman numerals (for each Plan) and serially by Arabic numbers. Tasks and subtasks are identified by a decimal system with corresponding secondary milestones designated in lower case letters. Priority ratings are assigned on the basis of a letter *H*, *M*, or *D* indicating the priority and a number *1*, *2*, or *3* indicating the time frame.

MAJOR MILESTONES

II.1

II. Plan II (Damage Analysis and Fundamental Studies)

1. Major Milestone (Level 1)

Major Topics, Tasks, Subtasks

II.A.1.1

II. Plan II (Damage Analysis and Fundamental Studies)

A. Major topic within Plan (Topic A in Plan II: Environmental Characterization)

1. Task Number

1. Subtask number

Subtask Milestones

II.A.1.a Milestone (Level 2) within task II.A.1

Priorities

H: Highest priority data needed to achieve Level 1 milestone either because the data are urgently needed or because the work is on a critical path for the accomplishment of other important milestones.

M: Important data needed to complete a milestone but on a less time-restricted basis than H.

D: Data required for a more complete understanding of important effects, desirable but not essential at this time.

1: Near-term impact, defined as extending through TFTR.

2: Intermediate-term impact, defined as affecting EPR and DEMO.

3: Long-range impact, defined as affecting commercial reactors.

The Program Workshop held in January 1978 showed that approximately one-third of the tasks in Plans I, II, and III are adequately funded in FY 1978 (where adequate funding is defined as the application of 50 percent of the required manpower postulated for the task). Another one-third of the needed tasks is receiving some support in FY 1978, while work in the remaining tasks needs to be initiated. The number of tasks funded in Plan IV, *"Special Purpose Materials,"* is very small since these materials are primarily needed outboard of the first wall and such work is conducted on a longer time frame. It is estimated that full funding (in terms of 50 percent of the required man-years) of all tasks would require resources three to four times those available ($7.8M) in FY 1978.

It is important to realize that the Plans describe problem areas and the approach to solutions as seen today, and that these will have to be updated periodically. Furthermore, the Plans should be regarded as outlining the major avenues to be explored rather than as detailed road maps. Although a task structure has been outlined, the detailed approach to the solution of specific problems will be proposed by individual investigators.

In conclusion, I would like to thank the many individuals who participated in the planning process during the past 18 months. Special appreciation is due to the four Task Group Chairmen, their respective laboratories for support, and their respective secretaries who suffered through several drafts. Special thanks are also due to my colleagues in the Materials and Radiation Effects Branch, ETM, who served as Counterparts to the Task Group Chairmen.

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I. EXECUTIVE SUMMARY

The objective of this task is the development of procedures and supporting technology for the application of materials irradiation data obtained in neutron and charged-particle test environments to fusion reactor design environments.

The scope of this program includes:

- Development of procedures for characterizing neutron environments of test facilities and fusion reactors,
- Theoretical and experimental investigations of the influence of irradiation environment on damage production, damage microstructure evolution, and mechanical and physical property changes,
- Identification and, where appropriate, development of essential nuclear and materials data, and
- Development of a methodology, based on damage mechanisms, for correlating the mechanical behavior of materials exposed to diverse test environments and projecting this behavior to magnetic fusion reactor (MFR) environments.

A. MAJOR PROBLEMS

The major problem areas addressed in this program are as follow:

- Accurate description of irradiation environments,
- Accurate description of the production of displaced atoms and transmutation products by high-energy neutrons,

- Accurate description of microstructural changes in materials, especially as influenced by high ejection energies of displaced atoms, transmutation products (particularly helium), and cycling of the radiation field, and

- Accurate description of mechanical behavior of materials irradiated in available test facilities in terms of damage mechanisms as influenced by differences in irradiation environments.

B. PROBLEM ANALYSIS

The genesis of most of the problems treated in this program is the absence of an MFR in which to test materials for radiation-induced changes in bulk properties. The only high-neutron-flux irradiation facilities with large test volumes are fission reactors. The fission reactor environment differs from the fusion reactor environment in several important respects:

- The neutron energy spectrum in fission reactors has few neutrons above 5 MeV, whereas an MFR first wall will experience an appreciable component at 14 MeV. This means that the average energy of a displaced atom in a fission reactor irradiation is lower than that in the first wall. It means also that the nuclear reactions that produce helium, hydrogen, and other transmutation products, which typically have high threshold energies, are generally much less probable in fission reactors than in a fusion first wall. An important exception to this is an unusual two-stage reaction in nickel that results in helium production rates in nickel-bearing alloys (stainless steel) irradiated in mixed-spectrum (i.e., comparable fast and thermal components) fission reactors that are even higher than in a fusion first-wall spectrum.

- The fission reactor environment is constant in time, not cyclic as in MFRs.
- The fission reactor environment lacks the charged-particle and X-ray fluxes that cause a surface dose and surface degradation.

The high-energy neutrons absent in fission reactors are present in accelerator-based neutron irradiation facilities utilizing the T(d,n) and Be(d,n) reactions but only for low-to-intermediate fluxes and very small test volumes. Cyclic irradiations are possible in some facilities. No high-energy, high-flux neutron irradiation facility currently exists. Only the proposed Fusion Materials Irradiation Test (FMIT) facility, which utilizes the Li(d,n) reaction, fits this description.

Another class of irradiation test facilities is charged-particle accelerators in which the charged particles themselves strike the specimen. They permit microstructural studies at very high damage rates and some bulk property studies at rates comparable to those in MFRs. Studies of cyclic effects are possible, but the energies of displaced atoms--and especially the production rates of transmutants--are different from those in an MFR. Several facilities under development will permit the continuous injection of helium during charged-particle irradiation.

To summarize, several irradiation test facilities are available, all of which differ in important respects from anticipated MFR irradiation conditions; of these only fission reactors have large test volumes. In delineating the problem areas listed in Section A, an important objective is to establish the technical basis on which to make effective use of these facilities. These problem areas are summarized briefly below.

1. Irradiation Environment Characterization

The calculation and measurement of neutron field characteristics is a cornerstone of this program since a major objective is to learn to account for differences in these characteristics. Some development is needed in describing the very nonuniform high-energy neutron fields produced by Be(d,n) and Li(d,n) stripping reactions and in accurately measuring the effects of tailoring the neutron spectrum in fission reactors to vary the helium-to-displacement ratio.

2. Damage Production

The changes in properties exhibited by materials exposed to radiation are initiated by the displacement of atoms from their regular lattice sites and by the introduction of foreign atoms, especially helium, through transmutation reactions. This primary damage production depends qualitatively and quantitatively on the type and energy of the radiation. One area needing development is the extension of available displacement and transmutation production cross sections to energies in the 15-40 MeV range. These data are needed for (d,n) high-energy neutron test facilities but will not be needed for describing real MFR environments; hence sensitivity studies are planned to define minimum data and accuracy requirements.

The principal research area is the development of improved models of lattice defect production through theory and experiment. These provide bases for correlating effects observed in different neutron and charged-particle irradiations and the necessary input to models of damage microstructure evolution.

3. Damage Microstructure Evolution

At fusion reactor operating temperatures, the spatial arrangement of lattice damage and foreign atoms will undergo continual change, termed "damage microstructure evolution." A knowledge of the dependence of the damage microstructure on the irradiation variables is basic to understanding changes in properties. Furthermore, the extremely limited test volumes of high-energy neutron and charged-particle irradiation facilities accommodate many microstructural specimens but few mechanical property specimens.

Helium is known to influence the nucleation and growth of the microstructure; gaining an understanding of how it does so has the highest priority. Other important near-term goals are to assess the effects of hydrogen production and cycling of the radiation field.

4. Mechanical Behavior

This problem area complements those being dealt with by the Alloy Development and Irradiation Performance (ADIP) Task Group. The emphasis here is on gaining a fundamental understanding of deformation and fracture mechanisms during and after irradiation. A high priority is given the development of deformation/fracture/microstructure maps to delineate conditions under which the various kinds of deformation, cracking, and fracture behavior may occur. A primary concern is understanding the mechanisms by which these phenomena are altered during irradiation, especially the effects of helium and of cyclic variations in the radiation, temperature, and stress fields. A major effort will be needed to interrelate the necessarily low-fluence, high-energy neutron irradiations (accelerator-based sources) with high-fluence, low-energy neutron (fission reactor) irradiations and with charged-particle irradiations.

5. Correlation Methodology

In the detailed program description in this report, this problem area is often implicit. It is listed here to reemphasize the absence of a suitable test bed, hence the need for procedures for correlating effects obtained in various test environments. The ultimate goal is the development of correlation models and procedures to enable confident projection of data obtained in FMIT and ancillary facilities to the prediction of effects in MFRs.

C. STRATEGY AND RATIONALE

This program plan describes a coordinated damage analysis program based on an understanding of damage mechanisms. Three interrelated Subtask Groups have been formed to deal, respectively, with environmental characterization, damage production, and damage microstructure evolution and mechanical behavior.

A fourth group coordinates the work of this Task Group with that of the ADIP Task Group; its chairman is a member of both. While this group structure is somewhat arbitrary, it reflects general divisions of scientific disciplines and expertise and is intended to promote depth of program planning and execution. The Task Group membership was kept small for efficiency, but many scientists outside the group have made and will continue to make important contributions to the plan and its execution.

In overview, the strategy is: 1) to utilize effectively those characteristics of various available radiation sources that either mimic the MFR environment in some respect or permit a controlled study of a significant variable or damage mechanism; 2) to develop, by theory and experiment, the correlation procedures necessary to confidently relate microstructural and property data obtained in these facilities and apply them to the prediction of the effects to be expected in FMIT when it becomes available; and 3) to refine and calibrate correlation procedures as necessary, using data accumulated in FMIT, and apply these procedures to the prediction of radiation effects in MFRs. It must be emphasized that FMIT is an essential element of this program, providing high-fluence data obtained in a high-energy neutron field. Theory, fission reactor data, and low-fluence high-energy neutron data will provide strong guidance for optimum use of the limited test volume of FMIT, but they will be insufficient in themselves to permit accurate predictions of effects in MFRs.

D. MAJOR RECOMMENDATIONS

Some recommendations of a general nature that may influence policy decision are as follow:

- FMIT should be constructed without delay. The Li(d,n) facility appears to best meet the need for a high-flux, relative large-volume field of high-energy neutrons yielding damage parameter values typical of an MFR first wall.

- An interlaboratory progress report should be issued periodically by this Task Group.
- High priority should be accorded efforts to scope as yet ill-defined problems such as hydrogen and solid transmutation product production and in-situ versus post-irradiation studies of failure mechanisms.
- A continual effort should be made by the Office of Fusion Energy (OFE) to keep agencies supporting fundamental research informed of the needs of this program.
- An openness to technique development, especially regarding neutron dosimetry and microstructure characterization, should be maintained by OFE.

II. INTRODUCTION

A. PROGRAM GOALS

The raison d'etre for the major portion of this program is the absence of MFR radiation environments in which to test materials. The primary objective is to enable predictions of material behavior in an MFR to be made from data obtained in other irradiation environments. Major program goals include:

- Adequate and systematic characterization of all irradiation environments,
- The development and verification of mechanistic models of damage production and evolution,
- The ability to correlate the mechanical behavior of materials irradiated in different environments on mechanistic bases, and
- The ability to extrapolate medium-exposure data to predict high-exposure behavior.

It is important to note certain premises on which the program plan is based. One is the objectivity of the planners. Every effort was made to eliminate concern for who would do the work and to concentrate solely on what should be done. A second premise, almost a corollary of the first, is that overlap with other Task Groups (TGs) is unimportant in the planning stages. It is assumed that good coordination among the TGs, as well as within TGs, will be maintained. A third premise for this initial planning phase is that there are no severe budget constraints. In this regard, no facility development was assumed other than that previously identified--however desirable such additional facilities might be. A fourth is that fundamental understanding of damage processes, not empiricism, is the goal.

B. TASK GROUP ORGANIZATION

This Task Group, organized in October 1976, has three Subtask Groups (STGs) chaired by TG members. Each generally has a core of three or four members plus consultants serving on an ad hoc basis. This Program Plan is the product of the TG members and consultants shown in Figure 1. The scope of each Task Group is as follows:

1. Subtask Group A: Environmental Characterization

The objective of this STG is characterization of appropriate magnetic fusion irradiation environments in terms of: 1) neutron flux, fluence, and spectral distribution, 2) physical parameters (temperature, experimental neutron attenuation and scattering effects, etc.), and 3) gamma-ray influence (activation, heating, etc.) in order to provide a standardized basis for intercomparison of damage data measured in various environments. The scope includes:

- The collection and dissemination of updated descriptions of design environments,
- Development of techniques and methodology necessary for characterizing the environment consistent with accuracy requirements of experiments,
- Identification of data needs and procurement of data if necessary, and
- Establishment of standardized dosimetry practices and standards for documentation of characterization data.

2. Subtask Group B: Damage Production

This STG is concerned with the study of the mechanisms whereby defects are introduced into solid materials under irradiation by neutrons and charged particles. This research is limited to the primary damage state and is not intended to consider the evolution of complex defect structures. The research activities include theoretical and experimental studies of defect production by neutrons and charged particles, both in bulk materials and near

DOE-OFE TASK GROUP

ON

DAMAGE ANALYSIS AND FUNDAMENTAL STUDIES

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DAFS SUBTASK GROUPS

ENVIRONMENTAL CHARACTERIZATION	DAMAGE PRODUCTION	DAMAGE MICROSTRUCTURE EVOLUTION AND MECHANICAL BEHAVIOR	JOINT COMMITTEE FOR COORDINATION OF EXPERIMENTS
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FIGURE 1. Task Group Organization - Current Members and Consultants.

surfaces, as well as theoretical and experimental studies of the fundamental properties of point defects, transmutation products, and their aggregates. The results of the research will take the form of materials-exposure parameters which will provide source terms for damage microstructure evolution models and which can be used directly in the planning and correlation of experimental radiation effects programs and in the assessment of probable radiation effects in proposed MFRs.

3. Subtask Group C: Damage Microstructure Evolution and Mechanical Behavior (Correlation Methodology)

The objective of this STG is to develop procedures and supporting technology for the correlation of microstructural and mechanical behavior data taken in a variety of available or proposed environments for application to future fusion reactor design environments. The scope of the effort includes theoretical and experimental investigations of the influence of the irradiation environment on microstructural evolution and mechanical behavior. More specific responsibilities include:

- Identification of significant primary and secondary irradiation environment variables,
- Development of a better understanding of significant damage mechanisms involving mobile defect diffusion and extended defect nucleation and growth, particularly as influenced by environmental variables,
- Development of a fundamental understanding of deformation and fracture mechanisms in metals and alloys and the influence of displacement damage and transmutation products,
- Development of comprehensive models of microstructural evolution and mechanical behavior,
- Identification and development of experiments and experimental methods to calibrate these damage models for pure metals, model alloys, and engineering alloy systems,

- Evaluation and development of physically-based correlation methods for damage microstructure and mechanical behavior, and
- Optimization of the use of available test environments.

Subtask Group B on Damage Production has a strong interface with STG C. The former will provide a description of displacement- and transmutation-related damage production to provide source terms in damage microstructure evolution models and to provide parameters for mechanical behavior correlations. It will also utilize such models and measurements to aid in validating and calibrating damage production models.

Subtask Groups B and C depend on the environmental characterizations of STG A to provide the quantitative basis for relating data obtained with various types and energies of radiation. Collaborative efforts between STGs A and B include the calculation and experimental validation of transmutation rates.

A second important set of interfaces is between this and the other OFE TGs. This TG is intended to provide the others with dosimetry and damage analysis state-of-the-art methodology and application as needed. Some examples at a fundamental level include applications of sputtering models by the Plasma-Materials Interaction TG and applications of microstructure evolution models by the ADIP TG in selecting materials and irradiation conditions. The conceptual interface with the ADIP TG has been given structure by establishing a Joint Subtask Group; its chairman is a member of both the DAFS and ADIP TGs. It is anticipated that the Joint Subtask Group will serve primarily in an ad hoc capacity to identify and implement collaborative efforts. Another important interface is with irradiation facility development, although no corresponding TG has been established.

A third group of interfaces is with groups or programs outside the Materials and Radiation Effects Branch (MREB) of the OFE. A clear example is the Materials Science Division of the Office of Energy Research which supports many programs having direct relevance to this one. Other examples are the dosimetry and damage analysis programs under the DOE Breeder Reactor Program and the Light Water Reactor programs supported by the Nuclear Regulatory Commission and the Electric Power Research Institute. These include pertinent characterization of fission reactors and both fundamental and applied studies of damage mechanisms. Other examples are the Cross Section Evaluation Working Group (CSEWG) and Interlaboratory Reaction Rate (ILRR) programs for developing general purpose cross section libraries and special applications files for dosimetry and helium production. Especially in the dosimetry area, these efforts involve international collaboration to validate and standardize procedures for both fission and fusion materials studies. Another interface awaiting better definition is with the research program on inertial confinement systems. The range of irradiation and material parameters addressed explicitly by this Task Group would have to be broadened in order to meet the needs of that program.

C. METHODOLOGY FOR PRODUCING PLAN

The plan was produced in two stages. The first was a problem analysis stage (Chapter III of this report) for which the STGs generally made wide use of consultants. Included in this stage were rough cuts at setting priorities and the development of strategy for solving problems.

The second stage was concerned with detailed program definition (Chapters IV and V of this report). The extent of the participation by consultants varied considerably among the STGs. Chapters I and II were then added and a first draft provided to members of the Fusion Materials Coordinating Committee (FMCC) and to the MREB for review. A subsequently revised second draft was also subjected to review.

III. PROBLEM DEFINITION AND ANALYSIS

The major problems addressed by this TG are discussed here briefly to minimize the need for repetition in what follows. The primary concern is the lack of a magnetic fusion reactor suitable for materials testing. Such a facility would have the following characteristics:

- A total neutron flux $>10^{14}$ n/cm^2-s,
- A neutron spectrum including an appreciable 14 MeV component from the T(d,n) reaction,
- Cyclic operation,
- Simultaneous charged-particle and X-ray bombardment causing surface degradation, and
- A test volume that is large enough to permit the requisite materials research and alloy development efforts.

In the absence of such a facility, irradiation effects must be predicted from studies using available radiation fields. The only large-volume, high-flux irradiation facilities are fission reactors.

In particular, the large body of radiation effects data currently available for elevated temperatures and high fluences was obtained primarily in fast fission reactors. The neutron spectra in fission reactors drop off rapidly above a few MeV. A well-known consequence is that helium and hydrogen production rates (per neutron) are much lower than in the higher energy (harder) MFR first-wall spectra because these gases are generally produced only by high-energy threshold nuclear reactions. A second consequence is that the energy spectrum of primary recoil atoms (those with which the neutrons interact) is softer in a fission reactor than in an MFR first wall. These two differences, which may be interdependent in the production of radiation effects, are potentially so significant as to preclude the direct application to MFRs of data obtained in fast reactors without further justification. Somewhat ironically, thermal reactors provide an opportunity to study the effects of high helium concentrations in nickel-bearing alloys without the complications of the hard recoil spectrum. Nature has provided a two-stage helium-producing reaction with a relatively high cross section in soft spectra, viz., $^{58}Ni(n,\gamma)^{59}Ni(n,\alpha)^{56}Fe$. It should be realized, however, that the distribution of helium between matrix and grain boundaries may be atypical of that expected in a first wall spectrum.

The type of surface degradation and the high cycling rate projected for fusion reactors are absent in fission reactor irradiations, although some limited aspects of cycling could be simulated by moving a specimen in and out of the neutron field.

The desired higher energy neutrons can be obtained in accelerator-based T(d,n) or Be(d,n) irradiation facilities; however, test volumes and fluxes are too low to permit acquisition of comprehensive engineering data. The principal use of these facilities will be to study damage mechanisms and to validate and calibrate models. Some studies of the effects of cyclic irradiation should be possible.

Another tool to help fill the test facility gap is charged-particle irradiations. They are particularly suited for studies of the effects of recoil energy, pulsing, damage rate, and very high exposures on the damage microstructure and, to a much lesser extent, on bulk properties. The requirement of a highly penetrating particle for experiments on bulk properties puts a severe constraint on parameter variations. On the other hand, in-situ irradiation experiments may be more readily performed in charged-particle beams than in reactors.

Problem areas defined by the STGs are presented in the remainder of this chapter. Three levels of priority have been assigned according to whether problem solution is deemed critical (H), necessary but with some flexibility (M), or desirable but not essential (D). The number indicating the time frame, as described in the Foreword, has been omitted from the priority designations. They should be understood to be H-1, M-1, and D-1, i.e., having near-term impact, inasmuch as the work of this TG provides fundamental support for the activities of other TGs and is not directly relatable to devices.

A. SUBTASK GROUP A: ENVIRONMENTAL CHARACTERIZATION

Several types of neutron environments may be used in fusion materials development. These include:

- Fast reactors (negligible thermal component),
- Mixed-spectrum reactors, in which the relative magnitudes of thermal and fast components normally can be altered by spectral tailoring,
- Accelerator-based sources producing 14-15 MeV neutrons by means of the T(d,n) reaction,
- Accelerator-based sources producing broad, high-energy spectra through Be(d,n) or Li(d,n) stripping reactions,
- Accelerator-based sources producing some very-high-energy neutrons by spallation reactions of high-energy protons, and
- An actual fusion first-wall environment.

In order to adequately characterize these neutron fields, the following problem areas must be addressed.

1. Problem List

a. Definition of neutron flux/fluence/spectrum in tailored, mixed-spectrum fission reactors.

b. Definition of flux/fluence/spectrum in accelerator-based, high-energy neutron facilities.

c. Sensitivity studies to assess the required accuracy of dosimetry (especially above 15 MeV) for damage correlations.

d. Determination of helium and hydrogen generation rates for materials in each neutron environment.

e. Development of dosimetry techniques for use in high-energy neutron fields with steep gradients.

f. Development of standardized dosimetry procedures.

g. Adaptation and extension of dosimetry techniques to real MFRs.

2. Problem Analysis

a. Definition of Neutron Flux/Fluence/Spectrum in Tailored, Mixed-Spectrum Fission Reactors - Mixed-spectrum fission reactors which possess a large component of fast neutron flux ($\geq 2 \times 10^{14}$ n/cm^2-s, E >0.1 MeV), as well as thermal flux, will play an important role in the study of the synergistic effects of high helium production and atomic displacement damage in nickel-bearing alloys. It is anticipated that "neutron spectrum tailoring" in core positions will be used to achieve He/dpa ratios anticipated for MFR first-wall materials. The primary neutron dosimetry at such a facility will continue to be passive foil activation coupled with neutronics calculations. Accurate neutronics calculations which describe the "tailored" spectrum changes are critical input to foil activation dosimetry techniques; existing transport or diffusion neutronics codes are adequate and can provide this calculational accuracy (5-10%). Neutron spectra unfolded from foil activation measurements are reliable (5-10%) for energies >1 MeV, provided good foil coverage exists. In energy regions where present foil detectors lack sensitivity, namely 0.01-0.5 MeV, the accuracy of the technique will be dependent upon the accuracy of the neutronics calculation that describes the facility.

The characterization of fast fission reactors is adequately covered under the Breeder Reactor Program. Spectrum and fluence measurement uncertainties are in the 15% and 10% range, respectively, and decreasing due to a coordinated interlaboratory research program.

b. Definition of Flux/Fluence/Spectrum in Accelerator-Based, High-Energy Neutron Facilities - Dosimetry for these facilities is generally considered to be inadequate except for the RTNS-I T(d,n) facility where present fluence uncertainties are in the range of 5-10%. However, for the RTNS-II and other planned facilities, established dosimetry techniques such as activation and recoil spectrometry will require adaptation and demonstration, and additional techniques such as helium accumulation, emulsions, etc., will require development.

Dosimetry techniques for Be(d,n) or Li(d,n) facilities are inadequate primarily because of insufficient reaction cross section data. The reliability of cross section data from 15-20 MeV is considered marginal, and from 20-40 MeV virtually no data exist. Meaningful estimates of dosimetry uncertainties are difficult, therefore, but uncertainties as large as a factor of 2 are possible at the higher (>20 MeV) neutron energies. Cross section data, both theoretical and experimental, must be obtained and integrally tested in the radiation environment to ensure that dosimetry and damage calculations are reliable for this type of facility.

Dosimetry for spallation sources is made more complex by the presence of a high-energy tail in the neutron spectrum extending to over 40 MeV. Sensitivity studies should help define nuclear data needs for such facilities.

Accelerator-based facilities provide opportunities for on-line flux and spectrum measurements that are generally absent in fission reactors. It will be important for new facilities to include appropriate provisions for viewing ports, flight tubes, collimeters, etc., as well as hardware and software for data reduction and interpretation.

Gamma-ray fluxes and energy distributions are not known for all these high-energy neutron facilities. While gamma fields are not of direct interest in damage studies, except perhaps in insulators and ceramics, they must be considered in order to determine the possible significance of gamma heating on specimen temperature and of (γ,n) reactions and photofission on dosimetry.

c. Sensitivity Studies to Assess the Required Accuracy of Dosimetry for Damage Correlation - Sensitivity studies are required in order to evaluate the effect of dosimetry measurement uncertainties on damage parameters. This is of special concern for accelerator-based environments requiring dosimetry above 15 MeV. Uncertainties in cross sections at high energies, coupled with steep radial and angular flux and spectral gradients associated with (d,n) sources, complicate the accurate determination of the neutron environment. For example, studies at Be(d,n) sources show that dpa rates can vary by a factor of two with an angular change of 12° (e.g., 2.1 mm at 1 cm from the Be target).

d. Determination of Helium and Hydrogen Generation Rates in Each Neutron Environment - Helium and hydrogen generation rates in proposed MFR wall and blanket materials must be considered important damage parameters until shown to be otherwise. Therefore these rates must be determined for each neutron test environment so that helium and hydrogen concentrations can be correlated with microstructural and material property changes. Current knowledge of the necessary cross sections is marginal-to-inadequate at energies ≤15 MeV and clearly inadequate at higher energies. Relatively crude differential data may suffice, however, for damage analysis purposes in the higher energy range since data above 14 MeV are not needed for direct MFR applications. Integral measurements can be made in high-energy test facilities. Likewise, inadequacies in lower energy data must be removed through integral testing.

e. Development of Dosimetry Techniques for Use in High-Energy Neutron Fields with Steep Gradients - Techniques to determine accurately the neutron fluence and energy distribution and their spatial variations for irradiations in accelerator-based, high-energy neutron environments are not well developed. The mass spectrometric helium accumulation method of measuring fluences, now being used in fission reactor irradiations, should be applied to these environments. Other dosimetry methods such as solid-state track recorders (SSTRs), emulsions, etc., should be investigated for advantages specific to the high-neutron energies and high gradients present in these neutron fields. From such technique development should come optimum methodology for application to eventual fusion reactor wall and blanket neutron dosimetry.

f. Development of Standardized Dosimetry Procedures - In the OFE materials program, it will be important to maximize the utility of data obtained in a variety of facilities. These facilities provide a wide variety of fluxes and spectra; some are characterized by strong flux and spectral gradients as well. Since flux, fluence, and spectrum are primary variables in the damage analysis program, it is imperative that questions regarding their measurement be minimized. One means of accomplishing this is to develop good measurement techniques and then request their universal application. Standardized methodology, materials, and documentation will be developed and recommended as minimum good practice.

g. Adaptation and Extension of Dosimetry Techniques to Real MFRs - The applicability of dosimetry techniques developed in well-characterized irradiation facilities will have to be demonstrated in a real fusion reactor environment. In such an environment, consideration will have to be given to higher temperatures, increased charged-particle and gamma-ray fluxes, and restricted accessibility.

3. Assignment of Problem Priorities

		Priority
a.	Definition of Neutron Flux/Fluence/Spectrum in Tailored Fission Reactors	H
b.	Definition of Flux/Fluence/Spectrum in Accelerator-Based High-Energy Neutron Facilities	H
c.	Sensitivity Studies to Assess the Accuracy Necessary for the Determination of Damage Parameters	D
d.	Determination of Helium and Hydrogen Generation Rates for Materials in Each Neutron Environment	H
e.	Development of Dosimetry Techniques for Use in High-Energy Neutron Fields with Steep Gradients	M
f.	Development of Standardized Dosimetry Procedures	M
g.	Adaptation and Extension of Dosimetry Techniques to Real MFRs	H

Good characterization of the radiation environments is basic to all damage analysis, hence all such characterizations have been assigned high priority.

4. Derived Materials Requirements

Dosimetry foil materials which are found to exhibit favorable neutron reaction cross sections must, in addition, possess desirable physical and chemical properties, i.e., high melting points, favorable isotopic content which is free of interfering impurities, and an adequate half-life of the reaction product. These materials are expected to be obtained through existing suppliers who conform to accepted quality control standards.

B. SUBTASK GROUP B: DAMAGE PRODUCTION

1. Problem List

The research problems identified by the STG on Damage Production fall into three broad groups:

a. Damage Production Parameters.
b. Theoretical Characterization of the Primary Damage State.
c. Experimental Characterization of the Primary Damage State.

The following paragraphs deal briefly with these three groups, indicating the important areas where additional research is needed.

2. Problem Analysis

a. Damage Production Parameters - The primary output of this STG effort is damage production parameters in support of damage correlation work in STG C and the other OFE Task Groups. The developmental work of the second and third problem areas must be formulated so as to provide useful descriptions of damage production for damage evolution modeling and for correlations of bulk and surface property change data. Included in this problem area is the determination of cross sections for production of lattice damage and foreign atoms by neutron and charged-particle irradiations. A description of lattice damage production requires information concerning all those nuclear reactions which can produce recoiling residual nuclei with energies greater than 10-100 eV, as well as information concerning the way in which these recoils dissipate their energies by exciting electrons and by displacing other atoms.

The primary recoil* energy, corrected for the energy lost in electron excitation, is termed the damage energy. This quantity can be related through simple models to the number of displacements produced. Internationally accepted procedures are available (though sometimes not employed) for calculating damage energy and displacement cross sections for use in defining the materials exposure unit, dpa (displacements per atom). For damage correlation studies based on physical damage mechanisms, however, the simple models are too imprecise even for determining the gross number of displaced atoms. Furthermore, knowledge of the numbers and configuration of the lattice defects is needed, as discussed under Problems b and c.

To be more specific, primary recoil target atoms are produced in solids by irradiation with neutrons, protons, helium ions, self ions, and the like. These recoils must be characterized in terms of their distribution in energy (near surfaces their distribution in momentum is required) and the distribution in space of their points of origin. In the high-energy neutron spectra characteristic of MFR devices and test facilities, many primaries will be produced in transmutation reactions. The distributions in mass and atomic number of the products, both heavy recoils and light charged particles, must be determined. The principal interest in the former concerns their role as impurities. The latter are of concern both as gaseous impurities and because they can add a high-energy tail to the primary recoil energy spectrum. The data required are the cross sections for the processes involved [elastic and inelastic scattering and nonelastic processes such as (n,2n) and (n,α) reactions] and angular and energy distributions for the various secondary particles.

Primary recoil spectra and displacement cross sections for most metals of interest have been calculated to 20 MeV using the most recent version (IV) of the ENDF/B evaluated nuclear data files. There do not appear to be serious inadequacies in the nuclear data for neutron energies below about 6-8 MeV. At a neutron energy of 14 MeV, reasonably complete data are also available. The quality and completeness of the data are generally much poorer between 8 and 14 MeV, and few points are available above $\sim$14 MeV.

*Also referred to in the literature as a primary knockon atom (PKA).

These data might yet be adequate for damage analysis purposes if all materials irradiations could be carried out in modified or unmodified T(d,n) spectra. Higher energy sources must be used, however, to get sufficient displacement and gas production rates and appropriate ratios of these rates. For example, a source utilizing the Li(d,n) stripping reaction yields a mean neutron energy near 14 MeV but appreciable fluxes to over 30 MeV. Some information on cross sections and angular and energy distributions in the 15-30 MeV range must be obtained; needed accuracies can be estimated from sensitivity studies.

Charged-particle irradiations are expected to play a significant role in the fusion materials program. Elastic scattering data are relatively well known (and calculable) over a wide energy range. Above $\sim$8 MeV/amu, however, nonelastic interactions become increasingly important and information is scarce. Not only are nuclear cross sections and models needed for damage calculations, but again the production of gaseous light ions per se, especially helium, may be significant.

The characterization of the production rates of particular transmutation products to the accuracy necessary for damage calculations or scoping studies is included in this problem area. Helium has been clearly identified as of primary concern; hydrogen will be the subject of scoping studies under other subtasks; certain solid transmutants or classes will be identified. Detailed energy-dependent cross sections will be needed only where suitable integral measurements cannot be made.

Data are also required concerning the slowing down of H, D, T, and He ions in matter, in connection with the simulation of neutron damage by ion irradiations and with gas injection problems, both by transmutation reactions and from the plasma. The slowing down of light ions in matter by electron excitation is not well understood theoretically at low energies (less than $\sim$0.5 MeV/amu) nor is very much reliable experimental data available.

This is especially the case at the energies (below $\sim$30 keV) which characterize stray particles escaping from the plasma. At energies above $\sim$0.5 MeV/amu, both theory and experiment appear to be more satisfactory but both need amplification, particularly for technologically important materials.

Damage production quantities, either singly or in combination, suitably averaged over test and design spectra, are parameters useful for correlating irradiation effects data. The primary recoil spectrum itself (or a suitable average over it) can serve as a basis for comparing the exposures of materials in different irradiation environments. More frequently two parameters are used: the number of displacements per atom (dpa) and the amount of helium produced by the irradiation. The research objective is to provide improved parameters by taking account of the defect annihilation and agglomeration that take place during so-called short-term annealing and to express these in terms of environmental parameters such as sample temperature, neutron fluence-spectrum, etc. The present procedures depend mainly on nuclear data and are also of somewhat limited accuracy. Their applicability to insulators, in which electronic defects can be produced, is dubious, and research in this area is needed. Improved correlation parameters can be developed, and it is likely that they will be more sensitive to atomic, and especially solid-state, properties than is currently the case.

b. Theoretical Characterization of the Primary Damage State - The energy of the primary target recoils is dissipated in part in atomic collisions, some of which produce additional recoiling atoms. The result is a branching cascade of displacement events. If a displacement cascade is produced near a target surface, some of its members may be sputtered. The development of a cascade can be considered to involve three stages. The first extends from the creation of the primary to that time at which the most energetic cascade atom falls below the displacement threshold energy. The second stage, characterized by numerous subthreshold encounters in a highly agitated lattice, lasts until local order is sufficiently reestablished for distinct defects to be identified.

The third, or short-term annealing, stage is characterized by thermally-activated defect migration resulting in the defects either annihilating one another, clustering, or escaping from the vicinity of the cascade. The defect configuration existing at the end of the third stage is termed here the primary damage state. It is a transient state except at temperatures so low that no thermally-activated defect migration (i.e., no third stage) exists. At such low temperatures the accumulation and eventual overlap of such localized primary damage results directly in property changes. At higher temperatures, property changes are caused both by primary damage and by damage microstructure that nucleates and grows due to the defects that escape from cascades. The description of such damage microstructural evolution is the responsibility of Subtask Group C.

Calculations of cascade development require data on the electronic stopping cross sections of various energetic atoms in solids. The available experimental data are rather limited, and present theories are not especially satisfactory. The data show complicated and only partially-understood dependences on the atomic numbers of the projectile and the stopping medium. The velocity dependence is more complicated than the commonly-used theories suggest. It is also necessary to have accurate descriptions of the stopping of energetic atoms in solids by quasielastic atomic collisions. There is ample evidence of significant differences between some experimentally-measured particle ranges and the most commonly used theories. The specific areas needing improvement for damage analysis purposes should be identified through limited sensitivity analyses.

The development of displacement cascades is treated theoretically by a variety of methods. The dynamic method, referred to here for convenience as MD (molecular dynamics), is based on the integration of the equations of motion of the atoms in a small crystallite, following the displacement of one or more of these atoms. Suitable computer codes are in use at several laboratories although none is generally available. Such calculations are usually restricted to rather low primary recoil energies (less than $\sim$1 keV). They are particularly useful in describing the conditions for defect stability and in studying replacement sequences, focusing processes, and the like. They can be used to estimate displacement threshold energy surfaces and vacancy capture polyhedra. Their application most often has been to idealized materials without surfaces, using central two-body forces. The use of MD methods for surface problems and for alloys and insulators, especially technologically important ones, has not been developed fully. Few calculations have considered heavily damaged materials or the influence of residual agitations in the lattice at the end of cascade development.

Binary collision approximation (BCA) models construct the trajectories of energetic particles as a series of isolated binary atomic encounters in a discrete lattice. Only one code of this type is widely available at the present time. Such models are conveniently applicable to a variety of problems including cascade development, sputtering, and plasma particle backscattering. Detailed justification of BCA procedures at low energies in terms of MD models is often lacking or of limited scope, but the problem is currently receiving attention. The main advantage of BCA methods is their speed, which is sufficient to permit calculations for statistically significant numbers of primaries.

Continuum methods based on transport theory have hitherto been applied to only a few aspects of cascade development (sputtering, primary particle ranges) and then mainly in rather severely approximated form. Numerical techniques, especially the discrete ordinates method, can probably be exploited usefully in a variety of problems. They would be the basis of very fast programs for damage analysis applications.

All theoretical methods of treating displacement cascade development show more-or-less marked sensitivities to computational details, including the choice of interatomic potentials, the types of boundary conditions used, and the like. The primary need is for the several techniques to be combined in an optimum way to describe cascade development over the whole energy range of interest, tens of eV to several MeV, for a variety of materials.

At the end of the second stage of development of a displacement cascade, the irradiated material contains an array of structural point defects: vacant lattice sites; interstitial (self) atoms; impurity atoms (substitutional or interstitial) either originally present or produced by transmutation; and light atoms (H, D, T, He) either injected from the plasma or produced by nuclear reactions. In addition, insulators may contain a variety of electronic defects which can interact with each other and with the structural defects. The detailed properties of these defects determine the course by which the nascent damage state develops with time into the complex structures which are observed experimentally in irradiated media. The properties required to analyze this evolution completely include the formation and migration energies of the simple defects, the energies of binding of defect aggregates, the migration energies of mobile aggregates, the energies of interaction of the various defects with dislocations and any nearby surfaces, and the structures of the various defects including lattice relaxations in their vicinity. All of these properties may be temperature-dependent; all may depend on the general state of order and the metallurgical state in the vicinity.

The behavior of point defects in dense cascades can be expected to differ from their behavior when isolated from one another, partly because of the locally high defect density and partly because of the residual agitation in the lattice in such regions. Such effects have been treated inadequately in previous work on modeling cascades. Point-defect properties are significant in several areas of plasma-material interactions as well, including gas bubble and blister formation and the surface topographical effects of sputtering. It is important, therefore, to determine the extent to which defect properties are altered by the proximity of surfaces. Not all defect properties are needed to the same accuracy, of course. Indeed, many appear as parameters in necessarily simplified models, and effective values must be estimated or experimentally determined. Theoretical calculations of defect properties can be based on the MD method or, in particular cases, on other techniques such as lattice statics.

Close attention must be given to the effects of model details on the results of such calculations, including the influence of the boundary conditions and the choice of interatomic potentials; indeed an important question is the extent to which pair interactions are an adequate description of nature. It should be noted, however, that the value of such calculations, even though they may be lacking in rigor, is often to point the way to correct phenomenological descriptions.

Appropriate descriptions of defect properties, then, must be combined with accurate descriptions of cascade development to provide a description of the primary damage state in terms of the numbers, types, and spatial configuration of defects. While the discussion has been couched in terms of cascades, it should be clear from the description of primary recoil energy spectra that the term cascade, as used here, refers to events that produce from one defect pair to many hundreds of pairs. The determination of the variation of the primary damage with cascade (or primary recoil) energy is a major objective of this problem area. Another perhaps strongly energy-dependent phenomenon is the effect of cascades on existing defects in a solid. In particular, such effects as re-solutioning of precipitates can affect the concentration of impurity in the matrix and have important consequences on microstructural development.

c. Experimental Characterization of the Primary Damage State - The theoretical models described in the preceding section lead to descriptions of the numbers and dispositions of the defects produced in an irradiation. These theoretical descriptions of the primary damage state must be validated by experimental studies. The experiments may be divided into two classes according to irradiation temperature. At sufficiently low temperatures ($\lesssim$10K for many metals), measurements of the primary damage itself can be made. The experiments may be indirect ones, such as measurements of electrical resistivity or anelasticity, or somewhat more direct measurements by diffuse X-ray scattering, transmission electron microscopy (TEM), or positron annihilation.

For particular materials, special techniques may be available such as field ion microscopy (FIM) for certain metals (generally refractory), special TEM techniques for ordered alloys, and optical or spin resonance methods for insulators. Measurements of low temperature damage rates as functions of dose can be supplemented by annealing studies which provide information on the damage structures produced.

While low temperature experiments help validate models, the accurate description of defect production at elevated temperatures is of more technological interest. As discussed briefly above, theoretical descriptions of the damage state at elevated temperatures must include damage evolution as well as primary damage. Furthermore, the measured property change must be related mechanistically to the damage state. Some properties (e.g., internal friction and order-disorder) are sensitive to free defect production while others (e.g., yield stress) are sensitive to immobile defect cluster production. The sensitivity of still other properties (e.g., creep) to the primary damage state is not known yet. The definition of such sensitivities and the validation of theoretical descriptions of damage production and evolution will be, in part, an iterative process.

The role of transmutation products in the production of primary damage and the effects of cascades on transmutant behavior must be explored by experiments at sufficiently high exposures, by the use of appropriately doped samples, or by simultaneous irradiation by two species of ions.

Inasmuch as accurate environmental characterization is an important requirement for these experiments, it should be clear that good collaboration of all segments of the DAFS Task Group is required.

The irradiation program should be based on 14 MeV T(d,n) and broad-spectrum Be(d,n) sources, supplemented by selected fission neutron irradiations. Tests of damage theory can also be based on ion irradiations selected either for their value in simulating fusion reactor conditions or because they are particularly useful in testing a point in the theory. The use of monoenergetic charged particles should be particularly instructive in elucidating the role of cascade density ("spike effects") in damage production.

d. Damage Production in Insulators - The emphasis throughout this Plan is on metals and alloys, with little mention of insulators. Clearly, there are potentially severe problems with insulators in fusion reactors. At this time these problems fall largely within the scope of the TG on Special Purpose Materials. It is anticipated, however, that as the needs for insulators come more clearly into focus, an active task on damage production in insulators will evolve in the DAFS program.

3. Assignment of Problem Priorities

		Priority
a.	Damage Production Parameters	H
b.	Theoretical Characterization of the Primary Damage State	M to D
c.	Experimental Characterization of the Primary Damage State	M to D
d.	Damage Production in Insulators	H

Assigning priorities to these rather broad problem areas is difficult. A few damage production parameters provide the current basis on which the relative damaging efficiencies of different irradiation facilities are evaluated. While this Program Plan emphasizes the importance of gaining an understanding of damage mechanisms through modeling of damage microstructure evolution, hence providing insight as to which defects are important and how they interact, more sophisticated correlation procedures will be formulated also in terms of damage production parameters. Hence the development of damage production parameters was assigned the highest priority. These parameters, however, can only reflect the status of our understanding of the primary damage state; therefore, problems b and c should also be given relatively high priority. The lower priorities reflect the wide range of questions that could be addressed profitably in these problem areas.

C. SUBTASK GROUP C: DAMAGE MICROSTRUCTURE EVOLUTION AND MECHANICAL BEHAVIOR (Correlation Methodology)

1. Problem List

The following problem areas have been identified.

a. Materials:

1) Material selection,
2) Material parameters (pre-irradiation microstructure, composition, and phase stability), and
3) Specimen design for fundamental studies.

b. Damage Microstructure Evolution:

1) Effect of helium,
2) Effect of hydrogen,
3) Effect of solid transmutants,
4) Effect of cycling, and
5) Effect of damage rate and primary recoil spectrum.

c. Fundamental Mechanical Behavior:

1) Effect of helium and displacements on flow and fracture,
2) Effect of hydrogen and displacements on flow and fracture,
3) Effect of solid transmutants on fracture,
4) Effect of primary recoil spectrum and flux on flow and fracture,
5) Effect of cycling on flow and fracture,
6) Effects of surface damage on fracture, and
7) Development of flow and fracture models.

d. Development and Testing of Composite Correlation Models

e. Supporting Studies:

1) Characterization of microstructure, and
2) Relating low- and high-exposure microstructure.

2. Problem Analysis

Problems b.1 through b.5 and c.1 through c.6 are directly concerned with irradiation conditions that differ between test and fusion environments. Problems a.1 and a.2 are concerned with those material types and parameters that are of generic importance in analyzing radiation effects data. Problems c.7 and d are concerned with systematizing data for the purpose of projecting test results to fusion environments. The remaining problems are critical support areas.

a. Materials:

1) Material Selection - The materials to be used in these studies should be representative of the Path A, B, and C alloy classes (see Glossary) of the ADIP program. Specific choices would be based on such factors as prior knowledge of mechanical behavior (with or without irradiation), radiation sensitivity, and simplicity. Materials must be identified early in the program to insure their availability in sufficient quantity and their proper pre-irradiation characterization.

2) Material Parameters - It is not possible to separate the effects of material and irradiation parameters in determining radiation damage response. In particular, it has become clear in the breeder program that phase stability is one of the most important considerations in designing radiation-resistant alloys. Damage correlation efforts must be cognizant that this phenomenon is generic to all irradiation environments. Radiation, elevated temperature, and stress--singly or in combination, constant in time or cycled--may cause precipitation or precipitate redistribution, segregation of alloying elements, and altered defect mobilities. These phenomena, and transmutation products as well, can have significant effects on microstructural evolution and on mechanical behavior. They may also influence the effect of variations in irradiation parameters on microstructural evolution and mechanical behavior.

3) Specimen Design - The primary responsibility for specimen design lies with the ADIP Task Group although this is an area in which inter-task group collaboration will be important. Specimen geometries must be chosen so as to allow valid comparisons of data and development of correlation parameters. Limiting conditions include the small test volumes in high-energy neutron and charged-particle facilities, the small penetration distances of charged particles, restriction on instrumentation in reactors, and restrictions on simulating cyclic loadings. Some specimen design problems may be unique to the fundamental studies effort.

b. Damage Microstructure Evolution:

1) Effect of Helium - Fusion environments are characterized by high helium production rates. Both experimental and theoretical evidence suggest that the generation of helium can profoundly influence damage microstructure evolution. Two critical questions emerge when helium is considered.

- What is the distribution of helium within the microstructure and how is this distribution influenced by material and environmental parameters?
- What is the influence of the distribution of helium on the nucleation and growth of other microstructural features?

Both helium and displacement generation rates and ratios, along with other irradiation parameters, are expected to be important.

Information needed to determine helium distribution includes mobility of atomic helium under irradiation, trapping and detrapping mechanisms, and bubble formation, growth, and mobility. Recrystallization, creep, or cyclic deformation may redistribute helium.

In addition to producing bubble swelling at high temperatures, helium is known to influence cavity and loop nucleation and may alter sink strengths and bias factors.

2) Effect of Hydrogen - Fusion environments also produce relatively high rates of hydrogen production. As with helium, the rate of production and ratio of hydrogen to displacements may influence microstructure evolution. Information is needed on the mobility, retention, and distribution of hydrogen and its influence on internal surfaces and interfaces. Internal chemical reactions to produce hydrides or insoluble gases may also be significant.

3) Effect of Solid Transmutants - Solid transmutants will be produced at rates up to 1000 appm/MWyr$\cdot$m^{-2} in fusion reactor environments. Impurities introduced by transmutations can alter microstructure evolution directly through precipitation or indirectly by perturbing the migration of other defects.

4) Effect of Cycling - Fusion reactor environments typically will be characterized by cycling of radiation, stress, and temperature. Cycle times, amplitudes, duty factors, and phase relationships are design-dependent. In principle, all of these factors could influence the nucleation and growth of microstructures. For example, defect recombination during high-intensity pulses of irradiation and dissolution of small clusters between burn cycles might retard the formation of some defect structures as voids or precipitates.

5) Effects of Damage Rate and Primary Recoil Spectrum - There is little physical basis for the single-parameter scaling factors which have been used to treat effects of damage rate and cascade structure in interparticle correlation studies. It is well known that different microstructures and different damage mechanisms respond differently to changes in damage rate. Time-at-temperature phase stability phenomena and the dependence of helium effects on the displacement rate are examples pointing to the necessity of a more general approach to damage rate and interparticle correlation.

The existence of very-high-energy neutrons in fusion reactor and test environments places special emphasis on the question of damage microstructure produced in the nascent damage state. Alternative theories of intra-cascade annealing and vacancy loop formation in cascades, both leading to the reduction in the number of defects reaching sinks, have been proposed. Strong input from the primary defect production effort (STG B) is needed to resolve the question of such cascade effects.

The direct usefulness of charged-particle irradiations to simulate high-exposure neutron damage may rest on better understanding of particle rate and cascade structure questions. Charged-particle irradiations have some unique potential advantages including: provision for precise parameter control in mechanism studies, high displacement rates (and helium production rates in dual-particle irradiations), cycling of irradiation parameters, and the ability to independently vary helium introduction and displacement rates in all alloy types. To make use of these advantages, however, correlation models must properly account for less desirable effects such as damage gradients and the presence of surfaces.

c. Fundamental Mechanical Behavior:

1) Effect of Helium and Displacements on Flow and Fracture - The creep of AISI 316 stainless steel during irradiation and its post-irradiation ductility are under intense study in the Breeder Reactor Program. While the emphasis is on describing the phenomena through design equations, considerable progress has been made in understanding the flow mechanisms. Helium concentrations are low; however, it has been shown already that the much higher concentrations expected in MFRs can further decrease the ductility of 316 stainless steel.

It is well known that helium can cause elevated temperature embrittlement of steels, at concentrations much lower than those expected in MFR first walls, by collecting at grain boundaries. The control of the transmutation-produced helium provides one basis for developing improved alloys. It has already been found that the effects of even hundreds of appm of helium in 316 stainless steel can be diminished by pre-irradiation cold-working and by the addition of titanium. Examining the mechanisms of these processes should have high priority. More generally, the behavior of helium in Path A, B, and C alloys, and its influence on flow and fracture, must be determined as a function of temperature, helium concentration, and the location of the helium-producing elements. The last point may be important because the segregation of elements such as carbon, which have high (n,α) cross sections, may cause high helium production rates at grain boundaries relative to those in the matrix.

The effects of helium on flow and fracture are intimately related to the effects of displacements on matrix hardening. Determination of their relative importance in various regimes of the irradiation variables, for the several alloy classes of interest, must be part of the model development effort.

2) Effect of Hydrogen and Displacements on Flow and Fracture - Hydrogen embrittlement is known to occur in a wide variety of alloys. While generally considered to be a low-temperature phenomenon, it has not been studied at elevated temperatures in materials under irradiation. Hydrogen will be introduced into an MFR first wall by transmutation reactions and by diffusion from the plasma and blanket. Equilibrium concentrations must be predicted. To do so requires knowledge of the mobility, retention, and distribution of hydrogen (see problem b.2) in the several alloy classes of interest. Given the equilibrium concentrations, the potential significance of hydrogen effects must be assessed. If scoping experiments are needed, hydrogen doping procedures will have to be developed because high hydrogen concentrations cannot be produced in any existing neutron irradiation test facility.

3) Effect of Solid Transmutation Products on Fracture - The composition of an alloy in an MFR first-wall environment changes with time due to transmutation reactions. The introduction of certain impurities that might precipitate or segregate to modify mechanical behavior is probably the most significant consequence. It is known, for example, that minute quantities of certain elements promote embrittlement. On the other hand, beneficial

effects also could result if, for example, the new impurity had a chemical affinity for an embrittling agent already present.

4) Effects of Damage Rate and Primary Recoil Spectrum on Flow and Fracture - It has already been demonstrated that radiation-induced creep is sensitive to the primary recoil spectrum. Creep rates in light-ion irradiations are higher, per calculated dpa, than rates observed in a fast reactor. This is presumably due to the difference in the ratio of free-to-clustered defects in the two environments. It is also known that post-irradiation tensile properties are sensitive to the primary recoil spectrum.

A strong collaboration is needed between STGs B and C to unfold a consistent description of defect production and its influence on flow behavior in order to include spectral effects in flow and correlation models. Included in this effort must be a consideration of damage rate effects since varying the spectrum at constant flux varies the damage rate also.

In fracture studies, secondary effects of primary recoil spectrum must be given consideration. In particular, re-solutioning of precipitates is spectrum-dependent and will influence the evolution of the damage microstructure.

5) Effect of Cycling on Flow and Fracture - Current tokamak technology indicates that the first wall will be subjected to cycling of flux, temperature, and stress. Such cycling, in combination with the other unique characteristics of an MFR environment, probably presents the most challenging problem faced by the fusion materials community. The accumulation of microstructural damage leading to failure will include contributions, both singly and in combination, from displacements, transmutation products, creep, and fatigue; the nature of the anticipated strong interactions is unknown. The number of significant experimental variables, including surface conditions, chemical environment, stress and strain amplitudes, stress and strain states, and cycling schedule, added to the usual material and irradiation variables, precludes an empirical shotgun approach.

Another important consideration is that test conditions may necessarily differ importantly from MFR conditions. In this regard, the limitations of post-irradiation testing must be determined early in the program. Stress relaxation occurring during in-situ tests may result in fracture behavior that is significantly different from that observed in post-irradiation testing.

Statistical analysis can be expected to assume increased emphasis in the area of fatigue. That is, knowledge of the behavior of an average flaw under average conditions is generally insufficient. Rather, a spectrum of flaws subject to a spectrum of conditions (including the nature of the microstructure at a flaw tip) must be studied. This recommended statistical approach is to be contrasted with a worst-case approach (largest flaw under most severe conditions). While the latter permits economies in the test program, it may be too conservative.

6) Effect of Surface Damage on Fracture - An MFR first wall is expected to be subject to surface erosion caused by low-energy ion and higher-energy neutron bombardment. In particular, high near-surface concentrations of helium may accelerate grain boundary failure as well as lead to the now familiar blistering. The effect of such surface treatment on crack initiation must be examined in conjunction with fatigue studies.

7) Development of Flow and Fracture Models - The fusion materials program will generate new data on the mechanisms of flow and fracture under various sets of irradiation and material variables. This information must be systematized in order to guide the experimental program and to lead to the desired predictive capability. Models must be developed relating mechanical behavior to microstructural features, such as dislocation structure, precipitates, and grain size, and the dependence of these features on the irradiation environment. Conceptual models must lead to mathematical models which will generally contain parameters to be evaluated by experiments. A systematic approach to such model development is described in Chapter IV.

d. Development and Testing of Composite Correlation Models - A fusion environment for materials testing will not be available for many years. Therefore, a description of the response of materials to an MFR environment will be obtained piecewise, using models in the design and analysis of experiments and experiments to refine models. The pieces must be combined in composite models that incorporate all significant mechanisms, and their interactions, in order that projections to fusion conditions can be made.

The testing and calibration of such models must await construction of a high-flux, high-energy neutron source. The limited test volume of such a facility clearly precludes an experimental matrix that encompasses the full range of irradiation and material parameters and their interactions. Confidence in the use of these correlation models, therefore, will be directly related to their mechanistic foundations.

e. Supporting Studies:

1) Characterization of Microstructure - The primary method of microstructural evaluation currently is TEM. While much detailed and useful data can be obtained, TEM suffers from limited defect size resolution. It is also time consuming; hence constraints on funding and manpower have severely limited the quantity of data produced. Innovative means should be sought to increase the quantity and resolution of microstructural data in order to increase the effectiveness of the proposed program.

2) Relating High- and Low-Exposure Microstructures - Particular emphasis has been placed on the early stages of microstructural evolution because of a sensitivity of this stage to damage parameters and because of the consensus that the total microstructural development may be sensitive to the early states in some cases. Further, flux level limitations of most potential neutron irradiation facilities will permit extensive intercorrelation only in low-dose regimes. It is clear, however, that for this information to be useful the relationship between the early microstructure and that which subsequently evolves at high damage levels must be established.

3. Assignment of Problem Priorities

	Priority
a. Materials:	
1) Material selection	H
2) Material parameters	M
3) Specimen design	H
b. Damage Microstructure Evolution:	
1) Effect of helium	H
2) Effect of hydrogen	M
3) Effect of transmutants	M
4) Effect of cycling	H
5) Effect of damage rate and primary recoil spectrum	M
c. Fundamental Mechanical Behavior:	
1) Effect of helium and displacements on flow and fracture	H
2) Effect of hydrogen and displacements on flow and fracture	H
3) Effect of solid transmutants on fracture	M
4) Effect of primary recoil spectrum and flux on flow and fracture	M
5) Effect of cycling on flow and fracture	H
6) Effect of surface damage on fracture	M
7) Development of flow and fracture models	M
d. Development of Testing of Composite Correlation Models	M
e. Supporting Studies:	
1) Characterization of microstructure	D
2) Relating low- and high-exposure microstructures	D

IV. PROGRAM STRATEGY AND MAJOR MILESTONES

This task group owes its existence in large measure to the nonexistence of a suitable fusion materials test facility. This is an essential point; it gives direction and scope to a task that, except for its neutron dosimetry function, is essentially open-ended. Because available test facilities cannot provide engineering data in MFR environments, the task objective is a coordinated damage analysis program that will permit confident projection of test data to MFR conditions. Such projections must be based on an understanding of damage mechanisms. The purpose of this chapter is to lay out a strategy, including major milestones, for developing this understanding.

The program is intended to focus efforts on solving the problems described in Chapter III. It is designed to: 1) utilize effectively those characteristics of various available irradiation test environments that either mimic the MFR environment in some respect or permit a controlled study of a significant variable; 2) develop by theory and experiment the correlation procedures necessary to relate microstructural and property data obtained in these facilities confidently and apply them to the prediction of the effects to be expected in FMIT when it becomes available; and 3) refine and calibrate correlation procedures as necessary using data accumulated in FMIT and apply them to the prediction of radiation effects in MFRs.

The primary concern is development of a radiation-resistant first-wall material. Its radiation resistance at high exposures will have to be demonstrated in fission reactors since no other high-flux, high-volume neutron sources exist. Major objectives, then, are to use available and planned irradiation facilities to gain an understanding of the similarities and differences between radiation effects produced in fission reactors and those anticipated in MFRs and to apply this understanding to maximizing the utility of fission reactor irradiations in MFR materials development.

An overview of program strategy is shown in Figure 2. The central effort is the development and validation of procedures for correlating test data and applying (often projecting) them to MFR conditions. Initial experiments and theoretical efforts are aimed at identifying the critical regimes of various damage parameters. The emphasis is on providing early guidance to high-fluence fission irradiations that require long irradiation times. Secondary emphasis is on assessing the magnitude of problems not directly accessible with fission reactors such as the effects of helium in non-nickel-bearing alloys, of hydrogen and other (solid) transmutation products, of cyclic operation of the radiation source, of the high-energy tail of the primary recoil spectrum, and of surface damage on fatigue. Subsequent experiments will gain focus by issues raised by the scoping experiments. The development of correlation techniques and models must proceed simultaneously with the experimental program.

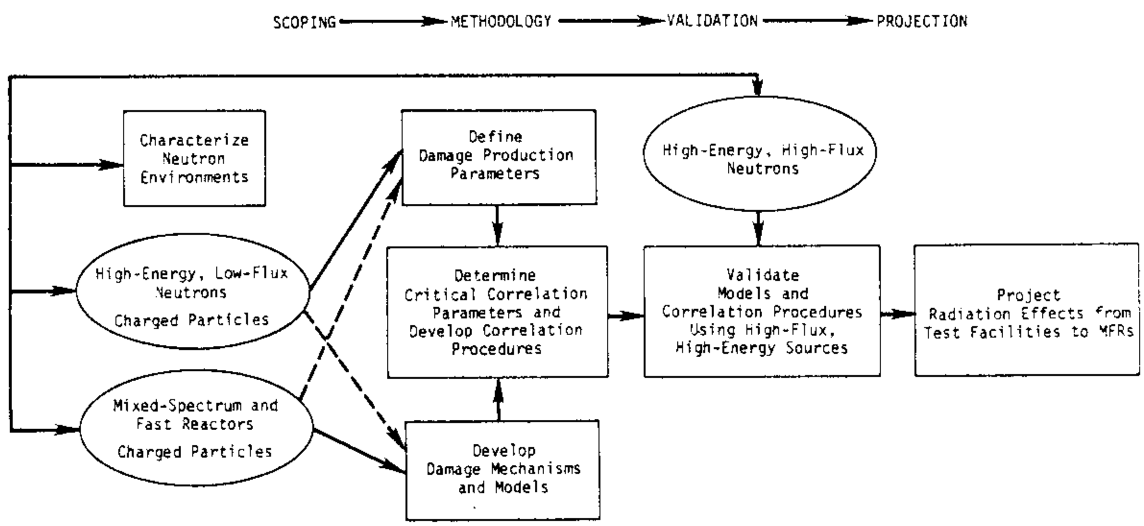

FIGURE 2. Strategy Overview of Task Group on Damage Analysis and Fundamental Studies. (Dashed arrows indicate secondary functions of the test facilities.)

The first opportunity for validating and calibrating correlation models in an environment that produces both transmutations and displacements at a rate characteristic of an MFR will be with an accelerator-based source. The test volume will be severely limited and long irradiations will be necessary. Hence it is important that development of damage mechanism and correlation models proceeds rapidly so as to provide a firm basis for setting irradiation priorities.

The final validation of correlation procedures must await a real fusion environment. By that time, however, important decisions regarding materials selection and evaluation will have been based on data obtained in fission reactors and in accelerator-based facilities. Thus the development of a sound correlation methodology is needed relatively early in the materials development program.

Three important supporting efforts are identified in Figure 2. Neutron environment characterization is the most easily quantified and milestoned. It provides the base data on which all damage analysis rests. Its central mission is to develop and standardize procedures for characterizing the spatial and temporal dependence of the neutron fluence and spectrum in fusion material irradiations. Development work unique to the fusion materials program is needed for accelerator-based neutron sources.

A second supporting effort is the development of damage production parameters. Current parameters are gross displacement rate and helium production rate. (Hydrogen production rates often are given but with less confidence in their significance.) The ratio of helium production to displacement production is a convenient index; however, it is sometimes applied to low-flux fields in which significant concentrations of helium cannot be achieved. It must be assumed that the spatial configurations in which displacements are produced has a significant impact on the production of lattice defects, hence on damage. The spatial configuration of displacements depends on the primary recoil spectrum--the precise dependence is a major objective of this supporting effort.

From this work will come defect production cross sections that can be used directly for data correlation and defect production descriptions for use in damage models. The approach is both theoretical and experimental. A major problem is the difficulty of direct experimental validation of theoretical models (often derived from atomistic computer simulation); major emphasis must be placed on narrowing the gap between theory and experiment. The most direct approach is through the effect of radiation type and energy on microstructure. However, additional models of defect kinetics usually must be invoked to deduce damage production quantities from such experiments. Less direct experiments involve the measurement of a change in a macroscopic property. In this case, self-consistent models of the damage mechanism and of damage production must be sought.

A third supporting effort is the identification of damage mechanisms and development of damage models. The purpose of this effort is to provide a conceptual framework for selecting and designing experiments and for the all important tasks of extrapolating and generalizing experimental results. Included in this effort is a new emphasis on microstructural characterization and modeling primarily because controlling the nucleation of the damage microstructure may offer the best hope of developing radiation-resistant alloys. A secondary consideration, however, is that planned high-energy neutron facilities have very limited test volumes; hence microstructural data will be obtainable in the largest quantity. The emphasis on microstructure considerably enhances the utility of low-flux, low-test-volume, high-energy sources.

The DAFS Task Group has been organized into three Subtask Groups to implement the program; they deal with environmental characterization, damage production, and damage microstructure evolution and mechanical behavior. This group structure reflects general divisions of scientific disciplines and expertise and is intended to promote depth of program planning and execution. This TG supports the other TGs of the fusion materials program, hence must retain strong ties to them. To facilitate coordination with the ADIP TG, a Joint Subtask Group has been formed; its chairman serves on both Task Groups.

Additional mechanisms for inter-Task Group communication are through meetings of the chairmen, periodic information meetings, and through periodic progress reports.

In Chapter III of this Plan, problems were defined and analyzed by each Subtask Group. The same organization is used here to present the program in detail. Table 1 lists the major milestones that have been identified for this program. These are indicated in Figures 3, 4, and 5 for each of the Subtask Group programs. (Detailed task descriptions are presented in Chapter V; they are related to the major milestones in Table 2 at the beginning of that chapter.) A description of each program follows.

TABLE 1

MAJOR MILESTONES

Designation	Description	Date
II-1	Determine energy dependence of gas production rates.	1983
II-2	Establish neutron dosimetry methodology for high-flux Li(d,n) facility.	1983
II-3	Establish neutron dosimetry methodology for MFRs.	1988
II-4	Assess needs and recommend program on damage production in insulators.	1979
II-5	Establish new defect production parameters and cross sections.	1983
II-6	Assess helium production simulation methods.	1981
II-7	Assess need and initiate program of hydrogen studies if warranted.	1980
II-8	Establish interim correlations for flow.	1981
II-9	Establish quantitative models for effects of helium and displacements on flow.	1983
II-10	Assess effects of cycling on flow and microstructure.	1983
II-11	Assess effects of primary recoil spectrum and damage rate on flow and microstructure.	1982
II-12	Establish composite model for flow in an irradiation environment.	1983
II-13	Establish interim correlations for fracture.	1981
II-14	Establish quantitative models for effects of helium and displacements on fracture.	1984
II-15	Establish composite model for fracture in an irradiation environment.	1984
II-16	Validate/calibrate composite models in high-energy, high-flux neutron environment.	1987-1988

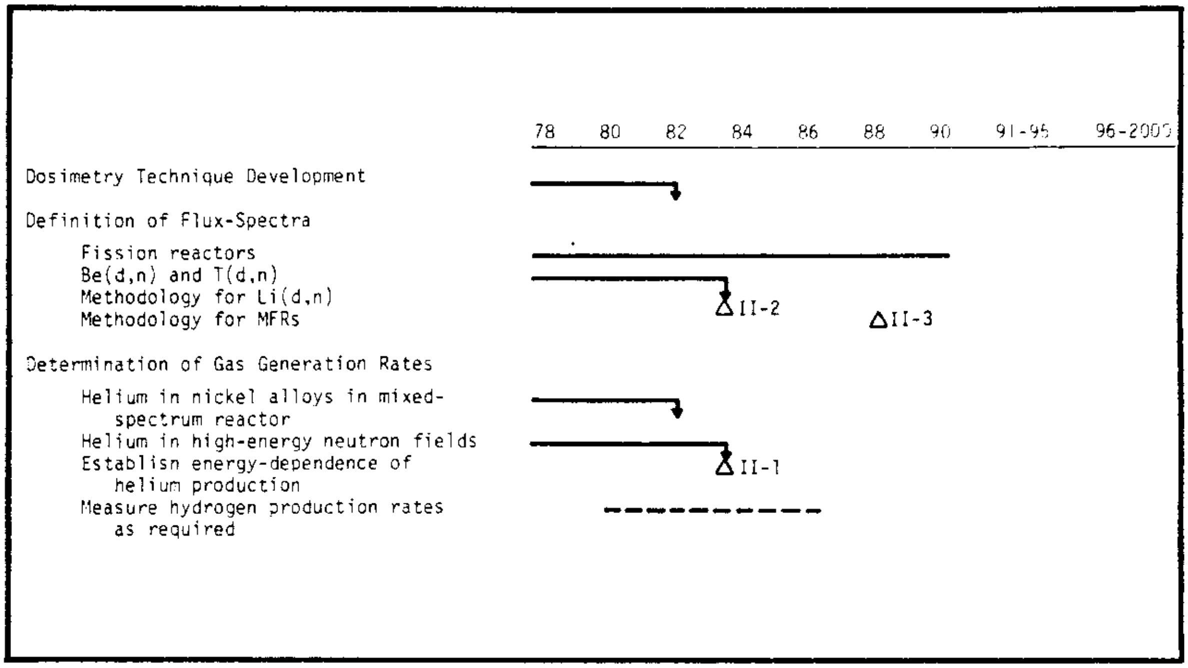

FIGURE 3. Damage Analysis Strategy: Environmental Characterization. (Arrows depict information flow.)

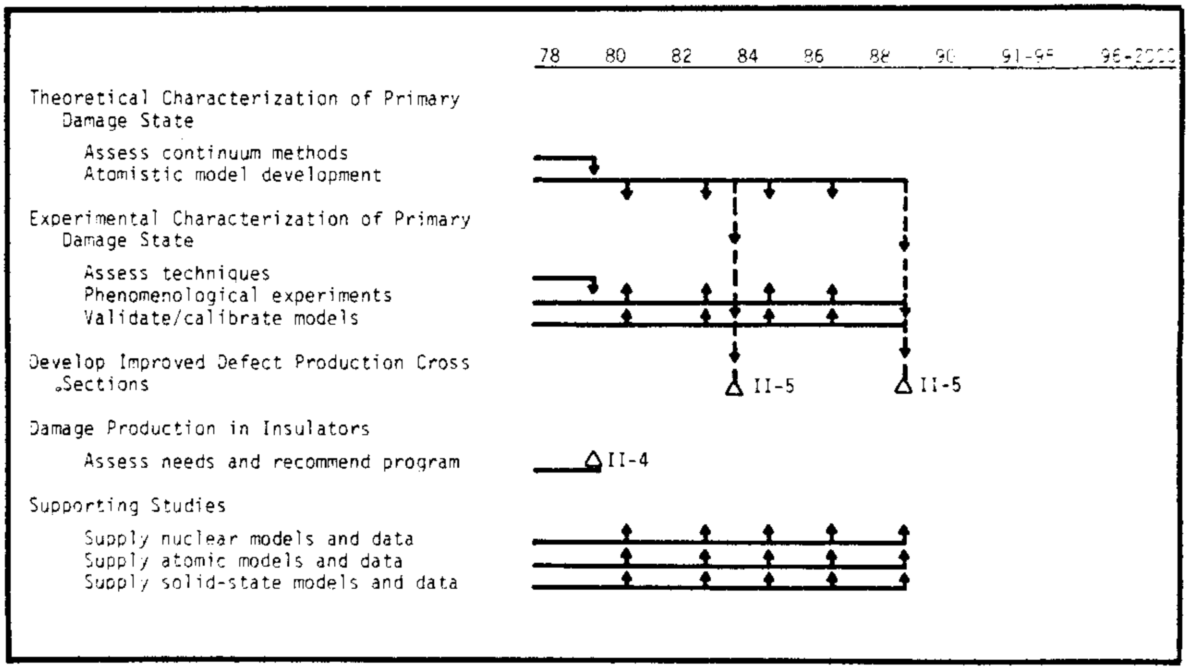

FIGURE 4. Damage Analysis Strategy: Damage Production. (Arrows depict information flow.)

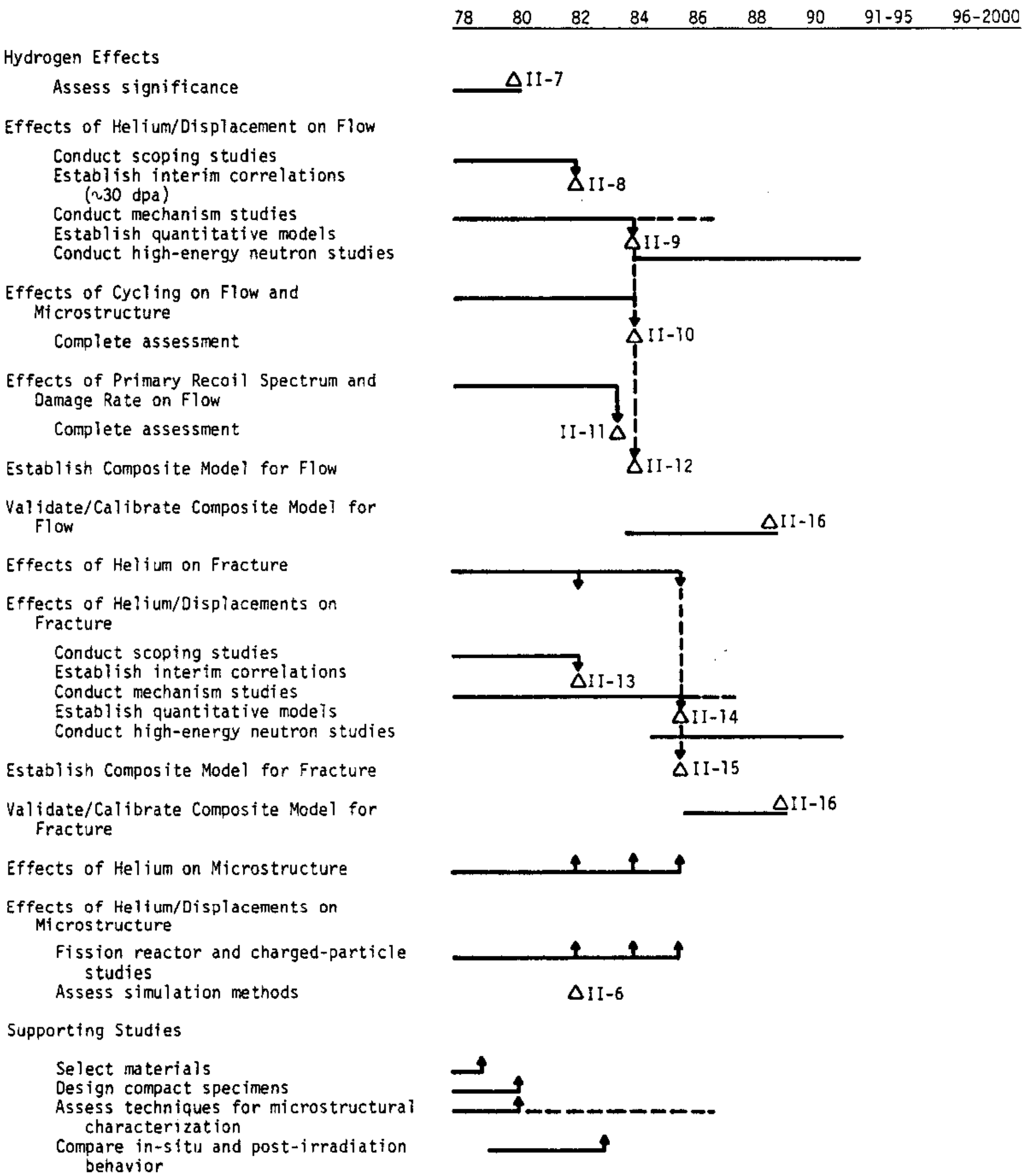

FIGURE 5. Damage Analysis Strategy: Correlation Methodology. (Arrows depict information flow.)

A. SUBTASK GROUP A: ENVIRONMENTAL CHARACTERIZATION

The primary technique for characterizing all OFE irradiation environments is expected to be passive foil activation complemented by neutronics calculations. This approach has been well established and documented through the efforts of national breeder reactor development programs. Nuclear cross section data are generally considered to be adequate for fast reactor and mixed-fission reactor irradiations. For nonfission high-energy neutron environments (E >10 MeV), nuclear cross section data are sparse (except near 14 MeV), and integral data testing methods must be employed in order to establish reliable techniques for the determination of neutron spectra. Any such nuclear data development and testing will be coordinated with other national programs such as CSEWG and ILRR. Because of the relatively large uncertainties possible in measuring flux/spectra in some environments, sensitivity studies should be made to evaluate the effects and importance these uncertainties have on damage parameter calculations.

Other dosimetry techniques are expected to find important application to (d,n) sources such as time-of-flight (T-O-F) spectrometry, stable product fluence monitors, nuclear emulsions, and track recorders. While some of the procedures developed in this program will be specific to the characterization of (d,n) stripping sources, little additional work should be required for characterization of real MFR environments. A possible exception could occur if gamma or charged-particle fluxes are found to be a problem.

1. Definition of Neutron Flux and Energy Spectra in Tailored, Mixed-Spectrum Fission Reactors

a. Using existing transport and diffusion codes, the neutron flux and spectral distributions will be calculated at strategic irradiation locations in a mixed-spectrum reactor. Foil activation rates will be measured at the same positions. Discrepancies between theory and experiment will be identified and parameters modified if necessary to achieve consistency.

b. Whenever reactor core or reflector modifications are significant, the procedure in 1.a must be repeated to characterize the new irradiation conditions.

c. New dosimetry reactions and new methodology which are applicable to the neutron energy range 0.01-0.5 MeV should be developed and tested.

2. Definition of Flux and Spectra in Nonfission High-Energy Neutron Facilities

a. Fluences and spectra at existing Be(d,n) facilities must be measured as a function of sample position by using a variety of passive techniques (radiometric, helium accumulation, nuclear emulsions) and by T-O-F and recoil spectrometry. If necessary, cross sections will be adjusted or normalized so that unfolded neutron spectra agree with T-O-F spectra. The goals are to establish a consistent set of cross sections and to characterize the neutron fields. This will be a bootstrap operation until cross sections are better established.

b. Established RTNS-I dosimetry techniques will be applied to RTNS-II; methodology must be validated for the higher neutron flux levels.

c. Any spectrum tailoring at a high-energy facility to more closely simulate a typical first-wall spectrum will require extensive dosimetry which includes neutronics calculations and experimental measurements.

d. Dosimetry methodology developed for a Be(d,n) facility must be applied to a future higher intensity Li(d,n) facility. The significance of gamma environments will be assessed by measuring gamma-ray flux and spectra as needed at all facilities as a function of sample position. The measurements will permit estimates of gamma heating and possible (γ,n) or (γ,f) reaction effects on dosimeters.

3. On-Line Dosimetry Requirements for Proposed or Planned High-Energy Neutron Facilities

Early in the design stage of planned facilities, a review should be made of requirements for on-line, real-time dosimetry instrumentation, e.g., flight paths, apertures, collimators, etc., in order to assure adequate environment characterization at the time of facility operation.

4. Sensitivity Studies to Assess the Accuracy of Dosimetry Needed for Damage Parameter Calculations

a. Using existing Monte Carlo codes, the propagation of estimated errors due to dosimeter positions, reaction cross sections, counting, etc., can be made and data uncertainty limits on the measured neutron flux/spectra estimated. The implications of these uncertainties on specific damage parameters can then be ascertained to evaluate the adequacy of the data coming from A.1 and A.2.

b. As new theoretical damage models develop, similar sensitivity studies can be made to establish guidelines for accuracy requirements for nuclear data and dosimetry.

5. Determination of Helium and Hydrogen Generation Rates for Use in Each Neutron Environment

a. Helium production rates can and should be determined directly through measurements by high sensitivity gas mass spectrometry. If initial assessments of hydrogen effects show the need, hydrogen isotope production should be measured by particle recoil methods and by radiometric techniques when a suitable reaction product exists. These determinations must include all the major elemental constituents of candidate materials in which gas production could be a significant damage mechanism (together with some separated isotopes for testing of nuclear cross section calculations).

b. Helium production must be measured in nickel-bearing alloys irradiated in a mixed-spectrum fission reactor to corroborate the efficiency of spectrum tailoring. Measurements on other specimens irradiated in mixed-spectrum and fast reactors may be necessary to check helium and hydrogen production cross sections.

c. Materials should be irradiated in T(d,n) and Be(d,n) neutron environments. In the latter, the use of different deuteron energies and more than one sample position can provide information on the neutron energy dependence of helium and hydrogen cross sections.

d. The integral helium and hydrogen production cross sections will be used, along with available energy-dependent cross section data, to predict gas production during materials test irradiations. The results of this study would permit the prediction of helium and hydrogen levels in a real fusion reactor environment.

6. Development of Dosimetry Techniques for Use in High-Energy Neutron Fields with Steep Gradients

a. Improved integral measurements of high-energy neutron spectra are needed for long-term irradiations. The helium accumulation technique using selected pure elements should be developed along with radiometric methods (products with long half-lives). Preliminary scoping calculations must be made, using theoretical high-energy cross sections where necessary, to identify a set of elements or isotopes having energy thresholds covering the desired range of neutron energies. Materials must be procured and irradiation tests performed in both T(d,n) and Be(d,n) neutron fields. Results would be compared with previously tested short-lived monitors.

b. High-energy neutron sources are characterized by rapid spatial variations of neutron flux and, in the case of stripping sources, energy spectrum also. These charateristics suggest that track recorders, emulsion and solid-state, might prove valuable for performing absolute measurements with good energy and spatial resolution and good signal-to-noise ratio. They have the potential for providing angular resolutions as well. Appropriate materials should be identified and the technique evaluated.

c. Innovative evaluation of new dosimetry techniques should be encouraged in order to maximize the utility of the limited neutron fields available for fusion materials studies.

7. Development of Standardized Dosimetry Procedures

a. Standardization of multiple-foil dosimetry procedures should follow the establishment of standard reaction cross section sets that adequately characterize the particular environments being used. Interlaboratory reaction rate calibrations should be performed for such cross section sets to assure consistent measurements of foil activities.

b. Standardized procedures should be developed for any dosimetry technique that achieves a recommended status.

c. Minimum standards for reporting dosimetry results should be established. A prime consideration is that the results be reported so completely that they cannot be made obsolete by later revisions in nuclear data, counter efficiencies, etc. Items should include:

- Description of dosimeter materials.
- Identification of nuclear data used (cross section set, half-lives, branching ratios, etc.).
- Counting data and foil disintegration rates at t_0 (end of irradiation).
- Irradiation history, i.e., reactor power levels and beam currents versus time. Pulse characteristics should be carefully described, whether from specimen motion, beam sweeping, intrinsic beam structure, etc.

- Description of dosimetry geometry relative to the specimen and, where applicable, relative to the neutron beam.
- Identification and magnitudes of necessary correction factors.
- Identification of any analysis procedures (SAND-II, SPECTRA, etc.) used in determining flux, fluence, and spectrum in sufficient detail to permit independent evaluation.
- Results and estimates of uncertainties.
- Although not a dosimetry result, the specimen temperature history and how it was determined should be reported.

d. Detailed dosimetry data should be stored in order to facilitate updating and future damage correlation studies.

8. Adaptation of Dosimetry Techniques to Real MFRs

a. Dosimetry methods that have been established for various test environments should be subjected to a paper study to guide their adaptation to the range of spectra characteristic of an MFR. Included must be consideration of the gamma and charged-particle environments. Experiments may be needed to confirm calculated gamma fields.

b. Dosimetry techniques must be tested and refined in an operating MFR.

B. SUBTASK GROUP B: DAMAGE PRODUCTION

The goals of this portion of the program plan include defect production cross sections on the one hand and phenomenological descriptions to aid in designing experimental matrices on the other. The approach is both theoretical and experimental as indicated in Figure 6; in fact, its success will be measured largely in terms of how well theory and experiments can be integrated.

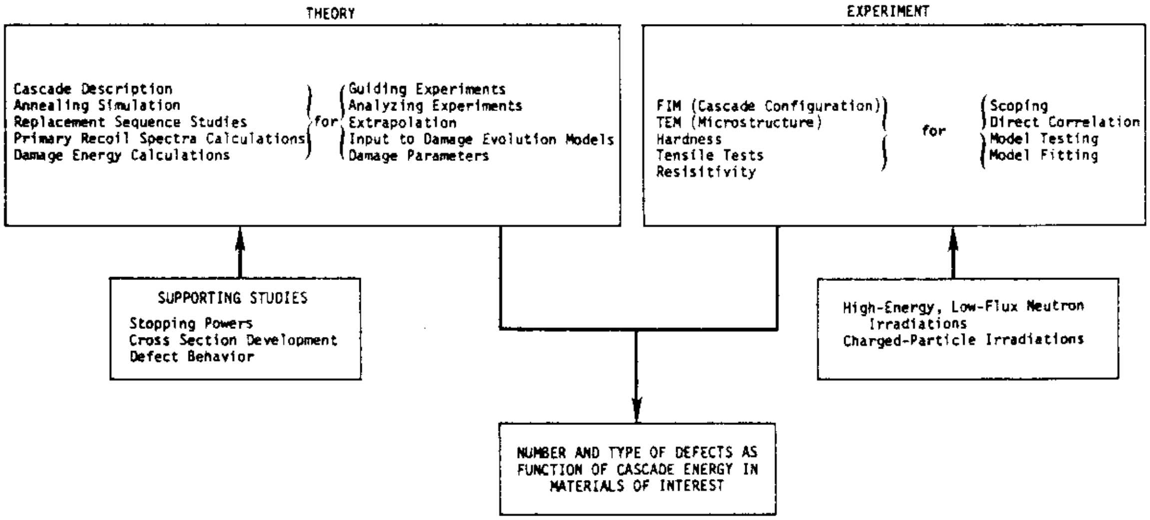

FIGURE 6. The Role of Theory and Experiment in Damage Production Research.

The intended stratgey is as follows. Primary recoil spectra calculations will be extended to neutron energies above 15 MeV as high-energy reaction cross sections are determined. Defect production cross sections are obtained by combining these spectra with functions expressing the dependence of the number of a given type of defect on the primary recoil energy. These functions are to be derived from computer models of cascade production and annealing or inferred from experiment. To have significance, cascade models must be made consistent with experiments in those cases where comparisons can be made.

Both theory and experiments will be used to scope phenomena; among the most important are replacement sequences and intra-cascade loop formation and the factors controlling them. (The recommended time frame for these studies was shown in Figure 4.)

The work needing to be done is outlined below as a series of tasks under each of the three major problem areas described in Chapter III. Each area begins with some suggested sensitivity studies to help define the level of activity needed under the other tasks. To complete the picture, the suggested priorities and levels of effort can be obtained from the milestone charts in Chapter V.

It should be noted that some of the tasks overlap the activities of the Task Group on Plasma Materials Interaction, especially the STG on Physical Sputtering and Neutron Effects.

1. Damage Production Parameters

a. Sensitivity Studies

1) Sensitivity of primary recoil spectra to the underlying nuclear data and to assumptions about the kinematics of nuclear reactions.

2) Sensitivity of materials exposure parameters to the details of the primary recoil spectra.

b. Acquisition of Supporting Nuclear Data (Theoretical and Experimental)

1) Cross sections and secondary particle angular and energy distributions.

a) Neutrons below 15 MeV: These data, directly applicable to an operating fusion system, generally exist but need to be supplemented and reevaluated in some cases.

b) Neutrons above 15 MeV: These data are needed only for materials testing activities using high-energy neutron sources. The data requirements are probably less stringent than at lower energies.

c) Charged particles above $\sim$8 MeV/amu: These data are needed for the interpretation of high-energy ion irradiations.

2) Total cross sections for the production of selected transmutation products--neutron and selected light-ion irradiations.

c. Acquisition of Supporting Atomic Data

1) Electronic stopping data for the light ions H, D, T, and He at particle energies from 100 eV to 30 keV (depending on the plasma temperature).

These data are needed in connection with the effects of stray plasma particles on the confinement vessel. Overlap with the activities of the PMI TG should be noted.

2) Stopping cross sections for particles of masses similar to those of the irradiated material. This will include both recoiling particles of the material (self ions) and transmuted particles produced by nuclear reactions. The data are needed at energies ranging from 100 eV to 1 MeV for recoils from nuclear reactions. Data are also needed at higher energies, up to 100 MeV or more, to improve analyses of heavy ion (that is, more massive than He) irradiations utilized for high-rate damage microstructure studies.

d. Calculation of Primary Recoil Spectra

1) Development of standard methods for evaluating primary recoil spectra and of communicating these to users (for instance, in computerized forms similar to ENDF/B).

2) Evaluations of primary recoil distributions for the materials requested by other TGs. Note that these distributions depend only on having adequate nuclear data, not on the detailed material compositions or on cascade development models.

e. Calculation of Displacement Cross Sections

1) Development of standard methods for evaluating displacement cross sections (or related quantities) and for communicating these to users.

2) Evaluation (and update) of displacement cross sections for materials requested by other TGs and calculations of spectral-averaged values for appropriate fusion device and test environments.

f. Calculation of Defect Production Cross Sections

1) Development of recommended procedures for evaluating cross sections for the production of various classes of defects, e.g., mobile defects escaping from cascades, defect clusters, etc.

2) Evaluation of these cross sections as required for fusion requirements.

g. <u>Evaluation of Transmutation Production in Fusion Test Environments, in Collaboration with STG A (for Neutrons and Energetic Charged Particles)</u>

2. <u>Theoretical Characterization of the Primary Damage State</u>

a. <u>Sensitivity Studies</u>

1) Sensitivity of the primary damage state to assumptions about the electronic stopping of recoils.

2) Comparisons of MD, BCA, and continuum calculations of displacement cascade development, including sensitivities of results to model details.

3) Comparisons of damage production in ideally pure materials and in technologically useful ones.

4) Sensitivity of the primary damage state to the properties of point defects and small clustered defects.

5) Definition of methods for characterizing the primary damage state in insulators. This subtask is only vaguely definable at present. It can be developed clearly only after OFE has better defined its needs for insulating materials.

b. <u>Acquisition of Supporting Atomic and Solid-State Data</u>

1) Cross sections for the stopping of heavy ions by electron excitation and atomic collisions. This is the theoretical counterpart of 1.c.2, above.

2) Dynamic defect properties such as displacement threshold energy surfaces and vacancy capture polyhedra. This area may have both experimental and theoretical components.

c. Cascade Production Methodology

1) Calculations of high-energy displacement cascades by atomistic methods (MD and BCA).

2) Application of transport theory methods to cascade production and sputtering.

3) Calculations of sputtering yields and related quantities.

a) For light-ion (H, D, T, He) irradiations.

b) For self-ion and plasma-impurity-ion irradiations.

d. Defect Property Methodology

1) Conditions for the formation of dislocation loops in single displacement cascades.

2) Theory of the radiation-enhanced mobility of defects, including helium.

3) Application of MD methods to materials with surfaces.

4) Extension of defect calculations to regions of high defect density.

5) Properties of point defects such as formation energies, migration energies, energies of interaction with other defects, for materials and conditions of fusion interest.

6) Properties of mobile and immobile defect aggregates.

3. Experimental Characterization of the Primary Damage State

a. Experimental Methodology

Assessment and comparison of techniques for their applicability to fusion needs.

b. Experimental Characterization of the Primary Damage State

1) Studies of damage produced in charged-particle irradiations using FIM, TEM, and electrical measurements.

2) Studies of damage production at low energies using electrons and thermal neutrons.

3) Studies of particular phenomena such as replacement sequence length, sub-threshold effects, radiation annealing, etc.

4) Studies of creep and post-irradiation property changes under high-energy light-ion bombardment.

5) Studies of high-energy neutron damage including comparisons with fission neutron and ion irradiations. These would include measurements of selected property changes at elevated temperatures.

6) Studies of radiation effects in insulators, including high-energy neutron effects. The analysis of many of these experiments would be carried out jointly with STG C.

4. Damage Production in Insulators

a. Interface with Designers and Other Tasks

Definition of specific types of insulating materials of interest and the design environments in which they would be employed.

b. Develop Theory of Spectral, Rate, and Fluence Effects

Phenomenological descriptions to provide guidance to experiments.

c. Experimental Validation/Calibration of Theory

Perform experiments to permit predictions of material behavior to assist in material selection.

C. SUBTASK GROUP C: DAMAGE MICROSTRUCTURE EVOLUTION AND MECHANICAL BEHAVIOR (Correlation Methodology)

1. Overview

The strategy adopted for meeting the objectives of this STG is shown schematically in Figure 7. It consists broadly of two parallel and interrelated efforts spanning three overlapping time periods. The two efforts are: 1) the development of correlation tools and models, and 2) the development of a data base. The three time periods correspond to a scoping stage, a damage mechanism development stage, and quantitative model development stage.

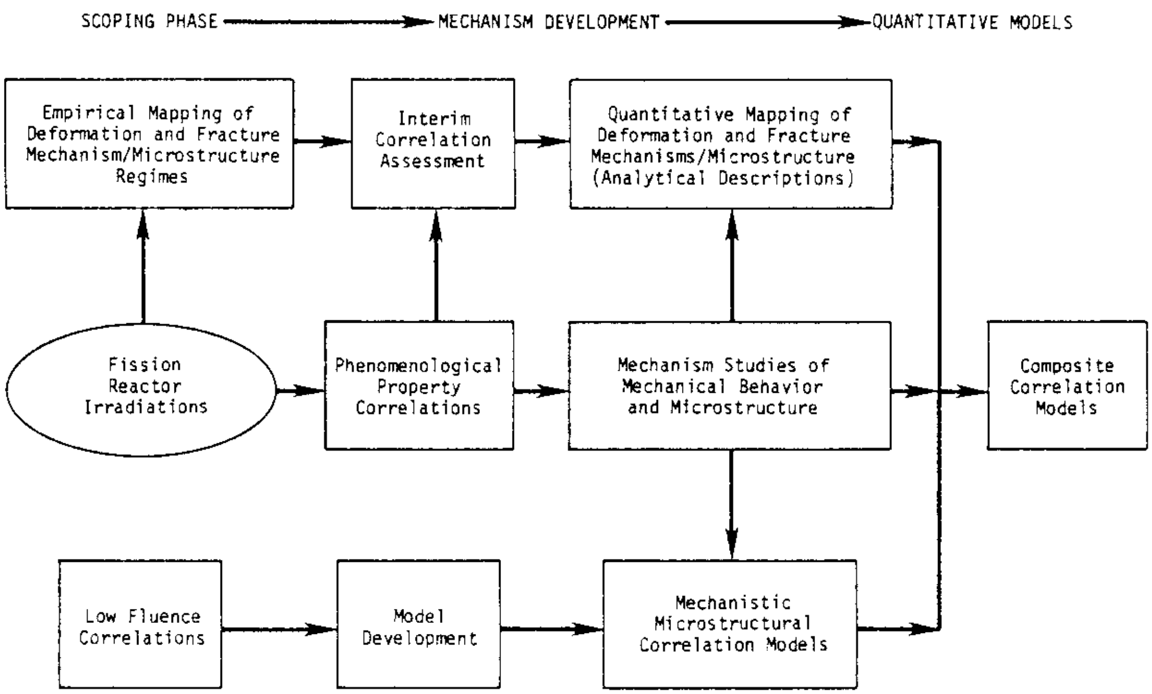

FIGURE 7. Damage Analysis Strategy: Correlation Methodology Overview.

The unifying framework within which this work is to be performed is the concept of deformation-mechanism and fracture-mechanism maps as developed by Ashby and others. The concept is broadened here somewhat to explicitly include microstructural characterization of the mapped regions. It will be important to concentrate on those stress, temperature, strain-rate, rupture time, etc., regimes that are most relevant to MFR first-wall development.

The purpose of employing the mapping methodology is severalfold. It is clearly a means of organizing data and provides a framework for developing quantitative models to fit the data. These models are needed to fill inevitable gaps in the data, to aid in the formulation of experimental matrices, and to project data to design environments. Especially for the last application, it is important that the models be mechanistically-based. The scoping stage of Figure 7 is for the purpose of grossly delineating behavioral and microstructural regimes in irradiation environment space. That is, irradiations would be conducted at a few selected damage rates, exposures, temperatures, stresses, etc. Emphasis would be on relatively high exposures of 10-30 dpa although some very low (<<1 dpa) exposure, high-energy neutron data would be used in correlation model development. Mapping would be largely empirical* and damage correlation phenomenological.** The purpose of the mechanism development stage is to gain an understanding of damage mechanisms and how they are influenced by the irradiation environment. This provides the foundation for developing physically-based analytical models of deformation and fracture--the third stage. The models will generally contain parameters to be adjusted to fit experimental data. Sets of such models, within the context of the deformation and fracture maps, constitute what we have termed "composite correlation models." This stage includes integral experiments using the FMIT to test, refine, and calibrate the composite models.

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*Without regard to mechanisms.

**Qualitative consideration of mechanisms.

2. <u>Materials</u>

The materials to be used in these studies should be representative of the Path A, B, and C alloy classes of the ADIP program. Specific choices would be based on such factors as prior knowledge of mechanical behavior (with and without irradiation), radiation sensitivity, and simplicity. Materials must be identified early in the program to insure their availability in sufficient quantity and their proper pre-irradiation characterization. It has become clear in the breeder program that phase stability is one of the most important considerations in designing radiation-resistant alloys.

Solid solution elements and precipitates strongly influence the mechanical behavior of alloys in the unirradiated condition. Radiation, temperature, and stress, singly or in combination, may cause segregation of alloying elements or the redistribution of precipitates; either phenomenon can have a significant effect on mechanical behavior. It must also be remembered that for MFR irradiations the elements in question may be transmutation products that were not present, or present in different concentrations, prior to irradiation. Initial scoping studies should be undertaken to determine the nature and magnitude of these microstructural changes.

The ADIP TG will, of course, have the major responsibility for resolving phase stability questions. The DAFS effort should be coordinated with the ADIP studies in the selection of relevant alloy compositions and the experimental matrix for correlation studies. The objective should be to display all significant damage mechanisms. The work of the DAFS TG should be in support of the ADIP program and be directed primarily at fundamental mechanisms and models and the problems associated with integrating the mechanisms into composite correlation models.

An important initial effort should be directed towards specimen design, especially miniaturization. Specimen geometry for the various mechanical tests must be established to allow valid comparison of data and development of correlation parameters. This is not a trivial problem considering the small test volumes in available and planned high-energy neutron and charged-particle facilities, the specimen thickness limitations imposed by charged-particle penetration distances, and the general inability to do instrumented tests in reactor irradiations.

3. Damage Microstructure Evolution

Some shift in emphasis of the microstructural studies from earlier work should be noted. Most past efforts have focused on high-exposure, gross-swelling regimes. It is likely, however, that controlling nucleation of damage microstructures or delaying the formation of stable microstructures offers the best hope of developing radiation-resistant alloys; therefore, this program also emphasizes the importance of lower-exposure regimes in which damage microstructures are initially formed. For example, controlling the matrix precipitation of helium in gas bubbles may reduce helium accumulation at grain boundaries. Not only is there substantial evidence that the initial formation of extended defect microstructures is sensitive to variations in critical irradiation parameters, but also that subsequent evolution is often influenced by this initial microstructure. Correlation experiments on nucleation microstructures may utilize relatively low neutron flux sources (1-10 dpa) and low damage rate charged-particle experiments. The utility of such experiments could be substantially enhanced by developing methods of characterizing defect structures in a size range below standard TEM resolution limits.

Radiation-scattering techniques may offer substantial promise in this regard, at least for model materials. High-exposure experiments will, of course, be needed to establish the correlation between high- and low-exposure behavior. Obviously, there is a strong, and we believe desirable, overlap between this STG and the in-reactor deformation STG of the ADIP TG. While the same physical phenomena are involved and experiments will often be common, the focus of the former will be on data analysis and extrapolation, while the latter will be on material parameters and alloy development. Efficient exchange of information concerning damage mechanisms, approaches to developing radiation-resistant alloys, and cooperation on experimental design should result from the Joint ADIP-DAFS STG.

Approaches to solving the specific problems described in Section C of Chapter III will now be discussed. While not always explicitly mentioned, the development of physically-based correlation models is an integral part of these studies.

a. Effect of Helium on Microstructure - Some microstructural influence of helium may be manifested early in an irradiation. This suggests a useful role for both modest-exposure studies and charged-particle simulation studies on neutron pre-irradiated materials. It should be noted that such exposures are generally beyond the maximum practical exposures in high-energy neutron sources limited to fluxes below $\sim 3 \times 10^{13}$ n/cm^2-s (existing Be(d,n), RTNS-II).

Because of the probable importance of interactions between helium and displacement damage, information from experiments with appropriate production rates and helium production-to-displacement ratios is of special value. Hence, the focus for nickel-bearing alloys should be on fast reactor versus mixed-spectrum reactor neutron correlations. A variety of other methods of introducing helium, such as simultaneous injection, pre-doping, and the "tritium trick," may be used for mechanism studies and other non-nickel-bearing alloys. Specific efforts should be directed at correlating data over the range of helium-to-dpa ratios found in fast and mixed-spectrum neutron irradiations of nickel-bearing alloys; and correlating data in all alloy systems of interest, including refractories, irradiated by both charged-particles and neutrons in experiments in which helium has been introduced by various techniques.

A key ancillary effort must be aimed at understanding the distribution and mobility of helium in specimens and the influence of the various means of introducing helium in the material. The most common macroscopic technique for determining helium distributions is α-α scattering. Microscopic techniques such as Secondary Ion Mass Spectrometry (SIMS) or TEM (for bubbles) should be used to look for helium segregation at grain boundaries or at other defects. An important question is the effect of the irradiation environment on helium mobility. Bubble growth, migration of bubbles in stress and temperature gradients, dissolution of bubbles by cascades, and transport of bubbles by dislocation need to be examined.

b. Effect of Hydrogen on Microstructure - Specific experiments and analytical efforts should be directed at predicting hydrogen concentrations in MFRs through hydrogen release and distribution studies, possibly using ion-scattering techniques for the latter. Irradiations should be performed of materials with a variety of initial microstructures, including those due to pre-irradiation, which have been charged with various concentrations of hydrogen. If significant influence of hydrogen is predicted or detected, follow-on studies should be planned with emphasis on mechanical property implications.

c. Effect of Solid Transmutants on Microstructure - The first step is to complete and document work on determining the expected concentrations of elements known to have a potential impact on the microstructure. Of particular concern are possible effects on phase stability and possible segregation to sinks. Specific experiments on doped materials may be warranted if it is not clear that any such effects will be inconsequential relative to other damage mechanisms.

d. Effect of Cycling on Microstructure - Scoping studies of microstructural changes due to radiation, stress, and temperature cycling can be carried out in charged-particle irradiations. Such studies should include consideration of cascade and rate effects so that the results can be extrapolated to neutron conditions. Stress and temperature cycling should be carried out in neutron environments. Data from all experiments should be analyzed mechanistically using damage models. Models including time dependence may be rather complex and need substantial development. Selection of appropriate cycling regimes should be based on preliminary modeling studies. Follow-on studies, both theoretical and experimental, may be needed.

e. Effect of Damage Rate and Cascade Structure on Microstructure - These studies would be closely coupled with the correlation efforts described under problem areas 3.a and 3.d. Charged-particle experiments carried out at very low damage rates to low exposure levels would allow direct assessment of rate effects on microstructure. Different types of charged particles would be used to assess the role of cascades in rate effects.

4. Fundamental Mechanical Behavior

The purpose of this portion of the program is to develop an increased understanding of flow and fracture mechanisms in metals and alloys and the influence of irradiation, including transmutation products, on these mechanisms. The Breeder Reactor Program provides a strong base for swelling and creep of Path A and, to a lesser extent, Path B materials. For most properties and materials, however, current knowledge is very limited, and scoping experiments must be performed to define the problems. These studies are aimed at developing mechanistic models of flow and fracture with the emphasis on incorporating irradiation parameters in the models. The work will utilize recent advances in the field of micromechanics of flow and fracture, particularly with regard to the influence of microstructure. Thus careful characterization of the microstructure will be required to develop the necessary structure-behavior relationships. This approach is essential for meaningful projections of data to MFR conditions and for providing insight for improvement of alloy performance in MFR environments.

As indicated previously, the effort will be oriented around the mapping approach to flow and fracture. Figure 8 illustrates schematically one type of fracture map in which major mechanistic regimes are plotted as a function of normalized stress and homologous temperature. Irradiation can change the regime boundaries, operative mechanisms, and the quantitative response (e.g., strain rate or time-to-failure) within a given regime.

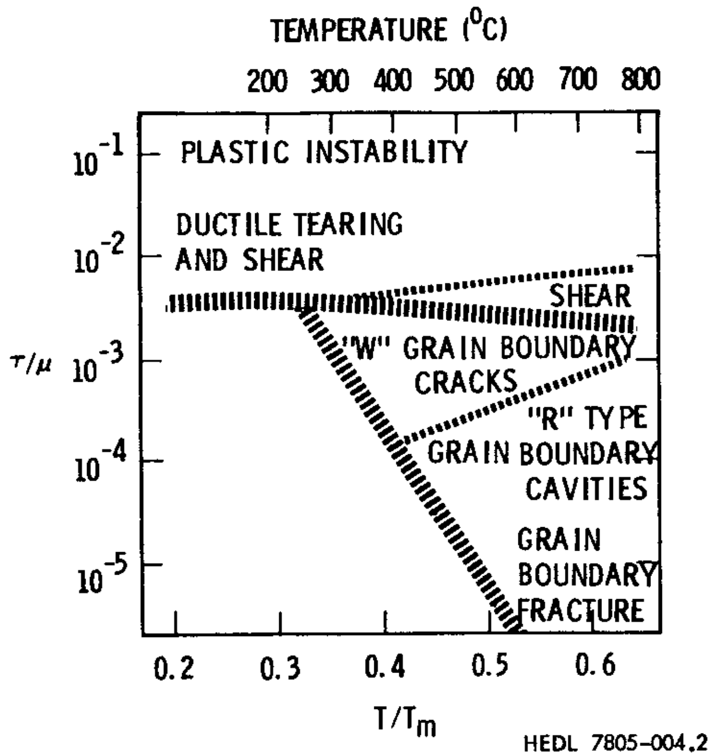


FIGURE 8a. Pre-Irradiation.

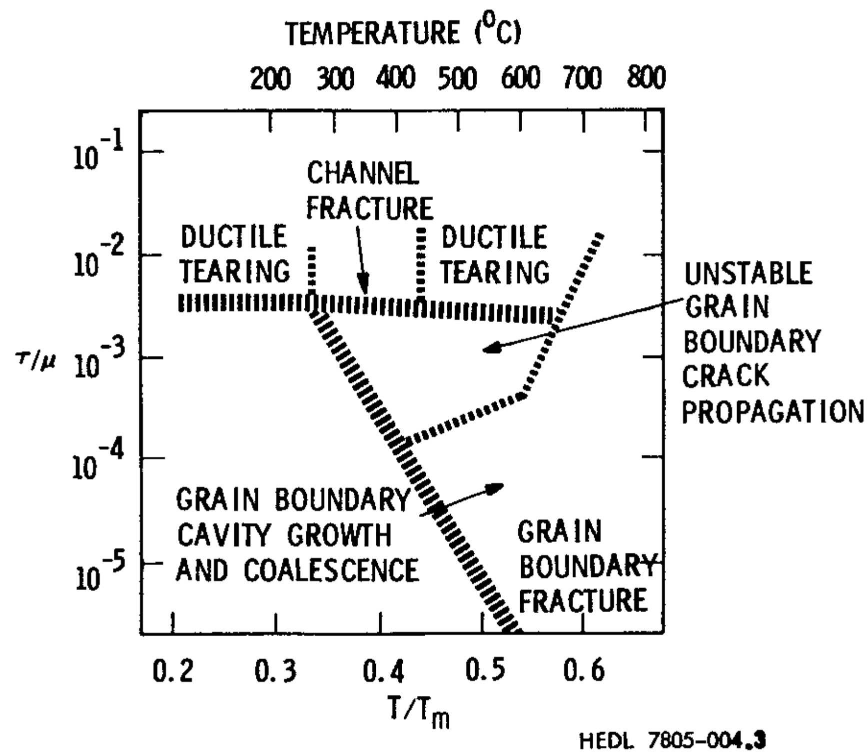


FIGURE 8b. Post-Irradiation [>5 x 10^{22} n/cm^2 (E >0.1 MeV)].

FIGURE 8. An Example of a Fracture Map for Austenitic Stainless Steels. (From M. L. Grossbeck, J. O. Stiegler, and J. J. Holmes, Radiation Effects in Breeder Reactor Structural Materials, M. L. Bleiberg and J. W. Bennett, eds, AIME, 1977.)

The flow and fracture behavior of materials will be affected by the combined set of all the irradiation variables extant in a given environment. Since the sets of variables in available irradiation facilities are not typical of an MFR, it is important to understand both the separate and combined effects of the several variables--especially helium, displacements, cycling, and cascade structure.

We first give a brief description of the proposed approach in terms of the basic damage variables followed by a description in terms of types of tests in available facilities. Implicit in the program is a dual approach to correlation: a direct empirical measurement of mechanical response as a function of the primary variables and parallel development of damage mechanisms to link primary variables to microstructure and microstructure to properties.

a. Damage Variables

1) Effects of Helium and Displacements on Flow and Fracture - A data base exists in the breeder program for the effect of displacing radiation on flow and fracture in Path A and B materials. The effect of the simultaneous, copious production of helium will be determined from experiments in fast (low-helium) and mixed-spectrum (high-helium) reactors for Path A and B materials and, with doping followed by irradiation, for Path C materials. Helium production will affect creep indirectly through its effect on microstructure evolution; however, it may have a direct effect also (enhanced Nabarro-Herring Creep). Most experiments will be done jointly with the ADIP program; the emphasis is on mapping, including microstructure.

Post-irradiation tensile tests are an integral part of these experiments to provide insight into specific damage mechanisms (e.g., dislocation channeling) and to provide standard baseline data.

Fatigue and stress-rupture experiments are to be performed with the objective of defining the degradation of fracture behavior due to combined helium and displacement damage. The relative roles of matrix hardening and grain boundary weakening will be determined, recognizing that helium-induced intergranular fracture is probably not controlled by a single mechanism. Microstructural characterization will be an integral part of this work. (Examination of helium-doping techniques and helium mobility and distribution are covered in paragraph 3.a of this chapter.) It is to be noted that this area of study is one in which environmental variables are not easily separated from material variables such as composition and grain boundary phases (helium-trapping), crystal type (slip modes), grain size, and dislocation density and configuration.

Fracture-mechanism mapping experiments will involve fission neutrons primarily although the feasibility of using charged particles should be carefully examined. The projection from a fission reactor spectrum to a fusion spectrum will be complicated by the difference in the principal sources of helium. For example, if higher concentrations of nickel and boron exist at grain boundaries than in the matrix of a Path A or B material, the fraction of helium produced at the grain boundaries will be higher in fission reactor irradiations than in fusion reactor irradiations. Careful experiments using various doping techniques must be carried out to scope this problem.

In projecting from fission to fusion spectra, and especially in considering the use of charged-particle irradiations for such studies, the possibility of secondary effects of differences in primary recoil spectra on the fracture process (e.g., on helium trapping, grain boundary phases, etc.) should not be overlooked.

2) Effects of Hydrogen and Displacements on Flow and Fracture - Hydrogen embrittlement is generally considered a low-temperature phenomenon. Realistic estimates must be made of the range of hydrogen concentrations to be expected in fusion materials. It is anticipated that scoping studies, with emphasis on the microstructure, will be needed to supplement the literature (paragraph 3.b). If further work is warranted, careful doping with

hydrogen will be necessary since the hydrogen-to-dpa ratio in fission reactor irradiations of all materials of interest is much lower than it would be in a fusion spectrum.

3) Effect of Solid Transmutation Products on Fracture - The first step, microstructural considerations, is covered in paragraph 3.c. As pointed out previously, it is likely that until more radiation-resistant alloys are developed any effects of solid transmutants will be overshadowed by other damage mechanisms. Nevertheless, a low-level program is included to try to avoid surprises at a late stage of alloy development.

4) Effects of Primary Recoil Spectrum and Flux on Flow - The principal problem is to develop a quantitative understanding of the influence of primary recoil spectrum on primary defect production, hence on flow (particularly tensile strength), to assist in projecting fission reactor data to a fusion environment. Effects such as re-solutioning on damage evolution cannot be ignored, however. Light-ion and possibly electron irradiations will be used in conjunction with neutron irradiations to vary the type of cascade. Closely coupled with this work will be supportive damage production calculations since achieving a sound basis for comparison of energetic light-ion and neutron irradiations is not trivial; for electrons, it is even more difficult. Flux effects will be considered simultaneously because varying the primary recoil spectrum at constant flux will generally vary the damage rate.

5) Effects of Cycling on Flow and Fracture - Cyclic effects of flux, temperature, and stress on creep rate, first singly and then in combination, must be determined. Cyclic experiments are probably most easily performed under light-ion irradiation. An additional advantage is that helium concentration can be controlled by doping. However, innovative use of fission reactor facilities should permit stress and temperature cycling and some flux cycling over limited regimes of the variables. In addition, post-irradiation creep tests at high dpa levels can be made with cyclic stress and/or temperature, but the helium-to-dpa ratio must be controlled.

6) Crack Initiation and Propagation - Failure by rapid crack initiation or propagation due to loss of toughness may be an important problem in MFRs. This is certainly anticipated for some Path C alloys and is likely to be true for other materials also. Post-irradiation toughness testing is therefore included in this program with emphasis on the influence of the helium-to-displacement ratio on damage correlation. Advanced test and analysis procedures for small specimens will be required.

7) Model Development - The point has already been made that deformation/fracture mechanism mapping is to provide the framework for integrating the experimental data generated. An important aspect of the program is the development of the analytical models of flow and fracture behavior that permit quantification of the maps. Modeling will build on the results obtained in the Breeder Reactor Program. Early scoping experiments will be aimed at determining how to incorporate helium, cyclic, and cascade effects. Changes in behavior will be related to modifications in the initial microstructure and to radiation-induced changes in the microstructure.

Analytical flow and fracture models will contain adjustable parameters; the need to determine these parameters will provide guidance for experimentation in the fundamental studies area.

b. Test Types - To better specify the operational approach to the program, we now describe a series of test types, the facilities in which they will be carried out, and a brief rationale for the choices. Basically what is described is a series of essentially standard mechanical property tests for materials irradiated in fast and mixed-spectrum reactors which will be carried out in conjunction with the ADIP effort. The focus on technique is intended to facilitate practical understanding of what is proposed; it should not obfuscate the intent of the work, which is to gain an adequate understanding of flow and fracture so that reasonable projections to MFR conditions are possible.

1) Post-Irradiation Tensile Testing - Post-irradiation tensile tests will cover a wide range of temperatures in the high-stress region of Figure 8. While the stresses delineating this flow and fracture region are generally higher than nominal design stresses, hence of limited direct engineering interest, tensile tests are convenient and useful in illuminating basic damage mechanisms. Since microminiature specimen designs are available, it is expected that they will be commonly used in these tests.

Mixed-spectrum reactor/fast reactor comparison studies on nickel-bearing alloys will be used to study He/dpa effects. Similar tests will be carried out for Path C alloys pre-injected with helium. The information gained directly from such tests will be the relative influence of the He/dpa ratio on lattice hardening, plastic instability phenomena such as channel fracture, and local fracture mechanisms. The effect of radiation on tensile flow properties is manifested through the accumulated damage microstructure: void, loop, and bubble dislocation obstacles, altered dislocation structure and density, and precipitate redistribution and phase instabilities. An effort will be made to study tensile properties over the range of microstructures thought to be characterisitic of MFR conditions and to firmly establish the microstructure-property linkages.

A second important role for post-irradiation flow tests will be in developing defect-production parameters through correlations of low-fluence data obtained in various neutron (and/or primary recoil) spectra. (See paragraph B.3.b of this chapter.) Both model and engineering alloys will be used in these studies. Ancillary tests such as flow activation studies may be useful also.

2) Creep Tests - Post-irradiation creep tests (the low-stress, high-temperature region in Figure 8) are of limited value in predicting creep and creep rupture in irradiation environments. The major effort, therefore, will be directed at in-reactor creep tests. Instrumented tests giving both accurate creep strains and time-to-failure are preferred, but they will

clearly need to be supplemented by uninstrumented tests (e.g., pressurized tubes and stress relaxation specimens developed under the breeder program).

Limited in-situ creep measurements using light-ion irradiations will be considered as will high-energy neutron irradiations. These would be aimed at understanding some particular creep mechanism or for defect production studies or both. Some experiments would use neutron pre-irradiated specimens.

Post-irradiation creep studies will be directed at studying individual mechanisms of damage, particularly the effect of grain boundary embrittlement on creep rupture. Tensile specimens will be irradiated to produce a range of He/dpa ratios. Emphasis will be on the range of microstructures anticipated in fusion environments. However, since knowledge of helium mobility and grain boundary nucleation and growth kinetics are so critical to understanding irradiation creep rupture, some experiments with helium-injected, unirradiated specimens will be required.

One creep mechanism for which post-irradiation tests may permit predictions of behavior in an irradiation environment is a form of Nabarro-Herring diffusional creep. This may result when high-temperature swelling is assisted by internal helium pressure in cavities and by an external stress. Post-irradiation experiments could be carried out on specimens containing nearly helium-free cavities and on specimens containing helium-stabilized cavities; the displacement levels and other microstructural features should be similar. Creep rates, creep strains, and time-to-rupture would be measured.

3) Fatigue, Crack Growth, and Creep-Fatigue Interaction - This service regime is characterized by a large number of potentially significant variables. The interactions contributing to the accumulation of microstructural damage which leads to fracture are largely unknown; therefore, an exploratory program will be initiated to scope the dimensions of the problem and to indicate profitable directions for experiments.

Post-irradiation creep-fatigue interaction experiments are expected to have an important place in the program. These would be carried out with a range of He/dpa ratios and appropriate microstructures. Such tests can be used to determine the validity of such approaches to analysis as "life fraction" and "strain partitioning."

If previous experience holds, however, post-irradiation tests alone will not be sufficient and in-situ fatigue and crack-growth experiments will be required. The basic vehicle for such studies will be the Oak Ridge Research Reactor (ORR) and eventually the Fast Flux Test Facility (FFTF) where specimen instrumentation is possible. The exact tests and specimen forms have not been delineated yet; one suggestion is to use flawed, pressurized tubes with loadings (and perhaps temperatures) varied periodically. A high priority should be given to design studies to determine the optimal test type. The results of in-situ and corresponding post-irradiation tests should be compared. These tests will be difficult and expensive and will consume large amounts of irradiation volumes; hence only a limited number will be carried out. Since high helium/dpa ratios are possible only in nickel-bearing alloys, initial emphasis in exploratory studies should be placed on Path A, and, to some extent, Path B alloys.

The possibility of using electron or light-ion irradiations of thin, crack-growth specimens will be explored. Various combinations of cyclic stresses, temperatures, and radiation fluxes could be studied over a limited range of parameters. Of particular concern, in addition to the poor simulation of an MFR environment, is the practical limitation on the number of cycles, and potential problems due to the gradients induced by the finite beam size.

4) Crack Initiation and Propagation Toughness - The resistance to rapid crack propagation leading to failure (in the case of an MFR it is notable that a through-wall leak constitutes failure) of structural components during cooldown phases or under off-normal operating conditions will be

an important design consideration. In principle, post-irradiation measurements of toughness parameters (for the MFR stress state) can provide an adequate basis for the information needed. Major consideration must be given to the kinds of flaws expected to exist due to intrinsic metallurgical defects, surface damage, and in-reactor crack growth. Post-irradiation tests again will make use of irradiations producing a range of He/dpa ratios and appropriate microstructures. However, relatively more emphasis should be placed on the bcc Path C alloys because of their greater intrinsic susceptibility to brittle fracture.

The major difficulty in this effort will be in specimen design since large, plane-strain, fracture specimens are neither practical nor appropriate to the thicknesses characteristic of first-wall designs. An effort to develop and validate appropriate miniaturized toughness specimens (e.g., J-integral tests) will have a high priority. Further, the program should remain open to possible innovative ways of deducing fracture data (e.g., hot hardness and "appropriate" tensile ductility measurements) and advanced ways of analyzing test data (e.g., finite element computer simulation of a test in the elastic-plastic fracture regime).

5. Composite Model Development and Testing

The scoping and mechanism studies described in previous sections should produce improved models for specific damage mechanisms and their dependence on the radiation environment. These elements must be integrated into composite models that parametrically incorporate all the significant damage mechanisms expected in a high-energy, high-flux neutron field. A primary role for the FMIT facility is to validate and calibrate such models.

6. Supporting Studies

a. Microstructural Characterization - Techniques are needed to provide meaningful integral or averaged microstructural data quickly. Potentially useful developments include computer-aided data reduction, improved resolution using advanced TEM techniques, and increased communication between experimentalists and modelers to define more precisely what information is needed and what can be generated at a given cost. Some radiation-scattering methods such as small-angle X-ray scattering and positron annihilation show promise; however, the appropriate utilization of these methods is somewhat controversial and in need of objective assessment.

In addition, experimental and analytical efforts to relate material response to irradiation parameters should include a search for meaningful methods to monitor particular radiation-induced microstructural changes by easily measurable secondary effects; current examples are density changes and step-height measurements to determine macroscopic swellings. If similar techniques can be found to measure other microstructural changes, it will be possible to speed up the rate at which the evolution of important microstructural features is determined.

It is also recommended that microstructural information such as spatial distributions, commonly obtained but not always reported, should be made accessible to damage modeling and correlation efforts, perhaps in the form of a microstructure data bank.

b. Relating High- and Low-Exposure Microstructures - A high priority should be placed on gaining a practical understanding of nucleation as influenced by irradiation parameters. High-resolution microstructural studies can provide direct information on nucleation, while growth regime studies can provide such information indirectly and establish the critical link between nucleation and growth.

Early correlation studies must be aimed at showing whether initial microstructures, established under various irradiation conditions, can be grown to high damage levels at accelerated damage rates to yield approximately the same final structure. If this could be established, the number of long-term experiments might be substantially reduced. Mixed-spectrum reactors are probably most appropriate for the initial irradiation of nickel-bearing alloys. It may be feasible to produce "seed" microstructures in TEM samples for other candidate alloys using high-intensity, high-energy neutron irradiation when such are available. Extension of void growth models to other microstructural features and answers to some current critical questions concerning mechanisms of microstructure growth should provide a sound basis for quantifying the relationship between nucleation microstructures and those which have undergone substantial growth.

c. In-Situ vs Post-Irradiation Fracture Behavior - The applicability of post-irradiation mechanical property measurements is in question. An early comparison between in-reactor tests and post-irradiation tests is needed, especially for stress rupture and fatigue. Current Breeder Reactor Program experiments on pressurized tubes should be used as a starting point. Light-ion bombardment of pre-irradiated specimens is another promising technique. It may be difficult to apply to fatigue studies, however, because of practical limits on number of cycles and on beam size.

d. Effects of Surface Damage on Fracture Behavior - Scoping experiments should be performed to study the effect of near-surface helium on the fatigue life of materials. The effects of blisters and implanted helium without blisters on fatigue life should be compared to the fatigue life without helium and with a uniform distribution of helium. (See paragraph C.4.b.3 of this chapter.) Because near-surface helium is expected to affect fatigue crack initiation and not propagation, experimental emphasis should be on the range of stresses or strains for which fatigue life is crack-initiation limited.

V. TASK DEFINITION

In the following milestone charts, the task number prefixes relate to the three Subtask Groups as follows:

- II.A Environmental Characterization
- II.B Damage Production
- II.C Damage Microstructure Evolution and Mechanical Behavior

Priorities (see introduction to Chapter III) were assigned to the subtasks as follows:

- H Highest priority to achieve major milestones.
- M Necessary to complete major milestone, but less critical.
- D Desirable but not critical.

In Chapter III these priorities were assigned to specific problems. Since several subtasks may address a single problem, the subtask priorities do not always agree with the associated problem priority.

For convenient reference, the subtasks are listed together in Table 2 and their relationships to the major milestones are indicated.

TABLE 2

RELATIONSHIP OF TASKS TO MAJOR MILESTONES

TASKS	MAJOR MILESTONES II-	1 Energy Dependence Gas Production Rate	2 Li(d,n) Dosimetry Methodology	3 MFR Dosimetry Methodology	4 Damage Production in Insulators	5 Defect Production Cross Sections	6 Assess He Production Simulation Methods	7 Assess Hydrogen Effects	8 Interim Correlations for Flow	9 Quantitative Models for He and Displacement on Flow	10 Cyclic Effects on Flow	11 Cascade and Rate Effects on Flow	12 Establish Composite Flow Model	13 Interim Correlations for Fracture	14 Quantitative Models for He and Displacement on Fracture	15 Establish Composite Fracture Model	16 Validate/Calibrate Composite Models
II.A.1	Fission Reactor Dosimetry	X					X		X		X			X			X
II.A.2	High Energy Neutron Dosimetry	X	X	X							X	X					X
II.A.3	Sensitivity Studies	X	X	X		X											
II.A.4	Gas Generation Rates	X	X	X				X		X					X		
II.A.5	Technique Development for Dosimetry Applications		X	X													
II.A.6	Dosimetry Standardization		X	X													
II.A.7	Dosimetry for MFRs			X													
II.B.1	Defect Production Cross Sections				X	X			X	X		X	X	X	X	X	X
II.B.2	Theoretical Primary Damage State				X	X						X					
II.B.3	Experimental Primary Damage State				X	X						X					
II.B.4	Damage Production in Insulators				X	X											
II.C.1	Effects of Material Parameters on Microstructure						X	X		X	X		X		X	X	
II.C.2	Effects of He on Microstructure						X		X	X	X		X	X	X	X	
II.C.3	Effects of H on Microstructure							X		X	X		X		X	X	
II.C.4	Effects of Solid Transmutants on Microstructure									X	X		X		X	X	
II.C.5	Effects of Cycling on Microstructure						X				X		X		X		
II.C.6	Effects of Rate and Cascades on Microstructure						X			X	X	X	X		X	X	
II.C.7	Effects of He and Displacement on Flow						X		X	X	X	X	X				
II.C.8	Effects of He and Displacement on Fracture						X							X	X	X	
II.C.9	Effects of H on Fracture							X						X		X	
II.C.10	Effects of Solid Transmutation Products on Fracture Behavior															X	
II.C.11	Effects of Cascades and Flux on Flow								X	X	X	X	X				
II.C.12	Effects of Cycling on Flow and Fracture										X		X			X	
II.C.13	Effects of He and Displacement on Crack Initiation and Propagation													X	X	X	
II.C.14	Models of Flow and Fracture Under Irradiation						X	X		X	X		X		X	X	
II.C.15	Effect of Near-Surface Damage on Fatigue														X	X	
II.C.16	Composite Correlation Models and Experiments												X			X	X
II.C.17	Microstructural Characterization						X	X				X			X		X
II.C.18	Relating Low- and High-Exposure Microstructures						X			X	X		X		X	X	X
II.C.19	Comparison of in-situ and Post-Irradiation Fracture Behavior							X						X	X	X	

TASK NUMBER: II.A.1

TASK TITLE: Fission Reactor Dosimetry

INPUT TO MAJOR MILESTONE: II-1, 6, 8, 10, 13, 16

Objective: Establish the best practicable dosimetry for mixed-spectrum reactors.

Scope: Includes all mixed-spectrum fission reactors, with or without spectrum tailoring, utilized for fusion materials testing.

SUBTASK NO.	ACTIVITY	PRIORITY	MAN-YEARS FY 78-82	78	79	80	81	82	FUTURE
II.A.1.1	Flux-spectral definition in a tailored fission reactor.	H	3.5		a	b c			
II.A.1.2	Enhance technique.	D	2.5			d,e			
II.A.1.3	Applications.	H	2.4			f	f	f	Continuing

MILESTONES

II.A.1.a Complete neutronics calculations.

II.A.1.b Complete multiple foil irradiations.

II.A.1.c Complete reconciliation of a and b, including uncertainty estimates.

II.A.1.d Complete testing of new reactions.

II.A.1.e Complete methodology development.

II.A.1.f Routine dosimetry.

TASK NUMBER: II.A.2

TASK TITLE: High-Energy Neutron Dosimetry

INPUT TO MAJOR MILESTONE: II-1, 2, 3, 10, 11, 16

Objective: Establish the best practicable dosimetry for high-energy neutron facilities.

Scope: Includes existing and planned T(d,n), Be(d,n), and Li(d,n) facilities.

SUBTASK NO.	ACTIVITY	PRIORITY	MAN-YEARS FY 78-82	78	79	80	81	82	FUTURE
II.A.2.1	Flux-spectral definition in Be(d,n) field.	H	6		a b		c	d	Reevaluation
II.A.2.2	Flux-spectral definition in RTNS-II.	H	2		e	f			Reevaluation
II.A.2.3	Flux-spectral definition in FMIT.	H	3	g	a				Continuing
II.A.2.4	Applications.	H	3			h	h	h	Continuing

MILESTONES

II.A.2.a Assess gamma environment.

II.A.2.b Perform damage parameter sensitivity study to assess dosimetry needs.

II.A.2.c Complete mapping.

II.A.2.d Establish consistent cross section set.

II.A.2.e Validate RTNS-I techniques.

II.A.2.f Complete mapping.

II.A.2.g Review characterization plans.

II.A.2.h Routine dosimetry.

TASK NUMBER: II.A.3

TASK TITLE: Sensitivity Studies

INPUT TO MAJOR MILESTONE: II-1, 2, 3, 5

Objective: To determine sensitivity of calculated damage parameters to uncertainties in neutron flux/spectra.

Scope: Includes all OFE materials radiation test environments.

SUBTASK NO.	ACTIVITY	PRIORITY	MAN-YEARS FY 78-82	78	79	80	81	82	FUTURE
II.A.3.1	Evaluate damage parameter sensitivity to flux/spectra uncertainties.	D	1	a △		b △			
II.A.3.2	Sensitivity studies based on new damage models to define nuclear data requirements.	D	0.5						Continuing

MILESTONES

II.A.3.a Complete initial estimates for application to FMIT.

II.A.3.b Complete study using improved cross sections.

TASK NUMBER: II.A.4

TASK TITLE: Gas Generation Rates

INPUT TO MAJOR MILESTONE: II-1, 2, 3, 7, 9, 14

Objective: To provide helium and hydrogen gas production data for irradiation correlations and MFR applications.

Scope: Includes measurements of production rates and comparisons with calculations for all facilities used for fusion materials testing. Emphasis on helium until need for hydrogen work identified.

SUBTASK NO.	ACTIVITY	PRIORITY	MAN-YEARS FY 78-82	78	79	80	81	82	FUTURE
II.A.4.1	Mixed-spectrum fission reactor.	H	1			a			Continuing
II.A.4.2	T(d,n)	H	2			b		c	Continuing
II.A.4.3	Be(d,n)	H	4			d		e	
II.A.4.4	Li(d,n)	H	0						Check predictions when facility available
II.A.4.5	Establish energy dependence of total He and H production cross sections.	H	1						Continuing

MILESTONES

II.A.4.a Complete first set of ORR measurements.

II.A.4.b Complete RTNS-I analysis.

II.A.4.c Complete corroboration experiment in RTNS-II.

II.A.4.d Complete close-in location measurements in available Be(d,n) source.

II.A.4.e Complete measurements with spectrum varied by changing location and/or deuteron energy.

TASK NUMBER: II.A.5

TASK TITLE: Technique Development for Dosimetry Applications

INPUT TO MAJOR MILESTONE: II-2, 3

Objective: To permit routine measurement of neutron fluence and energy spectra, and their spatial variations, for long-term irradiations in high-energy sources.

Scope: Test new techniques in all facilities used for fusion materials irradiation.

SUBTASK NO.	ACTIVITY	PRIORITY	MAN-YEARS FY 78-82	78	79	80	81	82	FUTURE
II.A.5.1	He accumulation monitor development.	M	2		a b	c	d		Continuing application
II.A.5.2	Track recorder development.	D	3		e	f	g		Continuing application
II.A.5.3	Develop and test new techniques as required.	D	2						Continuing

MILESTONES

II.A.5.a Select reactions.

II.A.5.b Test in T(d,n) field.

II.A.5.c Test in Be(d,n) field.

II.A.5.d Apply to RTNS-II.

II.A.5.e Scoping studies in T(d,n) and Be(d,n) fields.

II.A.5.f Optimize procedures.

II.A.5.g Apply to RTNS-II.

TASK NUMBER: II.A.6

TASK TITLE: Dosimetry Standardization

INPUT TO MAJOR MILESTONE: II-2, 3

Objective: To establish standardized dosimetry procedures in order to reduce uncertainties in damage analysis and correlation studies.

Scope: Establish where necessary and participate in existing interlaboratory calibration programs; promote standardization; establish a dosimetry file.

SUBTASK NO.	ACTIVITY	PRIORITY	MAN-YEARS FY 78-82	78	79	80	81	82	FUTURE
II.A.6.1	Interlaboratory calibration programs.	M	3						Continuing
II.A.6.2	Establish standard reporting procedure.	D	0.4			a			Complete
II.A.6.3	Establish a permanent standard dosimetry file.	M	0.4			b			Continuing
II.A.6.4	Recommend standard dosimetry procedures.	D	0.5			c	d	e	Update

MILESTONES

II.A.6.a Complete and disseminate.

II.A.6.b Begin data storage.

II.A.6.c Recommendation for mixed-spectrum reactors.

II.A.6.d Recommendation for T(d,n) reactors.

II.A.6.e Recommendation for Be(d,n) reactors.

TASK NUMBER: II.A.7

TASK TITLE: MFR Dosimetry

INPUT TO MAJOR MILESTONE: II-3

Objective: Establish accurate dosimetry for MFRs based on techniques developed in test environments.

Scope: Includes experimental and demonstration power reactors and operating commercial reactors.

SUBTASK NO.	ACTIVITY	PRIORITY	MAN-YEARS FY 78-82	78	79	80	81	82	FUTURE
II.A.7.1	Establish preliminary dosimetry procedures for MFR environments.	H	0.05	———	———	———	———	———	Continuing
II.A.7.2	Evaluate effects of predicted gamma and charged-particle environments on MFR dosimetry.	H							To be initiated
II.A.7.3	Test procedures in real MFR environment.	H							To be initiated
II.A.7.4	Optimize procedures.	H							To be initiated

TASK NUMBER: II.B.1

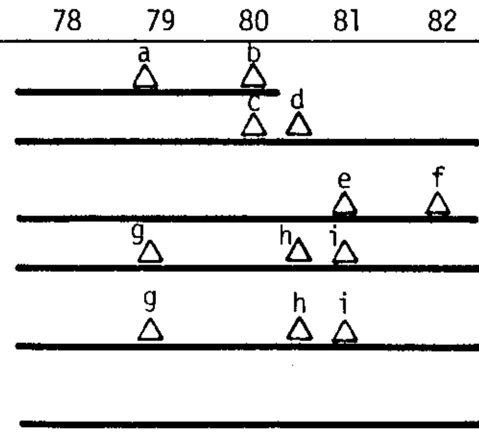
TASK TITLE: Calculation of Defect Production Cross Sections

INPUT TO MAJOR MILESTONE: II-4, 5, 8, 9, 11, 12, 13, 14, 15, 16

Objective: To describe the production of displaced atoms in materials and environments of interest in MFR development.

Scope: Calculate and distribute to users the displacement cross sections needed for MFR neutron and ion irradiations.

SUBTASK NO.	ACTIVITY	PRIORITY	MAN-YEARS FY 78-82	FUTURE
II.B.1.1	Sensitivity studies.	D	1	
II.B.1.2	Acquisition of nuclear data.	H	5	Reevaluation
II.B.1.3	Acquisition of atomic data.	M	5	Continuing
II.B.1.4	Calculation of primary recoil spectra.	H		Reevaluation
II.B.1.5	Calculation of displacement cross sections.	H	2	Reevaluation
II.B.1.6	Calculation of defect production cross sections.	H		Continuing



MILESTONES

II.B.1.a Determine sensitivity of primary recoil spectra to nuclear data and kinematics.

II.B.1.b Determine sensitivity of damage parameters to primary recoil spectra.

II.B.1.c Light-ion cross sections for displacing interactions.

II.B.1.d Neutron cross sections for energies >15 MeV (primarily).

II.B.1.e Electronic stopping cross sections for light ions <30 MeV.

II.B.1.f Stopping cross sections for heavy ions.

TASK NUMBER: II.B.1 (Continued)

MILESTONES

II.B.1.g Standardize calculational methods.

II.B.1.h Calculations for light ions.

II.B.1.i Calculations for neutrons, E >15 MeV (primarily).

TASK NUMBER: II.B.2

TASK TITLE: Theoretical Characterization of the Primary Damage State

INPUT TO MAJOR MILESTONE: II-4, 5, 11

Objective: To develop theoretical descriptions of the production of radiation damage in metals and insulators subjected to MFR environments.

Scope: Atomistic and continuum methods of describing displacement cascade production and short-term annealing in fcc, bcc, and hcp metals; extension to damage mechanisms in insulators.

SUBTASK NO.	ACTIVITY	PRIORITY	MAN-YEARS FY 78-82	78	79	80	81	82	FUTURE
II.B.2.1	Sensitivity studies.	D	5		a	b			Continuing
II.B.2.2	Acquisition of supporting atomic and solid-state data.	M to D	5			c	d		Continuing
II.B.2.3	Cascade production methodology.	H to D	10			e	f, g		Continuing
II.B.2.4	Defect property methodology.	H to D	10				h, i		Continuing

MILESTONES

II.B.2.a Sensitivity of primary damage state to assumptions about electronic stopping.

II.B.2.b Comparison of different kinds of cascade calculations.

II.B.2.c Atomic stopping cross sections.

II.B.2.d Displacement threshold energy surface and vacancy capture polyhedra in fcc metals.

II.B.2.e Development and assessment of continuum theory of cascade development.

II.B.2.f Sputtering yield calculations.

II.B.2.g Atomistic description of cascades over full energy range in fcc metals.

II.B.2.h Assess radiation-enhanced defect mobility.

II.B.2.i Define conditions for loop formation in cascades.

TASK NUMBER: II.B.3

TASK TITLE: Experimental Characterization of the Primary Damage State

INPUT TO MAJOR MILESTONE: II-4, 5, 11

Objective: To experimentally characterize the primary damage state in MFR environments.

Scope: Experimental validation and calibration of theoretical models of the primary damage state.

SUBTASK NO.	ACTIVITY	PRIORITY	MAN-YEARS FY 78-82	78	79	80	81	82	FUTURE
II.B.3.1	Experimental methodology.	D	2		Δ a				Reevaluate
II.B.3.2	Studies of metals.	H to D	8					Δ b	Continuing
II.B.3.3	Studies of insulators.	H to D	3			Δ c			Continuing

MILESTONES

II.B.3.a Complete assessment of techniques.

II.B.3.b Complete simple metals and alloys.

II.B.3.c Define insulator requirements for MFRs.

TASK NUMBER: II.B.4

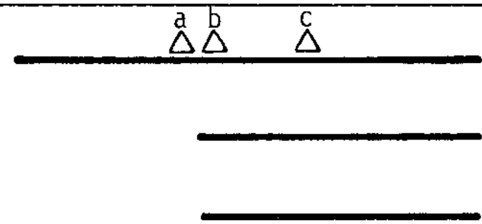
TASK TITLE: Damage Production in Insulators

INPUT TO MAJOR MILESTONE: II-4, 5

Objective: To provide Task Group on Special Purpose Materials with information necessary to evaluate insulating materials for use in radiation fields.

Scope: Theoretical and experimental studies of damage production in specific types of insulating materials subjected to MFR environments.

SUBTASK NO.	ACTIVITY	PRIORITY	MAN-YEARS FY 78-82	78	79	80	81	82	FUTURE
II.B.4.1	Interface with designers and other tasks.	H	2						Continuing
II.B.4.2	Develop theory of spectral, rate, and fluence effects.	H	3						Continuing
II.B.4.3	Experimental validation/ calibration of theory.	H	6						Continuing



MILESTONES

II.B.4.a Define needs.

II.B.4.b Critical survey of materials; recommend course of study.

II.B.4.c Update needs (continuing).

TASK NUMBER: II.C.1

TASK TITLE: Effects of Material Parameters on Microstructure

INPUT TO MAJOR MILESTONE: II-6, 7, 9, 10, 12, 15, 16

Objective: To understand the effect of material parameters, including prior microstructure and composition, and phase stability on damage microstructure evolution.

Scope: Selection of the material matrix for correlation studies will be critical to achieving this objective and must be closely coordinated with the ADIP effort. Fundamental studies, using a variety of radiation sources, will be aimed at elucidating the critical mechanisms of redistribution of chemical constituents and alteration of prior microstructures during irradiation.

SUBTASK NO.	ACTIVITY	PRIORITY	MAN-YEARS FY 78-82	78	79	80	81	82	FUTURE
II.C.1.1	Phase stability mechanism experiments.	H	5	——— a	——— b	———	———	———	Continuing
II.C.1.2	Modeling and analysis.	H	3	———	———	———	———	———	Continuing

MILESTONES

II.C.1.a Initial selection of material matrix for correlation studies.

II.C.1.b Modify material matrix to reflect selection of Path B alloys.

TASK NUMBER: II.C.2

TASK TITLE: Effects of Helium on Microstructure

INPUT TO MAJOR MILESTONE: II-6, 9, 10, 12, 14, 15

Objective: Understand behavior of helium in metals and its effects on microstructure evolution.

Scope: Helium mobility and distribution, with and without stress and radiation; helium effects on microstructure of FeNiCr, refractory, and reactive alloys through variation of He/dpa ratio.

SUBTASK NO.	ACTIVITY	PRIORITY	MAN-YEARS FY 78-82	78	79	80	81	82	FUTURE
II.C.2.1	Mobility, distribution, and bubble nucleation.	H	18						Completed
II.C.2.2	Fast-spectrum/mixed-spectrum correlations for FeNiCr alloys.	H	15		△ a				Completed
II.C.2.3	Charged-particle/neutron correlations for refractory and reactive alloys.	H	15						Completed
II.C.2.4	Modeling	H	6						Continuing

MILESTONES

II.C.2.a Assess implications of spectrum tailoring to vary He/dpa ratio.

TASK NUMBER: II.C.3

TASK TITLE: Effects of Hydrogen on Microstructure

INPUT TO MAJOR MILESTONE: II-7, 9, 10, 12, 14, 15

Objective: Assess effects of hydrogen on microstructure evolution.

Scope: Hydrogen mobility, concentrations, and distribution; irradiation of doped materials (selected for hydrogen sensitivity) if warranted by Subtasks II.C.9.1 and II.C.9.2.

SUBTASK NO.	ACTIVITY	PRIORITY	MAN-YEARS FY 78-82	78	79	80	81	82	FUTURE
II.C.3.1	Mobility and distribution	H	4	▬	▬	▬			Possible follow-on
II.C.3.2	Irradiation of hydrogen-doped alloys.	*	2			▬	▬	▬	Possible follow-on

*See Task II.C.9.

TASK NUMBER: II.C.4

TASK TITLE: Effects of Solid Transmutation Products on Microstructure

INPUT TO MAJOR MILESTONE: II-9, 10, 12, 14, 15

Objective: Understanding the effect of chemical transmutants on damage microstructure.

Scope: Irradiation of transmutant-doped alloys. Follow-on studies, if needed, in conjunction with other Subtask Groups.

SUBTASK NO.	ACTIVITY	PRIORITY	MAN-YEARS FY 78-82	78	79	80	81	82	FUTURE
II.C.4.1	Identify important transmutants and quantify production rates.	M	0.5	———	——— △a				Reevaluation
II.C.4.2	Irradiate selected doped alloys.	M	1.5		———	———	——— △b	———	Reevaluation

MILESTONES

II.C.4.a Assess importance of problem and define critical experiments.

II.C.4.b Interim recommendations to ADIP Task Group.

TASK NUMBER: II.C.5

TASK TITLE: Effects of Cycling on Microstructure

INPUT TO MAJOR MILESTONE: II-6, 10, 12, 15

Objective: Scoping of effects of cyclic variations in stress, temperature, and radiation.

Scope: Assessment of potential effects of irradiation cycling on microstructure evolution. be carried out in accelerated, charged-particle irradiations. Neutron irradiation studies with cycled temperature and stress should be possible in ORR. Coordinate with Task II.C.8.

SUBTASK NO.	ACTIVITY	PRIORITY	MAN-YEARS FY 78-82	78	79	80	81	82	FUTURE
II.C.5.1	Charged-particle scoping studies.	H	6			△a			
II.C.5.2	ORR scoping studies.	H	4			△b			
II.C.5.3	Modeling and analysis.	H	3						

MILESTONES

II.C.5.a Assess effects of radiation cycling on microstructure evolution.

II.C.5.b Assess effects of temperature and stress cycling on microstructure evolution (see II.C.8).

TASK NUMBER: II.C.6

TASK TITLE: Effects of Damage Rate and Cascade Structure on Microstructure

INPUT TO MAJOR MILESTONE: II-6, 9, 10, 11, 12 14, 15

Objective: To understand effects on microstructural evolution of differences in damage rate and displacement damage structure.

Scope: Extend charged-particle irradiations to low damage rates. Analyze data obtained with electrons, ions, and neutrons for evidence of phenomena associated with differences in primary defect production.

SUBTASK NO.	ACTIVITY	PRIORITY	MAN-YEARS FY 78-82	78	79	80	81	82	FUTURE
II.C.6.1	Charged-particle/neutron correlations.	M	8				a		
II.C.6.2	Modeling and analysis	M	2					b	Continuing
II.C.6.3	Low-energy/high-energy neutron correlations.	M	5					c	Continuing

MILESTONES

II.C.6.a Complete rate study.

II.C.6.b Complete interim correlation model incorporating rate and cascade effects.

II.C.6.c Incorporate data from RTNS-II.

TASK NUMBER: II.C.7

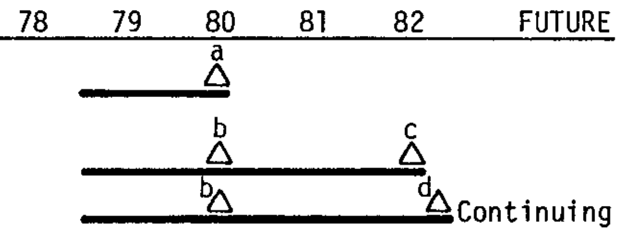
TASK TITLE: Effects of Helium and Displacements on Flow

INPUT TO MAJOR MILESTONE: II-6, 8, 9, 10, 11, 12

Objective: Determine the effects of helium and displacements on flow.

Scope: The influence of helium on creep and tensile flow behavior will be evaluated for representative alloys irradiated in fast and mixed-spectrum reactors. Post-irradiation and in-situ testing will be performed. Limited experiments on helium-injected, unirradiated material may be conducted. Tests under this task will generally be integrated with those under Task II.C.8.

SUBTASK NO.	ACTIVITY	PRIORITY	MAN-YEARS FY 78-82
II.C.7.1	Helium injection experiments.	M	1
II.C.7.2	Post-irradiation testing.	M	3
II.C.7.3	In-situ testing.	H	6



MILESTONES

II.C.7.a Complete scoping study of bubble-assisted creep.

II.C.7.b Complete baseline data for unirradiated Path A, B, and C alloys.

II.C.7.c Complete ORR/EBR-II (FFTF) creep test comparisons.

II.C.7.d Complete initial scoping studies using pressurized tubes.

TASK NUMBER: II.C.8

TASK TITLE: Effects of Helium and Displacements on Fracture

INPUT TO MAJOR MILESTONE: II-6, 13, 14, 15

Objective: Determine the effects of helium and displacements on fracture mechanisms and parameters.

Scope: The influence of helium on fracture behavior will be evaluated for representative alloys irradiated in fast and mixed-spectrum reactors. Post-irradiation and in-situ testing will be performed. Limited experiments on helium-injected, unirradiated material may be conducted to study grain boundary fracture mechanisms. Tests under this task will often be integrated with those under Task II.C.7.

SUBTASK NO.	ACTIVITY	PRIORITY	MAN-YEARS FY 78-82	78	79	80	81	82	FUTURE
II.C.8.1	Helium-injection experiments.	M	3					△a	
II.C.8.2	Post-irradiation testing of ORR and EBR-II specimens.	H	13					△b	Continuing
II.C.8.3	In-situ testing (ORR and FFTF).	H						△c	Continuing

MILESTONES

II.C.8.a Calibrate grain boundary fracture models.

II.C.8.b Complete evaluation of He/dpa effects in representative Path A and B alloys.

II.C.8.c Complete initial scoping study in ORR.

TASK NUMBER: II.C.9

TASK TITLE: Effects of Hydrogen on Fracture

INPUT TO MAJOR MILESTONE: II-7, 13, 15

Objective: Evaluate the potential significance of hydrogen effects in fusion materials.

Scope: Initial effort will be limited to a literature survey and analytical scoping studies.

SUBTASK NO.	ACTIVITY	PRIORITY	MAN-YEARS FY 78-82	78	79	80	81	82	FUTURE
II.C.9.1	Literature search.	H	0.5		a				
II.C.9.2	Analytical study of hydrogen concentrations.	H	0.25			b			
II.C.9.3	Experimental program	?	0.25			c			

MILESTONES

II.C.9.a Summarize data and understanding of elevated temperature mechanical behavior in a hydrogen environment.

II.C.9.b Estimate expected hydrogen concentrations in fusion materials.

II.C.9.c Complete formulation of experimental program (if warranted by Subtasks 9.1 and 9.2).

TASK NUMBER: II.C.10

TASK TITLE: Effects of Solid Transmutation Products on Fracture Behavior

INPUT TO MAJOR MILESTONE: II-15

Objective: Anticipate adverse effects on mechanical behavior caused by transmutation-induced composition changes.

Scope: Predict concentrations and potential effects; perform scoping experiments with doped materials as needed.

SUBTASK NO.	ACTIVITY	PRIORITY	MAN-YEARS FY 78-82	78	79	80	81	82	FUTURE
II.C.10.1	Predict concentrations (see II.C.4).	M	0.5						
II.C.10.2	Evaluate potential effects.	M	4			a		b	

MILESTONES

II.C.10.a Complete for Path A materials.

II.C.10.b Complete for Path B materials.

TASK NUMBER: II.C.11

TASK TITLE: Effects of Cascades and Flux on Flow

INPUT TO MAJOR MILESTONE: II-8, 9, 10, 11, 12

Objective: Determine the effect of cascade structure and flux on irradiation creep rate and flow stress.

Scope: Charged-particle and neutron irradiations will be utilized to determine the effects of cascade structure on irradiation creep rate. The influence of flux on creep rate will be examined. Post-irradiation tensile testing will be performed also. Materials will include Path A, B, and C representative alloys.

SUBTASK NO.	ACTIVITY	PRIORITY	MAN-YEARS FY 78-82	78 79 80 81 82 FUTURE
II.C.11.1	Light-particle irradiations.	M	5	a, b, c
II.C.11.2	High-energy electron* irradiations.	D	1	a, c
II.C.11.3	Fission reactor irradiations.	H	3	a, c
II.C.11.4	High-energy neutron irradiations.	H	8	d, Continuing

MILESTONES

II.C.11.a Complete initial irradiations (probably use 316 SS).

II.C.11.b Complete second particle and additional energies if warranted.

II.C.11.c Complete irradiations.

II.C.11.d Complete RTNS-II and Be(d,n) irradiations (<<1 dpa) if feasible.

*Such a study should be preceded by a critical evaluation of the problem of relating electron irradiation to neutron and ion irradiations.

TASK NUMBER: II.C.12

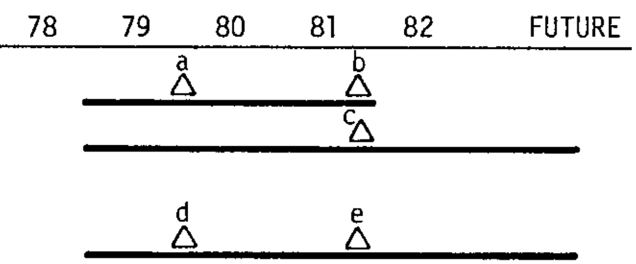
TASK TITLE: Effects of Cycling on Flow and Fracture

INPUT TO MAJOR MILESTONE: II-10, 12, 15

Objective: Determine the effect of cycling of flux, stress, and temperature on flow and fracture.

Scope: Scoping studies using light ions will be made for pulsing of flux, stress, and temperature. Post-irradiation, fatigue-creep interaction studies will be conducted. In-situ tests in ORR and FFTF will be used to study partial cycling phenomena. Path A, B, and C alloy types will be studied.

SUBTASK NO.	ACTIVITY	PRIORITY	MAN-YEARS FY 78-82
II.C.12.1	Light-ion irradiations.	H	4
II.C.12.2	Post-irradiation creep-fatigue tests (ORR and EBR-II irradiations).	H	6
II.C.12.3	In-situ stress and temperature cycling (ORR and FFTF).	H	6



MILESTONES

II.C.12.a Complete assessment of technique.

II.C.12.b Complete scoping study if warranted.

II.C.12.c Complete ORR/EBR-II tests; determine interim correlation procedure for crack growth and creep-fatigue failure.

II.C.12.d Complete design for stress and temperature cycling in ORR.

II.C.12.e Complete initial ORR in-situ test.

TASK NUMBER: II.C.13

TASK TITLE: Effects of Helium and Displacements on Crack Initiation and Propagation

INPUT TO MAJOR MILESTONE: II-13, 14, 15

Objective: Determine the effect of helium and displacement damage on crack initiation and propagation.

Scope: Post-irradiation tests will e conducted on EBR-II and ORR irradiated toughness specimens. Small specimen and test technique development are included in the program. Path A, B, and C alloys will be studied with early emphasis on Path C alloys.

SUBTASK NO.	ACTIVITY	PRIORITY	MAN-YEARS FY 78-82	78	79	80	81	82	FUTURE
II.C.13.1	Method and specimen development.	H	4		———	———	a △ ———	b △	Continuing
II.C.13.2	Comparative	H	8		———	———	c △ ———	d △	Continuing

MILESTONES

II.C.13.a Validate fission reactor procedures.

II.C.13.b Complete development of toughness test for use in high-flux, high-energy neutron facilities.

II.C.13.c Intermediate evaluation of J-integral toughness in Path A, B, and particularly C alloys.

II.C.13.d Complete fission reactor intercorrelation of toughness for a range of He/dpa ratios.

TASK NUMBER: II.C.14

TASK TITLE: Models of Flow and Fracture Under Irradiation

INPUT TO MAJOR MILESTONE: II-6, 7, 9, 10, 12, 14, 15

Objective: Develop mechanistic models for interpretation and extrapolation of in-reactor deformation and fracture behavior.

Scope: Early stages of this effort will be directed toward adapting deformation and fracture models to include features relevant to fusion application. Special emphasis will be placed on spectrum effects, helium effects, and cyclic behavior. Fundamental relationships between microstructure and rate controlling deformation and fracture mechanisms will be established for Path A, B, and C alloys. The flow and fracture mapping approach will be used to structure the research.

SUBTASK NO.	ACTIVITY	PRIORITY	MAN-YEARS FY 78-82	78	79	80	81	82	FUTURE
II.C.14.1	Model development.	H	10		a, b	c		d	Continuing
II.C.14.2	Mechanistic analysis of mechanical and microstructural data through flow and fracture maps.	H	10				e	f	Continuing

MILESTONES

II.C.14.a Complete critical survey of models developed in Breeder Reactor Program.

II.C.14.b Incorporate spectrum effects (interim).

II.C.14.c Incorporate cyclic effects (interim).

II.C.14.d Begin incorporating refinements from other tasks.

II.C.14.e Complete initial EBR-II/ORR mapping study.

II.C.14.f Complete interim model/map correlation.

TASK NUMBER: II.C.15

TASK TITLE: Effect of Near-Surface Damage on Fatigue

INPUT TO MAJOR MILESTONE: II-14, 15

Objective: Determine the effect on fatigue life of large concentrations of helium in the near-surface region and the blisters which result.

Scope: The fatigue life of 316 SS with helium injected into the near-surface region to levels sufficient to produce blisters will be studies at 400-500°C.

SUBTASK NO.	ACTIVITY	PRIORITY	MAN-YEARS FY 78-82	78	79	80	81	82	FUTURE
II.C.15.1	Scoping study.	M	3		a△ b△	c△ d△			

MILESTONES:

II.C.15.a Select specimen configuration.

II.C.15.b Measure fatigue life without helium.

II.C.15.c Measure fatigue life with near-surface helium.

II.C.15.d Measure fatigue life with blisters.

TASK NUMBER: II.C.16

TASK TITLE: Composite Correlation Models and Experiments

INPUT TO MAJOR MILESTONE: II-12, 15, 16

Objective: Develop damage correlation procedures; test and calibrate them in high-energy, high-flux environments and extrapolate to fusion conditions.

Scope: Develop composite models, parametrically inclusive of significant damage mechanisms, to predict microstructural response. Use experiments in high-energy, high-flux environments to verify and calibrate correlation models. Extrapolate test data to fusion conditions with these models.

SUBTASK NO.	ACTIVITY	PRIORITY	MAN-YEARS FY 78-82	78	79	80	81	82	FUTURE
II.C.16.1	Correlation model development.	H	5	———	———	———	———	———	Continuing
II.C.16.2	Experiments in high-energy, high-flux facility.	H	0						When available

TASK NUMBER: II.C.17

TASK TITLE: Microstructural Characterization

INPUT TO MAJOR MILESTONE: II-6, 7, 11, 14, 16

Objective: Assess new means of providing high resolution and/or averaged microstructural data.

Scope: Initial assessment of positron annihilation, radiation scattering, and other promising methods (implementation of STEM assumed). Continuing assessment of new methodologies.

SUBTASK NO.	ACTIVITY	PRIORITY	MAN-YEARS FY 78-82	78	79	80	81	82	FUTURE
II.C.17.1	Monitor and assess new methodologies.	D	2	———	———△ a	———	———	———	———

MILESTONES

II.C.17.a Complete initial assessment.

TASK NUMBER: II.C.18

TASK TITLE: Relating Low- and High-Exposure Microstructures

INPUT TO MAJOR MILESTONE: II-6, 9, 10, 12, 14, 15, 16

Objective: To understand the nucleation of microstructures and the influence of the nucleation microstructure on subsequent growth.

Scope: Relatively low-exposure, charged-particle and neutron irradiation experiments would be used to study nucleation phenomena as influenced by material and irradiation parameters. Preconditioned microstructures would be prepared using a variety of irradiation sources and means of introducing helium. High-exposure irradiations using both fast neutrons and charged particles would be used to grow the seed microstructures.

SUBTASK NO.	ACTIVITY	PRIORITY	MAN-YEARS FY 78-82	78	79	80	81	82	FUTURE
II.C.18.1	Nucleation experiments.	H	8			a			Continuing
II.C.18.2	Growth of preconditioned materials.	H	3			b			Continuing
II.C.18.3	Modeling and analysis.	H	3						Continuing

MILESTONES

II.C.18.a Compare fission and 14 MeV neutron data (RTNS-II).

II.C.18.b Complete pre-irradiations.

TASK NUMBER: II.C.19

TASK TITLE: Comparison of In-Situ and Post-Irradiation Fracture Behavior

INPUT TO MAJOR MILESTONE: II-7, 13, 14, 15

Objective: To evaluate the need for in-reactor fracture testing vis-a-vis post-irradiation testing.

Scope: The fatigue crack-growth rate and creep rupture of 316 SS will be determined at $\sim 0.2\ T_m$ and $\sim 0.4\ T_m$ under in-situ and post-irradiation conditions.

SUBTASK NO.	ACTIVITY	PRIORITY	MAN-YEARS FY 78-82	78	79	80	81	82	FUTURE
II.C.19.1	Irradiate in ORR.	H	3			a			
II.C.19.2	Test irradiated specimens.						b		
II.C.19.3	In-reactor testing.					c	d	e	

MILESTONES

II.C.19.a Complete ORR irradiation.

II.C.19.b Complete post-irradiation testing.

II.C.19.c Complete technique development.

II.C.19.d Initial results of in-situ tests.

II.C.19.e Complete in-situ testing.

GLOSSARY

ADIP	Alloy Development for Irradiation Performance
AMU	Atomic Mass Unit
BCA	Binary Collision Approximation (refers to treatment of a cascade as a series of binary collisions)
CSEWG	Cross Section Evaluation Working Group
DAFS	Damage Analysis and Fundamental Studies
DOE	Department of Energy
EBR-II	Experimental Breeder Reactor - II
ENDF/B	Evaluated Nuclear Data File, Part B
FFTF	Fast Flux Test Facility
FIM	Field Ion Microscopy
FMCC	Fusion Materials Coordinating Committee
FMIT	Fusion Materials Irradiation Test Facility
ILRR	Interlaboratory Reaction Rate Program
MD	Molecular Dynamics (often used synonymously with "dynamic" to refer to an atomistic simulation in which the equations of motion of the atoms of a crystallite are solved simultaneously)
MFR	Magnetic Fusion Reactor
OFE	Office of Fusion Energy
ORR	Oak Ridge Research Reactor
Path A Alloys	Austenitic Steels
Path B Alloys	Fe-Cr-Ni Superalloys
Path C Alloys	Reactive and Refractive Materials and Alloys
RTNS-I & II	Rotating Target Neutron Source - I & II
SIMS	Secondary Ion Mass Spectroscopy
SSTR	Solid-State Track Recorder
STG	Subtask Group
STG-A	Subtask Group A: Environmental Characterization
STG-B	Subtask Group B: Damage Production
STG-C	Subtask Group C: Microstructural Evolution and Mechanical Behavior (Correlation Methodology)
TEM	Transmission Electron Microscopy
TG	Task Group