292
1-6-77
UC-98, htk
plus UK & Germany

MASTER

ERDA-76/146
UC-79B,-H,-K

UNITED STATES LIQUID METAL FAST BREEDER REACTOR PROGRAM

Summary of U.S. LMFBR PROGRAMS on HIGH TEMPERATURE STRUCTURAL DESIGN and ASSOCIATED MATERIALS TESTING OCTOBER 1976

APPLIED TECHNOLOGY

Any further distribution by any holder of this document or of the data therein to third parties representing foreign interests, foreign governments, foreign companies and foreign subsidiaries or foreign divisions of U.S. companies should be coordinated with the Director, Division of Reactor Research and Development, Energy Research and Development Administration.

Over 25 years

This document is
PUBLICLY RELEASABLE
Dave Hamrin
Authorizing Official
Date: 6/15/07

Division of REACTOR DEVELOPMENT and DEMONSTRATION
U.S. ENERGY RESEARCH and DEVELOPMENT ADMINISTRATION

Compiled by OAK RIDGE NATIONAL LABORATORY
Operated by UNION CARBIDE CORPORATION

Released For Announcement in Energy
Research Abstracts. Distribution Limited
to Participants in the LMFBR Program.
Others request from TDS

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Printed in the United States of America. Available from
the Energy Research and Development Administration,
Technical Information Center
P. O. Box 62, Oak Ridge, Tennessee 37830
Price: Printed Copy \$6.00; Microfiche \$3.00

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the Energy Research and Development Administration/United States Nuclear Regulatory Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

ERDA-76/146
UC-79b, -h, -k

UNITED STATES
LIQUID METAL FAST BREEDER REACTOR PROGRAM

SUMMARY OF U.S. LMFBR PROGRAMS
ON HIGH TEMPERATURE STRUCTURAL DESIGN
AND ASSOCIATED MATERIALS TESTING
OCTOBER 1976

Date Published: December 1976

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

DIVISION OF REACTOR DEVELOPMENT AND DEMONSTRATION
U.S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

COMPILED BY OAK RIDGE NATIONAL LABORATORY
OPERATED BY UNION CARBIDE CORPORATION FOR THE
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
(Contract No. W-7405-eng-26)

This document is
PUBLICLY RELEASABLE
Dave Hamrin
Authorizing Official
Date: 6/15/07

Released For Announcement in Energy
Research Abstracts. Distribution Limited
to Participants in the LMFBR Program.
Others request from TIC

0112102
Dense Haze

PREFACE

This document, "Summary of U.S. LMFBR Programs on High Temperature Structural Design and Associated Materials Testing," was prepared at the request of the Division of Reactor Development and Demonstration (DRDD), U.S. Energy Research and Development Administration.

Four general areas of research and development are included:

- A.1 High-Temperature Structural Design
- A.2 Irradiation Effects — Mechanical Properties
of Structural Materials
- A.3 Sodium Environmental Effects — Influence of Sodium on
Mechanical Properties
- A.4 General Material Qualification

Section A.1 was coordinated by J. M. Corum, Manager, High-Temperature Structural Design Program, Division of Engineering Technology, Oak Ridge National Laboratory, and consists of contributions from the following:

- Oak Ridge National Laboratory (ORNL)
- Westinghouse Research and Development Center (WRDC)
- Westinghouse Advanced Reactors Division (WARD)
- Atomics International (AI)
- Battelle Columbus Laboratories (BCL)
- Liquid Metal Engineering Center (LMEC)

Sections A.2, A.3, and A.4 were coordinated by C. R. Brinkman, Group Leader, Mechanical Properties, Engineering Materials Section, Metals and Ceramics Division, Oak Ridge National Laboratory, and consists of contributions from the following:

- Oak Ridge National Laboratory (ORNL)
- Hanford Engineering Development Laboratory (HEDL)
- Naval Research Laboratory (NRL)
- Argonne National Laboratory (ANL)
- Westinghouse Advanced Reactors Division (WARD)
- General Electric Company (GE)
- Westinghouse Electric Corporation-Tampa Division (W-TD)
- Idaho National Engineering Laboratory (INEL)
- University of California Los Angeles (UCLA)
- Combustion Engineering, Inc. (CE)

CONTENTS

<u>Section</u>	<u>Subject</u>	<u>Installation</u>	<u>Page</u>
A.1	High-Temperature Structural Design		1
A.1.1	Development		
A.1.1.1	Constitutive Equations for Inelastic Design Analysis	ORNL	4
A.1.1.2	Structural Tests and Computer-Based Analysis Methods	ORNL	5
A.1.1.3	Design Criteria and Rules for Time-Dependent Deformation and Failure	ORNL	6
A.1.1.4	Simplified Design Methods	ORNL	7
A.1.1.5	Thermal Ratchetting Tests	ORNL	8
A.1.1.6	Design Analysis Methods for Weldments . . .	ORNL	9
A.1.2	Validation		
A.1.2.1	Basic Specimen Testing	WRDC	11
A.1.2.2	Tubular Specimen Testing	WARD	12
A.1.2.3	Structural Testing	WARD	13
A.1.2.4	Nozzle Ratchetting Tests	WARD	14
A.1.2.5	Crack Propagation	WARD	15
A.1.3	Application		
A.1.3.1	Design Criteria and Standards	WARD	16
A.1.3.2	Simplified Inelastic Analysis Methods . . .	WARD	17
A.1.3.3	Computer Program Validation, Implementation, and Distribution	WARD	18
A.1.3.4	Piping Integrity	WARD	19
A.1.4	Piping		
A.1.4.1	Development of Piping Integrity Plan	AI	20
A.1.4.2a	Assess and Catalog Piping Failure Data . . .	AI	21
A.1.4.2b	Survey of Construction Data	AI	22
A.1.4.2c	Analysis of Systems with Prior Successful Operating History	AI	23
A.1.4.3	Sensitivity of Piping Design Margins to Geometric Material and Loading Uncertainties	AI	24
A.1.4.4	Interaction of Steady and High Oscillatory Loads	AI/BCL	25

<u>Section</u>	<u>Subject</u>	<u>Installation</u>	<u>Page</u>
A.1.4.5	Simplified Methods for High-Temperature Piping Analysis	AI/BCL	26
A.1.4.6	Design Methods and Criteria for LMFBR Piping	AI	27
A.1.4.7	Pipe Component Testing	AI/LMEC	28
A.1	Major Test Equipment — High-Temperature Structural Design		29
	Oak Ridge National Laboratory		31
	Westinghouse Research and Development Laboratory		35
	Liquid Metal Engineering Center		37
A.2	Irradiation Effects — Mechanical Properties of Structural Design		39
A.2.1	Tensile and Creep Properties		
A.2.1.1	Determination of the Effect of LMFBR Operating Parameters on the Tensile and Creep-Rupture Properties of Reactor Structural Materials	HEDL	41
A.2.2	Fatigue		
A.2.2.1	Evaluation of Elevated-Temperature Low-Cycle Fatigue and Creep-Fatigue Interaction Behavior of Unirradiated and Irradiated LMFBR Structural Materials	HEDL	42
A.2.2.2	Study Elevated-Temperature Fatigue and Crack Propagation and Plastic Flow of LMFBR Structural Alloys as a Function of Irradiation.	NRL	43
A.2.3	Toughness		
A.2.3.1	Evaluation of the Fracture Toughness Behavior of LMFBR Structural Materials	HEDL	44
A.2.3.2	Study Elevated-Temperature, Elastic-Plastic Toughness of LMFBR Alloys as a Function of Irradiation	NRL	45
A.2	Major Test Equipment — Irradiation Effects — Mechanical Properties of Structural Materials		49
	Hanford Engineering Development Laboratory		50
	Naval Research Laboratory		53

<u>Section</u>	<u>Subject</u>	<u>Installation</u>	<u>Page</u>
A.3	Sodium Environment Effects — Influence of Sodium on Mechanical Properties		55
A.3.1	Creep Properties		
A.3.1.1	Effect of Sodium on the Creep-Rupture Properties of Types 304, 316, and Ti-Modified 316 Stainless Steel	ANL	57
A.3.1.2	Time-Dependent Characteristics of Materials in Sodium	WARD	58
A.3.1.3	Sodium Effects on Annealed 2 1/4 Cr-1 Mo Steel	ORNL	60
A.3.2	Fatigue Properties		
A.3.2.1	Effect of Sodium on the Low-Cycle Fatigue Properties of Normalized and Isothermal- Annealed Fe-2 1/4 Cr-1 Mo Steel	ANL	61
A.3.2.2	Effect of Sodium on the Low-Cycle Fatigue Behavior of Types 304 and 316 Stainless Steel	ANL	62
A.3.3	Tensile Properties		
A.3.3.1	Effect of Sodium Preexposure on the Tensile Properties of Types 304, 316, and Ti-Modified 316 Stainless Steel.	ANL	63
A.3.3.2	Effect of Sodium on the Tensile Properties of Normalized and Isothermal-Annealed Fe-2 1/4 Cr-1 Mo Steel	ANL	64
A.3.4	Alloy 718		
A.3.4.1	Mechanical Property Development for Alloy 718 in Sodium	WARD	65
A.3.5	Carbon Transfer		
A.3.5.1	Validation of Strength Degradation Allowance for Decarburization of 2 1/4 Cr-1 Mo Steel in Sodium	GE	67
A.3.5.2	Study of Mechanical Properties of Carburized Stainless Steel in Sodium	GE	68
A.3	Major Test Equipment — Sodium Environment Effects — Influence of Sodium on Mechanical Properties		69
	Argonne National Laboratory		71
	Westinghouse Advanced Reactors Division		72

<u>Section</u>	<u>Subject</u>	<u>Installation</u>	<u>Page</u>
A.4	General Material Qualification		75
A.4.1	Time-Dependent Properties		
A.4.1.1	Materials Behavior in Support of Development and Evaluation of Flow and Failure Criteria for Materials	ORNL	77
A.4.1.2	Mechanical Property Characterization of Type 304 Stainless Steel Reference Heat .	ORNL	78
A.4.1.3	Mechanical Property Characterization of Type 316 Stainless Steel Reference Heat .	ORNL	80
A.4.1.4	Heat-to-Heat Variation of Mechanical Properties of Types 304 and 316 Stainless Steel and Inconel Alloy 718	ORNL	82
A.4.1.5	Exploratory Mechanical Property Studies of High-Temperature Structural Alloys — Types 304 and 316 Stainless Steel and 2 1/4 Cr-1 Mo Steel	ORNL	83
A.4.1.6	Generation of Long-Term Creep and Stress- Rupture Data for Alloy 800	W-TD	84
A.4.1.7	Determination of Creep and Stress-Rupture Properties of Alloy 718	ORNL/INEL	85
A.4.1.8	Determination of Tensile Properties of Alloy 718	INEL	86
A.4.1.9	The Influence of Prestrain on the Creep Behavior of Type 304 Stainless Steel . .	UCLA	87
A.4.1.10	Tensile Properties of Annealed 2 1/4 Cr-1 Mo Steel for Constitutive Equation Development and Safety Analyses	ORNL	88
A.4.1.11	Creep Properties of Annealed 2 1/4 Cr-1 Mo Steel for Constitutive Equation Development	ORNL	89
A.4.1.12	Creep-Rupture Properties of Annealed 2 1/4 Cr-1 Mo Steel for Design	ORNL	90
A.4.1.13	Heat-Treatment Effects on the Tensile Properties of Annealed 2 1/4 Cr-1 Mo Steel	ORNL	91
A.4.1.14	Heat-to-Heat Variation in the Mechanical Properties of Annealed 2 1/4 Cr-1 Mo Steel	ORNL	92
A.4.1.15	Effect of Thermal Aging on Annealed 2 1/4 Cr-1 Mo Steel	ORNL	93
A.4.1.16	Relaxation Properties of Annealed 2 1/4 Cr-1 Mo Steel	ORNL	94
A.4.1.17	Cyclic Creep of Annealed 2 1/4 Cr-1 Mo Steel for Constitutive Equation Development	ORNL	95

<u>Section</u>	<u>Subject</u>	<u>Installation</u>	<u>Page</u>
A.4.1.18	Multistep Creep Tests on Annealed 2 1/4 Cr-1 Mo Steel for Constitutive Equation Development	ORNL	96
A.4.1.19	Determination of Physical and Elastic Properties of Alloy 718	INEL/ORNL	97
A.4.1.20	Microstructures and High-Temperature Mechanical Properties of 2 1/4 Cr-1 Mo Steel	UCLA	98
A.4.1.21	Complex Uniaxial Materials Behavior Studies	ORNL	99
A.4.1.22	Development of Modified 9 Cr-1 Mo Steel for LMFBR Structural Applications . . .	CE	100
A.4.2	Fatigue Properties		
A.4.2.1	Uniaxial and Biaxial Fatigue and Creep- Fatigue Interaction in 2 1/4 Cr-1 Mo Steel	ORNL	101
A.4.2.2	Evaluation of the Effect of Various Operating Parameters Upon the Fatigue Crack Propagation Behavior of LMFBR Structural Materials	HEDL	102
A.4.2.3	The Effect of Notches on the Low-Cycle Fatigue Behavior of Type 304 Stainless Steel	ANL	103
A.4.2.4	Fatigue Crack Growth Rates in Type 304 Stainless Steel	ANL	104
A.4.2.5	Evaluation of Biaxial Low-Cycle Fatigue Behavior of Metals at Elevated Temperature	ANL	105
A.4.2.6	Investigation of the Effect of Ultrahigh Vacuum and Other Controlled Gaseous Envir- onments on Elevated-Temperature Low-Cycle Fatigue Behavior of Types 304 and 316 Stainless Steel.	ANL	106
A.4.2.7	Determination of Low and High Cycle Fatigue and Creep-Fatigue Interaction Behavior of Alloy 718	INEL	107
A.4.2.8	Characterization of Crack Growth Behavior of 304 Stainless Steel	UCLA	108
A.4.2.9	Corrosion Fatigue of 2 1/4 Cr-1 Mo Steel in DNB Environments	GE	109

<u>Section</u>	<u>Subject</u>	<u>Installation</u>	<u>Page</u>
A.4.3	Weld Metal and Weldment Behavior		
A.4.3.1	Low-Cycle Fatigue and Cyclic Stress-Strain Behavior of 16-8-2 ASA Weld Metal	ANL	110
A.4.3.2	Low-Cycle Fatigue Behavior of Type 308 Stainless Steel Weld Metal	ANL	111
A.4.3.3	Fatigue and Creep-Fatigue Behavior of Transition Joint Pipe Weld Metals and Weldments	ORNL	112
A.4.3.4	Creep and Creep-Rupture Studies of Inconel 82 Weld Metal	ORNL	113
A.4.3.5	Tensile Studies of Inconel 82 Weld Metal	ORNL	114
A.4.3.6	Tensile Properties of Transverse Weldments	ORNL	115
A.4.3.7	Study of the Fracture Toughness Properties of 2 1/4 Cr-1 Mo Steel Heavy Thickness Base Material and Weldments	GE	116
A.4.3.8	Characterization of Welds and Weldments to Provide Data Base for Developing Improved Elevated-Temperature Design Methods	ORNL	117
A.4.4	Large-Diameter Pipe and Fittings		
A.4.4.1	Procure and Characterize Large-Diameter, Thin-Wall Stainless Steel Sodium Coolant Piping and Fittings Materials	ORNL	118
A.4	Major Test Equipment -- General Material Qualification		119
	Oak Ridge National Laboratory		121
	Idaho National Engineering Laboratory		125
	Hanford Engineering Development Laboratory		126
	Argonne National Laboratory		127

A.1 HIGH-TEMPERATURE STRUCTURAL DESIGN

A.1 HIGH-TEMPERATURE STRUCTURAL DESIGN

There are currently four complementary programs with primary emphasis on high-temperature structural design methods and criteria. Three of these deal with development, validation, and application of design analysis methods, design criteria, and design guidelines and procedures. The emphasis in these three programs is on a technology generally applicable to all LMFBR components and on the transfer of that technology to the component designer. Because the application of the technology to the design of high-temperature piping systems presents special problems, the fourth high-temperature structural design program deals exclusively with piping.

Consistent with the primary emphasis of each of the four programs, their titles are:

- High-Temperature Structural Design - Development (A.1.1)
- High-Temperature Structural Design - Validation (A.1.2)
- High-Temperature Structural Design - Application (A.1.3)
- High-Temperature Structural Design - Piping (A.1.4)

The objective of the Development Program is to develop verified high-temperature structural design methods and criteria applicable to LMFBR components and nonreplaceable core structures that operate at temperatures in the creep range, and to make the current technology available in analysis tools and in recognized design codes, RDT Standards, and other appropriate forms for guidance of designers of FFTF, CRBRP, and PLBR systems and components. The objective of the Validation Program is to validate structural design methods and criteria for LMFBR components through a combined analytical and testing effort involving selected specimen configurations and components. The objective of the Application Program is to provide the structural designer with qualified analysis methods, design procedures, design limits and criteria, and the guidance required to assure their proper application. Finally, the objective of the Piping Program is to provide a proven and demonstrated design methodology for assuring a high level of structural integrity for high-temperature piping.

As indicated by the objectives of the four programs, their missions and scopes overlap. However, the activities of the programs are closely coordinated to assure that they are properly integrated and that unnecessary duplication is avoided. Close coordination is also maintained with related on-going materials programs.

The various subtasks of each of the four high-temperature structural design programs are individually outlined on the following pages.

A.1 HIGH-TEMPERATURE STRUCTURAL DESIGN

(A.1.1 Development)

- A. Subject: Constitutive Equations for Inelastic Design Analysis (A.1.1.1)
- B. Laboratory: Oak Ridge National Laboratory
- C. Problem and Objective: The ASME elevated-temperature Code Case 1592 recognizes the likelihood of inelastic material response in criteria for determining the acceptability of stresses and strains. However, detailed inelastic analyses may be required to demonstrate conformance with these criteria, and the code case gives no guidance regarding the techniques and methods to be used in performing these analyses. The objective of this subtask is to develop and verify mathematical descriptions (constitutive equations) of elastic-plastic and creep behaviors of LMFBR structural metals through combined theoretical and experimental investigations. As constitutive equations and guidelines for their implementation are developed, they are placed in RDT Standards, such as F9-5T (Guidelines and Procedures for Design of Nuclear System Components at Elevated Temperatures), for use by LMFBR structural designers.
- D. Scope: Currently, elastic-plastic and creep behaviors are considered separately to the extent possible, followed by consideration of interactions and couplings. Exploratory uniaxial and multiaxial experiments at temperatures up to 593°C (1100°F) are performed in each category, and they generally emphasize cyclic loadings. In the multiaxial experiments, which are performed in specially developed tubular specimen test facilities, nonradial loadings are emphasized. Behavior descriptions are derived for type 304 stainless steel through detailed examinations of a reference heat of material, and their appropriateness for type 316 stainless steel, 2 1/4 Cr-1 Mo steel, and other metals of interest is evaluated by more limited studies.
- E. Time Schedule and Extent of Program: This effort began in late 1969. Interim equations have been recommended, and are being used, for types 304 and 316 stainless steel and for 2 1/4 Cr-1 Mo steel. Presently these recommendations are being verified and improvements made as required. Longer range goals include the development and verification of a more accurate and consistent theory, which accounts for competing softening and hardening mechanisms and in which time is inherent for describing creep and rate-sensitive yielding. Other LMFBR metals will also be considered. The subtask is scheduled to extend through 1983.

A.1 HIGH-TEMPERATURE STRUCTURAL DESIGN

(A.1.1 Development)

- A. Subject: Structural Tests and Computer-Based Analysis Methods (A.1.1.2)
- B. Laboratory: Oak Ridge National Laboratory
- C. Problem and Objective: The development and evaluation of inelastic analysis methods and computer codes is an integral part of the development of high-temperature structural design methods. Analysis methods must be identified and evaluated simultaneously with the development of constitutive equations. Once the material behavior descriptions and analysis methods are available, their validity must be evaluated. This is best done by comparing analysis predictions with the results of carefully selected inelastic structural tests. Thus, the primary objectives of this subtask are, first, to develop, evaluate, and improve computer-based techniques for solving inelastic boundary value problems, and, second, to provide structural test data for evaluating analysis procedures, constitutive equations, and computer codes.
- D. Scope: In the analysis methods area, computer codes and supportive software (pre- and postprocessors) are acquired and/or assembled. These codes are used in-house as research codes and to analyze structural tests; they are also made available to LMFBR design analysts. In the area of inelastic structural testing, structural geometries ranging from the simple to the complex are being investigated. Included are beams, circular plates, rectangular plates with circular holes, shear-lag panels, capped cylindrical shells, elbow-pipe assemblies, nozzle-to-spherical shell attachments, and nozzle-to-cylindrical shell attachments. Test temperatures range up to 649°C (1200°F) for the austenitic stainless steels and up to 556°C (1050°F) for 2 1/4 Cr-1 Mo steel. This subtask also includes the generation of elastic-plastic and creep materials data that are used as input to the inelastic analyses of the structural tests.
- E. Time Schedule and Extent of Program: This effort began in 1970 and is expected to continue through 1982. Four special-purpose elastic-plastic creep computer codes, which employ the recommended constitutive relations, have been acquired and/or developed, and these have been used to analyze structural tests and thereby evaluate current inelastic design analysis methods. To date, some 28 inelastic structural tests have been completed, and special facilities exist for all of the test types except the nozzle-to-cylindrical shell, which is scheduled for testing in the future. Loadings have been both load- and deformation-controlled; they have generally involved short-time load changes superimposed on long-term hold periods; and the average test duration has been about one month. Most of the tests to date have utilized specimens from a special reference heat of type 304 stainless steel. A minimum number of type 316 stainless steel and 2 1/4 Cr-1 Mo steel specimens are now being tested. In the future, specimens of additional materials will be tested and the more complex geometries will be emphasized.

A.1 HIGH-TEMPERATURE STRUCTURAL DESIGN

(A.1.1 Development)

- A. Subject: Design Criteria and Rules for Time-Dependent Deformation and Failure (A.1.1.3)
- B. Laboratory: Oak Ridge National Laboratory
- C. Problem and Objective: The prevention of failure due to excessive cracking and rupture is a major consideration in elevated-temperature design. The need to design for time-varying, multiaxial thermal and mechanical loadings provides the motivation for investigations of low-cycle fatigue, creep rupture, and creep-fatigue damage. Likewise, excessive deformation must be guarded against. Thus ratchetting-type behavior is also a major consideration. A primary objective of this subtask is to assess and develop aspects of design criteria aimed at precluding time-dependent failure and excessive deformation. More generally, the subtask is aimed at supporting the development and evaluation of codes and standards for LMFBR components and nonreplaceable core structures.
- D. Scope: The subtask includes the preparation of interpretive reports that summarize and place in perspective current knowledge on these subjects and suggest courses of action for improving design methods and establishing appropriate data bases. While design data bases are generated in other programs, high-temperature experiments are performed through this program to examine biaxial low-cycle fatigue and to investigate creep rupture and creep damage under uniaxial and multiaxial loadings. Tests are carried out on type 304 stainless steel at temperatures ranging from 538 (1000) to 649°C (1200°F). Tests on other alloys and structural configurations are planned. Design rules in the ASME Code and RDT Standards are assessed, both experimentally and analytically, to establish applicability; current analytical efforts are assessing the impact of material variabilities and uncertainties on intended margins of safety in the codes and standards. We have assembled preliminary criteria for components inside high-temperature reactor vessels (exclusive of fuel pins and ducts) where environmental conditions are most severe. Continuing participation on pertinent ASME Code groups and RDT Standard task forces is maintained.
- E. Time Schedule and Extent of Program: A first interpretive report on creep-fatigue was completed in 1970 and contributed to the identification of experiments for design data generation for type 304 stainless steel. A comprehensive interpretive report on time-dependent fatigue under joint authorship of recognized experts is now being published. Liaison is maintained with, and recommendations are periodically made to, appropriate materials programs charged with generating design data. Biaxial fatigue and creep-fatigue testing of type 304 stainless steel started in 1970 and will continue through 1978; experiments for other materials will continue through 1982. Multiaxial creep-rupture experiments have been underway for two years. Assessment of criteria is to continue through 1983. Development of core structures criteria began in 1970, but the effort has now been reduced to committee participation since completion of a preliminary report recommending design criteria.

A.1 HIGH-TEMPERATURE STRUCTURAL DESIGN(A.1.1 Development)

- A. Subject: Simplified Design Methods (A.1.1.4)
- B. Laboratory: Oak Ridge National Laboratory
- C. Problem and Objective: Detailed inelastic analyses are required to rigorously predict ratchetting and creep-fatigue damage in LMFBR components. However, inelastic analyses can be expensive, and probably more importantly, time consuming. Thus the designer must employ simplified methods of assessing these effects in most routine design applications. Simplified methods are required that are widely applicable and that have been shown to be conservative relative to detailed inelastic analysis assessments. The objective of this subtask is to verify and extend the range of applicability of existing simplified methods, which are frequently overly conservative, and to develop and verify additional, less conservative, methods that minimize the cost and time of design analysis.
- D. Scope: This subtask is being approached in two phases. The goal in the first phase is to extend the range of loadings and geometries over which elastic analyses can be used to conservatively assess ratchetting and creep-fatigue damage. The basic approach is to perform a relatively small number of carefully planned and coordinated detailed inelastic (elastic-plastic-creep) ratchetting-type analyses and damage assessments on geometries ranging from simple cylinders with notches and discontinuities to nozzle-to-sphere and nozzle-to-cylinder geometries with nonaxisymmetric loadings. The various simplified methods are assessed relative to the results of the detailed inelastic analyses. The second phase of the subtask is concerned with the development and verification of less conservative, more economical simplified rules and procedures.
- E. Time Schedule and Extent of Program: This effort was initiated in 1975 and is expected to extend through 1983. The first phase is essentially complete. All of the large and expensive detailed inelastic analyses have been completed, and the results of these will serve as benchmarks for evaluating various simplified methods throughout the duration of the effort. Also, methods have been identified for broadening the range of applicability of existing methods based on elastic analysis results. The second phase will follow with emphasis on simplified inelastic analyses such as bounding techniques, etc.

A.1 HIGH-TEMPERATURE STRUCTURAL DESIGN(A.1.1 Development)

- A. Subject: Thermal Ratchetting Tests (A.1.1.5)
- B. Laboratory: Oak Ridge National Laboratory
- C. Problem and Objective: Many of the structural design problems requiring inelastic analyses in high-temperature LMFBR system components result from the frequent thermal transients that can occur. These thermal transients can produce progressive inelastic deformations (ratchetting) and significant creep-fatigue damage. Questions of the validity of design analysis methods used to predict, or assess, these effects are particularly pertinent. Thus, the objective of this subtask is to provide carefully obtained ratchetting test data for evaluating basic design analysis methods and for verification and qualification of inelastic analysis computer programs by benchmark problem calculations.
- D. Scope. A specially designed and constructed sodium test facility [ORNL Thermal Transient Test Facility (TTTF)] is used to subject relatively simple structural specimens to periodic thermal downshocks (in the internal sodium temperature) separated by sustained periods under internal pressure at temperatures to 593°C (1100°F). Temperature distributions and outside surface strains are recorded during each test, and the measured response is compared to analysis predictions. Although the test facility was designed primarily for testing straight lengths of pipe, and only such specimens have been tested to date, other relatively simple geometries can be accommodated. The subtask includes not only the test effort but also an analysis effort and the generation of appropriate materials data required as input into the analyses.
- E. Time Schedule and Extent of Program: This subtask (including the design and construction of the TTTF) began in 1971 and it is currently scheduled to continue until 1982. Three pipe thermal ratchetting tests have been undertaken to date, with the third test still underway. The first two tests were on straight sections of type 304 stainless steel pipe. The specimen for the third test is a section of 2 1/4 Cr-1 Mo steel pipe welded to a section of type 316 stainless steel pipe. A fourth specimen, which consists of a section of seamless type 316 stainless steel pipe welded to a section of seam-welded type 316 stainless steel pipe, has been fabricated and will be tested immediately after completion of the third test. The duration of each test is several months, and roughly one test is completed each year. Candidates being considered for future test specimens include an additional type 304 stainless steel pipe ratchetting test, pipe ratchetting tests of other metals of interest such as Incoloy 800, a triplex piping transition joint, a precracked piping specimen for crack growth determinations, and a small nozzle attachment model.

A.1 HIGH-TEMPERATURE STRUCTURAL DESIGN

(A.1.1 Development)

- A. Subject: Design Analysis Methods for Weldments (A.1.1.6)
- B. Laboratory: Oak Ridge National Laboratory
- C. Problem and Objective: The mechanical and physical properties of a weldment can differ markedly from those of the surrounding base metal, even when the chemical compositions are similar. Furthermore, properties can vary significantly through the weld metal and heat-affected zone of a single weldment. Because of the scarcity of data and because of the metallurgical and structural complexity of structural weldments, current high-temperature structural design practice does not generally take detailed account of the behavior of the weldments, either in terms of criteria limits or in terms of material behavior representations for structural analysis. The general objective of this subtask is to develop and evaluate more suitable high-temperature structural design methods for weldments through a combined analytical and experimental investigation. The subtask is closely related and coordinated with pertinent activities of other high-temperature structural design and materials programs.
- D. Scope: This subtask, which considers both similar and dissimilar metal welds, has a number of specific objectives:
- to determine the comparative deformation and failure behavior of specific weldments and base metal in specific structural configurations,
 - to identify and evaluate methods for approximately predicting stresses and deformations in such structural weld regions,
 - to establish appropriate criteria (stress and strain limits) commensurate with the level of analysis,
 - to identify and evaluate simplified design procedures, including the use of special stress concentration, strain concentration, and life-reduction factors for weldments,
 - to assess the role of preexisting flaws in weldment behavior.

The test effort includes both exploratory uniaxial materials tests and simple structures tests. In the latter category, creep-rupture tests are being conducted on type 304 stainless steel capped cylindrical shell specimens containing welds in various locations. The specimens are tested to failure under internal pressure at 593°C (1100°F). In addition, uniaxial, in-plane loading tests of flat plates containing welds are included. The emphasis in the latter is on detailed deformation behavior, flaw growth, and failure. Finally, verification

tests will be performed on prototype joints. Analysis effort plans concentrate on detailed analyses which consider the weldment properties only on a fairly gross zone basis. Simplified analysis methods based on elastic analyses are also considered.

- E. Time Schedule and Extent of Program: Although this effort began in 1971 with the initiation of tests on capped cylindrical shell structures containing weldments,* initiation of the main thrust of the subtask has had to await the development of the methodology for base metal and a better understanding of weldment properties. The main thrust of the subtask will be initiated in late 1976, with current plans calling for continuation until 1983.

*To date, six of these tests have been completed, with test times up to more than one year.

A.1 HIGH-TEMPERATURE STRUCTURAL DESIGN(A.1.2 Validation)

- A. Subject: Basic Specimen Testing (A.1.2.1)
- B. Laboratory: Westinghouse Research and Development Center
- C. Problem and Objective: Only a limited amount of creep data are available to characterize the behavior of austenitic stainless steels under nonuniform stress conditions and complex geometry. The objectives of this task are to test and analyze 304 and 316 stainless steel specimens made from reference heats of plate and bar to determine the influence of nonuniform states of stress, welds, and geometric discontinuities on creep behavior. Results will be used to validate constitutive equations and damage factors proposed for describing material behavior.
- D. Scope. Creep tests are being performed at 593°C (1100°F) on four basic specimen designs selected to determine the elastic, plastic, and creep behavior of common design features: (1) uniform section plate under plane stress, (2) uniform section plate under plane strain, (3) uniform section plates with a central hole, and (4) notched bars. Specimens will be made from reference heats of 304 and 316 stainless steel and will include axial and transverse welds in the gage length. Stress levels will be systematically varied, and both monotonic and stepped-loading conditions will be investigated. Strain measurements will be made using extensometers, strain gages, and surface grids with interim photographic measurements. Crack initiation and propagation will also be monitored by interim photography and examination of the test specimens.
- E. Time Schedule and Extent of Program: Approximately 30 specimens from a reference heat of 304 stainless steel have been completed with test durations ranging from 138 to 13,650 hours. Tests are now being performed on a similar number of 316 stainless steel specimens with completion scheduled for late 1977.

A.1 HIGH-TEMPERATURE STRUCTURAL DESIGN(A.1.2 Validation)

- A. Subject: Tubular Specimen Testing (A.1.2.2)
- B. Laboratory: Westinghouse Advanced Reactors Division
- C. Problem and Objective: There are very few test results on the creep behavior of austenitic stainless steel under multiaxial loading conditions. The objective of this task is to test and analyze 304 and 316 stainless steel tubular specimens made from reference heats of material to verify constitutive equations and design criteria for time-dependent material response of shells under multiaxial loading.
- D. Scope: Tests are being conducted on specimens of approximately 22.9-cm (9-in.) length with 0.13 to 0.25-cm (0.05 to 0.1-in.) wall and 4.57 cm (1.8 in.) diameter. Initial tests were under uniaxial loading to provide a comparison with results from other product forms made from the same reference heat of material. Multiaxial loading is induced by a combined axial load and internal pressurization. Constant load and stepped loads are included. Measurements of pressure, temperature, axial strain, and circumferential strain are recorded at sufficient time intervals to describe the behavior during test load changes and test periods. Test specimen measurements are processed to determine equivalent, uniform, and constant values for temperature, pressure, and effective stress, and for radial, circumferential, and axial strains.
- E. Time Schedule and Extent of Program: The test matrix on specimens from a reference heat of 304 stainless steel has been completed, and it included 8 uniaxial specimens, 12 constant-load multiaxial specimens, and 4 stepped-load multiaxial specimens. Test data are being reduced and compared to constitutive equations developed from simple creep tests. Testing of 316 stainless steel material has been started and the test matrix of 13 specimens is scheduled for completion in late 1977.

A.1 HIGH-TEMPERATURE STRUCTURAL DESIGN(A.1.2 Validation)

- A. Subject: Structural Testing (A.1.2.3)
- B. Laboratory: Westinghouse Advanced Reactors Division
- C. Problem and Objective: Structural analysis methods have been developed to predict piping component behavior in LMFBR plants; however, the adequacy of these methods can be assessed only by comparison with experimental results from component tests. The primary objective of this task is to experimentally validate analysis methods and material representation in tests on full-scale LMFBR piping components such as elbows, straight pipe, tees, and reducers.
- D. Scope: A test facility has been designed and constructed to perform creep tests on piping components up to 71.1-cm (28 in.) diameter with temperatures up to 649°C (1200°F), internal pressures up to 4.14 MPa (600 psi), and external force applied by load- or displacement-controlled load actuators. The following tests have been identified using 40.6-cm (16-in.)-diameter elbow test sections:
1. Short-time inelastic response under in-plane bending moment.
 2. Short-time inelastic buckling under in-plane and out-of-plane bending moments.
 3. Creep under in-plane and out-of-plane bending moments.
 4. Creep buckling under in-plane bending moment.

Structural tests on straight pipe, tees, and reducers will be performed after completion of the elbow tests. In addition to the full-scale component test program, a supplementary scale model testing program is planned to provide confirmatory data and to study second-order effects. Test component material will be characterized by small specimen mechanical testing to provide basic material properties for analytical input and test planning.

- E. Time Schedule and Extent of Program: Two tests of 40.6-cm (16-in.)-diam, type 304 stainless steel elbows are scheduled for completion in 1976 with primary emphasis on buckling behavior. Two more 40.6-cm (16-in.)-diam elbow tests are planned for 1977, and the schedule thereafter will be prepared on the basis of the information obtained from the elbow tests.

A.1 HIGH-TEMPERATURE STRUCTURAL DESIGN(A.1.2 Validation)

- A. Subject: Nozzle Ratchetting Tests (A.1.2.4)
- B. Laboratory: Westinghouse Advanced Reactors Division
- C. Problem and Objective: Initial analyses of an LMFBR intermediate heat exchanger inlet nozzle indicated that creep ratchetting strain may exceed ASME Code limits. Subsequently, more detailed and less conservative analysis has shown that the nozzle will not exceed 0.5% strain. The principal objective of this task is to provide a creep ratchetting proof test on a prototypic plant inlet nozzle under worst-case thermal transient conditions. A secondary objective is to obtain and analyze experimental data to validate analytical techniques for design of components subjected to creep ratchetting.
- D. Scope: A shell test section has been fabricated which contains three 16-in.-diam type 304 stainless steel prototypic inlet nozzles and one axisymmetric outlet nozzle in one of the two end closure hemispherical heads. One nozzle will be used for checkout test evaluation and characterization of test facility performance, temperature distribution, and strain measurement techniques. The second nozzle will be used for proof testing, and the third nozzle will be tested at higher temperatures and pressures for validation of analysis methods. Only one nozzle at a time will be subjected to test conditions, the others will be isolated by insulation and the shell section will be long enough to attenuate end effects. Thermal transients will be produced by a high flow rate of argon through the test section which will be at 566 to 649°C (1050 to 1200°F).
- E. Time Schedule and Extent of Program: Checkout testing and proof testing using the first two nozzles is scheduled for completion in 1977. The third shell nozzle will be tested in 1978, and then the shell section will be removed and the hemispherical heads welded together to provide a test section containing an axisymmetric outlet test nozzle that could be tested at pressures up to 4.14 MPa (600 psi) at 649°C (1200°F).

A.1 HIGH-TEMPERATURE STRUCTURAL DESIGN(A.1.2 Validation)

- A. Subject. Crack Propagation (A.1.2.5)
- B. Laboratory: Westinghouse Advanced Reactors Division
- C. Problem and Objective: The objective of this task is to characterize ductile crack propagation behavior in LMFBR piping components with specific emphasis on crack morphology and determination of critical crack sizes.
- D. Scope: Fatigue tests have been performed on 304 stainless steel material in the form of plates and elbows to study crack growth morphology. The aim of this testing is to demonstrate that cracks will penetrate the wall thickness to cause a small detectable leak as opposed to propagating to form a large crack before breaking through the wall to cause massive leakage. Tests have also been performed on model and full-scale plant elbows to define the type and size of crack that will bulge open under plant operating conditions. The behavior of the bulging crack is also of interest because this would determine the flow area for leakage.
- E. Time Schedule and Extent of Program: Fatigue tests and critical crack size studies have been completed in 1976 to provide input to plant safety analyses. Additional testing emphasizing rupture area will be performed in 1977.

A.1 HIGH-TEMPERATURE STRUCTURAL DESIGN(A.1.3 Application)

- A. Subject: Design Criteria and Standards (A.1.3.1)
- B. Laboratory: Westinghouse Advanced Reactors Division
- C. Problem and Objective: Structural design standards used in LMFBR structural design include the ASME Boiler and Pressure Vessel Code Section III, Code Case 1592 for design of Class 1 components at elevated temperatures, RDT Standard F9-4T which provides supplementary requirements to Code Case 1592, and RDT Standard F9-5T which provides interpretations, guidance, and analysis procedures for meeting requirements of F9-4T. These standards are undergoing continuous revision in response to technological advances and the needs of the designer for elevated-temperature applications. The objectives of this task are to assure that LMFBR requirements are reflected in the development of industry standards, and to provide guidance in the use of industry standards through the development of RDT Standards and Guidelines.
- D. Scope: Current work includes revisions to ASME Code Case 1592 to reflect new information on elevated-temperature service, development of a Code Case for Class 2 and 3 components, development of a Code Case for core support structures, development and implementation of design criteria for core components, periodic revisions to RDT Standards to reflect new developments in Code Case 1592, and investigation of new approaches to strain limits and creep-fatigue.
- E. Time Schedule and Extent of Program: The Code Case for Class 2 and 3 components, Code Case for core support structures, and criteria for core components should be completed in 1977. Development of Code Case 1592, modification of RDT Standards, and investigation of strain limits and creep-fatigue are ongoing.

A.1 HIGH-TEMPERATURE STRUCTURAL DESIGN(A.1.3 Application)

- A. Subject: Simplified Inelastic Analysis Methods (A.1.3.2)
- B. Laboratory: Westinghouse Advanced Reactors Division
- C. Problem and Objective: The cost and calendar time required for detailed, time-dependent, inelastic analysis make it impractical for use in routine design analysis. Simplified methods are required for scoping analysis in the early stages of design to provide efficient and realistic means for achieving interaction between design and analysis. Qualified methods are required for inclusion in RDT Standard F9-5 to provide adequate guidance to the designer. The objective of this task is to provide the structural designer with simplified methods, verified experimentally and/or analytically, for predicting the complex response of LMFBR components and satisfying structural design limits.
- D. Scope: Current work is focused on the development of methods for predicting buckling loads in straight pipe and vessels due to axial compression and bending loads, and for predicting buckling of piping elbows due to in-plane bending loads. Future work will include development of methods for bounding creep strains in piping components, application of the reference stress method for predicting creep rupture and creep buckling, and development of simplified procedures for calculating creep-fatigue damage.
- E. Time Schedule and Extent of Program: Development of methods for predicting buckling loads in piping components should be completed in 1978. Development of bounding techniques for creep strains, application of the reference stress method, and development of simplified procedures for creep-fatigue evaluation will be ongoing.

A.1 HIGH-TEMPERATURE STRUCTURAL DESIGN(A.1.3 Application)

- A. Subject: Computer Program Validation, Implementation, and Distribution (A.1.3.3)
- B. Laboratory: Westinghouse Advanced Reactors Division
- C. Problem and Objective: Computer programs have been developed that can model geometry, loading, and material response in great detail. Although they have been well tested on linear elastic analysis, they are relatively untried for the nonlinear problems typical of elevated-temperature design such as time-dependent response to thermal transients, long-time creep deformation, cyclic inelastic loading, thermal ratchetting, and creep buckling. It is necessary to validate these programs by comparison with experimental results and/or other theoretical results, and to provide standardized procedures for their use in the design of LMFBR components. The objectives are to identify computer programs in the public domain of potential use to the LMFBR program, validate the programs to a reasonable level of confidence, implement the programs in a form readily usable by designers, and distribute the programs to LMFBR contractors.
- D. Scope: Current work includes adaptation and verification of selected public domain special-purpose computer programs with emphasis on shell analysis, shell buckling, and pre- and post-processors. Verification of general-purpose computer programs and solution methods is concentrated on the constitutive relations, nonlinear and time-dependent response, and cyclic response. Program scope includes maintenance of reference versions of commonly used programs to assure retrievability of design data.
- E. Time Schedule and Extent of Program: This is an ongoing program.

A.1 HIGH-TEMPERATURE STRUCTURAL DESIGN(A.1.3 Application)

- A. Subject: Piping Integrity (A.1.3.4)
- B. Laboratory: Westinghouse Advanced Reactors Division
- C. Problem and Objective: Assurance of piping integrity is a major requirement in the licensing of LMFBR plants. Although the ASME Boiler and Pressure Vessel Code provides design limits to avoid pipe rupture, the evaluation procedure does not provide quantitative assessment of margins against failure. Nor does the procedure allow assessment based on the size of flaws or cracks that may actually exist at the beginning of service, or that develop during service. The objectives of this task are to assess those aspects of design and construction that affect piping integrity and to develop procedures for the assurance of piping integrity.
- D. Scope: Current work includes identification of national development needs to assure piping integrity, development and application of procedures for predicting crack growth rates under design conditions, and determination of effects of geometrical and material nonuniformities on piping design.
- E. Time Schedule and Extent of Program: Identification of development needs for piping integrity should be completed in 1976. Remaining work is ongoing.

A.1 HIGH-TEMPERATURE STRUCTURAL DESIGN(A.1.4 Piping)

- A. Subject: Development of Piping Integrity Plan (A.1.4.1)
- B. Laboratory: Atomics International
- C. Problem and Objective: Piping reliability is basic to assurance of both a high level of plant availability and protection of the public safety. A carefully developed and coordinated plan is required which identifies those specific tasks required to assure piping integrity for current and future LMFBR plants. The objectives of the Piping Integrity Plan (PIPLAN) are twofold,
- to develop methods and procedures for assuring the structural reliability of piping for FFTF, CRBR, and commercial size LMFBR plants,
 - to provide the data base necessary for a probabilistic assessment of structural integrity of piping for LMFBR plants.
- D. Scope:
1. Obtain inputs from research and engineering organizations knowledgeable in the area of high-temperature design technology as related to piping systems and integrate these inputs into a plan developed by co-chairmen from Atomics International and Westinghouse Advanced Reactors Division.
 2. Update and revise PIPLAN as required.

A.1 HIGH-TEMPERATURE STRUCTURAL DESIGN(A.1.4 Piping)

- A. Subject: Assess and Catalog Piping Failure Data (A.1.4.2a)
- B. Laboratory: Atomics International
- C. Problem and Objective: Information on sodium piping system operation and failures (leaks) necessary to assess LMFBR primary piping integrity is not widely distributed, and no up-to-date collection and compilation of these data exists. This task is to assess and catalog relevant operating experience and failures in piping of SRE, HNPF, Fermi, EBR-II, SCTL, LCTL, and other operating sodium systems and foreign reactors. These data will provide:
- a basis for selecting one or more elevated-temperature piping loops which were designed to a less stringent criteria than Code Case 1592, yet have been operating successfully without failures,
 - support for piping integrity assessments which have taken the position that low-level leakage would precede any large rupture,
 - substantiation for judgmental assumptions, with regard to causes and modes of piping failures which must be made in a probabilistic reliability evaluation of piping.
- D. Scope:
1. Collection, compilation, and categorization of data.
 2. Data sources include facilities in U.S. and in foreign countries.
 3. Failures will be limited to those in piping per se (straight sections, tees, elbows, etc.).
- E. Time Schedule and Extent of Program: An interim report will be published in November 1976, and the final report will be published in August 1977.

A.1 HIGH-TEMPERATURE STRUCTURAL DESIGN(A.1.4 Piping)

- A. Subject: Survey of Construction Data (A.1.4.2b)
- B. Laboratory: Atomics International
- C. Problem and Objective: This activity is required to assess the integrity of LMFBR primary piping. The principal mode of failure of such piping involves leakage from a through-wall crack which is developed by fatigue crack propagation from an initial defect. The likelihood of occurrence of a through-wall crack depends upon the initial defects which are present. This activity will provide the necessary characterization of potential initial defects.
- D. Scope: This investigation will emphasize construction and service experience with sodium piping. However the relevance of LWR experience will be considered and examined to the extent appropriate and practical. Attention must also be given to the question of relevance to LMFBR primary piping in investigating available experience with sodium piping. The scope of this investigation should include sodium test loops at LMEC, Westinghouse ARD, HEDL, and elsewhere, as well as reactors such as Fermi, EBR-II, and FFTF. (The FFTF construction experience will be the most relevant.) Foreign reactors and test loop experience should also be considered.
- E. Time Schedule and Extent of Program: The final report will be published August 1977.

A.1 HIGH-TEMPERATURE STRUCTURAL DESIGN(A.1.4 Piping)

- A. Subject: Analysis of Systems with Prior Successful Operating History
(A.1.4.2c)
- B. Laboratory: Atomics International
- C. Problem and Objective: Service experience with elevated-temperature piping designed to the new rules is very limited, so that the argument that conservatism exists cannot yet be made very strongly on the basis of historical successes. Showing that piping which operated extensively at elevated temperature does not satisfy the current rules would be an alternative way of demonstrating adequacy and conservatism in the new rules. The primary objective of the proposed analysis is to demonstrate that the design rules currently contained in Code Case 1592 are conservative when applied to piping at elevated temperatures.
- D. Scope: Initially, the SNAP 8-ER outlet piping will be analyzed to the elastic and inelastic criteria of Code Case 1592-7. Later, other piping systems with successful operating histories will be selected and evaluated in a similar manner.
- E. Time Schedule and Extent of Program:
- Elastic evaluation SNAP 8-ER — July 1976,
 - Inelastic evaluation SNAP 8-ER — September 1976,
 - Selection of additional piping systems — September 1977,
 - Complete evaluations and final report — September 1978.

A.1 HIGH-TEMPERATURE STRUCTURAL DESIGN(A.1.4 Piping)

- A. Subject: Sensitivity of Piping Design Margins to Geometric Material and Loading Uncertainties (A.1.4.3)
- B. Laboratory: Atomics International
- C. Problem and Objective: The current design practices and the methods for substantiation of piping designs are based on the concepts that that component geometry, material behavior, and the loading are known exactly or as an alternative that they can be characterized conservatively. The problems with this type of design philosophy are that the design variables are not exactly known, and the conservative assumptions may be different for different types of loadings and failure mode assessments. A means of quantitatively assessing the variability of design parameters (geometry, materials, loads) is through a sensitivity evaluation of the major design parameters in light of the elevated-temperature failure modes.
- D. Scope: Evaluations of data uncertainty will be applied to critical piping components such as tees, elbows, and welds.
- E. Time Schedule and Extent of Program:
- Sensitivity plan - June 1976,
 - Interim report, simplified studies - September 1977,
 - Interim report, detailed studies and verification tests - September 1978,
 - Final report, detailed studies, verification tests, safety margin definition - September 1979.

A.1 HIGH-TEMPERATURE STRUCTURAL DESIGN(A.1.4 Piping)

- A. Subject: Interaction of Steady and High Oscillatory Loads (A.1.4.4)
- B. Laboratory: Atomics International/Battelle Columbus Laboratories
- C. Problem and Objective: Vibration sources such as internal noise and fluid oscillations, external mechanical sources such as rotating machinery attached to the pipe, and thermal oscillations such as DNB in superheater tubes could accumulate 10^{12} or more cycles. Although these oscillations may be small and their effects on fatigue life in the sub-creep temperature range may be negligible, the same cannot be concluded for operation in the creep temperature range. The objective of this task is to experimentally evaluate the creep-fatigue damage produced by high cycle, small amplitude oscillations in the presence of sustained stresses in the creep temperature range.
- D. Scope: This task will be initiated by performing tests on 2 1/4 Cr-1 Mo steel specimens in excess of 10^6 cycles with both strain-controlled and load-controlled sustained stress. A base case will be established by extending the fatigue curve 10^6 cycles at zero mean stress. These tests will be at constant amplitude on unnotched specimens. Subsequent testing will be performed on notched specimens and will also consider variable amplitude to identify load-history effects. The testing will be expanded to cover additional materials such as 304 and 316 stainless steel.
- E. Time Schedule and Extent of Program: The interim report on zero mean stress on unnotched tests will be published October 1976, and the interim report on mean stress and variable amplitude tests will be published September 1977.

A.1 HIGH-TEMPERATURE STRUCTURAL DESIGN(A.1.4 Piping)

- A. Subject: Simplified Methods for High-Temperature Piping Analysis
(A.1.4.5)
- B. Laboratory: Atomics International/Battelle Columbus Laboratories
- C. Problem and Objective: The detailed analysis of transient response of complex structures operating in the creep regime is expensive and time consuming. The cost of time-dependent analysis has been found to be an order of magnitude greater than time-independent analysis for LMFBR design conditions; and the calendar time required for detailed analysis makes it impractical for use in routine design analysis. Simplified methods are necessary, especially in the preliminary stages of design, for scoping the effects of design parameters and assessing alternate design configurations. The objective of simplified methods is to approximate complex behavior adequately to assure designs will meet Code limits without time-consuming complex modeling and solution of nonessential detail.
- D. Scope: Simplified methods will be developed both for total piping system analysis to determine location and magnitude of strain accumulation and for analysis of piping components such as elbows, tees, and reducers.
- E. Time Schedule and Extent of Program:
- Interim report, stress indices, PIRAX verification — 1977,
 - Interim report, stress indices, computer programs — 1978,
 - Final report, refined studies, parametric studies — 1979.

A.1 HIGH-TEMPERATURE STRUCTURAL DESIGN(A.1.4 Piping)

- A. Subject: Design Methods and Criteria for LMFBR Piping (A.1.4.6)
- B. Laboratory: Atomics International
- C. Problem and Objective: Very limited detailed guidance is currently available to the elevated-temperature sodium piping designer as to methodology of design. The objective of this task is to provide interpretive reports presenting the methodology for the design of elevated-temperature sodium piping systems. The reports will present practical guidelines for the design and required analysis of LMFBR high-temperature piping systems. Detailed presentation of technical and mathematical derivations, proofs, and formulations will be avoided, but an extensive bibliography and references will be provided.
- D. Scope:
- Initial routing/mathematical modeling,
 - Thermal expansion analysis,
 - Dynamic/seismic analysis,
 - Transient analysis,
 - Inelastic analysis methods,
 - Elastic analysis code evaluations,
 - Inelastic analysis code evaluations,
 - Detailed piping component evaluations.
- E. Time Schedule and Extent of Program: Report preparation will be initiated in September 1977, and first interim report will be issued in September 1978.

A.1 HIGH-TEMPERATURE STRUCTURAL DESIGN

(A.1.4 Piping)

- A. Subject: Pipe Component Testing (A.1.4.7)
- B. Laboratory: Atomics International/Liquid Metal Engineering Center (TTF)
- C. Problem and Objective: The design of piping components including piping supports involves complex geometries and complex loadings, the evaluation of which may require extensive and costly calculations and possibly over-conservative analytical assumptions. The objective of this task is to conduct tests on prototypic piping components to evaluate existing analytical methods and to develop improved analytical methods.
- D. Scope: Prototypic piping components will be subjected to mechanical and thermal loads representative of, or more severe than, those expected in service. Mechanical loading can be by internal pressurization and external mechanical forces. Thermal transients can be imposed simultaneously with mechanical loading by means of a controlled nitrogen gas system. Test articles have not yet been selected.
- E. Time Schedule and Extent of Program: Test article selection in 1976 is planned.

MAJOR TEST EQUIPMENT

A.1 HIGH-TEMPERATURE STRUCTURAL DESIGN

MAJOR TEST EQUIPMENT

A.1 HIGH-TEMPERATURE STRUCTURAL DESIGN

Laboratory: Oak Ridge National Laboratory

- A. Multiaxial Creep Machines (3). These three machines are designed to subject tubular specimens to time-varying histories of combined axial and torsional loads at elevated temperatures for relatively long times to provide guidance in the development of verification of mathematical descriptions (constitutive equations) of material behavior for input to inelastic design analyses.

Each machine consists of a rigid load frame, linear and rotary actuators, water-cooled grips, high-temperature resistance furnace, and thrust/torque load cell. The hydraulic actuators are supplied by accumulators pressurized with bottled nitrogen gas for long-term load stability with minimum energy consumption. Electronic control of load and temperature, conditioning circuits for high-temperature resistance strain gages and differential capacitance strain transducers, and monitoring and recording devices for load, strain, and temperature (thermocouples) are provided. Transition to a state-of-the-art, biaxial strain transducer is under way. Transient load-strain control and a fourth machine are planned.

Test Capabilities.

Maximum thrust, lb	±25,000 and ±10,000
Maximum torque, in.-lb	±12,500 and ±5,000
Maximum displacement, in.	± 3
Maximum rotation, deg	± 90
Maximum temperature, ^a °F	1750
Typical test specimen dimensions, ^b	
mean diameter, in.	1
wall thickness, in.	0.075
gage length, in.	3

- B. Multiaxial Elastic-Plastic-Creep Machines (2). These machines are designed to subject tubular test specimens to combined axial and torsional load histories at elevated temperatures, with particular emphasis on short-time elastic-plastic behavior. The results are used in the development and verification of mathematical descriptions of the behavior of LMFBR structural metals.

^aResistance strain gages are limited to 1000°F; capacitance strain transducers to 1500°F.

^bPresent furnace dimensions, 2 1/2 in. I.D., 10 in. long

Laboratory: Oak Ridge National Laboratory (continued)

Each machine consists of a closed-loop, electrohydraulic test system supplied by MTS. Provision is available on both systems for subjecting specimens to combined axial and torsional loading. In addition, provision is available on one system for subjecting tubular specimens to internal pressurization. Two methods of system control are possible. Conventional function generators are available on both systems and can be used to program standard waveforms. In addition, a unique form of computer control is available which can be used to investigate the most general forms of combined loading and consequent deformation response and yield surface behavior.

To date, most tests have been conducted on tubular specimens with 1.4-in. O.D., 1.25-in. I.D., and 2.25-in. parallel working section length. The axial load capacity of both load frames is 50,000 lb, and the torsional load capacity is 25,000 in.-lb. The maximum axial displacement available is 6 in., and the maximum angular rotation is 100°. Both systems are equipped with parabolic clamshell radiant heaters capable of heating specimens to about 1500°F. The hydraulic actuators are serviced by two hydraulic pumps. A 3 gpm unit is currently used for the bulk of the testing, but a 20 gpm unit is available for tests involving rapid cycling.

- C. Beam and Plate Structural Test Facilities. These two separate facilities are used to provide inelastic structural test data for evaluating design analysis procedures and constitutive equations and to provide benchmark problem data for the verification and qualification of computer programs used in the inelastic structural design of LMFBF components.

Each facility consists of a load frame, a deadweight load control system, a servo-controlled hydraulic system (shared by the two facilities), a furnace, and a temperature control system. The deadweight system is used to provide the load during long-term hold periods in load-controlled tests. The hydraulic system is used to provide the load during transient test conditions, such as load reversals or step-load changes, and during deflection-controlled tests. An MTS controller and a Datatrak programmer are used with the hydraulic system.

The load frames are designed to accommodate 20,000-lb loads. Center deflections of up to 3 in. can be imposed. Transient load conditions of up to 1000 lb/sec have been used. The limit of the furnaces and temperature control systems is 1200°F with a variation from set point of $\pm 5^\circ\text{F}$.

- D. Nozzle-to-Sphere Structural Test Facility. This facility is used to provide inelastic structural test data from nozzle attachment geometries for evaluating design analysis procedures and constitutive equations and to provide benchmark problem data for the verification

Laboratory: Oak Ridge National Laboratory (continued)

and qualification of computer programs used in the inelastic structural design of LMFBR components.

This facility consists of a load frame, two load-controlled systems for providing time-varying loadings, a furnace, and a temperature-control system. The load-controlled systems provide an internal pressure and a bending moment applied to the nozzle. The two loads are independently controlled. A hydraulic system is used for transient moment conditions and deflection tests. A deadweight system is used during long-term hold periods in which the applied moment is maintained constant. Currently the facility is used for room-temperature elastic-plastic tests. The furnace and temperature-control system for high-temperature testing will be added in FY 1977.

The load frame and load-control systems are designed to provide a maximum internal pressure of 1000 psig and a maximum bending moment of 20,000 in.-lb applied to the nozzle. The furnace and temperature-control system are designed to provide a maximum temperature of 1200°F with a maximum variation from set point of $\pm 5^\circ\text{F}$. Typical specimen dimensions are a nozzle outside diameter and thickness of 4.080 and 0.112 in., respectively, and a spherical shell outside diameter and thickness of 24.94 and 0.330 in., respectively.

E. Auxiliary Equipment for A., B., C., and D (above).

Biaxial Creep Machines. Teletype and hook-up to Datum Data Acquisition System described below.

Multiaxial Elastic-Plastic-Creep Machines. The various components of the computer-control system comprise the major part of the auxiliary equipment. The system includes a DEC PDP 8e computer, an RK8 magnetic disk with 1.6 m of total storage, and an ASR-33 teletype. In addition, a T611 scope is available for visual display and a HP 7202-A graphic plotter is available for plotting data. The system uses FOCAL as a language, the necessary software having been developed over the past five years at ORNL.

Beam, Plate, and Nozzle-to-Sphere Structural Test Facilities. Two computer-based data-acquisition systems are used to record data. One system, which was supplied by Datum and is PDP-81 computer based, is capable of scanning, digitizing, and recording signals at a rate of 1000 channels per second. It has 32 channels with a range of ± 5 V and approximately 650 channels with a range of ± 100 mV. The other system is a 9603 Hewlett-Packard system. It consists of 48 channels with a range of ± 10 V and 96 channels with ranges of ± 800 mV and ± 10 mV. The Hewlett-Packard system is capable of recording data signals at a rate of 8000 channels per second. Data from both systems are processed on IBM 360/75 or IBM 360/91 ORNL computers.

Laboratory: Oak Ridge National Laboratory (continued)

- F. Thermal Transient Test Facility (TTTF). The facility is designed to subject a test specimen to internal pressures and intermittent thermal downshocks at high temperatures to produce thermal ratcheting. Test pieces can be subjected to relatively long-term test periods at design temperatures and membrane stress levels, and thermal downshocks up to $30^{\circ}\text{F}/\text{sec}$ for 10 sec duration, starting with sodium temperatures up to 1100°F , can be imposed. Membrane stress levels in the test piece can be varied with the pressure of an inert gas blanket that can be controlled from 0 to 700 psig. The initial test pieces are straight sections of 8-in.-diam pipe.

For the isothermal mode of operation, the sodium system is filled and the source tank, which also acts as the thermal expansion volume, is pressurized with inert gas to obtain the required membrane stress level in the test piece.

To impose the thermal downshock, the sodium in the pipe nest is temperature-graded over the required temperature range, the gas pressure in the source tank is set to attain the required membrane stress in the test piece, and the gas pressure in the storage tank is set at approximately 5 psig. The difference between the gas pressures in the two tanks provides the potential for flowing the temperature-graded sodium through the test piece at the velocity required to obtain the proper thermal transient. The facility can provide a constant flow rate up to 125 gal/min for about 40 sec at 700 psi with the existing flow-control orifice section. For a given total temperature drop, the internal pressure and the thermal downshock rate are related in a fixed manner. With the existing orifices this relation is essentially linear and varies from 700 psig and $30^{\circ}\text{F}/\text{sec}$ to approximately 180 psig and $15^{\circ}\text{F}/\text{sec}$. A cold-trap system, including an electromagnetic pump connected to the storage tank, permits control of the oxide content of the sodium. A shielded enclosure is provided to contain sodium jet spray, resist motion of the piping in case of double-ended rupture, and protect personnel from contacting high-temperature equipment.

The facility is installed in a large building having 50-ft headroom and equipped with a 20-ton traveling bridge crane having a 35-ft lift. There is adequate space on both sides and the front of the facility for test piece installation, facility control, and facility maintenance activities. Exhaust ventilation is provided in case of sodium fires.

The test section of the facility is designed to accommodate 8-in.-diam pipe and also can be made to accommodate various pipe fittings and sodium valves. The test piece is installed into the sodium system by welding it at upstream and downstream ends. An oven, equipped with several heater controls, can maintain the test piece at the required temperature.

MAJOR TEST EQUIPMENT

A.1 HIGH-TEMPERATURE STRUCTURAL DESIGN

Laboratory: Westinghouse Research and Development Center

- A. Basic Specimen Testing. Conventional creep testing equipment is being used for this program with modifications to provide for photography of the specimen at selected time intervals. Creep strains are measured with extensometers and strain gages.
- B. Tubular Specimen Testing. Two types of creep machines are being used in the present investigation: one type of unit is supplied by Applied Test Systems, Inc., and the other by Satec Corporation. The test machines are similar in design, except the Applied Test Systems units have quick-change connections in the alignment couplings and an extra-wide 22-in. load frame. Furnaces and temperature controllers are basically the same in both cases. A split test furnace constructed with three 5-in. zones provides access ports for diametral extensometers at three locations. Electronic Control Systems (ECS) Model 6821 controllers are used for temperature control. These controllers have a sensitivity of 0.2 μ V and stability of 0.01% per $^{\circ}$ C.

Capacitive-type SLVC transducers are used to measure strain. These transducers have a standard accuracy of better than 25 μ in. and excellent stability. In this case, both the axial and diametral extensometers are Inconel 601 alloy of rod and tube construction. They are also equipped with adjustable gaging platforms with provision for mounting the Model 1081 SLVC transducers and micrometer heads for adjustable zero setting. In addition, the SLVC transducers and extensometers are integral parts of the strain-measuring system, thus providing a very mechanically stable arrangement.

- C. Structural Testing. The Multi-Load Test Facility (MLTF) located at ARD is being used for this test program. The major features of this facility are summarized below:
- (a) reaction frame to support the test sections with a load actuator system to provide mechanical loading on a variety of test sections.
 - (b) Sodium supply to provide an excellent heat-transfer medium in the test section, thereby minimizing temperature fluctuations which have a pronounced effect on creep rates in stainless steels at 1100 $^{\circ}$ F.
 - (c) Argon cover gas supply and inerting system whereby the test cubicle would be flooded with argon in the event of a leak.

Laboratory: Westinghouse Research and Development Center (continued)

- (d) instrumentation and control for test-section temperature, internal pressure, external force, displacement, strain measurement; sodium and argon supply system; data acquisition and reduction.

D. Nozzle Ratchetting Tests. The Creep Ratchetting Test Facility (CRTF) has been designed and built for this program. The test facility consists of a reinforced concrete test cell (40 x 25 x 25 ft), a concrete block control room, an equipment storage room, personnel facilities, an electrical equipment room, cryogenic storage, cryogenic high-pressure pumping and vaporization equipment, high-pressure gas storage tubes, and a once-through argon flow test loop. The gas flow rate and pressures are controlled by several pneumatic valves during the test as the gas storage pressure decays. The storage tubes can be recharged to full pressure by the cryogenic vaporization and pumping equipment between transients. The concrete test cell, which will handle gases such as air, argon, nitrogen, helium, and hydrogen, affords approximately 90 lb TNT equivalent blast protection. The adjacent control room for remote test operation provides for visual observation of the test section.

The gas supply system is capable of storing 300,000 standard cubic feet of inert gas at 2400 psig supplied from a cryogenic liquid storage system that has a capacity of 2600 gal and a vaporization rate of 800 standard cubic feet/min to a pressure of 2400 psig. The gas flow control system has been designed to provide a transient capability of up to 4°F/sec in a 16-in. nozzle.

Auxiliary equipment at the facility provides high-speed digital data acquisition, analog data acquisition, 100 kw, 5-zone temperature control system and high-temperature strain-monitoring system.

E. Crack Propagation. Conventional fatigue test equipment with servo-controlled load actuators has been used for the crack morphology studies. A test section is currently being designed to fit into an existing sodium test loop to provide the required capability to perform rupture area tests.

MAJOR TEST EQUIPMENT

A.1 HIGH-TEMPERATURE STRUCTURAL DESIGN

Laboratory: Liquid Metal Engineering Center

- A. Thermal Transient Facility. This facility was originally developed for simulating the thermal transient effects of liquid sodium on LMFBF components and uses computer-controlled, high-velocity nitrogen gas to induce thermal stresses in a wide variety of components.

The use of inert gas instead of molten sodium significantly reduces testing hazards, operation and maintenance costs, system downtime and test article changeover.

This simulation concept increases test system versatility and allows combinations of thermal transients and mechanical prestressing. Testing up to and including failure can be performed safely and with easy access for test article inspection in between testing phases.

The single-pass, gas-blowdown system is designed to supply a pre-programmed flow of inert gas through a thermally preconditioned test component. The facility contains two test bays, each of which is provided with two parallel gas inlets (of different size) to accommodate a range of test flows spanning two orders of magnitude. One of the test bays contains a massive steel support structure equipped with hydraulic jacks and rams which can be used for subjecting test articles to mechanical stress-loading alone, or in conjunction with thermal transient testing.

The system is capable of upramp or downramp transient testing of thermally preconditioned components using variable flow, constant temperature gas. Mechanical loads and moments can be applied to a component in combination with thermal transient testing, thereby simulating structural conditions and thermal stresses that would occur in actual service. Mechanical loading can also be applied separately, without transient testing. The system incorporates flow calibration of gas or (by simulation) liquid flowmeters, relief valves, control valves and other flow-control devices. Control of test parameters and data acquisition are fully automatic and computerized with 250 instrument channels available for pressure, temperature, strain and other measurements.

The system can handle full-size components, sections or models up to 25 x 30 x 30 ft. A 5-ton crane is available; however, with special rigging there is virtually no weight limitation. Typical test components include full-size valves, piping, fitting, pump casings, shafts, impellers, heat-exchanger sections, nozzles, flowmeters, mixing tees, instrument probes, reactor core internals, bellows liners, and finned tubing.

Laboratory: Liquid Metal Engineering Center (continued)

Additional applications include thermal shocking of bimetallic weld joints, thermal shocking of instrumentation ports, ratchetting curve development for nonaxisymmetric structures, and transient effects on seamless versus welded pipe.

Typical thermal transients include the following:

<u>Down Transients</u>	<u>Up Transients</u>
60°F/sec for 5 sec as a typical maximum transient on a 48-in.-pump impeller	11°F/sec for 13 sec as a typical maximum transient on an L-shaped evaporator
0.16°F/sec for 150 sec as a typical minimum transient on a small valve	0.2°F/sec for 150 sec as a typical minimum transient on a small valve

Test article preheat — ambient to 1200°F at 20 to 50°F/hr heat up rate

In addition, 200,000 lb in any direction, 2.8×10^6 ft/lb total combined load, and 20 hydraulic load points are available per test article. Load cycling is available up to 8 cycles/min.

A.2 IRRADIATION EFFECTS — MECHANICAL PROPERTIES
OF STRUCTURAL MATERIALS

A.2 IRRADIATION EFFECTS — MECHANICAL PROPERTIES OF STRUCTURAL MATERIALS

(A.2.1 Tensile and Creep Properties)

- A. Subject: Determination of the Effect of LMFBR Operating Parameters on the Tensile and Creep-Rupture Properties of Reactor Structural Materials (A.2.1.1)
- B. Laboratory: Hanford Engineering Development Laboratory
- C. Problem and Objective: Design, design confirmation, safety analyses, and operations support of LMFBR systems require detailed descriptions of tensile properties and creep-rupture behavior of structural materials used in these systems. Of special significance is the effect of neutron irradiation on these properties. To provide the desired data a series of irradiation experiments are in progress which contain a wide variety of LMFBR structural materials including welds. Data from these experiments will provide necessary mechanical properties information relative to LMFBR operating conditions.
- D. Test Parameters:
- Materials: Annealed types 304 and 316 stainless steel and weldments, Inconel 600, Inconel 718 and weldments, A-286, CF-8, tungsten, TZM, and 2 1/4 Cr-1 Mo steel and welds
- Irradiation Temperatures: 370–650°C
- Neutron Fluences: 10^{21} – 10^{23} neutrons/cm² ($E > 0.1$ MeV)
- Test Temperatures: 22°C and at T_I (Irradiation Temperature)
- Strain Rates: 10^{-5} to 1 sec⁻¹
- E. Time Schedule and Extent of Program:
- Time Schedule: 1973–1985
- Experimental: Approximately 1200 specimens (700 irradiated)

A.2 IRRADIATION EFFECTS — MECHANICAL PROPERTIES
OF MECHANICAL PROPERTIES

(A.2.2 Fatigue)

- A. Subject: Evaluation of Elevated-Temperature Low-Cycle Fatigue and Creep-Fatigue Interaction Behavior of Unirradiated and Irradiated LMFBR Structural Materials (A.2.2.1)
- B. Laboratory: Hanford Engineering Development Laboratory
- C. Problem and Objective: Limited knowledge of the irradiation effects on fatigue properties of materials of interest to LMFBR design preclude reliable prediction of the structural behavior of many components in these systems. The objective of this program is to provide low-cycle fatigue data on irradiated materials for design, safety, and operation support of LMFBR's.
- D. Test Parameters:
- Materials: 20% CW type 316 stainless steel, Alloy 718, annealed types 304 and 316 stainless steel
- Temperature: 425–650°C
- Total Strain Ranges: 0.5–2.0%
- Neutron Fluences: 10^{21} – 10^{23} neutrons/cm² (E > 0.1 MeV)
- Irradiation Temperatures: 425–650°C
- E. Time Schedule and Extent of Program:
- Testing Period: 1976–1985
- Experimental: Approximately 200 specimens (120 irradiated)

A.2 IRRADIATION EFFECTS — MECHANICAL PROPERTIES
OF STRUCTURAL MATERIALS

(A.2.2 Fatigue)

A. Subject: Study of Elevated-Temperature Fatigue and Crack Propagation, and Plastic Flow of LMFBR Structural Alloys as a Function of Irradiation (A.2.2.2)

B. Laboratory: Naval Research Laboratory

C. Problem and Objective: Determine effects of high-temperature and fast neutron irradiation on the plastic flow and fatigue crack propagation of high-temperature metals. Assess influence of alloy history and composition on deformation substructure and fracture behavior developed by fatigue and creep-fatigue crack propagation in EBR-II irradiated alloys.

D. Test Parameters:

Materials: Types 304 and 316 stainless steel, Inconel Alloy 718, Inconel Alloy 600, Inconel Alloy 625, Inconel Alloy X-750, Nimonic PE-16, and welds of these alloys

Irradiation Temperatures: 427–650°C

Neutron Fluence: 10^{21} – 10^{23} neutrons/cm² ($E > 0.1$ MeV)

Specimen Type: Compact-tension fatigue, single-edge-notch fatigue, and uniaxial tensile

Loading Rate: static and cyclic

Cyclic Frequency: 0, 0.91, 5, 10 cpm

E. Time Schedule and Extent of Program:

Main Test Phase: 1975–1980

Experimental: Approximately 160 irradiated specimens

A.2 IRRADIATION EFFECTS — MECHANICAL PROPERTIES
OF STRUCTURAL MATERIALS

(A.2.3 Toughness)

- A. Subject: Evaluation of the Fracture Toughness Behavior of LMFBR Structural Materials (A.2.3.1)
- B. Laboratory: Hanford Engineering Development Laboratory
- C. Problem and Objective: The degradation in the fracture toughness response of LMFBR structural alloys resulting from exposure to neutron irradiation needs to be incorporated into a fracture control plan that accurately predicts structural failure. Consequently, the objective of this investigation is to characterize the ductile fracture toughness (J_{IC}) behavior of unirradiated and irradiated LMFBR structural materials^c for the design, safety analysis, and operations support of LMFBR systems.
- D. Test Parameters:

Materials: Austenitic steels (type 304 stainless steel base metal and weldments,^a type 316 stainless steel,^b SA-351 grade CF8,^c SA-453 grade 660 condition B,^c and Incoloy 800^b)

Nickel-base alloys (Inconel 600,^a Inconel 625,^c Inconel 706,^c Inconel 718 base metal and weldments,^a Inconel X-750,^b Hastelloy X-280^c)

Ferritic steels^b (SA-387 grade C,^c SA-387 grade D base metal and welds^b)

Irradiation Temperatures: 400–640°C

Test Temperatures: 25, 230, 400–640°C

Fast Neutron Fluences: 10^{21} – 10^{23} neutrons/cm²

- E. Time Schedule and Extent of Program:

Time Schedule: 1975–1985

Experimental: Approximately 300 unirradiated specimens and 700 irradiated specimens

^aIn-depth coverage of various parameters.

^bLess complete coverage of parameters.

^cLimited coverage.

A.2 IRRADIATION EFFECTS — MECHANICAL PROPERTIES
OF STRUCTURAL MATERIALS

(A.2.3 Toughness)

- A. Subject: Study Elevated-Temperature, Elastic-Plastic Toughness of LMFBR Alloys as a Function of Irradiation (A.2.3.2)
- B. Laboratory: Naval Research Laboratory
- C. Problem and Objective: Define the elastic-plastic fracture toughness of fast breeder reactor alloys at elevated temperatures as a function of specimen geometry, fluence level, chemistry and processing variables. Both J-Integral and impact energy methods are employed. Develop a method to evaluate elastic-plastic toughness, including the significance of stable (rising load) crack extension, in terms of structural integrity. Secondary objectives include: (1) evaluate strength and notch toughness of Alloy 718 as a function of heat treatment, melting practice, and fluence level for plate, weld, and forging; and (2) assess the significance of delta ferrite content and morphology to the fracture resistance of stainless steel weld deposits in unirradiated, irradiated and aged conditions.
- D. Test Parameters:
- Materials: Types 304 and 316 stainless steel, Alloy 718, and welds of these alloys
- Irradiation Temperature: 426 and 650°C
- Neutron Fluence: 10^{22} – 10^{23} neutrons/cm² (> 0.1 MeV)
- Test Temperature: Room temperature to 650°C
- Specimen Type: Three-point bend, Charpy-V, Dynamic tear
- Loading Rate: Static, impact
- E. Time Schedule and Extent of Program:
- Main Test Phase: 1975–1979
- Experimental: Approximately 250 irradiated specimens

MAJOR TEST EQUIPMENT

A.2 IRRADIATION EFFECTS — MECHANICAL PROPERTIES OF STRUCTURAL MATERIALS

MAJOR TEST EQUIPMENTA.2 IRRADIATION EFFECTS — MECHANICAL PROPERTIES
OF STRUCTURAL MATERIALS

Laboratory: Hanford Engineering Development Laboratory

- A. Fatigue, Fracture, and High Strain-Rate Machines. See Table I.
- B. Uniaxial Creep Machines. See Table II.
- C. Biaxial Test Machines. See Table III.

TABLE I. FATIGUE, FRACTURE, AND HIGH-STRAIN RATE FACILITY

Test Machine	Instron TT (2 Machines)	Instron TT (1 Machine)	Baldwin (2 Units)	MTS 10K High Rate	MTS 20K 2 Post	MTS 100 Kip 4 Post	MTS 100 Kip 3 Post	MTS 500 Kip
Max Static Load	10,000 lb	20,000	60,000	10,000	20,000	70,000	100,000	500,000
Max Dynamic Load	10,000 lb ^a	20,000		10,000	10,000	50,000	50,000	250,000
Tension	X	X	X	X		X		
Compression	X	X	X	X		X		
Tension-Compression						X		
Stroke Control Accuracy	±0.1% ^b	±0.1%		±3.0%		±1.0%		
Load Control Accuracy				±0.75% Load Range		±0.75%		
Load Measuring Accuracy	±0.5% ^c	±0.5%	1.0%	>±0.5% Overall		>±0.5%		
Load Cycling	X ^d			X		X		
Load Holding	X			X		X		
Strain Cycling	X ^e			X		X		
Strain Holding				X		X		
Programming	Fixed crosshead rates 0.0002 to 20 in./min			Programmable on arbitrary function of load rate or strain rate including ramping, cycling, holding, and combinations thereof. Practical range of rates obtained from all units in combination from 10 ⁻⁴ to 10 ² in./sec.				

^a1% accuracy for full-scale chart deflection time >3 sec.

^bFor selected crosshead speed.

^cIndicated load.

^dTension-tension or compression-compression only at selected crosshead speeds.

^eElastic only.

TABLE II. UNIAXIAL CREEP APPARATUS

Designation	Loading Method	Number of Machines	Environment	Load Stability	Temperature, °F Stability/Gradient	Strain Accuracy	Alignment
TLP	Lever arm	8	Argon	±1%	±3/±2	$\pm 2 \times 10^{-4}$	15%
AS	Bellows	10 in-cell 9 out-of-cell	Argon	±1%	±3/±2	$\pm 1 \times 10^{-4}$	15%
M-3	Lever arm	6	Air	±1%	±3/±2	$\pm 2 \times 10^{-4}$	15%
Ex-Reactor	Bellows	4	Helium	±1%	±3/±2	$\pm 1 \times 10^{-4}$	25%
Satec	Lever arm	6	Air	±1%	±3/±2	$\pm 1 \times 10^{-4}$	15%

TABLE III. BIAXIAL TEST APPARATUS

Designation	Loading Method	Number of Furnaces	Test Capability	Environment	Load Stability	Temperature Stability	Strain Accuracy	Notes
Clad Characterization	Dynamic gas pressurization	6	198	Argon	±1%	±3°F	0.2×10^{-5}	Rupture strain only
324 Building Stress Rupture	Dynamic gas pressurization	3	36	Argon	±1%	±3°F	0.2×10^{-5}	Rupture strain only
<u>Under Construction</u>								
326 Building Stress effects controls	Closed end Pressurized tubes	8	>1000	Argon	Stress Stability 1%	±3°F	2×10^{-5}	Laser diameter measurement upon removal from furnace
<u>Under Development</u>								
Modification of	Closed end	8	~500	Argon	Stress Stability ±1%	±3°F	2×10^{-5}	Same as above

MAJOR TEST EQUIPMENTA.2 IRRADIATION EFFECTS — MECHANICAL PROPERTIES
OF STRUCTURAL MATERIALSLaboratory: Naval Research LaboratoryA. Fatigue Crack Growth and Plastic Flow Machines.

MTS Machines (2) (inert gas or vacuum to 1×10^{-7} torr planned)
SEN Fatigue Machines (3)
Sheet Fatigue Machines (2) (inert gas or vacuum to 1×10^{-7} torr)
Instron Tensile Machines (2) (inert gas or vacuum to 1×10^{-7} torr)

B. Fracture Toughness Machines.

Instrumented Charpy-V Machine
2700 J Dynamic Tear Machine
Krafft-Hahn Dynamic Universal Loader
MTS Machines

A.3 SODIUM ENVIRONMENT EFFECTS — INFLUENCE OF SODIUM ON MECHANICAL PROPERTIES

A.3 SODIUM ENVIRONMENT EFFECTS — INFLUENCE OF SODIUM
ON MECHANICAL PROPERTIES

(A.3.1 Creep Properties)

- A. Subject: Effect of Sodium on the Creep-Rupture Properties of Types 304, 316, and Ti-Modified 316 Stainless Steel (A.3.1.1)
- B. Laboratory: Argonne National Laboratory
- C. Problem and Objective: The objective of this work is to determine the effect of carbon and nitrogen transfer between the steels and sodium on the uniaxial and biaxial creep-rupture properties of the materials. The sodium-exposure conditions and compositional changes in the materials were the same as those outlined for the uniaxial tensile and low-cycle fatigue specimens. Creep correlations that relate the rupture life, minimum creep rate, and time to tertiary creep are being developed for the steels in the solution-annealed and sodium-exposed conditions.
- D. Test Parameters:

Materials: Types 304 (heat 9T2796), 316 (heat V87210), and
Ti-modified 316 (heat 82190) stainless steels

Specimen Types: Sheet-type creep specimens 0.038 and 0.127 cm thick with a 2.22-cm gage length fabricated according to ASTM standard E8-69. Biaxial tube creep specimens of types 316 and Ti-modified 316 stainless steel 0.585-cm O.D. × 0.038-cm wall × 10 cm long.

Test Temperatures: 600, 650, and 700°C

Stress Range: 55 to 240 MPa

- E. Time Schedule and Extent of Program:

Testing Period: 1974–1978

Experimental: Approximately 360 specimens

A.3 SODIUM ENVIRONMENT EFFECTS — INFLUENCE OF SODIUM
ON MECHANICAL PROPERTIES

(A.3.1 Creep Properties)

- A. Subject: Time-Dependent Characteristics of Materials in Sodium (A.3.1.2)
- B. Laboratory: Westinghouse Advanced Reactors Division
- C. Problem and Objective: Current technology does not adequately cover several important aspects of thermally induced creep and fatigue damage in liquid sodium in the temperature range of 427 to 704°C. The design mechanical properties specified in the high-temperature code cases have been established using data which were obtained from specimens tested in air environments. Because of environmental effects of high-temperature liquid sodium, the in-air properties may be a poor representation of in-sodium mechanical properties. This program is conducted to experimentally qualify, supplement, or clarify methods and criteria presently required by the ASME Code and RDT Standards for assessing the structural adequacy of critical CRBRP components in high-temperature fast breeder reactor sodium environments. Tests are conducted in both air and flowing sodium on specimens in the as-received, thermally aged, and presodium corroded conditions.
- D. Test Parameters:
- Materials: Types 316 and 304 stainless steel
- Temperatures: 482–732°C
- Environment: Air or dynamic sodium
- Sodium Conditions: Turbulent flow past gage. Specimen in hot leg of system. Oxygen content of sodium, 1.5–2.0 ppm
- Specimen Pretreatment: Argon aged for 2000–10,000 hr or sodium preexposed for 2000–10,000 hr or no pretreatment
- Types of Tests: Fatigue, stress rupture, tensile, interaction (fatigue then creep, creep followed by fatigue, etc)
- E. Time Schedule and extent of Program:
- Type I Tests (Conventional Test Specimen): Complete December 1978
- Type II Tests (Simple Geometric Shapes): Complete December 1980

(continued)

Number of Sodium Systems Utilized: Four for mechanical properties,
two for preexposures

Number of Specimens to be Tested (see table below):

	Screening			Follow-On
	As Received	Argon Aged	Sodium Preexposed	Sodium Preexposed
Fatigue				
Bar			6	
Plate	48	45	51	69
Weld			3	
High-Cycle Fatigue				
Type 304 Stainless			12	
Steel Bar				
Stress Rupture				
Bar			4	
Plate	48	30	48	78
Weld			3	
Interaction				
Bar			6	
Plate		6	33	
Weld			6	
Tensile	9	15	24	12
	<u>105</u>	<u>96</u>	<u>196</u>	<u>159</u>

A.3 SODIUM ENVIRONMENT EFFECTS — INFLUENCE OF SODIUM
ON MECHANICAL PROPERTIES

(A.3.1 Creep Properties)

A. Subject: Sodium Effects on Annealed 2 1/4 Cr-1 Mo Steel (A.3.1.3)

B. Laboratory: Oak Ridge National Laboratory

C. Problem and Objective: To determine the effect of decarburization by sodium on creep-rupture properties of annealed 2 1/4 Cr-1 Mo steel.

D. Test Parameters:

Materials: 2 1/4 Cr-1 Mo steel decarburized in sodium for 26,500 hr at 566°C; control specimens aged in helium for 26,500 hr at 566°C.

Test Temperatures: 510 and 566°C

E. Time Schedule and Extent of Program:

Testing Period: 1975-1977

Experimental: To date approximately six tests have been completed.

A.3 SODIUM ENVIRONMENT EFFECTS — INFLUENCE OF SODIUM
ON MECHANICAL PROPERTIES

(A.3.2 Fatigue Properties)

- A. Subject: Effect of Sodium on the Low-Cycle Fatigue Properties of Normalized and Isothermal-Annealed Fe-2 1/4 Cr-1 Mo Steel (A.3.2.1)
- B. Laboratory: Argonne National Laboratory
- C. Problem and Objective: The objective of this work is to determine the effect of the sodium environment on the low-cycle fatigue behavior of the Fe-2 1/4 Cr-1 Mo steel in support of the CRBRP steam generator design. The effects of thermal aging and sodium preexposure on the fatigue life in sodium will be determined.
- D. Test Parameters:
- Materials: Fe-2 1/4 Cr-1 Mo steel (heat 3P5601) in the isothermal-annealed and normalized conditions
- Specimen Type: Axially loaded uniform gage cylindrical specimens
- Test Temperatures: 427, 482, and 538°C
- Strain Range: 0.5 to 2.0%
- Strain Rate: $4 \times 10^{-3} \text{ s}^{-1}$
- Sodium Preexposure and Thermal-Aging Periods: 1000–5000 hr
- Sodium Purity: 0.1 ppm C, 1.0 ppm O
- E. Time Schedule and Extent of Program:
- Testing Period: 1977–1979
- Experimental: Approximately 140 specimens

A.3 SODIUM ENVIRONMENT EFFECTS — INFLUENCE OF SODIUM
ON MECHANICAL PROPERTIES

(A.3.2 Fatigue Properties)

- A. Subject: Effect of Sodium on the Low-Cycle Fatigue Behavior of Types 304 and 316 Stainless Steel (A.3.2.2)
- B. Laboratory: Argonne National Laboratory
- C. Problem and Objective: The objective of this program is to determine the effect of the sodium environment on the low-cycle fatigue behavior of types 304 and 316 stainless steel. These data will provide a basis for incorporating environmental effects into elevated-temperature component design. Materials in the as-received (solution annealed), thermally-aged, and sodium-exposed conditions are being tested in sodium under an axial stroke-control mode at a strain rate of $4 \times 10^{-3} \text{s}^{-1}$, with a fully reversed triangular waveform and zero mean strain.
- D. Test Parameters:
- Materials: Types 304 (heat 9T2796) and 316 (heat 87210) stainless steel
- Specimen Type: Axially loaded uniform gage cylindrical specimens
- Test Temperatures: 550, 600, 650, and 700°C
- Strain Range: 0.5 to 2.0%
- Strain Rate: $4 \times 10^{-3} \text{s}^{-1}$
- Sodium Preexposure and Thermal-Aging Periods: 120–5000 hr
- Sodium Purity: 0.3 ppm C, 1.0 ppm O
- E. Time Schedule and Extent of Program:
- Testing Period: 1974–1978
- Experimental: Approximately 216 specimens

A.3 SODIUM ENVIRONMENT EFFECTS — INFLUENCE OF SODIUM
ON MECHANICAL PROPERTIES

(A.3.3 Tensile Properties)

A. Subject: Effect of Sodium Preexposure on the Tensile Properties of Types 304, 316, and Ti-Modified 316 Stainless Steel
(A.3.3.1)

B. Laboratory: Argonne National Laboratory

C. Problem and Objective: The objective of this work is to determine the effect of carbon and nitrogen transfer between the steels and sodium on the tensile properties of the materials. The sodium-exposure times (120–5000 hr) were adjusted to produce carbon penetration depths of ~0.01, 0.02, and 0.038 cm in the 0.038- and 0.127-cm-thick materials. The surface carbon concentrations ranged from ~0.05–0.15, 0.25–0.30, 0.30–0.50, and 0.60–0.65 wt % for temperatures of 700, 650, 600, and 550°C, respectively. The Voce equation is being used to represent the tensile flow curves for plastic strains above 0.005 at all temperatures and strain rates.

D. Test Parameters:

Materials: Types 304 (heat 9T2796), 316 (heat 87210), and Ti-modified 316 (heat 82190) stainless steel

Specimen Type: Sheet tensile specimens with a 2.22-cm gage length fabricated in accordance with ASTM Standard E8-69

Test Temperatures: 550, 600, 650, and 700°C

Strain Rates: 4×10^{-5} to $2 \times 10^{-2} \text{ s}^{-1}$

E. Time Schedule and Extent of Program:

Testing Period: 1974–1976

Experimental: Approximately 290 specimens

A.3 SODIUM ENVIRONMENT EFFECTS — INFLUENCE OF SODIUM
ON MECHANICAL PROPERTIES

(A.3.3 Tensile Properties)

- A. Subject: Effect of Sodium on the Tensile Properties of Normalized and Isothermal-Annealed Fe-2 1/4 Cr-1 Mo Steel (A.3.3.2)
- B. Laboratory: Argonne National Laboratory
- C. Problem and Objective: The objective of this work is to determine the effects of thermal aging and sodium preexposure, which results in decarburization of the steel at the higher temperatures, on the tensile properties of the material. These results will be compared with available data on the tensile properties of thermally aged material with a range of carbon contents.

D. Test Parameters:

Materials: Fe-2 1/4 Cr-1 Mo steel (heat 3P5601) in the isothermal-annealed and normalized conditions

Specimen Type: Sheet tensile specimens 0.127 cm thick with a 2.22-cm gage length fabricated according to ASTM Standard E8-69

Test Temperatures: 500, 550, 600, and 650°C

Sodium Exposure Times: 500–5000 hr at the above temperatures

Strain Rates: 4×10^{-5} to $2 \times 10^{-2} \text{ s}^{-1}$

E. Time Schedule and Extent of Program:

Testing Period: 1976–1978

Experimental: Approximately 80 specimens

A.3 SODIUM ENVIRONMENT EFFECTS — INFLUENCE OF SODIUM
ON MECHANICAL PROPERTIES

(A.3.4 Alloy 718)

- A. Subject: Mechanical Property Development for Alloy 718 in Sodium
(A.3.4.1)
- B. Laboratory: Westinghouse Advanced Reactors Division
- C. Problem and Objectives: Current technology, while providing some design information on the tensile and creep properties of Alloy 718 in air, provides almost no data on the mechanical performance of this material in liquid sodium. Several of the CRBRP components make extensive use of this alloy in sodium at temperatures up to 649°C and for time periods up to 30 years. Hence, the objective of this program is to determine the effects of high temperature, corrosive sodium on the mechanical properties of Alloy 718. The primary testing effort is on material given the standard 954°C solution heat treatment prior to aging. Secondary efforts are applied to weldments and to base material given a special preweld heat treatment. Tests are conducted in both air and in flowing sodium on specimens in the as-received, thermally aged, and presodium-corroded conditions.
- D. Test Parameters:
- Material: Alloy 718
- Temperatures: 649 and 704°C
- Environment: Air or dynamic sodium
- Sodium Conditions: Turbulent flow past gage. Specimen in hot leg of system. Oxygen content of sodium, 1.5–2.0 ppm
- Specimen Pretreatment: Argon aged for 2000–8000 hr or sodium pre-exposed for 2000–8000 hr or no pretreatment
- Types of Tests: Short-term tensile, creep rupture, fatigue, creep/fatigue
- E. Time Schedule and Extent of Program:
- Schedule: Complete testing by December 1979
- Number of Sodium Systems Utilized: Two for mechanical properties testing and one for sodium preexposure

Number of Specimens to be Tested: See table below

<u>Type of Test</u>	<u>Number of Specimens</u>		
	<u>As Received</u>	<u>Argon Aged</u>	<u>Sodium Preexposure</u>
Tensile	18	24	24
Creep Rupture			
In air	33	39	39
In sodium			33
Fatigue			
In air	24	30	30
In sodium			24
Creep/Fatigue			
In air	27		
In sodium			27
	<hr/> 102	<hr/> 93	<hr/> 177

A.3 SODIUM ENVIRONMENT EFFECTS — INFLUENCE OF SODIUM
ON MECHANICAL PROPERTIES

(A.3.5 Carbon Transfer)

- A. Subject: Validation of Strength Degradation Allowance for
Decarburization of 2 1/4 Cr-1 Mo Steel in Sodium (A.3.5.1)
- B. Laboratory: General Electric Company, San Jose, California
- C. Problem and Objective: The program will assess the strength
degradation associated with decarburization of 2 1/4 Cr-1 Mo steel.
Both short-term and creep properties at elevated temperatures are
being evaluated as a function of decarburization conditions.
- D. Test Parameters:
- Material: 2 1/4 Cr-1 Mo steel, isothermal annealed and postweld
heat treated, prototypic internal bore TIG weldments of
tubing
- Environment: Titanium-gettered sodium
- Temperature: 510°C
- Test Time: Up to 5×10^3 hr
- Creep Stress Range: 115 to 205 MPa
- Hot Tensile Rate: 10^{-3} s^{-1}
- Number of Specimens: Creep, 50; hot tensile, 20
- E. Time Schedule and Extent of Program: 1974-1979

A.3 SODIUM ENVIRONMENT EFFECTS — INFLUENCE OF SODIUM
ON MECHANICAL PROPERTIES

(A.3.5 Carbon Transfer)

- A. Subject: Study of Mechanical Properties of Carburized Stainless Steel in Sodium (A.3.5.2)
- B. Laboratory: General Electric Company, San Jose, California
- C. Problem and Objective: An objective of the activity on the mechanical properties of carburizing stainless steel in sodium is to define stress, strain, and cyclic life allowances for the CRBR Intermediate Heat Transport System (IHTS), under carburizing conditions. It has been shown that carburization of stainless steel components in the IHTS will occur because of the carbon derived from the ferritic 2 1/4 Cr-1 Mo steel in the secondary loop steam generators. It is anticipated that recurring carburization at a growing fatigue or creep crack could increase the crack propagation rate. Earlier crack initiation, and the preclusion of high creep strains and of tertiary creep are also expected, because of the brittle nature of a high carbon case. Fracture mechanics will be employed to evaluate the influence of high carbon sodium on fatigue crack growth rate. Creep rupture and high-temperature tension tests will determine creep stress and strain limitations.
- D. Test Parameters:

Material: Type 316 stainless steel base metal and GTAW 16-8-2 welds

Environment: Carbon-saturated sodium; control tests in air

Temperature: 510°C

Preexposure: 1000 hr in air or carbon-saturated sodium

Creep Test Conditions: To 5000 hr, 377 to 446 MPa, 0 to 16% prestrain, tubular specimen

Fatigue Crack-Growth Conditions: 0.5 to 0.033 cpm frequency, saw-tooth wave, 0 to 1 min hold at peak load, $R = 0.05$ to about 0.4, $\Delta K = 11$ to 38 MPa $\sqrt{\text{in.}}$, ASTM E399 12.7-mm-thick 3-point bend specimen

Number of Specimens: Creep test, 40; fatigue crack-growth test, about 80

- E. Time Schedule and Extent of Program:

Creep Test: 1974-1977

Fatigue Crack-Growth Test: 1974-1977

MAJOR TEST EQUIPMENT

A.3 SODIUM ENVIRONMENT EFFECTS — INFLUENCE OF SODIUM ON MECHANICAL PROPERTIES

MAJOR TEST EQUIPMENTA.3 SODIUM ENVIRONMENT EFFECTS — INFLUENCE OF SODIUM
ON MECHANICAL PROPERTIESLaboratory: Argonne National Laboratory

- A. Fatigue Testing Machines. Three stroke-controlled servo-hydraulic low-cycle fatigue testing machines with sodium loops in which the sodium purity can be controlled and monitored.
- B. Creep Testing Machines. Fifteen constant-load creep-rupture machines with static-argon test chambers.
- C. Tensile Testing Machines. Four Instron tensile testing machines with vacuum/inert gas, high-temperature furnaces.

MAJOR TEST EQUIPMENT

A.3 SODIUM ENVIRONMENT EFFECTS — INFLUENCE OF SODIUM ON MECHANICAL PROPERTIES

Laboratory: Westinghouse Advanced Reactors Division

Six sodium systems are presently utilized for testing types 304 and 316 stainless steel. Four of these are for obtaining mechanical property test data and two for preexposing specimens to sodium for time periods up to 10,000 hr. The mechanical testing systems are all similar in their configuration with two being used for stress rupture tests and the other two for fatigue testing. Additionally, the systems employed for fatigue tests contain two test stations, used alternately, to reduce down-time.

Three sodium systems will be utilized for testing of Alloy 718; two for conducting mechanical property tests and one for preexposing specimens to sodium for periods up to 8000 hr. One of the mechanical testing systems is utilized for fatigue or creep/fatigue tests while the other is used for creep-rupture testing.

Various in-air mechanical testing stations are also used in the program to obtain base-line data for comparison with the in-sodium results. Numerous furnaces are employed to thermally age specimens in an argon atmosphere also for the purpose of obtaining base-line data. General descriptions of the sodium facilities are given below.

- A. Mechanical Property Systems (MPS). Each system consists of three major parts; a sodium supply loop, a mechanical property test machine(s), and test vessel(s). MPS-1 and -2 have Satec creep machines for stress-rupture testing. MPS-3 and -4 each have two MTS fatigue machines. Maximum sodium temperature obtainable in the systems is 1325°F and the maximum flow rate is 2.5 gpm. The flow is channeled past the gage section of test specimen to give Reynold's numbers greater than 10,000. The specimens are located in the hot leg of the system and a temperature differential of approximately 122°F is maintained on the system to give corrosive sodium conditions. The oxygen content of the sodium is kept in the range from 1.5–2.0 ppm and is maintained at that level by continuous cold-trapping. The oxygen concentration is measured with a Vanadium Wire Equilibration Device. The carbon activity of the sodium is monitored using thin foils of type 304 or 18-8 stainless steel. Mechanical properties are measured only under decarburizing conditions.
- B. Sodium Preexposure Facilities. The sodium facilities used to pre-corrode the test specimens are versatile, multilegged systems constructed entirely of types 304/316 stainless steel. Specimens are placed in the facility in rising temperature regions at the temperature level identified by the test specification. A temperature differential of at least 300°F is maintained on the system during

Laboratory: Westinghouse Advanced Reactors Division (continued)

operation. Specimen positioners are used to channel the flow past the gage sections of the samples to give a Reynolds' number greater than 15,000 during the preexposure period. The oxygen content of the sodium is kept in the range from 1.5-2.0 ppm, maintained at that level by continuous cold-trapping, and measured with a Vanadium Wire Equilibration Device. The carbon activity of the sodium is monitored with thin foils of types 304 and/or 18-8 stainless steels. After exposure in this facility the specimens are cleaned in alcohol/water baths and stored in plastic bags until ready for testing in the Mechanical Property Systems.

A.4 GENERAL MATERIAL QUALIFICATION

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.1 Time-Dependent Properties)

- A. Subject: Materials Behavior in Support of Development and Evaluation of Flow and Failure Criteria for Materials (A.4.1.1)
- B. Laboratory: Oak Ridge National Laboratory
- C. Problem and Objective: Design of elevated-temperature reactor systems requires that methods for describing and predicting long-term flow and failure criteria be established. The objective of this task is to use experimental data (elastic, plastic, inelastic, crack growth, etc) generated from other tasks under this program and from literature to define meaningful flow and failure criteria for reactor structural and component materials. The flow and failure criteria are being developed for unirradiated stainless steel of types 304 and 316 in mill- and laboratory-annealed conditions as well as Inconel Alloy 718.
- D. Test Parameters: There are no direct test parameters under this task. Test parameters for data used in analysis are described under other tasks.
- E. Time Schedule and Extent of Program: Started in 1973. Creep (strain time) behavior of types 304 and 316 stainless steel has been described with success. Methods are being developed to define strain limits and failure. Models for describing tensile and creep behavior are being refined. Work on Alloy 718 was initiated in 1976.

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.1 Time-Dependent Properties)

- A. Subject: Mechanical Property Characterization of Type 304 Stainless Steel Reference Heat (A.4.1.2)
- B. Laboratory: Oak Ridge National Laboratory
- C. Problem and Objective: Mechanical property characterization of a single heat of material is required to generate a data base for defining behavior of complex structural components undergoing tests at various laboratories. Use of a single heat also permits definition of the behavior of various product forms - all fabricated from the same heat. The reference heat is being subjected to the following types of testing: tensile tests, creep tests, aging studies, effect of prior creep deformation on short-term properties, and product-form characterization.
- D. Test Parameters:

Tensile Test

Temperature: Room temperature to 704°C

Strain Rate: 0.0004 to 0.4/min

Material Condition: Reannealed for 0.5 hr at 1093°C, reannealed and aged

Creep Tests

Temperatures: 427, 482, 538, 593, 649, and 704°C

Test Times: 5×10^4 hr

Stress Levels: 4 to 8 stresses at each temperature

Material Condition: Reannealed for 0.5 hr at 1093°C, reannealed and aged

Aging

Temperatures: 482, 593, and 649°C

Times: 1000, 2000, 4000, 10,000, 20,000, and 50,000 hr

Atmosphere: Air

Materials: Reannealed blocks

Prior Creep Studies

Temperatures: 427, 482, 538, 593, and 649°C

Test Times: 100, 1000, and 10,000

Stress Levels: Three to four stress levels at each temperature

Material: Reannealed for 0.5 hr at 1093°C

Tensile Tests on Prior Creep Specimens

Temperatures: Same as aging or prior creeping

Strain Rate: 0.04/min

Product-Form Characterization Tests

Tensile: Room and one elevated temperature

Creep: One temperature and three stresses

E. Time Schedule and Extent of Program:

Start of Tests: 1972-1973

Tensile: 70% complete

Creep: Test times on several tests are 20,000-30,000 hr

Aging: Reached 20,000 hr, 50,000 hr need 3 1/2 more years

Prior Creep Deformation: 30% complete

Product-Form Characterization: Completed

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.1 Time-Dependent Properties)

- A. Subject: Mechanical Property Characterization of Type 316 Stainless Steel Reference Heat (A.4.1.3)
- B. Laboratory: Oak Ridge National Laboratory
- C. Problem and Objective: Mechanical property characterization of a single heat of type 316 stainless steel is required to generate a data base for defining behavior of complex structural components undergoing tests at various laboratories. Use of a single heat also allows to compare the behavior of various product forms all fabricated from the same heat. The reference heat of type 316 stainless steel is subjected to the following types of testing: tensile, creep, aging, effect of prior creep deformation on short-term properties, and product-form characterization.
- D. Test Parameters:

Tensile Tests

Temperature: Room temperature to 760°C
Strain Rate: 0.0004 to 0.4/min
Material Condition: As received, reannealed and aged

Creep Tests

Temperatures: 538, 565, 549, and 704°C
Test Times: 5×10^4
Stress Levels: 4 to 8 stresses at each temperature
Material Condition: As received, reannealed and aged

Aging

Temperatures: 482, 593, and 649°C
Times: 1000, 2000, 4000, 10,000, 20,000, and 50,000 hr
Atmosphere: Air
Materials: As received and reannealed blocks

Prior Creep Studies

Temperatures: 538, 593, 649, and 704°C
Test Times: 100, 1000, and 10,000 hr
Material: As received and reannealed

Tensile Tests on Prior Creep Specimens

Temperatures: Same as aging or prior creeping
Strain Rate: 0.04/min

Product-Form Characterization Tests

Tensile: Room to 649°C (6 temperatures)
Creep: At one temperature and three stresses

E. Time Schedule and Extent of Program:

Start of Tests: 1975-1976

Tensile: Complete at one strain rate in unaged condition

Creep: Few tests past 6000 hr

Aging: Reached 10,000 hr

Prior Creep Deformation: To be started

Product-Form Characterization: Initiated in 1976

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.1 Time-Dependent Properties)

- A. Subject: Heat-to-Heat Variation of Mechanical Properties of Types 304 and 316 Stainless Steel and Inconel Alloy 718 (A.4.1.4)
- B. Laboratory: Oak Ridge National Laboratory
- C. Problem and Objective: Heat-to-heat variations in mechanical properties of types 304 and 316 stainless steel and Inconel alloy 718 are being determined to establish minimum and average values of specific mechanical properties and equation parameters required for design purposes. This study also allows one to estimate the nature of heat-to-heat variations in austenitic stainless steels purchased in accordance with ASTM specifications and help understand reasons for the observed variations.
This task involves testing of 20 heats of type 304 and eight heats of type 316 stainless steels. These heats are being subjected to tensile and creep testing.
- D. Test Parameters:
- Tensile Tests (Both elastic and plastic properties are defined)
Temperatures: Room temperature, 427, 593, and 649°C
Strain Rate: 0.04/min
Material Condition: As received and reannealed
- Creep Tests
Temperatures: 538, 593, and 649°C
Stresses: One at 538 and 649°C and 2 stresses at 593°C
Time: Short-term tests with few long-term
Material Condition: As received and reannealed
- E. Time Schedule and Extent of Program
- Start of Tests: 1972-1973
- Tensile: Completed
- Creep: Short-term completed and long-term are in progress

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.1 Time-Dependent Properties)

A. Subject: Exploratory Mechanical Property Studies of High Temperature Structural Alloys — Types 304 and 316 Stainless Steel and 2 1/4 Cr-1 Mo Steel (A.4.1.5)

B. Laboratory: Oak Ridge National Laboratory

C. Problem and Objective: The development of improved inelastic design methods is an iterative process that requires a close coupling between materials studies, constitutive equation development, computation methods development, and structures tests. The objectives of the exploratory materials tests are to provide information to (1) guide the development of constitutive equations, (2) develop a data base for the aerospace analysis of test structures, and (3) assist in the development of failure criteria.

D. Test Parameters

Material: Primary effort on type 304 stainless steel with secondary efforts on type 316 stainless steel and 2 1/4 Cr-1 Mo steel.

Temperatures: Room to 650°C

Tested Properties: Tensile, strain-cycling, creep, creep-to-rupture, relaxation, cyclic creep, and creep-plasticity interactions.

Test Durations: 10,000 hr

E. Time Schedule and Extent of Program

Period: 1970-1980

Extent: Creep and rupture: 300 tests, Tensile: 200, Strain cycling: 100, Relaxation, Cyclic Creep, and Creep-plasticity interactions: 200.

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.1 Time-Dependent Properties)

- A. Subject: Generation of Long-Term Creep and Stress-Rupture Data for Alloy 800 (A.4.1.6)
- B. Laboratory: Westinghouse Tampa Division
- C. Problem and Objective: The ASME B&PV Code has not approved annealed Alloy 800 for use in elevated temperature nuclear steam supply systems. One problem in obtaining Code acceptance of this grade relates to the fact that few creep data exists in the temperature range 900-1100°F where steam generation systems for LMFBR's are being designed. Extrapolation of high temperature creep data to these temperatures of interest penalizes the annealed grade of Alloy 800 relative to other accepted materials because of the tertiary creep criteria. Thus, the program is aimed at generation of long term data for the alloy compositions and heat treatments that are of prime interest.
- D. Test Parameters
- Material: Annealed alloy 800 (formerly Grade 1)
- Temperatures: 1000 and 1100°F
- Stress Levels: 20,000 to 50,000 psi
- E. Time Schedule and Extent of Program
- Testing Period: 1975-1978
- Experimental: Approximately 60 specimens of 5 different heats

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.1 Time-Dependent Properties)

- A. Subject: Determination of Creep and Stress-Rupture Properties of Alloy 718 (A.4.1.7)
- B. Laboratory: Oak Ridge National Laboratory/Idaho National Engineering Laboratory
- C. Problem and Objective: Available data is not sufficient to fully characterize the creep and stress-rupture behavior of Alloy 718 to meet design requirements of the CRBRP. The objective of this investigation is to fill data gaps and extend times to be more relevant to service conditions and to develop creep equations that will allow extrapolations and define time-dependent values needed for isochronous stress-strain curves.
- D. Test Parameters:
- Material: Alloy 718 base metal given the 954°C SA plus 718/621°C duplex aged heat treatment
Aged base metal, 593, 649, 704, 760°C up to 3 years
Alloy 718 weldment given a modified heat treatment (to be determined)
- Temperatures: 538 to 760°C
- Time: 10 to 10⁵ hours
- E. Time Schedule and Extent of Program
- Testing Period: 1976-1988 (Base Metal) 1978-1981 (Weldments)
- Experimental: 74 specimens (Base Metal) 36 specimens (Weldment)

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.1 Time-Dependent Properties)

A. Subject: Determination of Tensile Properties of Alloy 718 (A.4.1.8)

B. Laboratory: Idaho National Engineering Laboratory

C. Problem and Objective: Available data is not sufficient to fully characterize the tensile behavior of Alloy 718 to meet design requirements of the CRBRP or to satisfy requirements for ASME Code approval. The objective of this investigation is to fill data gaps with various heats and conduct a series of tests with one heat through the entire temperature range. Also the effect of long term aging on tensile properties will be investigated.

D. Test Parameters:

Material: Alloy 718 base metal given the 954°C SA plus 718/621°C duplex age heat treatment

Aged base metal, 593, 649, 704, 760°C up to 3 years

Alloy 718 weldment given a modified heat treatment
(to be determined)

Temperatures: Room temperature to 760°C at 55°C intervals

E. Time Schedule and Extent of Program:

Testing Period: 1976-1979 (Base Metal) 1978-1980 (Weldments)

Experimental: 100 specimens (Base Metal) 20 specimens (Weldments)

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.1 Time-Dependent Properties)

- A. Subject: The Influence of Prestrain on the Creep Behavior of Type 304 Stainless Steel (A.4.1.9)
- B. Laboratory: University of California Los Angeles
- C. Problem and Objective: Previous studies of the creep strength improvement derived from cold working have concentrated mainly on the secondary creep rate and the rupture life. This study is limited to the primary and secondary stages of the creep curve. The investigation includes a detailed analysis of the effect of prestrain on the transient creep parameters, the substructural changes accompanying transient creep, and the correlation of the microstructure with the observed creep behavior.
- D. Test Parameters:
- Material: AISI 304 stainless steel, reference heat 62213
- Cold Work Levels Imposed: 0, 2, 4, 6, 8, and 10%, in tension at 23°C
- Temperatures: 650–800°C
- Stress Levels: 50–250 MN/m²
- E. Time Schedule and Extent of Program
- Design and Construction of the Creep Apparatus: 1973–1974
- Testing Period: 1975–1977
- Experimental: 150 specimens

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.1 Time-Dependent Properties)

- A. Subject: Tensile Properties of Annealed 2 1/4 Cr-1 Mo Steel for Constitutive Equation Development and Safety Analyses (A.4.1.10)
- B. Laboratory: Oak Ridge National Laboratory
- C. Problem and Objective: To determine the tensile properties of annealed 2 1/4 Cr-1 Mo steel over the temperature range of interest for design and safety calculations of LMFBR steam generator.
- D. Test Parameters:
- Materials: Annealed 2 1/4 Cr-1 Mo steel
- Temperatures: 25 to 566°C (ten temperatures)
- Strain Rates: 2.67×10^{-6} to 144/sec (eight strain rates)
- E. Time Schedule and Extent of Program:
- Testing Period: 1973-1975
- Experimental: Approximately 120 specimens were tested

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.1 Time-Dependent Properties)

- A. Subject: Creep Properties of Annealed 2 1/4 Cr-1 Mo Steel for Constitutive Equation Development (A.4.1.11)
- B. Laboratory: Oak Ridge National Laboratory
- C. Problem and Objective: To determine the creep properties of annealed 2 1/4 Cr-1 Mo steel over the stress and temperature range of interest for design of LMFBR steam generator.
- D. Test Parameters:
- Materials: Annealed 2 1/4 Cr-1 Mo steel
- Temperatures: 454, 510, 538, 566, and 593°C
- Stresses: 27 to 207 MPa (4 to 30 ksi)
- E. Time Schedule and Extent of Program:
- Testing Period: 1973-1976
- Experimental: Approximately thirty-five tests were made

A.4 GENERAL MATERIAL QUALIFICATION(A.4.1 Time-Dependent Properties)

- A. Subject: Creep-Rupture Properties of Annealed 2 1/4 Cr-1 Mo Steel for Design (A.4.1.12)
- B. Laboratory: Oak Ridge National Laboratory
- C. Problem and Objective: To determine the creep-rupture properties of annealed 2 1/4 Cr-1 Mo steel and to determine the effect of heat treatment on the creep-rupture properties.
- D. Test Parameters:
- Materials: Annealed 2 1/4 Cr-1 Mo steel
- Temperatures: 454, 510, and 566°C
- Stresses: 103 to 448 MPa (15 to 65 ksi)
- Heat Treatments: Two full annealed and one isothermal anneal
- E. Time Schedule and Extent of Program:
- Testing Period: 1973-1976
- Experimental: Approximately forty tests were made

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.1 Time-Dependent Properties)

- A. Subject: Heat-Treatment Effects on the Tensile Properties of Annealed 2 1/4 Cr-1 Mo Steel (A.4.1.13)
- B. Laboratory: Oak Ridge National Laboratory
- C. Problem and Objective: To determine the effect of heat treatment on the tensile properties of annealed 2 1/4 Cr-1 Mo steel.
- D. Test Parameters:
- Materials: Annealed 2 1/4 Cr-1 Mo steel
- Temperatures: 25 to 593°C (ten temperatures)
- Strain Rates: 2.67×10^{-6} to 6.67×10^{-3} /sec (four strain rates)
- Heat Treatments: Two full anneals and one isothermal anneal
- E. Time Schedule and Extent of Program:
- Testing Period: 1973-1976
- Experimental: Approximately 180 tests were made

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.1 Time-Dependent Properties)

- A. Subject: Heat-to-Heat Variation in the Mechanical Properties of Annealed 2 1/4 Cr-1 Mo Steel (A.4.1.14)
- B. Laboratory: Oak Ridge National Laboratory
- C. Problem and Objective: To determine the heat-to-heat variations in tensile and creep-rupture properties of annealed 2 1/4 Cr-1 Mo steel.
- D. Test Parameters:
- Materials: Five heats of air-melted tubing, three VAR heats, three ESR heats, two air melted plates
- Temperatures: 22 to 566°C (tensile); 566°C (creep rupture)
- E. Time Schedule and Extent of Program:
- Testing Period: 1974-1978
- Experimental: Approximately fifty tensile tests and ten creep tests have been completed

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.1 Time-Dependent Properties)

- A. Subject: Effect of Thermal Aging on Annealed 2 1/4 Cr-1 Mo Steel
(A.4.1.15)
- B. Laboratory: Oak Ridge National Laboratory
- C. Problem and Objective: To determine the effect of prolonged exposure at elevated temperatures on the tensile and creep-rupture properties of annealed 2 1/4 Cr-1 Mo steel.
- D. Test Parameters:
- Materials: One plate and four tubing heats of 2 1/4 Cr-1 Mo steel
- Aging Times: 1000, 2500, 5000, 10,000, and 20,000 hr
- Aging Temperatures: 454, 510, and 566°C
- Test Temperatures: 25, 454, 510, and 566°C for tensile,
454, 510, 566°C for creep
- E. Time Schedule and Extent of Program:
- Testing Period: 1974-1978
- Experimental: To date material has been aged to 5000 hr and testing has begun

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.1 Time-Dependent Properties)

- A. Subject: Relaxation Properties of Annealed 2 1/4 Cr-1 Mo Steel
(A.4.1.16)
- B. Laboratory: Oak Ridge National Laboratory
- C. Problem and Objective: To determine the relaxation behavior of annealed 2 1/4 Cr-1 Mo steel over the temperature and stress range of interest for design calculations.
- D. Test Parameters:
- Materials: Annealed 2 1/4 Cr-1 Mo steel
- Temperatures: 454, 510, 538, and 566°C
- Starting Stresses: 138 to 310 MPa (20 to 45 ksi)
- E. Time Schedule and Extent of Program:
- Testing Period: 1975-1978
- Experimental: Approximately 10 tests have been completed to date

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.1 Time-Dependent Properties)

- A. Subject: Cyclic Creep of Annealed 2 1/4 Cr-1 Mo Steel for Constitutive Equation Development (A.4.1.17)
- B. Laboratory: Oak Ridge National Laboratory
- C. Problem and Objective: To determine the creep behavior under stepwise-alternating stresses (tensile-compressive).
- D. Test Parameters:
- Material: Annealed 2 1/4 Cr-1 Mo steel
- Temperatures: 510 and 566°C
- Stresses: 69 to 172 MPa (10 to 25 ksi)
- E. Time Schedule and Extent of Program:
- Testing Period: 1975-1978
- Experimental: Approximately ten specimens have been tested to date

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.1 Time-Dependent Properties)

- A. Subject: Multistep Creep Tests on Annealed 2 1/4 Cr-1 Mo Steel for Constitutive Equation Development (A.4.1.18)
- B. Laboratory: Oak Ridge National Laboratory
- C. Problem and Objective: To determine the hardening laws for annealed 2 1/4 Cr-1 Mo steel.

D. Test Parameters:

Materials: Annealed 2 1/4 Cr-1 Mo steel

Temperatures: 510, 538, and 566°C

Stresses: Variable

E. Time Schedule and Extent of Program:

Testing Period: 1974-1978

Experimental: Approximately fifteen tests have been completed to date

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.1 Time-Dependent Properties)

- A. Subject: Determination of Physical and Elastic Properties of Alloy 718 (A.4.1.19)
- B. Laboratory: Idaho National Engineering Laboratory/
Oak Ridge National Laboratory
- C. Problem and Objective: Data available in the literature is not sufficient to fully characterize the physical and elastic properties of Alloy 718 to allow design and stress analysis to be performed for the CRBRP. The objective of this investigation is to determine these properties on more than one heat and extend the temperature range as found in the literature.
- D. Test Parameters:
- Material: Alloy 718 base metal given the 954°C SA plus 718/621°C duplex age heat treatment
- Properties to be Measured: Density, mean thermal expansion,
instantaneous thermal expansion,
thermal conductivity, heat capacity,
elastic modulus, and Poisson's ratio.
- Test Temperatures: Room temperature to 760°C
- E. Time Schedule and Extent of Program:
- Testing Period: 1976-1978
- Experimental: 40 specimens

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.1 Time-Dependent Properties)

A. Subject: Microstructures and High Temperature Mechanical Properties of 2 1/4 Cr-1 Mo Steel (A.4.1.20)

B. Laboratory: University of California Los Angeles

C. Problem and Objective: Mass transfer phenomenon in LMFBR heat exchanger decarburizes this material and alters its microstructure and mechanical properties in combination with long time high temperature exposure. The objective of this study is to characterize these changes due to carbon level variation and long-term-tempering conditions, and to evaluate strain bursts and stress effects on microstructural changes.

D. Test Parameters:

Material: 2 1/4 Cr-1 Mo steels

Long-Term-Tempering: 1 ~ 48 months at 455-565°C

Creep Testing: 455° ~ 565°C, 10^{-7} ~ 10^{-3} hr⁻¹

Tensile Testing: 23-565°C

E. Time Schedule and Extent of Program:

Time Schedule: 1971-1977

Experimental: About 200 specimens

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.1 Time-Dependent Properties)

- A. Subject: Complex Uniaxial Materials Behavior Studies (A.4.1.21)
- B. Laboratory: Oak Ridge National Laboratory
- C. Problem and Objective: The objective of these tests is to provide information about some salient aspects of loading-history effects associated with time-dependent deformations of three structural materials. Through these tests, time-dependent material behavior under other than sustained tensile loading conditions will be obtained, and bases will be provided for verifying or modifying inelastic analysis methods.

D. Test Parameters:

Materials: Types 304 and 316 stainless steels, and 2 1/4 Cr-1 Mo steel

Temperatures: 427-704°C

Stress: -138 to +138 MPa

Types of Tests: Constant load, tensile and compressive creep
Tensile and compressive relaxation
Constant stress tensile and compressive creep
Stepwise alternating stress creep
Creep with stress oscillations superimposed on sustained stresses
Creep interrupted by strain cycles

Strain Rates: 0.005, 0.005, 0.025, and 0.25 min⁻¹

E. Time Schedule and Extent of Program:

Time Period: 1976-1981

Experimental: Testing system being installed

Starting Time of Tests: 1976

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.1 Time-Dependent Properties)

- A. Subject: Development of a Modified 9 Cr-1 Mo Steel for LMFBR Structural Applications (A.4.1.22)
- B. Laboratory: Combustion Engineering Metallurgical Laboratory, Chattanooga, Tennessee
- C. Problem and Objective: Sufficient problems are inherent in the use of 18-8 stainless steels as LMFBR primary pressure boundaries (stress corrosion, thermophysical properties, material availability, weld-related problems, etc.) to justify consideration of an alternate material. The 8-14 Cr-Mo steels are attractive, and a modified 9 Cr-1 Mo composition in the normalized-and-tempered or annealed condition has been identified on weldability, toughness, and strength bases. Design data gathering, including tensile, creep, fatigue, and creep-fatigue data is in progress to qualify this material under ASME criteria for acceptable materials for elevated-temperature service. Other representative large heats in needed product forms will be procured and characterized.
- D. Test Parameters:
- Material: Modified 9 Cr-1 Mo in annealed and normalized-and-tempered condition
- Tensile Testing: Room temperature to 1200°F, 4 to 4×10^{-3} /min strain rate
- Creep Testing: 800 to 1200°F, rupture times to 20,000 hr
- Creep-Fatigue Testing: 800 to 1100°F, 0.5 to 2% strain range
- Fatigue Testing: Room Temperature to 1100°F
- E. Time Schedule and Extent of Program:
- Testing Period: 1976-1980
- Experimental: Approximately 150 specimens of 5 different heats

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.2 Fatigue Properties)

A. Subject: Uniaxial and Biaxial Fatigue and Creep-Fatigue Interaction in 2 1/4 Cr-1 Mo Steel (A.4.2.1)

B. Laboratory: Oak Ridge National Laboratory

C. Problem and Objective: The objectives of this effort are to collect (1) sufficient continuous low- and high-cycle fatigue data to establish ASME design curves for this material, (2) sufficient hold time and frequency variation data to formulate creep-fatigue design rules, (3) adequate data covering the influence of melting practice heat treatment, and heat-to-heat variations, and (4) data covering other effects such as thermal aging, mean stress, environment, and notch behavior.

D. Test Parameters:

Heat-to-Heat and Melting

Practice Variations: Air-melt heats (2), VAR, ESR, EBR-II (aged material from piping in service for 10 years - 20 specimens)

Heat Treatments: Annealed, isothermal annealed, annealed with post-weld heat treatment (PWHT), isothermal annealed with PWHT aged material (10,000 hr at 900, 1000, or 1100°F)

Temperature Range: 20-593°C

Strain Controlled Tests: (a) Continuous cycling at constant strain rate, (b) constant strain on stress hold periods introduced each cycle

Stress Controlled Tests: Low and high cycle

Specimens: Hourglass (5-mm diam) or uniform gage (6.35-mm diam)

Environments: Air or high vacuum

E. Time Schedule and Extent of Program:

Tests: Started 1974

Experimental: 50-100 specimens from each heat of material

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.2 Fatigue Properties)

- A. Subject: Evaluation of the Effect of Various Operating Parameters Upon the Fatigue Crack Propagation Behavior of LMFBR Structural Materials (A.4.2.2)
- B. Laboratory: Hanford Engineering Development Laboratory
- C. Problem and Objective: In order to conduct design and safety analyses on LMFBR components in terms of fracture mechanics techniques, it is necessary to know the effect of various operating parameters upon the fatigue crack propagation behavior of component materials. Hence, the objective of this study is to characterize the effect of parameters such as temperature, cyclic frequency, environment, neutron irradiation, etc, on the crack propagation properties of LMFBR Structural Materials.
- D. Test Parameters:

Materials: Austenitic steels (type 304 stainless steel base metal and weldments,^a type 316 stainless steel,^b SA-351 grade CF8,^c SA-453 grade 660 condition B,^c and Incoloy 800^b)

Nickel-base alloys (Inconel 600,^a Inconel 625,^c Inconel 706,^c Inconel 718 base metal and weldments,^a Inconel X-750,^b Hastelloy X-280,^c and Nimonic PE16^c)

Ferritic steels (SA-387 grade C,^c SA-387 grade D base metal and welds,^b and SA-516 grade 60 base metal and welds^c)

Parameter Coverage: Temperature, frequency, stress ratio, environment (air, vacuum, Na, N₂), neutron irradiation, loading waveform (hold time), heat treatment and aging, cold work, crack orientation, heat-to-heat variations.

- E. Time Schedule and Extent of Program:

Testing Period: 1969-1985

Experimental: Approximately 700-800 specimens of which approximately 480 have been tested to date.

^aIn-depth coverage of various parameters.

^bLess complete coverage of parameters.

^cLimited coverage.

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.2 Fatigue Properties)

- A. Subject: The Effect of Notches on the Low-Cycle Fatigue Behavior of Type 304 Stainless Steel (A.4.2.3)
- B. Laboratory: Argonne National Laboratory
- C. Problem and Objective: The objective of this program is to determine the effect of geometric stress concentrations (notches) on the low-cycle fatigue behavior of this material. These findings can then be used to predict the creep-fatigue behavior of structural components containing discontinuities. Specimens with several notch sizes will be tested under fully-reversed axial loadings at 593°C (1100°F) and a strain rate of $4 \times 10^{-3} \text{ s}^{-1}$ to establish the base data. The effects of different strain rates, temperatures, and tensile hold times will also be investigated.
- D. Test Parameters:
- Material: Type 304 stainless steel (heat 9T2796)
- Specimen Type: Axially loaded bars with circumferential grooves having stress concentration factors of 1.5, 2, 3, and 4
- Test Temperatures: 482°C (900°F) and 593°C (1100°F)
- Strain Rates: 4×10^{-3} and $4 \times 10^{-5} \text{ s}^{-1}$
- Tensile Hold Times: 0, 1, 10, and 60 min
- Cyclic Life Range: $10^{-2} - 10^{-5}$ cycles
- E. Time Schedule and Extent of Program:
- Testing Period: 1976-1978
- Experimental: 40 specimens

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.2 Fatigue Properties)

- A. Subject: Fatigue Crack Growth Rates in Type 304 Stainless Steel (A.4.2.4)
- B. Laboratory: Argonne National Laboratory
- C. Problem and Objective: The objective of this program is to provide fatigue crack growth rate data at cyclic frequencies and under environmental conditions (482 and 593°C in air) which will be useful to designers for extrapolation to long lines. Creep crack growth rate and block loading tests are also included.
- D. Test Parameters
- Material: Type 304 stainless steel (heat 9T2796)
- Specimen Type: Compact tensile type specimens 51 mm (2 in.) × 13 mm (0.5 in.) thick
- Test Temperatures: 482°C (900°F) and 593°C (1100°F)
- Cyclic Frequencies: 0.001 to 10 Hz
- E. Time Schedule and Extent of Program:
- Testing Period: 1976-1977
- Experimental: 24 specimens

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.2 Fatigue Properties)

- A. Subject: Evaluation of Biaxial Low Cycle Fatigue Behavior of Metals at Elevated Temperature (A.4.2.5)
- B. Laboratory: Argonne National Laboratory
- C. Problem and Objective: Most low cycle fatigue design analysis of elevated temperature components are currently based on test data generated under uniaxial loading condition. The extent to which multi-axiality of the stress state affects the low cycle fatigue life at elevated temperature is still unresolved. The purpose of this study is to explore the effect of biaxial stress state on the low cycle fatigue behavior of materials at elevated temperature.
- D. Test Parameters:
- Material: Type 304 stainless steel (heat 9T2796)
- Specimen Type: Thin walled tubular specimens subjected to internal pressure and axial loading
- Test Temperatures: Room temperature and 593°C
- E. Time Schedule and Extent of Program:
- Testing Period: 1976-1980
- Experimental: Approximately 20 specimens will be tested per year

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.2 Fatigue Properties)

- A. Subject: Investigation of the Effect of Ultrahigh Vacuum and Other Controlled Gaseous Environments on Elevated-Temperature Low-Cycle Fatigue Behavior of Types 304 and 316 Stainless Steel (A.4.2.6)
- B. Laboratory: Argonne National Laboratory
- C. Problem and Objective: The majority of high-temperature low-cycle fatigue data of austenitic stainless steels have been generated in an air environment. Both creep and environment appear to influence the low-cycle fatigue behavior, but their relative roles are not well defined. The objective of this study is to determine the effects of high vacuum (and other gaseous environments) on the high-temperature low-cycle fatigue properties of type 304 stainless steel, to establish the regimes where corrosion or creep-fatigue interaction or both are important, to provide a better understanding of creep-fatigue damage in different environments, including, sodium, and finally to incorporate environmental effects in the creep-fatigue damage rules that are being developed.
- D. Test Parameters:
- Material: Type 304 stainless steel (heat 9T2796)
- Test Temperature: 482-593°C
- Total Strain Range: 0.5-2.0%
- Strain Rate: $10^{-2} - 10^{-6} \text{ s}^{-1}$
- Tensile Hold Times: 1 - 600 min
- Compressive Hold Times: 1 - 30 min
- E. Time Schedule and Extent of Program:
- Testing Period: 1976-1978
- Experimental: 55 specimens

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.2 Fatigue Properties)

- A. Subject: Determination of Low and High Cycle Fatigue and Creep-Fatigue Interaction Behavior of Alloy 718 (A.4.2.7)
- B. Laboratory: Idaho National Engineering Laboratory
- C. Problem and Objective: A number of critical components in the CRBRP as well as follow-on LMFBR's will be fabricated from Alloy 718 where high strength at elevated temperatures are required. The loading is often cyclic in nature and includes both low cycle and high cycle regimes as well as creep and fatigue combinations. The data base available in the literature is not sufficient for design needs. The objective of this investigation is the determination of cyclic behavior of base metal as well as welded joints in both smooth bar and notched conditions.
- D. Test Parameters:
- Material: Alloy 718 base metal given the 954°C SA plus 718/621°C duplex age heat treatment. Alloy 718 weldments given a modified heat treat (to be determined)
- Aged at 593, 649, 704, and 760°C up to 3 years
- Temperatures: Room temperature to 704°C
- Strain Levels: $\Delta\epsilon = 0.6 - 5.0\%$
- E. Time Schedule and Extent of Program:
- Time Schedule: 1974-1980 (Base Metal) 1978-1981 (Weldments)
- Experimental: 550 specimens (Base Metal) 250 specimens (Weldments)

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.2 Fatigue Properties)

A. Subject: Characterization of Crack Growth Behavior of 304 Stainless Steel (A.4.2.8)

B. Laboratory: University of California Los Angeles

C. Problem and Objective: One of the potential problems in the IHX is interstitial transport via the sodium loop. The objective of this study is to characterize the crack extension rates of type 304 stainless steel in both inert and carburizing atmospheres.

D. Test Parameters:

Material: Type 304 stainless steel, reference heat 72535

Temperatures: 650, 700, 750, 800°C

Atmospheres: Helium, $H_2 + CH_4$ with several carburizing potentials

E. Time Schedule and Extent of Program:

Time Schedule: 1973-1977

Experimental: 100 specimens

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.2 Fatigue Properties)

- A. Subject: Corrosion Fatigue of 2 1/4 Cr-1 Mo Steel in DNB Environments (A.4.2.9)
- B. Laboratory: General Electric - San Jose/Vallecitos
- C. Problem and Objective: The 2 1/4 Cr-1 Mo steel corrosion fatigue activity will provide data to account for environment influences on the design basis curve describing fatigue under the condition of the Departure from Nucleate Boiling. The CRBR evaporators operated with the conditions of DNB. The temperature oscillations associated with this condition result in a local cyclic stress with a frequency of application such that the fatigue design condition is marginal. In a water/steam evaporator environment, especially in a region where impurities will concentrate (DNB zone), the fatigue strength is likely to be lower. This uncertainty must be evaluated.
- D. Test Parameters:
- Temperature: 316°C
- Environment: Pressurized water/steam/NaOH evaporator conditions at 12.4 MPa pressure; 1-10% NaOH
- Specimen: Hourglass tapered fatigue specimen
- Loading: 1 Hz frequency, load control, fully reversed, strain monitored, strain ranges to give fatigue lives to 10⁶ cycles
- Test Material: 2 1/4 Cr-1 Mo steel, ESR, isothermally annealed + PWHT; air melt for control tests and calibration
- Number of Specimens: 50
- E. Time Schedule and Extent of Program:
- January 1976-May 1978

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.3 Weld Metal and Weldment Behavior)

- A. Subject: Low-Cycle Fatigue and Cyclic Stress-Strain Behavior of 16-8-2 ASA Weld Metal (A.4.3.1)
- B. Laboratory: Argonne National Laboratory
- C. Problem and Objective: The goal of this program is to determine the fatigue and cyclic stress-strain properties of this metal and to compare the results with existing data on type 316 stainless steel. This will allow designers to assess the suitability of this weld metal in structural components.
- D. Test Parameters:

Material: 16-8-2 weld metal

Specimen Type: Axial loaded uniform-gage cylindrical specimens

Test Temperature: 593°C (1100°F)

Strain Ranges: 0.5 to 2.0%

Tensile Hold Times: 0, 0.1, 1.0, and 10.0 hr

- E. Time Schedule and Extent of Program:

Testing Period: 1976

Experimental: 16 specimens

A.4 GENERAL MATERIAL QUALIFICATION(A.4.3 Weld Metal and Weldment Behavior)

A. Subject: Low-Cycle Fatigue Behavior of Type 308 Weld Metal (A.4.3.2)

B. Laboratory: Argonne National Laboratory

C. Problem and Objective: This program will provide the base data on type 308 stainless steel weld metal which is used to join structural components fabricated from type 304 stainless steel. The results from these tests will enable designers to assess the fatigue life capabilities of welds in relation to the base metal.

D. Test Parameters:

Material: Type 308 weld metal

Specimen Type: Axial loaded uniform gage cylindrical specimens

Test Temperature: 593°C (1100°F)

Strain Ranges: 0.5 to 2.0%

Strain Rate: $4 \times 10^{-3} \text{ s}^{-1}$

Tensile Hold Times: 0, 1, and 10 min

E. Time Schedule and Extent of Program:

Testing Period: 1973-1978

Experimental: Approximately 60 specimens

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.3 Weld Metal and Weldment Behavior)

- A. Subject: Fatigue and Creep-Fatigue Behavior of Transition Joint Pipe Weld Metals and Weldments (A.4.3.3)
- B. Laboratory: Oak Ridge National Laboratory
- C. Problem and Objective: The initial objective of this effort is to collect sufficient uniaxial data characterizing the continuous cycling and creep-fatigue behaviors of Inconel 82 and 16-8-2 weld metals in reference to selected base metals, i.e., 2 1/4 Cr-1 Mo steel, type 316 stainless steel, and Incoloy Alloy 800. This activity will then be followed by fatigue studies of composite material specimens. Limited triaxial tests may also be conducted.

D. Test Parameters:

Materials: Inconel 82 and 16-8-2 weld metals

Strain-Controlled Tests: Continuous cycling at constant strain rate
Constant strain or stress hold periods introduced each cycle

Temperature Range: 20-538°C

Specimens: Uniform gage axial and transverse to the weld direction specimen (6.35 mm diam)
Composite weld joints

E. Time Schedule and Extent of Program:

Tests Started: 1976

Experimental: 50-100 specimens of each material.

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.3 Weld Metal and Weldment Behavior)

- A. Subject: Creep and Creep-Rupture Studies of Inconel 82 Weld Metal
(A.4.3.4)
- B. Laboratory: Oak Ridge National Laboratory
- C. Problem and Objective: To determine the creep and rupture behavior of Inconel 82 weld metal for use in design of LMFBR transition joints.
- D. Test Parameters:
- Materials: Inconel 82 weld metal
- Temperatures: 454, 510, 566, 621, 677, and 732°C
- Stresses: 103 to 517 MPa (15 to 75 ksi)
- E. Time Schedule and Extent of Program:
- Testing Period: 1975-1978
- Experimental: Approximately 20 tests have been completed to date

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.3 Weld Metal and Weldment Behavior)

- A. Subject: Tensile Studies of Inconel 82 Weld Metal (A.4.3.5)
- B. Laboratory: Oak Ridge National Laboratory
- C. Problem and Objective: To determine the tensile behavior of Inconel 82 weld metal for use in the design of LMFBR transition weld joints.
- D. Test Parameters:
 - Material: Inconel 82 weld metal
 - Temperatures: 25-732°C
 - Strain Rates: 2.96×10^{-6} and $2.96 \times 10^{-4}/\text{sec}$
- E. Time Schedule and Extent of Program:
 - Testing Period: 1975-1978
 - Experimental: Approximately 30 tests have been completed to date

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.3 Weld Metal and Weldment Behavior)

- A. Subject: Tensile Properties of Transverse Weldments (A.4.3.6)
- B. Laboratory: Oak Ridge National Laboratory
- C. Problem and Objective: To determine the tensile behavior of transverse weldment specimens that contain weld metals and base metals in the gage section that are of interest for LMFBR transition joints.

D. Test Parameters:

Materials: Transverse weldments of 2 1/4 Cr-1 Mo/Inconel 82/Incoloy 800; Incoloy 800/16-8-2/316 SS; 2 1/4 Cr-1 Mo/Inconel 82/316 SS

Temperatures: 25 to 732°C

Strain Rates: 2.96×10^{-4} /sec

E. Time Schedule and Extent of Program:

Testing Period: 1976-1977

Experimental: Eight tests have been completed to date

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.3 Weld Metal and Weldment Behavior)

- A. Subject: Study of the Fracture Toughness Properties of 2 1/4 Cr-1 Mo Steel Heavy Thickness Base Material and Weldments (A.4.3.7)
- B. Laboratory: General Electric — San Jose/Vallecitos
- C. Problem and Objective: Data on the fracture toughness of 2 1/4 Cr-1 Mo steel are necessary for satisfying the intent of Appendix G (Protection Against Nonductile Fracture) of the ASME Code for LMFBR Steam Generators. Such information will determine whether current Code curves, derived for other materials, are applicable to 2 1/4 Cr-1 Mo steel base material and shell welds. The resistance to fracture, as evaluated in these tests, will be employed to determine the test temperature for component hydrostatic tests, set the precautions necessary during shipment, and quantify safe operating conditions. Prototypic heavy section base material, weld fusion, and heat-affected zone regions will be assessed to prevent brittle (low temperature) and low energy tear (high temperature) failures.
- D. Test Parameters:
- Temperatures: 24 to 510°C
- Stroke Rate: 1.5 mm/min
- Specimen: Deep-cracked ASTM E399 50.8-mm-thick Compact Tension Specimen, Charpy V-notch and tension test specimens
- Material: 2 1/4 Cr-1 Mo steel plate (full annealed + PWHT) and SMAW and SAW weldments. As-treated, and aged at 510°C for 1000 hr
- Number of Specimens: 120 CTS
500 Charpy V-notch
100 tension tests
20 drop-weight nil-ductility transition (NDT) tests
- E. Time Schedule and Extent of Program:
- July 1975–September 1978

A.4 GENERAL MATERIAL QUALIFICATION

(A.4.3 Weld Metal and Weldment Behavior)

- A. Subject: Characterization of Welds and Weldments to Provide Data Base for Developing Improved Elevated-Temperature Design Methods (A.4.3.8)
- B. Laboratory: Oak Ridge National Laboratory
- C. Problem and Objective: Modern design rules use base metal properties in weld regions. Data on weld-to-weld variability, heterogeneity within a weld, anisotropy of properties, and fracture characteristics are being obtained. Computer modeling of elastic, plastic, and creep behavior of welds based on these data are used to assess local stress and strain concentrations, as compared with large-section measurements. (This is a part of an overall program with aspects not related to structural design methods.)
- D. Test Parameters:
- Temperatures: 25-649°C
- Test Times: 1 hr (tensile), 10-50,000 hr (creep)
- Materials: Types 304, 316, 16-8-2 stainless steel welds (10-20)
made by GTA, SA, SMA processes
- E. Time Schedule and Extent of Program:
- Testing Period: 1972-1982

A.4 GENERAL MATERIAL QUALIFICATION(A.4.4 Large-Diameter Pipe and Fittings)

- A. Subject: Procure and Characterize Large-Diameter, Thin-Wall Stainless Steel Sodium Coolant Piping and Fittings Materials (A.4.4.1)
- B. Laboratory: Oak Ridge National Laboratory
- C. Problem and Objective: Large-diameter thin-wall stainless steel pipe and fittings in the size ranges needed for LMFBR sodium coolant applications are not common. Several manufacturing methods may be used, and the selection may affect the finished pipe or fitting tolerances or material properties. Characterization of features important to designers will be performed as part of the overall program.
- D. Test Parameters:
- Temperatures: 25-649°C
- Test Times: 1 hr (tensile), 100-1,000 hr (creep rupture), 1-1,000 hr (creep fatigue)
- Materials: Types 304 and 316 stainless steel, welds of types 308, 316 and 16-8-2 stainless steel (where appropriate) made by GTA and/or SA processes
- E. Time Schedule and Extent of Program:
- Procurement: 91.4-cm-diam pipe and fittings through calendar year 1978, 122-cm-diam pipe and fittings through calendar year 1980.

MAJOR TEST EQUIPMENT

A.4 GENERAL MATERIAL QUALIFICATION

MAJOR TEST EQUIPMENT

A.4 GENERAL MATERIAL QUALIFICATION

Laboratory: Oak Ridge National Laboratory

A. Principal Mechanical Properties Laboratory

Creep Testing Machines. See Table I

Fatigue Testing Machines.

- (3) Complex load; pneumatic and hydraulic loads of ± 6000 lb, air environment, 1800°F temperature limit
- (5) Fatigue; hydraulic loading $\pm 10,000$ lb, $\pm 55,000$ lb, $\pm 110,000$ lb, air environment, 1800°F temperature limit
- (2) Strain cycle; air pressure on 50 in.² piston, 1800°F temperature limit

Tensile Testing Machines.

- (4) Instron; screw-type, 10,000-lb capacity, air and vacuum environment, 2000°F temperature limit
- (1) Baldwin; hydraulic, 120,000-lb capacity, air environment, 2000°F temperature limit.
- (2) Axial torsion

Toughness Testing Machines.

- (1) Instrumented Charpy impact; 240 ft-lb capacity
- (1) Instrumented Charpy slow-bend; 4000-lb capacity
- (1) Charpy specimen precracking
- (1) Closed loop, servo-hydraulic Tinius-Olsen; 60,000-lb capacity
- (1) Closed loop, servo-hydraulic MTS; 22,000-lb capacity
- (1) Screw-driven Instron tensile; 10,000-lb capacity
- (1) Drop-weight impact

Laboratory: Oak Ridge National Laboratory (Continued)

TABLE I. CREEP TESTING MACHINES

Machine Type	Number of Machines	Loading Method	Wt. Pan Capacity (lb)	Environment	Max. Temperature (°F)
Creep	76	12:1 LA ^a	500	Air	2200
Creep	9	12:1 LA	500	Air	1800
Creep	2	4:1 LA	250	Air	1500
Creep	4	12:1 LA	250	Air	2200
Creep	3	12:1 LA	350	Air	1800
Creep	11	20:1 LA	500	Air	2200
Creep	1	4:1 LA	500	Air	2200
Creep	1	15.88:1	200	Air	1800
Creep	14	10:1 LA	500	Air	1800
Creep	14	Dead Load	500	Air	2200
Creep (Skutt Furnace)	20	6.5:1 LA	500	Air	2300
Creep	10	12:1 LA	200-250	10 ⁻⁸ Vac.	2000
Creep	6	Dead Load	150	10 ⁻⁷ Vac.	3000
Creep	2	Dead Load	500	Vac.	4000
Creep	1	DL Creep	250	Vac.	4000
Creep	10	12:1 LA	500	Inert Gas	2200
Creep	2	10:1 LA	500	Inert Gas	1800
Cyclic Creep	5	12:1-6:1	3-6000	Air	1800
Relaxation	1	Hydraulic			
Creep Plasticity	2				

^aLever Arm.

Laboratory: Oak Ridge National Laboratory (continued)B. Auxiliary Mechanical Properties Laboratory No. 1.Creep Testing Machines

- (22) 12:1 lever-arm ratio, 500-lb capacity, air environment, 2000°F temperature limit
- (8) 12:1 lever-arm ratio, 500-lb capacity, environmental control, 2000°F temperature limit
- (6) Dead load, 240-lb capacity, air environment, 2000°F temperature limit
- (9) Tube burst with maximum system pressure of 10,000 psi argon, argon environment, 1800°F temperature limit

Fatigue Testing Machines

- (5) Strain cycle; air pressure on 50 in.² piston, environmental control, 2000°F temperature limit

C. Auxiliary Mechanical Properties Laboratory No. 2.Fatigue Testing Machines

- (3) Gilmore; Brew vacuum furnace (10^{-7} torr) or inert gas, 4000°F, Astro clamshell three-zone furnace, 5 in. bore, 24 in. length, 2200°F, induction furnace.
Load: $\pm 25,000$ lb; position, ± 5 in.; strain control, $\pm 20,000 \times 10^{-6}$ in.
Frequency: 50 Hz maximum; ram speed, 200 in./min maximum
- (1) MTS air-circulating furnace; 14 × 14 × 18 in., 1600°F
Load: $\pm 150,000$ lb; position, ± 3 in.
Frequency: 120 Hz maximum; speed, 50 in./min maximum
- (1) MTS Precracker; induction heat and cryogenic to -150°F
Load: $\pm 10,000$ lb; position, ± 3 in.
Frequency: 120 Hz; no strain control
- (1) Gilmore axial torsion (simultaneous and independent) 18-in. clamshell Marshall furnace; three zone, 4-in. bore, 1800°F
Axial, Load: $\pm 25,000$ lb; position, ± 5 in., strain controlled
Frequency: 50 Hz maximum; speed, 200 in./min
Torsion: ± 2500 in.-lb maximum on any amount of rotation

Laboratory: Oak Ridge National Laboratory (continued)

(1) Gilmore; high strain rate

Load: $\pm 20,000$ lb; position, ± 5 in.; strain control

Frequency: 100 Hz; speed, 4000 in./min

Furnace: air, vacuum, or inert gas, 3640°F, 20,000°F/min
heating rate

Tensile Testing Machines.

(3) Tinius Olsen; open-loop hydraulic, 30,000, 60,000, and 120,000 lb

(1) Instron; 10,000 lb; load, 50 gm to 10,000 lb, crosshead speed,
0.002 to 2 in./min

(1) Tensile; 300,000-lb load

Torsion Machines;

(1) 10,000 in.-lb maximum; 360-deg rotation

MAJOR TEST EQUIPMENT

A.4 GENERAL MATERIAL QUALIFICATION

Laboratory: Idaho National Engineering Laboratory

A. Fatigue Testing Machines.(4) MTS low-cycle fatigue frames;

Load capacity; (1) 88,964 N (20,000 lb), (3) 44,482 N (10,000 lb); strain, load, or displacement control with hold times; air environment, room temperature to 1600°F

(2) Satec high-cycle frames; load control only, 22,241 N (5000 lb), air environment, room temperature to 1400°F(1) R. R. Moore rotating beam (up to 10,000 rpm); load control (200 in-lb), air environment, room temperature to 1400°FB. Creep Testing Machines.(3) Satec(1) Arcweld frames with extensometry

Load capacity: 53,378 N (12,000 lb)

Air environment: room temperature to 1600°F

C. Tensile Testing Machines.(1) Instron with high-temperature extensometry

Load capacity: 88,964 N (20,000 lb)

Air environment

MAJOR TEST EQUIPMENT

A.4 GENERAL MATERIAL QUALIFICATION

Laboratory: Hanford Engineering Development Laboratory

See Tables I, II, and III, A.2 Irradiation Effects — Mechanical
Properties Structural Materials

MAJOR TEST EQUIPMENT

A.4 GENERAL MATERIAL QUALIFICATION

Laboratory: Argonne National Laboratory

A. Low-Cycle Fatigue Testing Machines.

- (1) Load-controlled servo-hydraulic fatigue testing machine with induction heating
- (2) Strain-controlled servo-hydraulic fatigue testing machines with induction heating and axial extensometry
- (1) Strain-controlled (internal pressure plus axial loading) servo-hydraulic fatigue testing machine with diametral and axial extensometry and induction heating
- (1) Strain-controlled servo-hydraulic fatigue testing machine with induction heating, diametral extensometry, and an ultra-high vacuum chamber

B. Crack-Growth Rate Machine

- (1) Load-controlled servo-hydraulic testing machine with a furnace and traveling microscope

ERDA-76/146
 Distribution
 Category UC-79b, -h, -k

INTERNAL DISTRIBUTION

1-2. Central Research Library	32. G. G. Fee
3. Document Reference Section	33. W. O. Harms
4-8. Laboratory Records Department	34. W. R. Martin
9. Laboratory Records, ORNL RC	35. C. J. McHargue
10. ORNL Patent Office	36-45. P. Patriarca
11-20. C. R. Brinkman	46. D. B. Trauger
21-30. J. M. Corum	47. J. R. Weir, Jr.
31. R. G. Donnelly	

EXTERNAL DISTRIBUTION

- 48-67. ERDA DIVISION OF REACTOR DEVELOPMENT AND DEMONSTRATION,
 Washington, D. C. 20545
 Chief, Materials and Chemistry Branch (10)
 Chief, Materials and Structures Branch (10)
- 68-70. ERDA OAK RIDGE OPERATIONS OFFICE, P. O. Box E, Oak Ridge, TN
 37830
 Research and Technical Support Division
 Director, Reactor Division
- 71-357. ERDA TECHNICAL INFORMATION CENTER, Office of Information
 Services, P. O. Box 62, Oak Ridge, TN 37830
 For distribution as shown in TID-4500 Distribution Category,
 UC-79b (Fuels and Materials Engineering Development);
 UC-79h (Structural Materials Design Engineering);
 UC-79k (Components)