ORNL-5369

DATE ISSUED MAR 30 1978

Long-Range Program Plan for High-Temperature Structural Design

[redacted]

Printed in the United States of America. Available from
the Department of Energy,
Technical Information Center
P.O. Box 62, Oak Ridge, Tennessee 37830
Price: Printed Copy $6.50; Microfiche $3.00

ORNL-5369
Dist. Category UC-79,
-79e, -79h, -79k

Contract No. W-7405-eng-26

UNITED STATES BREEDER REACTOR PROGRAM

LONG-RANGE PROGRAM PLAN
FOR
HIGH-TEMPERATURE STRUCTURAL DESIGN

December 1977

Compiled and Published by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
DEPARTMENT OF ENERGY

CONTENTS

PREFACE

This Long-Range Program Plan for High-Temperature Structural Design was prepared to describe the activities under way or planned to establish a suitable high-temperature structural design technology for the U.S. Breeder Reactor Program. Responsibilities for carrying out the activities, which are sponsored by the Materials and Structures Branch of the Department of Energy's Division of Reactor Research and Technology, have been assigned to Oak Ridge National Laboratory, Westinghouse Advanced Reactors Division, and Atomics International.

The unified nature and the continuing coordination of the various program activities are ensured by a special Subgroup on High-Temperature Structural Design, which has been established by RRT. The subgroup membership consists of:

J. M. Corum, Chairman	Oak Ridge National Laboratory
D. S. Griffin	Westinghouse Advanced Reactors Division
R. I. Jetter	Atomics International
C. M. Purdy	DOE/RRT

It was under the auspices of the Subgroup on High-Temperature Structural Design Program Coordination that this program plan was prepared.

A second group established by RRT, the Working Group on High-Temperature Structural Design, has as one of its charters the task of establishing priority high-temperature structural design technology needs and of recommending base technology program activities to satisfy these needs – based both on near-term project requirements and on requirements for longer-range improvements in the base technology. These needs and priorities have been considered in the plan presented herein.

As formulated, the plan is consistent with current 189a documents at ORNL, WARD, and AI. In the long range, we have attempted to be consistent with realistic projections of funding levels. We have assumed neither drastic increases nor decreases in funding for the various tasks.

To be successful, any planning effort must be dynamic, and so we are continuing to assess our plans and activities to judge their adequacy and their responsiveness to identified needs. As new ideas are developed and as needs, priorities, program directions, and funding levels change, our plan will change. We anticipate that this document will be updated at least biennially.

Finally, it is our hope that both designers and technologists working in high-temperature structural design and related areas will find this plan both useful and informative. We invite your comments and criticisms, and we urge you to bring to our attention any significant needs or problem areas that are not addressed.

J. M. Corum
Oak Ridge National Laboratory

1. INTRODUCTION AND OVERVIEW

1.1 Program Objectives

In the context of this program plan, high-temperature structural design refers to that technology required for the design of metal components that operate in the temperature regime where time-dependent effects are significant. By implication, Sect. III of the ASME code defines this regime to begin at a temperature of 427°C (800°F) for the austenitic stainless steels and 371°C (700°F) for the ferritic steels, these being the limits of applicability of the low-temperature code. In addition to the failure modes considered for low-temperature service, it is necessary at the higher temperatures to guard against failure by creep rupture, creep-fatigue interaction, creep-enhanced ratchetting, creep buckling, and environmental enhancement of low-temperature modes.

Two ingredients are required to guard against these high-temperature failure modes. First, we must have a sufficient knowledge and understanding of the high-temperature behavior of both materials and structures to reliably predict the time-dependent inelastic response of a design component subjected to specified thermal and mechanical loading histories. Second, we must have experimentally verified design criteria that are commensurate with the accuracy of our predictive methods. Together, the predictive methods and associated criteria must provide an adequate margin of safety against rupture or excessive deformations by the various identified failure modes.

The program described herein is concerned with developing and validating the high-temperature structural design technology required for breeder reactor components and with the effective transfer of that technology to component designers. The primary objective of the program is thus to establish, and transfer to designers, a rationally sound and experimentally verified high-temperature structural design technology that will assure freedom from structural failure. More specific objectives are:

- To provide a technology for assuring that component designs will be both safe and reliable during their design lifetimes.
- To provide the designer with improved methods, procedures, tools, and criteria that are more economical to apply, are not overly conservative, and will allow increased component design flexibility, thus resulting in better and cheaper component designs and, ultimately, in increased flexibility in plant design and operation.
- To provide methods for better definition of design margins (against identified failure modes).
- To experimentally verify and validate each aspect of the technology.
- To improve reliability and confidence levels of component designs.
- To provide design methods, and thus designs, that are more defensible.
- To provide an improved technological basis for licensing.

The consequences of not having a strong, well-coordinated, national high-temperature structural design program effort can be stated as the converse of these objectives. Without such a program, not every aspect of the technology will have a rationally sound and experimentally verified basis; design methods will continue to be expensive, time consuming, and overly conservative; design options and flexibility will be significantly limited; design margins, although believed adequate, will continue to be ill-defined; demonstrable reliability and confidence levels will be lower than desired; and, finally, gaps will continue to exist in some areas of the technology, while other areas will not be adequately validated. The prospects of these consequences provide a strong impetus for the program described in this area.

Although the High-Temperature Structural Design (HTSD) Program was developed and implemented as a part of the overall U.S. Breeder Reactor Program, many of its aspects are equally applicable to other energy technologies being pursued by the Department of Energy. Included are the high-temperature gas-cooled reactor, fusion energy devices, coal conversion plants, and solar energy conversion equipment. All operate at high temperatures and all will directly benefit from the results and findings of this program.

1.2 Program Elements (189a Tasks)

Consistent with the objectives described in the previous section, the High-Temperature Structural Design Program has four program elements, or tasks, as follows:

- HTSD – Development (189a OH048)
- HTSD – Validation (189a CW063)
- HTSD – Application (189a CW138)
- HTSD – Piping (189a SA020)

The emphasis in the first three tasks is on a technology generally applicable to all breeder reactor 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 task deals exclusively with piping.

The Development task, which is the largest of the four, was initiated at the Oak Ridge National Laboratory in 1969. The objective of this task is to develop verified high-temperature structural design methods and criteria applicable to breeder reactor system components that operate at temperatures in the creep range and to assist in making the technology available to component designers in the form of design analysis tools, guidelines, codes, and standards.

The Validation task, which is the second largest of the four, was initiated at the Advanced Reactors Division of Westinghouse (WARD) in 1972. Its objective is to experimentally validate high-temperature structural design methods and criteria used in the design of breeder reactor components operating in the thermal creep range.

The Application task, which, along with the Piping task, is the smallest and newest of the four, was initiated at WARD in 1975. Its objective is to provide the designer with qualified analysis methods, design procedures, design limits and criteria, and the guidance required to assure their proper application. The emphasis here is on technology transfer as opposed to development of the basic technology.

Finally, the Piping task was initiated at Atomics International (AI) in 1975. The objective of the Piping task is to assess the applicability of current technology to the design of high-temperature piping systems, to survey current design and operating experience, and to provide a proven and demonstrated design methodology for assuring a high level of structural integrity for piping comparable to that for other high-temperature components.

Subsequent chapters of this program plan describe each of the four tasks in detail.

1.3 Background

Although most aspects of high-temperature structural design and the attendant time-dependent failure modes have been recognized for many years and, to some extent, accounted for in the design of fossil plants, chemical processing equipment, gas turbines, etc., it became apparent with the design of the Fast-Flux Test Facility (FFTF) in the late sixties that liquid-metal-cooled fast breeder reactors (LMFBRs) presented unique structural design problems. These were problems which were not so significant in other high-temperature equipment and which did not require consideration in the design of light-water reactor systems, for which a considerable structural design technology had developed.

The unique problems in LMFBRs arise primarily from the combination of relatively high operating temperature, large temperature rise through the reactor core, and good heat transfer characteristics of the sodium coolant. Changes in reactor power levels, including shutdowns and scrams, can result in large and sudden changes in the sodium coolant outlet temperature, and because of the good heat transfer characteristics of the sodium, these changes can be imposed on the major system components. Thus, each component can be subjected to frequent time-varying thermal loadings, both in the form of gross thermal-expansion-induced loadings and in the form of more localized loadings caused by through-the-wall thermal gradients. In either case, large cyclic stresses and deformations can result in yielding of the component material and thus in residual stresses, which relax due to subsequent creep.

From this brief overview of the possible response of a structural component subjected to thermal loadings, it is apparent that repeated loadings could cause ratchetting, creep damage, and fatigue damage. Indeed, the problems of ratchetting and creep-fatigue damage[1] were identified in the early FFTF design stages as having significant potential consequences. Likewise, since operating pressures are low and thermal gradient effects often dictate thin walls, creep buckling was recognized as a pertinent potential problem to be guarded against.

In summary, because of the special characteristics of LMFBR structural components and of the time-varying thermal and mechanical loadings to which they are subjected, the potential exists in these components for the occurrence of each of the time-dependent failure modes discussed earlier – creep rupture, creep fatigue, ratchetting, and creep buckling.[2] To guard against these, a new high-temperature structural design technology became a necessity.

This need was recognized early in the LMFBR development program, and programs and activities were initiated by the U.S. Atomic Energy Commission, the ASME code committees, and the Pressure Vessel Research Committee to produce the necessary technology to support high-temperature structural design. The HTSD Development task at ORNL was initiated in this early period. Also, activities were undertaken which resulted in the preparation of several suggested design criteria documents. The most historically significant of these was a Westinghouse document, FRA-152,[3] which was used for the early stages of FFTF design. The basic framework and content of FRA-152 were worked out by a committee of AEC LMFBR program contractors and consultants. Many of the members of this committee were also members of ASME code groups responsible for the development of the Code Case 1331 (and later, Code Case 1592) series of

1. At about the same time that the FFTF preliminary design was under way, a fairly substantial body of materials data on type 304 stainless steel and some other alloys became available showing that creep-fatigue interaction was a real and significant high-temperature material characteristic. That is, the combined damage of creep and fatigue occurring simultaneously could be worse than either acting alone.

2. Although failures in high-temperature fossil plant equipment, sodium system components, and LMFBRs operating in foreign countries are often attributed to a variety of interacting factors, failures can be cited that were caused primarily by each of the time-dependent failure modes listed. Transition joints fail after several years in service, apparently due to creep or creep-fatigue damage. Thermally induced fatigue cracks have been found in such components as high-temperature steam headers. Mixing tees fail by creep fatigue. Examples exist of excessive thermal ratchetting. And, finally, a structural failure in one of the IHXs of the French Phenix reactor was attributed to creep buckling.

3. *Interim Supplementary Structural Design Criteria for Elevated Temperatures,* FRA-152, rev. 3 (Nov. 6, 1970).

criteria documents. Not surprisingly, much of the philosophy and criteria in FRA-152 also appeared in the early code cases.

For the first time, these criteria recognized time explicitly in design. Primary stress limits utilized the summation of time fractions (the ratio of the expected time at a given condition to the allowable time at that condition) to assess design adequacy. Strain limits were provided to limit ratchetting strains, creep-fatigue criteria were adopted, and creep-buckling limits were provided.[4] To supplement these criteria and to provide guidance for their application, RDT Standard F9-1T[5] was published. It included detailed guidelines for performance of the inelastic analyses that could be required by the criteria.

With these early requirements and guidelines came experience as well as a more focused development and validation effort. Materials programs were expanded to provide the necessary mechanical properties data; the HTSD Validation task was initiated, and then the Application and Piping tasks; the required structural analysis computer codes were developed and became widely available; and the technology continued to be improved and expanded. As a result we have in place today in the United States a substantial high-temperature structural design technology, which is briefly outlined in the following section.

1.4 Current Status of High-Temperature Structural Design Technology

The years since 1969 have seen a rapid development and expansion of a high-temperature structural design technology tailored to the emerging needs of breeder reactor component designers. The basic elements of a technology are now in place. Included are:

- implemented design criteria and guidelines, including some simplified methods,
- inelastic analysis guidelines,
- structural analysis computer codes,
- some experimental verification and validation of the technology (from materials and structures tests),
- a minimum mechanical properties data base,
- a nucleus of experienced designers in vendor organizations.

Each of these is considered in more detail on the following pages.

First, criteria for class 1 components are now given in ASME Code Case 1592.[6] These criteria are augmented by RDT Standard F9-4T.[7] Guidelines for applying the rules and procedures are provided in RDT Standard F9-5T.[8] Included in these documents are some simplified rules and methods for satisfying the strain limits and creep-fatigue rules. Generally these rules and methods make use only of the results of

---

4. *Criteria for Design of Elevated-Temperature Class 1 Components in Section III, Division 1, of the ASME Boiler and Pressure Vessel Code,* American Society of Mechanical Engineers (May 1976).

5. RDT Standard F9-1T, *Requirements for Nuclear Components at Elevated Temperatures (Supplement to ASME Elevated-Temperature Code Case 1331),* U.S. Atomic Energy Commission (April 1973).

6. *Case 1592-10, Class 1 Components in Elevated-Temperature Service, Section III, Division 1,* American Society of Mechanical Engineers (1977).

7. RDT Standard F9-4T, *Requirements for Construction of Nuclear System Components at Elevated Temperatures (Supplement to ASME Code Cases 1592, 1593, 1594, 1595, and 1596),* U.S. Atomic Energy Commission (September 1974).

8. RDT Standard F9-5T, *Guidelines and Procedures for Design of Nuclear System Components at Elevated Temperature,* U.S. Atomic Energy Commission (September 1974).

elastic analysis. However, their applicability is limited because they have been shown to be valid only for a restricted class of component geometries and loadings.

To perform the detailed inelastic analyses required if the simplified rules and methods cannot be utilized, suitable computer codes must be available, and mathematical descriptions of the inelastic material response to multiaxial time-varying loads must be available as input to the codes. These mathematical descriptions, called constitutive equations, have been developed for types 304 and 316 stainless steels and for 2¼ Cr–1 Mo steel, and guidelines are included in RDT Standard F9-5T for their use. Likewise, computer codes, which have incorporated these guidelines, are generally available. Thus, inelastic design analyses, which a few short years ago were considered practically impossible, are now performed almost routinely.

A question arises, of course. How valid are these predictions? Many of the aspects of inelastic material behavior incorporated into the constitutive equation guidelines have been experimentally verified, and a limited number of high-temperature structural tests have produced data which generally compare reasonably well with analysis predictions.

The implementation of this technology requires a significant mechanical properties data base, both as a basis for establishing the various failure criteria and as input to the design analyses. Programs to generate these required data are coordinated with the HTSD Program tasks described herein, and they have resulted in the generation of at least a minimum data base, which is furnished to the designer in the *Nuclear Systems Materials Handbook.*[9]

The ongoing mechanical properties activities sponsored by the Department of Energy's Division of Reactor Research and Technology are summarized in Table 1.1 for the breeder reactor materials of

9. *Nuclear Systems Materials Handbook,* Hanford Engineering Development Laboratory.

Table 1.1 Mechanical properties test efforts closely related to high-temperature structural design tasks

Type of data	304 SS	316 SS	2¼ Cr–1 Mo	Alloy 800	Alloy 718	Weldments
Stress strain	ORNL[a] ANL	ORNL ANL	ORNL UCLA[d]	ANL[b]	ORNL INEL	INEL[c] (718) ANL (16-8-2) ORNL (1-82, 16-8-2, 308) HEDL[e] (308)
Creep, creep-rupture, relaxation	ORNL UCLA	ORNL	ORNL UCLA	W-Tampa[f]	ORNL INEL	INEL (718) ORNL (1-82, 308) HEDL (308)
Fatigue, creep-fatigue	ANL	ANL	ORNL GE[g]		INEL	INEL (718) ANL (16-8-2, 308) ORNL (1-82, 16-8-2)
Fracture toughness, crack growth	HEDL ANL UCLA	HEDL	HEDL GE	HEDL	HEDL	HEDL (308, 800, 718, 2¼ Cr–1 Mo) GE (2¼ Cr–1 Mo)
Environmental effects (sodium)	ANL WARD	ANL WARD	ORNL ANL GE		WARD[h]	

[a]Oak Ridge National Laboratory.
[b]Argonne National Laboratory.
[c]Idaho National Engineering Laboratory.
[d]University of California at Los Angeles.
[e]Hanford Engineering Development Laboratory.
[f]Westinghouse.
[g]General Electric.
[h]Westinghouse Advanced Reactors Division.

interest.[10] This table shows the types of pertinent data being generated and by what organization. Under weldments, only filler metals are listed; a variety of base–filler metal–weld process combinations are involved. There are obvious gaps in the table, and in some cases the activity at a given location is very small.

Finally, not the least in importance is the nucleus of experienced designers in vendor organizations who are familiar with the various aspects of the existing high-temperature structural design technology and who have developed an expertise in the application of the technology. Feedback from these designers serves to help identify remaining problem areas and needs and to further focus the base technology activities.

1.5 Remaining Problem Areas and Needs

Despite the existence of an in-place and usable technology, problem areas and needs do remain. In broad categories, some of the more significant of these include:

- weldments,
- piping,
- creep-fatigue criteria,
- limited use of inelastic analysis,
- lack of simplified methods,
- all materials are not covered by the criteria and guidelines,
- large material variability,
- limited materials data base,
- incomplete validation.

Each of these categories is discussed on the following pages.

The properties of weldments are not generally taken into account, neither in the criteria nor in the input to design analyses. Yet, our general experience tells us that we can expect a high percentage of any failures that occur to be in, or near, weldments. This, then, represents a significant gap in the technology.

Because of the thin walls and geometrical complexity of most high-temperature LMFBR piping systems and because of the complex loadings imposed on specific piping components (both gross thermal expansion loads, etc., and more localized discontinuity and thermal loadings), the application of the existing high-temperature structural design technology to piping is not as straightforward as it is to some other components. Because of the approximate design procedures that must consequently be utilized and because there is concern that all of the variables or mechanisms that affect the system's integrity or reliability may not have been properly accounted for, design methods for piping need special attention.

Time-dependent failure criteria for creep and fatigue damage represent a particularly important problem. A recent interpretive report[11] by experts in the area identified a number of shortcomings in our present creep-fatigue procedures. Although we believe these procedures to be adequately conservative, they are not based on an adequate understanding of the damage that occurs nor on an understanding of the proper measures to be used for counting and assessing that damage. As a result, the procedures are largely

---

10. *Summary of U.S. LMFBR Programs on High-Temperature Structural Design and Associated Materials Testing,* ERDA-76/146, compiled by Oak Ridge National Laboratory (October 1976).

11. L. F. Coffin, Jr., et al., *Time-Dependent Fatigue of Structural Alloys,* ORNL-5073 (January 1977).

empirical, they do not correlate equally well with data for different materials, and they have not been adequately verified for actual design loading conditions. A basic and comprehensive effort is thus required in the creep-fatigue area.

Inelastic analysis methods, though practical in relatively simple situations, are cumbersome, expensive, and time-consuming. Thus, although Code Case 1592 implies that inelastic analyses are to be frequently used for satisfying the strain limits, creep-fatigue criteria, and buckling rules, the use of detailed inelastic analyses is, in fact, avoided in the majority of design situations because of the limitations cited above. This, then, is a problem area.

Because detailed inelastic design analyses can be performed in only a critically few cases, designers must resort to simplified analysis methods for screening purposes and for many routine design situations. Unfortunately, generally applicable simplified methods are not readily available. Most of the methods in use are limited in their applicability, and they are often excessively conservative. Thus, improved simplified methods are an important need.

All materials of interest are not covered by the criteria and guidelines. For example, creep-fatigue rules for 2¼ Cr–1 Mo steel have not yet been included in Code Case 1592. Constitutive equation guidelines have not been developed for alloys 800 and 718. Going back to the first problem area listed, weldment filler metals are not covered. The technology must be extended to these and other materials which may be identified in the future.

Material variability is a particular concern because of the ill-defined effect that it might have on expected design margins. As an example of the variability to be expected, some 20 separate heats of type 304 stainless steel were tested at ORNL, and it was found that at 593°C (1100°F) the yield strengths varied by at least ±25% of the mean, steady-state creep rates varied by as much as an order of magnitude, and the total creep strain at any given time and stress level could vary by as much as a factor of ±2 about the mean. Yet, design analyses generally utilize a single material representation (stress-strain curve, creep law, etc.) to represent all heats and product forms of type 304 stainless steel. The variability needs to be better defined; sensitivity studies need to be carried out to determine the possible effects on design margins; and, perhaps, steps need to be taken to reduce the variations to acceptable limits.

The data on which the high-temperature structural design technology is based is relatively limited. First, most of it comes from accelerated testing in which stress levels, strain ranges, and strain rates are much higher than those to be encountered in design. And, of course, the test times are much shorter than the design life. Second, many of the correlations necessary to implement the various inelastic analysis options permitted by the guidelines of RDT Standard F9-5T are not yet available, even for type 304 stainless steel. And third, environmental effects are not fully known.

Finally, validation of the technology is incomplete. Many of the deformation and failure responses of the materials of interest have not been adequately explored under realistic nonradial multiaxial loading and temperature histories. An insufficient number of high-temperature structural tests have been performed to quantitatively establish the kind of agreement that can be expected between inelastic analysis predictions and experimental results. And we do not have comparisons of either our material behavior descriptions or our structural analysis predictions with experimental results for times approaching those of interest in design. A completely validated technology will require that these deficiencies be corrected.

In the above discussion, some of the more significant needs and problem areas were addressed in a general way. The formulation of the overall program described in this plan and of the plans of action for each individual task and subtask addresses these and other general needs. However, to assure that more specific needs are identified and addressed to the extent possible within funding limitations, an RRT Working Group on High-Temperature Structural Design has developed a detailed list of needs, which is periodically updated. The working group consists of representatives of reactor and componet manufacturers and of architect-engineering firms as well as representatives of the base technology tasks. Thus, the needs list prepared by the working group reflects both needs associated with application of the technology and needs associated with strengthening the technology.

Although the needs list prepared by the working group is too long and detailed to be included here, it will be informative to present a condensed version of that list (see Table 1.2). In addition to the identified needs, the table shows under which program task each need is being addressed or is to be addressed, in accordance with the plans presented in the subsequent chapters.

It should be emphasized that although one or more of the tasks may be addressing a given need, the corresponding effort may be small. With limited resources, each task of the overall HTSD Program must be focused primarily on a critically few needs having highest identified priorities. The RRT Working Group on

Table 1.2. Condensed version of list of specified needs identified by RRT Working Group on High-Temperature Structural Design

Identified need	Corresponding program task addressing need[a]
Verified constitutive equations	D, V
Validated analysis methods	D, V, A
Structural tests	D, V
Failure criteria	
Basic studies	D, V, A
Creep rupture	D, V, A
Creep fatigue	D, A, P
Buckling	A, V
Assessment of margins	D, A, P
General simplified methods	D, A
Piping	
Elbow ratchetting	V, P, A
Clamps	P
High-temperature stress indices	P
Simplified system analysis	P
Special fittings	P
Transition joints	D
Piping – specific criteria	A, P
Methods and criteria for weldments	D, V
Guidelines for specific components	A
Materials	
Guidelines for data extrapolation	D
Guidelines for treating cold work	
Codes and standards	
Core structures	D, A
Class 2 and 3 components	A
Improvements for class 1	A

[a]D = HTSD – Development (ORNL)
V = HTSD – Validation (WARD)
A = HTSD – Application (WARD)
P = HTSD – Piping (AI)

High-Temperature Structural Design has input to these priorities, and both the needs and priorities are frequently reviewed and adjusted to assure maximum responsiveness of the program tasks to the stated objectives.

1.6 Outline of Subsequent Chapters

The remaining four chapters of this program plan document describe each of the four HTSD Program tasks in a unified manner. Chapter 2 presents the Development task; Chapter 3, the Validation task; Chapter 4, the Application task; and Chapter 5, the Piping task.

In each case, the overall task objective, background, and plan of action are first presented. As a part of the plan of action, key milestones for the task as a whole are provided. Following these initial sections, each individual subtask is presented in detail. Again, the objective, background, and plan of action are given, and, as a part of the plan of action, milestones for the subtask are provided.

Since this is meant to serve as a long-range plan, the milestones generally extend into the 1980s. It should be emphasized, however, that this document is also intended to be a dynamic and changing plan. Thus, although the plans and milestones for the first year or two are reasonably firm, the longer-term plans are based on currently identified needs and projected funding levels. These will surely change with the passage of time, and future revisions to this document will reflect those changes.

2. HIGH-TEMPERATURE STRUCTURAL DESIGN – DEVELOPMENT

(Oak Ridge National Laboratory 189a OH048)

2.1 Introduction and Scope

2.1.1 Objective

The purpose of this task is to develop *verified* high-temperature structural design methods and criteria applicable to LMFBR and other reactor system components that operate at temperatures in the creep range and to assist in making the technology available to component designers in the form of design analysis tools, guidelines, codes, and standards. The task is multifaceted, embracing the areas of material testing, mathematical descriptions of material response (constitutive equations), inelastic design analysis methods, criteria and rules to preclude structural failures, and, finally, high-temperature structural testing. Both detailed and simplified analysis procedures and criteria are addressed.

Two objectives are being simultaneously pursued by the program. In addition to the development of the required technology as an end product, interim needs for structural design guidance, methods, and criteria are met on a continuing basis. In the initial phases of the task, existing knowledge concerning material behavior, constitutive theories, structural analysis methods, and design rules and criteria were exploited to help meet interim design requirements and identify task activities aligned with the twofold objective. Thus, the activities established for the near term naturally lead toward those for the long term.

The ultimate goal is a theoretically consistent and experimentally verified technology. The benefits of such a technology will include (1) improved component reliability and confidence levels, (2) more economical and defensible design procedures, (3) an improved technological basis for licensing, and (4) increased flexibility in plant design and operation.

2.1.2 Background

Early in the design of the FFTF, potential structural design problem areas were identified which stemmed from the combination of relatively high operating temperature, large temperature rise through the reactor core, and frequent thermal transients. Thermal ratchetting and creep-fatigue damage were of particular concern, and it was recognized that the existing structural design methods and criteria,[1] which were developed for light-water reactor needs, did not provide an adequate basis for the design of LMFBRs. It was from this early recognition of the special structural design needs for LMFBRs that the HTSD Development program was initiated in 1969.

From the beginning, it was felt that the development of an adequate high-temperature structural design technology would require a knowledge and understanding of essential features of inelastic material behavior and that the ability to predict inelastic structural behavior resulting from time-varying thermal and mechanical loadings should be an essential ingredient of that technology. The initial development effort was thus divided into two significant parts:

- development and evaluation of analysis methods for predicting inelastic structural behavior,
- development and evaluation of design rules and criteria to preclude structural failures.

1. Throughout this chapter, criteria refer to those correlations that describe material failure (by cracking or rupture) and/or to design rules aimed at precluding structural failure (by excessive deformations, cracking, or rupture).

Two additional parts – the development and evaluation of simplified methods and the development of design methods for weldments – make up the current task, as shown diagrammatically in Fig. 2.1. Because of the special problems introduced by weldments, including the fact that they represent special classes of materials differing from the base alloys, this part of the task is essentially a repeat of the other parts, but with the focus on weldments.

An additional important point recognized in the formulation of the Development task is that the effort would necessarily involve a relatively large experimental undertaking. Uniaxial and multiaxial exploratory materials tests would be required for formulating constitutive equations and failure criteria, and high-temperature structural tests would be required to verify analysis methods and design rules to preclude structural failures.

The task is currently divided into six technical subtasks as follows:

A. Constitutive equations for inelastic design analysis

B. Inelastic structural tests and analyses

C. Design criteria and rules for time-dependent deformation and failure

D. Simplified design methods

E. Thermal ratchetting tests

F. Structural design methods for weldments

The relation of these six subtasks to the four main parts of the task is depicted in Fig. 2.1.

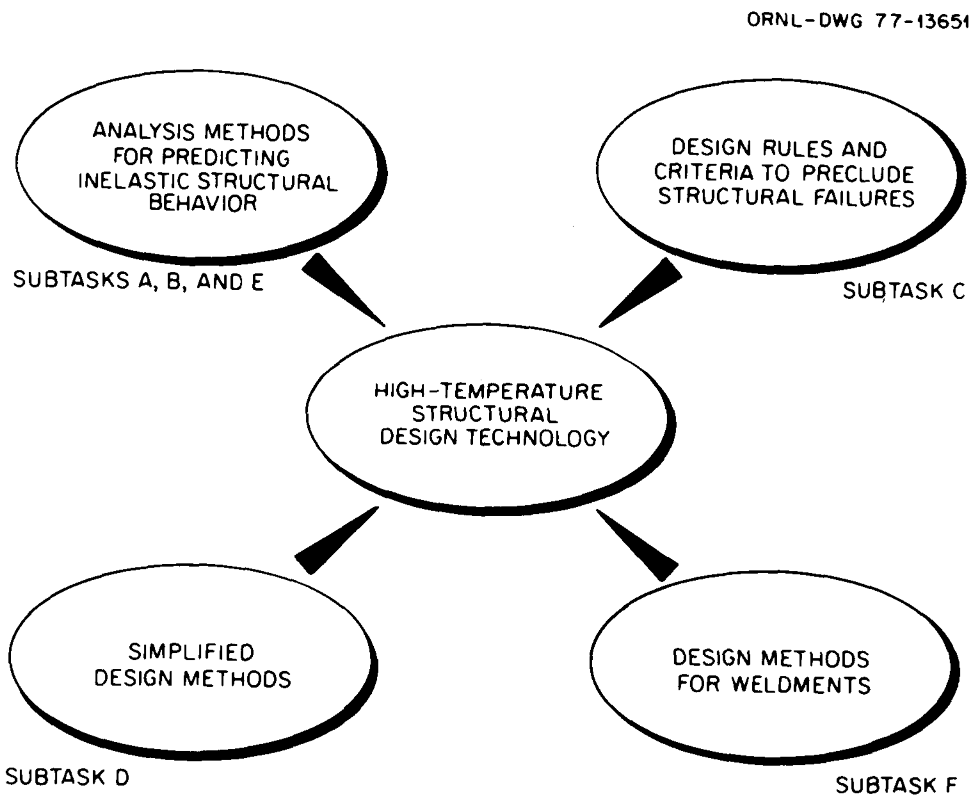


Fig. 2.1. Simplified diagram showing makeup of current development task.

Figure 2.2 diagrammatically shows the various interrelationships between subtasks A, B, C, and E. Considering the development and evaluation of analysis methods for predicting inelastic structural behavior, the upper left of the diagram begins with material behavior studies and progresses through the other study areas listed; subtask designations are given for reference. Integral ties exist between these areas, as shown, with the combined product being recommended inelastic analysis guidelines and software. The process is iterative and regenerative, with extensions and improvements being made on a continuing basis; the result at any given point in the cycle is an identification of the best available analytical procedures. These procedures are made available to industry and for use in associated areas of this program.

Similarly, the failure-related investigations, shown diagrammatically on the upper right, begin with material failure experiments and combine results of the efforts listed to yield recommended failure criteria for use in design. Again the process integrally links each study area and is iterative and regenerative in

ORNL–DWG 78–2105

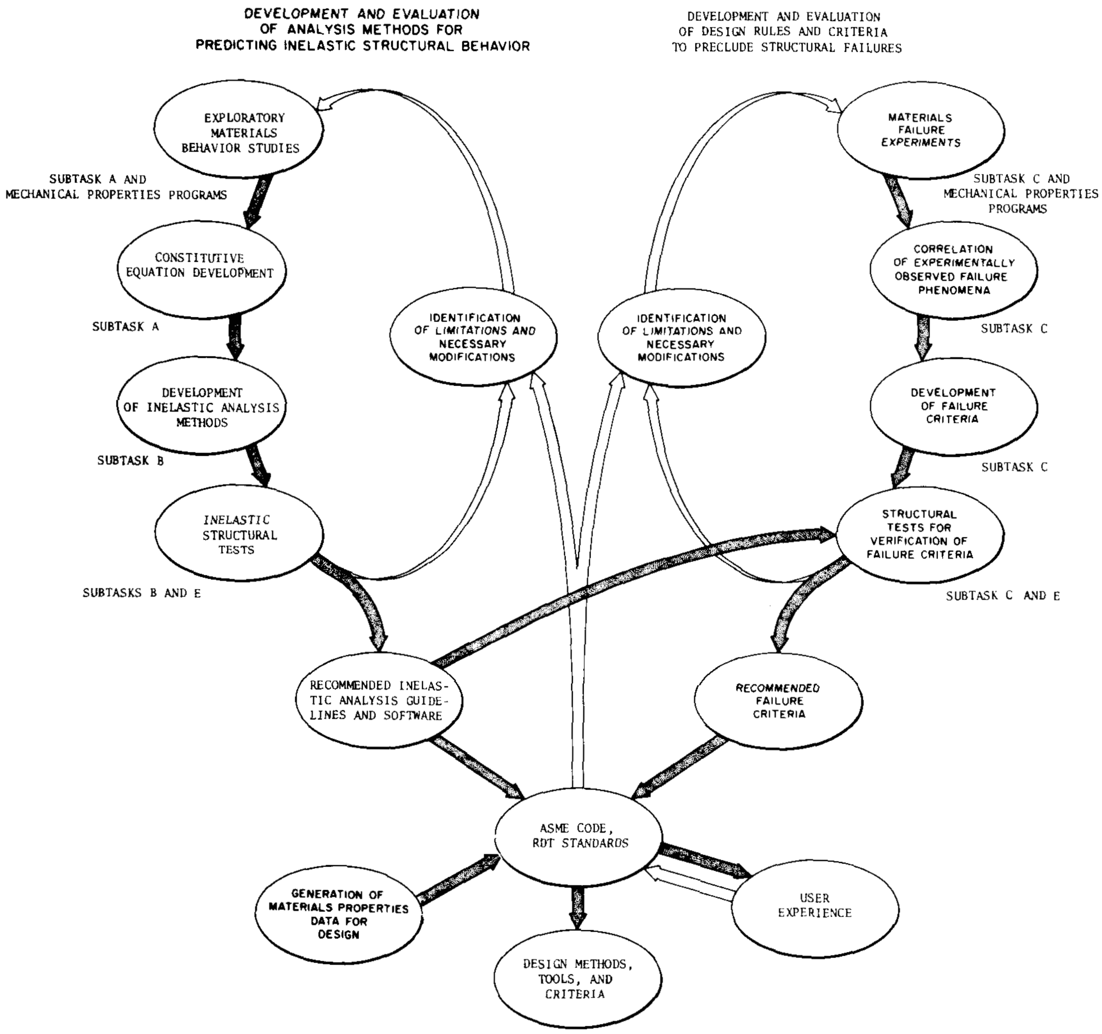


Fig. 2.2. Interrelationships between subtasks A, B, C, and E in the development effort. Subtask D (simplified design methods) deals with approximations to the methods and criteria developed here. Subtask F (structural design methods for weldments) repeats much of the effort shown here, but with emphasis on weldments.

nature. Requirements and directions for modifications and improvements are identified both within the developmental cycle and in other areas of the task.

Input to design methods and criteria studies comes from several sources, as shown in the lower portion of the diagram. Material properties data are obtained from various program tasks. Significant and continuous interactions are maintained with various organizations, groups, and industrial firms. Included are the American Society of Mechanical Engineers (ASME) code groups, the RDT standards groups, the Pressure Vessel Research Committee (PVRC), other Department of Energy laboratories, and reactor and component suppliers. Thus, the data, methods, and criteria recommended as end products are based on input from several sources in addition to that from this task.

The diagram of Fig. 2.2 is intended to give a simple, yet clear and effective, display of the elements of the task and the ties between them. The solid arrows represent continuous flows of information, not paths used at intervals when certain discrete developmental milestones are reached. The open arrows represent feedback paths, in keeping with multidirectional flow of information. Because of the nature of the task, almost fused interrelationships between the various subtasks, and strict demand for continuous interaction and flow of information, conventional PERT-type diagrams are not appropriate in this case. The diagram of Fig. 2.2 is actually a substitute for such a diagram.

Background information, including accomplishments, is given in subsequent sections for each of the six subtasks. Therefore, only a few key accomplishments will be noted here to allow the reader to make an assessment of the current overall status of the Development task. In the area of inelastic design analysis methods, interim constitutive equations have been developed and provided to designers for types 304 and 316 stainless steels and 2¼ Cr–1 Mo steel. These interim relations have recently been revised based on additional data and applications experience. Special-purpose inelastic analysis computer codes that incorporate the recommended constitutive equations have been developed and distributed, and some 32 inelastic structural tests have been completed. The data from these tests have been used in comparisons with analysis predictions to verify the general validity of the inelastic analysis guidelines for type 304 stainless steel and to identify areas where improvements were needed. These test data are available to computer code developers and design analysts for use in benchmark problem calculations for code verification and qualification.

In the failure criteria area, two interpretive reports on creep fatigue have been published, and limited multiaxial fatigue, creep-rupture, and creep-fatigue data have been generated on type 304 stainless steel. These data are being used to assess both current and potential failure criteria. Finally, a document was published recommending structural design criteria for reactor core structures. A companion document, recommending supporting research and development, was also published.

Simplified design methods have been made available to designers, but their conservative applicability was demonstrated for only limited design situations. More recently a significant analytical effort was completed to provide justification for more general application of these methods.

The level of effort under the weldment subtask was significantly increased in FY 1977. Prior to then an interpretive report was published, and a series of creep-rupture tests on simple structural models (capped cylindrical shells) with weldments was completed to obtain comparative deformation and failure response data on weldment and base metal.

Finally, a major accomplishment under this task has been the development of a number of high-temperature test facilities for accurately obtaining uniaxial exploratory inelastic materials data, multiaxial inelastic deformation and failure data, structural test data on simple structural geometries subjected to mechanical loadings, and, finally, thermal ratchetting structural test data obtained under realistic sodium conditions. These in-place facilities will continue to contribute heavily to future development efforts.

2.1.3 Plan of action

Plans are for the development task to continue along the lines of approach described in the previous subsection. It is believed that most of the presently established goals and objectives for the task can be met in approximately the next ten years, provided that presently projected funding levels are maintained. Much of the technology is, and is expected to continue to be, material dependent, so that each new alloy will require an additional effort, the extent of which will depend on how markedly different the behavioral characteristics of the alloy are from those of previously considered alloys. In addition to types 304 and 316 stainless steels and 2¼ Cr–1 Mo steel, three additional base alloys are identified in this plan; they are alloys 800 and 718 and an advanced ferritic steel.

A plan of action, together with a ten-year milestone schedule, is given in the following sections for each of the six developments subtasks. Here, the broad plans will be briefly outlined, and only key items in each subtask will be mentioned. For this discussion we will again consider the overall task as consisting of four basic parts, or major thrusts:

- analysis methods for predicting inelastic structural behavior,
- design rules and criteria to preclude structural failures,
- simplified design methods,
- design methods for weldments.

The development of inelastic analysis guidelines continues to be a cornerstone of the overall effort and will continue, with emphasis on (1) a continuing assessment and improvement of currently recommended guidelines; (2) development of a unified constitutive theory which accounts for material behavior features, such as the simultaneous occurrence of rate-sensitive yielding and time-dependent creep, which are not adequately described by current guidelines; and (3) treatment of additional materials other than types 304 and 316 stainless steels and 2¼ Cr–1 Mo steel. Emphasis must also be placed on multiaxial testing at elevated temperatures, and this necessitates the continued development of a suitable biaxial extensometer for elevated-temperature use.

Structural testing, which continues to be required to provide the data necessary for a thorough assessment and verification of inelastic analysis guidelines and computer software, will concentrate on (1) providing test data for additional materials (other than type 304 stainless steel) and (2) providing data for more realistic structural geometries. Because thermal ratchetting is a measurable manifestation of the much more basic inelastic response to thermal cycling, pipe thermal ratchetting tests will be continued. However, in the future these tests will extend to failure, thus providing creep-fatigue structural failure data.

Analysis methods, per se, will continue to be adapted to the utilization of modified, or new, constitutive equations. Software development will be undertaken only when required for efficient in-house analysis of the various structural tests.

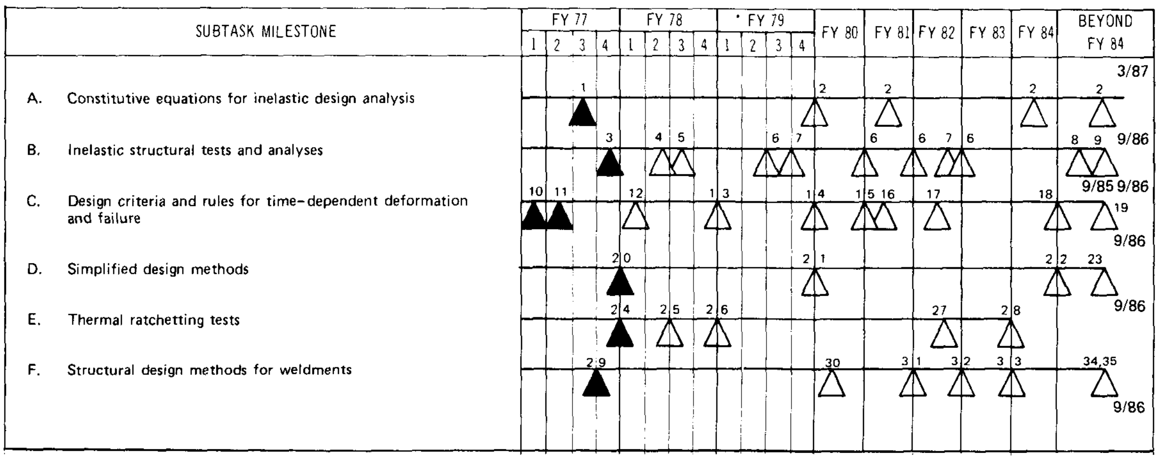
The second major area of the development task, design rules and criteria, will strive toward improved time-dependent failure rules through combined analytical and experimental efforts. Creep-rupture and time-dependent fatigue will receive much of the attention. Structural tests to failure under realistic thermal and mechanical load cycling, including thermal ratchetting tests to failure, will receive high priority. Also, efforts to assess design margins that exist when material variability is considered will receive priority. Continued coordination of design data needs with mechanical properties programs will be emphasized, both in the failure area and in the analysis methods area.

The development of simplified design methods will concentrate on (1) further extensions of the applicability of existing methods and approaches; (2) development of additional approaches, for example, those based on bounding techniques, reference stress procedures, etc.; and (3) development of design guidance for applying the various methods as preliminary screening rules or as final design qualification procedures.

Finally, the fourth area, weldments, will be directed toward developing a technology that approximately accounts for the properties and behavioral characteristics of individual weldments. This effort, which will consist of structural tests, development and assessment of design analysis procedures, and development and assessment of failure criteria, will draw heavily from other areas of the development task, and will strive for two levels of realism in the design methods and criteria. The first will be based on design analysis procedures that are as detailed as practical; the second will be based on simplified methods. The effects of preexisting flaws and of preexisting residual stresses will be assessed and included as required. Throughout the effort, only a few of the most commonly used and important weldments (base metal–filler metal–weld process combination) can, and will, be emphasized.

As previously emphasized, there has been, and will continue to be, an almost continuous flow of information from this task to designers and others in the form of assessments, recommended improvements in the technology, and design guidelines. This makes the establishment of a few key milestones difficult. Yet, some measurement criteria for assessing the pace and progress of the task are necessary. The milestone schedule that follows is intended to serve that purpose. Each of the six subtasks are listed, and significant milestones, which were selected from the more detailed milestone schedules in subsequent sections, are shown.

2.1.4 Subtask/milestone schedule



Milestones

1. Provide updated inelastic analysis guidelines (constitutive equations) for types 304 and 316 stainless steels and 2¼ Cr–1 Mo steel for inclusion in RDT Standard F9-5.
2. Issue, for trial use, unified inelastic analysis guidelines for the following alloys (listed in chronological order): 2¼ Cr–1 Mo steel, types 304 and 316 stainless steels, alloys 800 and 718, and an advanced ferritic steel.
3. Publish summary report of high-temperature tests of type 304 stainless steel beams and circular plates.

4. Complete transfer of special-purpose inelastic analysis computer codes PLACRE, EPACA, and CREEP-PLAST II to Argonne Code Center.
5. Publish report on high-temperature tests of type 304 stainless-steel-capped circular cylindrical shells.
6. Publish report on group of six basic high-temperature tests of beams and circular plates for each of the following alloys (listed in chronological order): 2¼ Cr–1 Mo steel, type 316 stainless steel, alloys 800 and 718, and an advanced ferritic steel.
7. Publish report on high-temperature tests of type 304 stainless steel nozzle-to-spherical-shell configurations.
8. Publish report on high-temperature tests of type 304 stainless steel nozzle-to-cylindrical-shell configurations.
9. Publish report on high-temperature test of an advanced ferritic steel nozzle-to-spherical-shell configuration.
10. Publish report on assessment of fatigue failure criteria based on available multiaxial data.
11. Publish comprehensive interpretive report on time-dependent fatigue prepared by group of national experts.
12. Publish summary report on multiaxial creep-rupture tests of type 304 stainless steel.
13. Publish report on analytical sensitivity study of current design rules, using data on heat-to-heat variations to assess design margins.
14. Complete comparative analytical assessment of candidate time-dependent fatigue rules.
15. Publish report on structural creep-fatigue test to failure.
16. Publish report assessing creep-rupture damage correlation methods on basis of uniaxial and multiaxial experiments.
17. Publish report on assessment of multiaxial cumulative damage design rules.
18. Recommend improved design rules to guard against time-dependent failure.
19. Complete final verification testing of recommended design rules.
20. Publish report summarizing phase 1 efforts to extend the range of applicability of simplified methods.
21. Publish report summarizing phase 2 efforts to extend the range of applicability of simplified methods.
22. Publish report recommending improved simplified procedures for predicting creep-rupture failure.
23. Complete development and verification of advanced simplified methods for materials of interest.
24. Publish report on test and analysis of 2¼ Cr–1 Mo steel welded to type 316 stainless steel pipe ratchetting specimen (TTT-3).
25. Publish report on test and analysis of two type 304 stainless steel pipe ratchetting specimens (TTT-1 and TTT-2).
26. Publish report on test and analysis of seamless and seam-welded pipe ratchetting specimen (TTT-4).
27. Publish report on test and analysis of type 304 stainless steel welded to alloy 800 to 2¼ Cr–1 Mo steel pipe ratchetting specimen (TTT-5).
28. Publish report on advanced ratchetting test and analysis (TTT-6).

29. Publish report on weldment creep-rupture tests of type 304 stainless-steel-capped cylindrical shell models.
30. Publish report on high-temperature plate weldment tests and analyses.
31. Provide interim constitutive equation guidelines for more common weldments; recommend relatively detailed (but practicable) inelastic analysis procedures and commensurate design criteria.
32. Recommend simplified scoping analysis procedures for weldments.
33. Publish report on effects of notches and flaws on failure behavior of commonly used weldments.
34. Recommend unified constitutive equations for common weldments; recommend final commensurate criteria; propose simplified assessment procedures.
35. Complete verification tests of prototypical structural joints.

2.2 Subtask A – Constitutive Equations for Inelastic Design Analysis

2.2.1 Objective

The design conditions for structural components of many advanced energy systems, such as fast breeder reactors, include temperature levels, thermal excursions, and mechanical loads that are severe enough to give rise to inelastic (plastic and creep) straining of the structural materials. The ASME elevated-temperature Code Case 1592[2] and RDT Standard F9-4[3] recognize such inelastic material response in criteria for determining the acceptability of predicted stresses and strains in high-temperature reactor system components. However, demonstration of conformance with these criteria may require inelastic analyses, and the code case does not give guidance regarding the techniques and methods to be used in performing these analyses. The objective of this subtask is therefore to make available, for use in design analyses, mathematical representations (constitutive equations) of the inelastic (plastic and creep) behavior of major structural alloys. To be generally applicable, recommended equations must be given in multiaxial form and be appropriate for all modes (monotonic, cyclic, nonradial, nonisothermal, etc.) of loading expected to be experienced by the components. The theoretical and experimental endeavors necessary to arrive at such recommendations for each alloy of interest are carried out here. As equations and guidelines for their implementation are developed, they are placed in reference documents such as RDT Standard F9-5T[4] for use by designers and analysts. The types of mechanical properties information required to implement the recommended equations are identified, and associated design data needs are comprehensively identified to the Department of Energy for potential incorporation into materials programs.

2.2.2 Background

From the outset (1969) of this program, the significance of incorporating inelastic material behavior into high-temperature structural design methods was recognized. The intent of efforts to date in this subtask has been to develop and recommend constitutive equations for major LMFBR structural alloys in

2. Code Case 1592-10, *Class 1 Components in Elevated-Temperature Service, Section III, Division 1,* American Society of Mechanical Engineers (1977).

3. RDT Standard F9-4, *Requirements for Construction of Nuclear System Components at Elevated Temperatures (Supplement to ASME Code Cases 1592, 1593, 1594, 1595, and 1596),* U.S. Energy Research and Development Administration (January 1977).

4. RDT Standard F9-5T, *Guidelines and Procedures for Design of Nuclear System Components at Elevated Temperature,* U.S. Atomic Energy Commission (September 1974).

order to provide a consistent basis for evaluation of current component designs. Specifically, interim equations have been recommended and are being used for types 304 and 316 stainless steels and 2¼ Cr–1 Mo steel. These recommendations have resulted from combined theoretical and experimental studies, and efforts are under way to obtain further data to improve these interim equations and also to develop unified theories that are more generally applicable. Provision of constitutive equations for other structural alloys used in LMFBR (and other nuclear system) components is also included in present plans and schedules for future developments.

The guidelines used in selecting current equations include the requirements that the equations be capable of predicting known features of material behavior for broad classes (monotonic and cyclic) of loadings, be compatible with practicable analysis techniques, and require mechanical properties information that can be obtained from test programs of reasonable scope. Up to the present, elastic-plastic and creep constitutive equations have been formulated separately, and mostly ad hoc procedures have been used to incorporate interactions. In the case of elastic-plastic behavior, a modified nonisothermal kinematic-hardening approach has been recommended in which limited isotropic changes in the yield behavior are permitted during the accumulation of inelastic deformations. For creep, an equation-of-state approach based on strain hardening is employed. For the stainless steels, classical creep strain-hardening concepts are modified by auxiliary rules for cases involving stress reversals. These rules are further modified for 2¼ Cr–1 Mo steel to include a creep-softening influence of reversed plastic strains. Although the premises on which these methods are based are not new, they have been measured against a sizable body of current experimental data and have been found to give reasonable predictions of material and structural response under many practical loading conditions. Before replacement techniques are adopted, superior predictive capabilities have to be shown over the broad range (cyclic, multiaxial, etc.) of loadings of interest.

Our initial constitutive equation recommendations for the stainless steels were submitted and incorporated in FRA-152[5] and RDT Standard F9-1T[6] for specific use with the Fast-Flux Test Facility design. Improvements were subsequently made, and the recommendations have been included in RDT Standard F9-5T for more general use. The equations for 2¼ Cr–1 Mo steel have been made available to ongoing design projects and are being incorporated into RDT Standard F9-5T. Three background reports[7–9] have been issued that state the recommendations that have been made along with much of their experimental and theoretical basis.

To be useful in design, the recommended constitutive equations are given for general multiaxial states of stress and strain. Therefore, the exploratory tests that are performed in support of evaluating candidate theories are both uniaxial and multiaxial (mostly general combinations of axial and torsional loads).

The uniaxial experiments have included stress-strain tests under monotonic and cyclic loadings, constant-load creep tests up to 10,000 hr, creep-strain recovery tests, creep tests under stepwise changing temperatures and loads, creep tests under cyclic (stepwise reversal) loads, relaxation tests, and tests to scope creep-plasticity interactions. Facilities were developed at ORNL to perform precise studies of the elastic-

---

5. *Interim Supplementary Structural Design Criteria for Elevated Temperatures,* FRA-152, rev. 3 (Nov. 6, 1970).

6. RDT Standard F9-1T, *Requirements for Nuclear Components at Elevated Temperatures (Supplement to ASME Elevated-Temperature Code Case 1331),* U.S. Atomic Energy Commission (April 1973).

7. C. E. Pugh et al., *Currently Recommended Constitutive Equations for Inelastic Design Analysis of FFTF Components,* ORNL/TM-3602 (September 1972).

8. J. M. Corum et al., *Interim Guidelines for Detailed Inelastic Analysis of High-Temperature Reactor System Components,* ORNL-5014 (December 1974).

9. C. E. Pugh et al., *Background Information for Interim Methods for Inelastic Analysis for High-Temperature Reactor Components of 2¼ Cr–1 Mo Steel,* ORNL/TM-5226 (May 1976).

plastic behavior under combined axial–torsion–internal pressure loadings of tubular specimens. A significant study of the room-temperature biaxial elastic-plastic behavior of type 304 stainless steel has been completed, including studies of yield surfaces and plastic deformations under radial and nonradial loadings. A smaller number of biaxial tests have been completed for type 316 stainless steel and 2¼ Cr–1 Mo steel. A limited number of biaxial creep tests under axial-torsion loadings have been completed for type 304 stainless steel through subcontracted efforts, and, more recently, similar testing has been initiated at ORNL. Extensive use is made of reference heats of each material and standardized heat treatments throughout the various test categories.

Assessments have been made of the mechanical properties data needed to implement the presently recommended equations (for 304 stainless steel, 316 stainless steel, and 2¼ Cr–1 Mo steel) in fast-reactor component design. Accordingly, comprehensive lists of tests have been recommended to DOE-RRT. Performance of those tests has been under way in DOE materials programs since about 1972, and coordination is maintained with those programs. Specifically, the test lists for the stainless steels were updated in 1976 on the basis of data from the tests that had been completed and revisions that had been made to the recommended constitutive equations.

2.2.3 Plan of action

The constitutive equation and analysis guidelines recommended earlier by this program for types 304 and 316 stainless steels and 2¼ Cr–1 Mo steel are considered to be interim and will be further revised or replaced as more is learned about the inelastic behavior of these materials and as more appropriate mathematical representations are established. Therefore, the theoretical and experimental efforts will continue in a combined fashion. However, in addition to working toward improved equations for these *three* materials, constitutive equations for *other* materials will be developed. In connection with LMFBR needs, studies for alloy 800, alloy 718, and an advanced ferritic alloy are definitely planned. Additional materials to be studied will be selected on the basis of identified usage in high-temperature structural applications. With the selection of additional materials, beyond those shown in the milestone schedule, the scope of this subtask will necessarily be extended; each material must be considered separately.

Development of equations for a particular alloy builds upon the earlier efforts associated with other alloys. The exploratory tests and theoretical developments are extended only to the degree necessary to understand and model the differences *between* the behavior of the new alloy and those studied earlier. Depending upon the specific alloy, these may be major or relatively minor extensions.

Shortcomings of current interim equation recommendations include lack of sufficient data for and associated representation of (1) responses under multiaxial loadings, especially yield and creep at elevated temperatures, (2) unified interactions between so-called plastic and creep strains, (3) competing characteristics of hardening and recovery (of state), and (4) continuous evolution of hardening (or state variables) during cyclic and nonradial loadings. Although some improvements can be expected through modifications to the interim equations, the major long-range goal is to develop unified theories that are more generally applicable. After suitable unified relations are released for trial use, they will undergo modifications, if required, on the basis of experience with their application. The need for new material properties design data will be identified as a part of recommending modified or replacement constitutive equations.

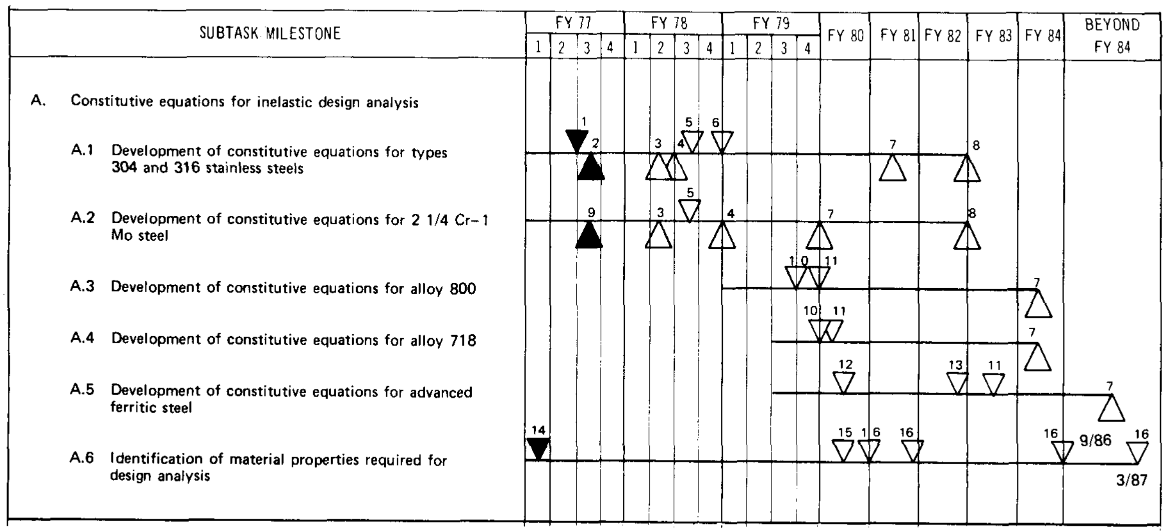
The theoretical studies are aimed at examining, in detail, the capability of candidate theories to reasonably represent material behavior under expected loading conditions. In a general way, the process is one of searching out (state) variables that are capable of describing the state of the material following an inelastic deformation history. The constitutive equations then consist of a *flow law* expressing the inelastic strain rate in terms of stress and state variables along with a *growth law* (or evolutionary law) which specifies how the state variables change during the loading and/or temperature history. Examination of promising formulations leads to the definition of many of the uniaxial and biaxial exploratory tests in the experimental part of this subtask. The predictive capability of a candidate theory is compared with the accumulated data base for the specific alloy under study.

The importance of multiaxial theory formulation and multiaxial experiments is emphasized in the overall developments. This is illustrated by the fact that many candidate state variables are tensorial rather than scalar quantities, and examination of their appropriateness or associated growth laws requires multiaxial experiments under both short- and long-term loadings. The status of multiaxial testing is described in Sect. 2.2.2, and expansion of testing is planned. High priority is assigned to tests to study yield characteristics at elevated temperatures (in the creep regime). The greatest numbers of such tests are planned for type 304 stainless steel and one of the ferritic steels; tests for the other alloys are planned to the extent necessary to verify similarities or differences. Studies of responses during various histories (radial, nonradial, cyclic, nonisothermal, etc.) are planned. Concurrent with these tests, long-term biaxial (axial-torsion loading) tests are planned under both load- and deformation-controlled histories. The combination of these two sets of multiaxial experiments and the uniaxial exploratory tests serves as the major basis for evaluating candidate constitutive theories.

Although considerable uniaxial exploratory testing has been completed for type 304 stainless steel and 2¼ Cr–1 Mo steel, further experiments are planned with emphasis on loading histories relevant to the type of uncertainties associated with existing equations. For example, further tests involving recovery during unloaded intervals, cyclic loads, and interspersed short-time and long-term inelastic deformations are expected to be particularly necessary. Over the longer term, test emphasis will increase for the other alloys, and tests for the stainless steels and 2¼ Cr–1 Mo steel will be decreased appropriately.

Accurate measurements of strain are essential to the success of many of the exploratory (uniaxial and multiaxial) tests. Efforts are under way to develop acceptable techniques to measure strains in the biaxial tubular specimens. Both capacitive gages and multidimensional extensometers are being pursued. Interim techniques will continue to be employed until the development of a satisfactory biaxial system is completed. Although this is a peripheral activity, its completion is necessary for the success of this subtask.

2.2.4 Subtask/milestone schedule



Milestones

1. Complete initial biaxial elastic-plastic tests of type 316 stainless steel and publish report on all previous and similar tests for type 304 stainless steel.
2. Update interim equations (in RDT Standard F9-5T) to provide improved representation of influence of prior inelastic deformations (elastic-plastic and creep) on subsequent yield characteristics.
3. Complete initial high-temperature biaxial yield experiments on types 304 and 316 stainless steels and 2¼ Cr–1 Mo steel.
4. Complete exploratory high-temperature biaxial yield experiments.
5. Complete definition of and initiate exploratory tests on alloys 800 and 718.
6. Complete a series of exploratory torsional creep tests.
7. Issue unified constitutive equations on basis of evaluations of candidate theories and interpretation of accumulated exploratory data (uniaxial and biaxial).
8. Issue modifications (based on application experience) to unified constitutive equations.
9. Update recommended interim constitutive equations to incorporate a strong influence of reversed plastic strains on subsequent creep rates and submit statement of entire set of constitutive equations for RDT F9-5T approval.
10. Assess the applicability of interim (RDT Standard F9-5T) constitutive equations on the basis of existing data.
11. Define and initiate exploratory (yield, creep, relaxation, etc.) tests (loadings that range from sustained to cyclic) as required to improve behavioral representation.
12. Define and initiate exploratory (yield, creep, relaxation, etc.) tests (loadings that range from sustained to cyclic) in support of milestone 13.
13. Assess the applicability of interim (RDT Standard F9-5T) constitutive equations on basis of initial exploratory tests.
14. Recommend revisions to types 304 and 316 stainless steel design data test matrices.
15. Define design data tests for advanced ferritic steel in coordination with other programs.
16. Update design data test needs for specific materials as unified equations are issued.

2.3 Subtask B – Inelastic Structural Tests and Analyses

2.3.1 Objective

The development of constitutive equations for inelastic design analysis (subtask A) must proceed hand in hand with the development and assessment of inelastic analysis procedures that incorporate the constitutive equations. Likewise, the analysis methods must be incorporated into computer software, and the entire system – consisting of constitutive equations, analysis procedures, and software – must be verified. Thus, the primary objective of this subtask, which is closely related to subtask A, is to develop, evaluate, and improve computer-based techniques for solving inelastic design problems and to provide structural test data for evaluating analysis procedures, constitutive equations, and computer codes. Specifically, the subordinate objectives are:

1. to develop and evaluate structural analysis methods and associated computer codes for conducting inelastic analysis;
2. to utilize these codes in the evaluation and improvement of constitutive theories;
3. to provide structural test data for evaluation of constitutive theories and analysis procedures;
4. to provide benchmark problem data for computer code verification and qualification.

2.3.2 Background

Under this subtask, four special-purpose computer codes have been developed:

1. EPACA – a thin- and thick-shell elastic-plastic-creep finite-element code;
2. PLACRE – a two-dimensional elastic-plastic-creep finite-element code developed as a research tool rather than a production program;
3. CREEP-PLAST II – a production two-dimensional elastic-plastic-creep code;
4. PLANS-HEX – a production three-dimensional elastic-plastic code.

With the exception of PLANS-HEX, which currently includes only plasticity, the basic ORNL-recommended constitutive equations have been implemented in each of these codes, and the EPACA, PLACRE, and CREEP-PLAST codes have been distributed to LMFBR designers and transmitted to the Argonne Code Center for further distribution.

These codes have been, and are being, used to analyze structural tests and thereby evaluate and demonstrate the utility of current design analysis methods. The two-dimensional codes are used to analyze beam, plate, capped cylinder, and pipe thermal ratchetting tests, while the shell and three-dimensional codes are used to analyze the more complex structural tests such as the nozzle to sphere.

Verification and qualification of computer codes that employ complex constitutive theories and analysis procedures to perform inelastic design calculations can best be carried out by *benchmark calculations*, that is, by solving a limited number of carefully chosen problems with known solutions. At high temperatures where inelastic behavior predominates, these known solutions can come only from structural tests that have been carefully planned and carried out to provide the necessary benchmark problem information.

Recognizing, in 1969, the need for experimental benchmark problem data, plans for a series of inelastic structural tests on a variety of structural geometries ranging from the simple to the complex were initiated as an integral part of the development program. The initial series of tests was to be on structures from a single heat of type 304 stainless steel, and a companion mechanical properties test effort was initiated to characterize the material and to provide the material behavior data required as input to benchmark calculations. Only a minimal number of tests, largely on beams and plates, were to be performed on type 316 stainless steel, 2¼ Cr–1 Mo steel, and the other alloys to be considered in the future.

To date, some 23 structural tests have been completed on type 304 stainless steel specimens.[10] All but two of the tests were performed at 593°C (1100°F) and involved time-varying loadings or deflections contrived to provide information on significant aspects of inelastic response. The test specimens included

10. This number does not include pipe thermal ratchetting tests, which, because of their scope and special significance, are included as a separate subtask (subtask E).

simply supported beams and circular plates, two uniaxially loaded flat plates with holes, a shear-lag specimen, a circular cylindrical shell with a flat head, two elbow-pipe assemblies, and a nozzle-to-spherical-shell configuration. Special facilities were developed and built for each type of test.

Typical experimental data from many of these tests were published in ref. 11, and they are available to computer code developers and design analysts for verification and qualification use. Reference 11 also includes comparisons of many of the test results with inelastic analysis predictions, and it provides the mechanical properties data necessary as input to inelastic analyses.[12]

The testing of type 304 stainless steel beams and plates is complete, and the test effort is now addressing type 316 stainless steel and 2¼ Cr–1 Mo steel. To date, one type 316 stainless steel beam and one plate have been tested; three 2¼ Cr–1 Mo steel beams have been tested. Only the more complex structures (nozzle-attachment geometries) to be tested in the future will utilize type 304 stainless steel.

2.3.3 Plan of action

Analytical efforts will concentrate on computer codes to accommodate more complex structural geometries and revised constitutive equations. Included in these analysis methods will be the ability to perform geometrically nonlinear (large deformation) analyses. These codes will be used to analyze structural tests and thereby assess constitutive equations and analysis methods.

Future structural tests will concentrate on materials other than type 304 stainless steel and on more complex geometries. A minimum number of beam and plate tests will be used to assess analysis methods for type 316 stainless steel, 2¼ Cr–1 Mo steel, alloy 800, alloy 718, and an advanced ferritic steel. Nozzle-attachment tests will be used to assess the applicability of analysis methods to realistic three-dimensional component geometries.

Specifically, the PLANS-HEX computer code will be modified to analyze creep response of the high-temperature nozzle-to-sphere and nozzle-to-cylinder tests. Also, for accident analysis, large-deformation theory and analysis methods will be verified by comparisons between analytical and experimental results.

The planned beam and plate tests have been reduced to a basic set of tests *for each material:* (1) a load-controlled beam test, (2) a deformation-controlled test, (3) a slotted-beam test,[13] (4) a fourth beam test (defined on the basis of the results from the first three tests), (5) a load-controlled plate test, and (6) a deformation-controlled plate test. These six tests can be done over a two-year period for each material. After the tests on a material have been completed, a summary report on the tests with accompanying analyses will be published.

It should be noted that concurrent with the structural tests on each new alloy, there must be a materials testing effort to provide the cyclic stress-strain data and creep representations necessary as input to inelastic analysis. These test efforts can be a significant requirement.

The nozzle-attachment tests will be done using nozzle-to-spherical-shell and nozzle-to-cylindrical-shell specimens. These tests will include room-temperature elastic-plastic tests and elevated-temperature elastic-plastic-creep tests. All of the nozzle-attachment models will be made of type 304 stainless steel except for an advanced ferritic steel nozzle-to-spherical-shell model. Each nozzle-attachment test will have a summary experimental report and an analysis report.

---

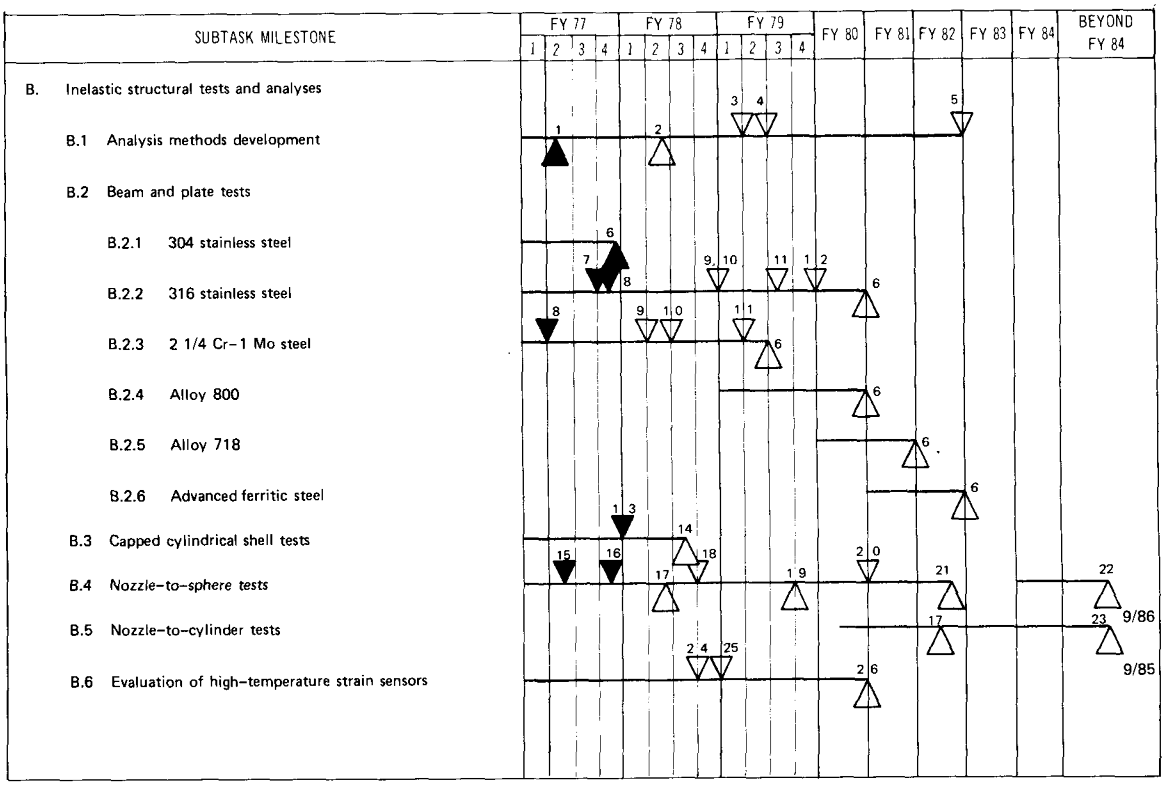
11. *Pressure Vessels and Piping: Verification and Qualification of Inelastic Analysis Computer Programs,* ed. by J. M. Corum and W. B. Wright, ASME (1975).

12. The material for the test specimens came from the same heat of type 304 stainless steel as used throughout the program.

13. Used to precisely evaluate the interactions of creep and plasticity under cyclic relaxation conditions.

Evaluation of high-temperature strain sensors will continue and will be updated as new devices and methods are tested.

2.3.4 Subtask/milestone schedule



Milestones

1. Publish user's manual for PLACRE code and transfer PLACRE and EPACA codes to Argonne Code Center.
2. Publish user's manual and verification report for CREEP-PLAST II code and transfer code to Argonne Code Center.
3. Complete modifications to PLANS-HEX code to analyze creep response of high-temperature nozzle-attachment model tests (Grumman Aerospace).
4. Assess methods and software for performing geometric nonlinear (large-deformation) analyses.
5. Complete verification effort for large-deformation analyses.
6. Publish summary report.
7. Complete load-controlled plate test.
8. Complete slotted-beam test.
9. Complete load-controlled beam test.
10. Complete deflection-controlled plate test.

11. Complete deflection-controlled beam test.
12. Complete fourth and final beam test.
13. Complete long-term test (to failure).
14. Publish report on capped cylindrical shell tests.
15. Complete room-temperature elastic-plastic test.
16. Complete modifications to test facility for high-temperature use.
17. Publish report on room-temperature elastic-plastic test.
18. Complete test of first high-temperature inelastic test.
19. Publish report on first high-temperature inelastic test.
20. Complete test of second high-temperature inelastic test.
21. Publish report on second high-temperature inelastic test.
22. Publish reports on advanced ferritic steel test.
23. Publish reports on high-temperature inelastic test(s).
24. Complete long-term evaluation test of high-temperature strain gages in current use.
25. Publish report on assessment of current high-temperature strain gages.
26. Publish report updating evaluations of high-temperature strain sensors.

2.4 Subtask C – Design Criteria and Rules for Time-Dependent Deformation and Failure

2.4.1 Objective

Potential time-dependent structural failure modes include creep rupture from long-term loadings, creep-fatigue (or time-dependent fatigue) failure, gross distortion due to incremental collapse and ratchetting, and creep buckling due to long-term loadings. The first three of these failure modes are addressed in this subtask, while the fourth, creep buckling, is addressed as a part of the HTSD Validation and Application tasks. The primary objective of this subtask is thus to assess and develop design rules and procedures aimed at precluding time-dependent failure through excessive deformation, cracking, and rupture, and to support the development and evaluation of codes and standards in this area. Emphasis here is on time-varying loadings and multiaxial stress states.

Because failure is multifaceted in nature, specific areas have, of necessity, been singled out for individual studies. The long-range goal, however, is the cohesion of microstructural observations of damage mechanisms and macrostructural phenomenological manifestations and the incorporation of such a unified approach into design correlations and into improved design rules.

Only base metals are considered here. Weldments are addressed in subtask F.

2.4.2 Background

Individual failure studies under this subtask have been grouped into three categories:

- mechanisms of damage, crack initiation, and crack growth,
- creep-rupture and creep-cumulative damage,
- time-dependent fatigue.

The first has made, and will continue to make, use of results from activities funded under other programs. However, small efforts have been sponsored to focus these activities and to publish review reports.[14]

Studies of creep-rupture and creep cumulative damage were initiated in early 1972 on type 304 stainless steel at Babcock and Wilcox with emphasis placed on both uniaxial (variable and sustained) as well as multiaxial loadings. The uniaxial phase of this study is drawing to an early close, partly due to difficulties that arose in correlating the cumulative damage results because of the variations in the data obtained. Multiaxial creep-rupture testing has continued, however, and the results are being used to assess available correlation procedures.

Efforts in the time-dependent fatigue, or creep-fatigue, area began in 1970 with the preparation of an interpretive report[15] which primarily addressed existing data for type 304 stainless steel and proposed a test program that was aimed at fulfilling near-term data needs. A slightly modified test plan was recommended, and the tests were initiated at Argonne National Laboratory. The recommendations were updated in 1974 on the basis of the tests that had then been completed at ANL and the progress made in model development. A second and much more comprehensive interpretive report[16] on time-dependent fatigue was more recently prepared by a group of experts assembled to present and evaluate the current state of knowledge. The fatigue process was generally considered to be composed of three phases (crack initiation, a period of crack growth, and the onset of instability, or rupture), and each aspect was examined. The broad, diverse background and experience of the authors were brought to bear in the assessments. Areas of future work that would increase understanding of time-dependent fatigue behaviors and provide improved bases for establishing design methods were identified. Throughout the preparation of this report, liaison was maintained with a large number of individuals, groups, and companies in order to factor in designers' needs to the maximum degree possible.

Concurrent with the early time-dependent fatigue activities, an analytical and experimental study of failure under multiaxial loadings was initiated. A subcontract was placed at Pennsylvania State University in 1970 to conduct multiaxial fatigue tests (304 stainless steel) at room and elevated temperatures. Much of the continuous-cycling fatigue testing has been completed, and the data were used as a basis for evaluating current multiaxial design rules and correlations. Tests at elevated temperature with and without hold periods are in progress, and initial results from these creep-fatigue tests are being assessed relative to available correlation procedures.

In addition to failure studies per se, this subtask has supported, through committee activities, the development and assessment of the design rules provided in ASME Code Case 1592 and RDT Standard F9-4. Also, criteria for LMFBR core structures have been addressed in an interim way. Arrangements were made (in 1969–1970) for the three major reactor manufacturers to individually prepare criteria they thought applicable to the design of core components and to recommended associated research and development needs. An assessment of the information received formed the bases for two reports[17,18] which have provided DOE with preliminary criteria formulations and guidance for R&D planning. The core structures

14. R. K. Bhargava, J. Moteff, and R. W. Swindeman, "Correlation of the Microstructure with the Creep and Tensile Properties of AISI 304 Stainless Steel," *Structural Materials for Service at Elevated Temperatures in Nuclear Power Generation,* ASME Publication MPC-1, pp. 31–54 (December 1975).

15. E. P. Esztergar, *Creep-Fatigue Interaction and Cumulative Damage Evaluations for Type 304 Stainless Steel,* ORNL-4757 (June 1972).

16. L. F. Coffin et al., *Time-Dependent Fatigue of Structural Alloys, A General Assessment (1975),* ORNL-5073 (January 1977).

17. W. J. McAfee and T. W. Pickel, *Preliminary Elevated-Temperature Core Structures Design Criteria,* ORNL/TM-4932 (March 1976).

18. W. J. McAfee, *Research and Development Needs for LMFBR Core Structural Design Methods and Criteria,* ORNL/TM-5735 (December 1976).

design criteria developed under this subtask are to be used by the Application task as input to codes and standards.

2.4.3 Plan of action

Efforts under this subtask will proceed along several analytical and experimental fronts, as will the coordination with ongoing mechanical properties programs, such as those at ANL and ORNL. Although the studies are mainly phenomenological, summary reports will continue to be prepared periodically to synthesize the available information on mechanisms associated with crack initiation and growth, including environmental influences.

Activities will continue to emphasize creep-rupture and time-dependent fatigue. In addition to the basic failure studies, relatively simple structural tests will be introduced to assess failure prediction rules. Initial emphasis in these tests will be on creep-rupture failure due to relaxing residual stresses and on failure under thermal ratchetting conditions – both common concerns in LMFBR designs.

As in the case of constitutive equation development (subtask A) and structural testing (subtask B), experimental efforts under this subtask initially center on type 304 stainless steel. It is anticipated that these studies will provide the framework for correlations and rules which can be adapted to other alloys as well. Thus, a smaller test effort will be required for these other alloys. Nonetheless, the test efforts will be significant, and the total magnitude of the subtask will depend strongly on the number of new alloys to be addressed in the coming years.

Understanding and modeling creep-rupture damage alone (no cyclic straining) is considered important both as a potential failure mode and as an ingredient in understanding time-dependent fatigue. A renewed emphasis is planned in this area. Experimentally, coordinated uniaxial and multiaxial rupture tests will be performed under variable-load and variable-temperature histories and will include examinations of microstructural changes and progression of crack initiation. Notched-specimen tests will be included. Analytically, variables for measuring rupture damage will be examined, and rules for damage accumulation will be evaluated on the basis of the experimental results (e.g., initially, time fractions and strain fractions will be further assessed).

The recently completed interpretive report on time-dependent fatigue identifies areas for future work. A synthesis of that information and the status of ongoing programs will guide efforts in the time-dependent fatigue area and form the basis for recommendations to be made to RRT on future endeavors. However, the current intent is for this subtask to continue an emphasis on multiaxial experiments and development of improved multiaxial time-dependent fatigue damage models. It is planned that upon completion of tests on type 304 stainless steel, Pennsylvania State University will continue multiaxial cyclic experiments at elevated temperatures on other alloys. In addition to providing elevated-temperature fatigue data to fulfill design needs, other programs will be looked to for developing experimental information on such items as long-term uniaxial exploratory fatigue data, crack characteristics and morphology, environmental influences, and metallurgical stability.

The structural-model tests will augment the more basic failure studies by providing failure points carefully obtained under more realistic thermal and mechanical loading conditions. One group of axially restrained cylindrical models will be tested to failure under repeated relaxation of thermally induced residual stresses.[19] The feasibility of conducting a thermal transient test to failure, possibly using one of the former pipe thermal ratchetting specimens (see subtask E), will be studied. Such a test would require

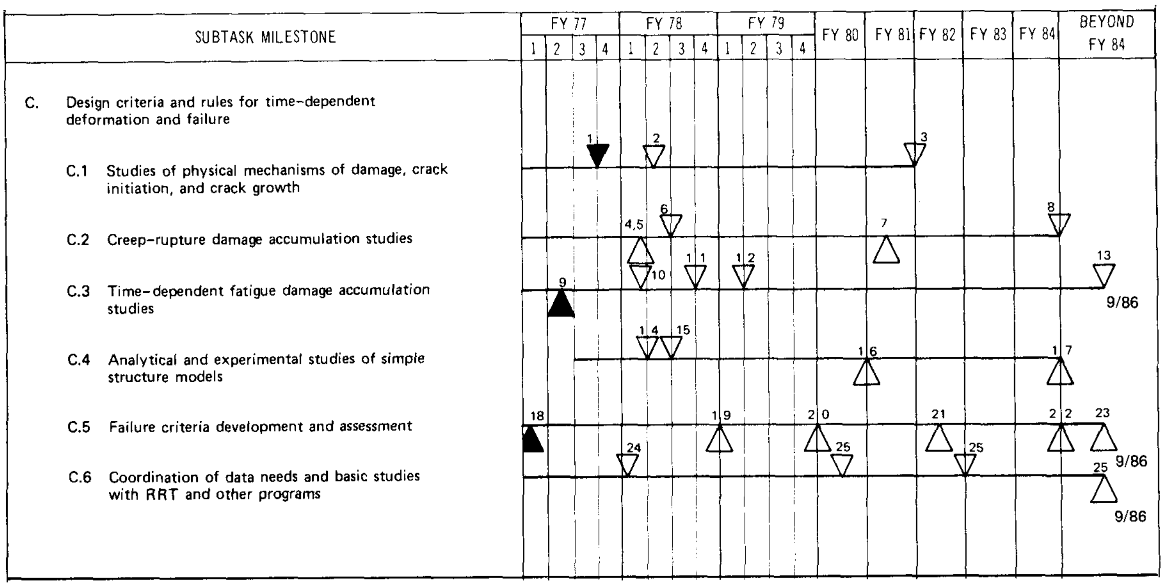
19. Some of these cylinders will have notches and other discontinuities. Others, containing weld regions, will be tested in conjunction with subtask F.

use of the Thermal Transient Test (TTT) facility at the Liquid-Metals Engineering Center. The results of such tests will be compared with the life predictions of current design rules and those under development. Thermal transient tests on notched specimens will be performed in the TTTF at ORNL under subtask E.

Available data from the uniaxial and biaxial tests are continuously used to assess existing and proposed failure criteria. The sensitivity of current design rules to expected variations in material properties will be analytically examined in the near future to assess design margins. Methods (e.g., strain-range partitioning, frequency separation, and the ANL damage rate approach) that show promise as alternatives to existing creep-fatigue procedures will be examined in detail and criteria recommended for design use when justified. Tests will be conducted to further verify or to improve any such recommended design procedures.

Materials data needed for the implementation of current or subsequently recommended criteria will be formally identified by this subtask. Needs will be periodically updated as tests are completed and results synthesized.

2.4.4 Subtask/milestone schedule



Milestones

1. Publish report on metallographic examination of type 304 stainless steel specimens tested in creep and fatigue.
2. Recommend basic research required on mechanisms of crack initiation.
3. Publish interpretive report on basic nature of creep-fatigue-environmental damage mechanisms.
4. Publish final report (B&W) on multiaxial creep-rupture tests of type 304 stainless steel.
5. Initiate constant- and cyclic-load creep-rupture tests of notched bars of type 304 stainless steel.
6. Initiate variable-load and variable-temperature uniaxial and multiaxial creep-rupture tests.
7. Publish report assessing creep-rupture damage and time fraction on basis of uniaxial and multiaxial experiments.

8. Complete variable-load and variable-temperature uniaxial and multiaxial creep-rupture tests on candidate alloys other than type 304 stainless steel.
9. Publish interpretive report on time-dependent fatigue.
10. Make recommendations to RRT on future time-dependent fatigue studies based on interpretive report recommendations.
11. Publish report assessing multiaxial generalizations of uniaxial time-dependent fatigue theories in light of existing data.
12. Complete multiaxial creep-fatigue tests of type 304 stainless steel.
13. Complete multiaxial creep-fatigue tests of candidate alloys other than type 304 stainless steel.
14. Initiate restrained-cylinder tests to investigate creep rupture from relaxing residual stresses.
15. Issue test plan for structural creep-fatigue test to failure (contingent on results of feasibility study).
16. Publish report on structural creep-fatigue test to failure.
17. Complete series of simple structural model tests under creep-rupture conditions.
18. Publish report on assessment of fatigue failure criteria based on available multiaxial data.
19. Publish report on sensitivity study of current design rules, using data on heat-to-heat variations to assess design margins.
20. Complete comparative analytical assessment of candidate time-dependent fatigue rules.
21. Publish report on assessment of multiaxial cumulative damage design rules based on available data.
22. Recommend failure criteria based on available information.
23. Complete verification testing of recommended failure criteria for available materials.
24. Revise creep-fatigue data requirements on basis of recent data and recommendations of time-dependent fatigue interpretive report.
25. Update design data test needs for specific materials to implement recommended failure criteria.

2.5 Subtask D – Simplified Design Methods

2.5.1 Objective

Inelastic analyses are generally required to satisfy the ASME Code Case 1592 deformation and strain limits and creep-fatigue criteria. However, inelastic analyses are costly and time-consuming, and the code case states that elastic and simplified inelastic methods of analysis may sometimes be justified and used. The objective of this subtask is to provide such simplified methods and to carefully verify their range of applicability.

Simplified methods, or screening procedures, for use in the initial stages of design need not always yield conservative predictions relative to those of more refined detailed inelastic analysis. On the other hand, simplified methods used for final design qualification must always be conservative relative to the detailed inelastic analysis results, but the margin of conservatism should be as small as practical. It is the goal of this subtask to provide both kinds of simplified methods.

It should be emphasized that simplified methods cannot completely remove the need for detailed inelastic analysis in critical locations. Their use can, however, minimize the number of locations in a structure requiring detailed inelastic analysis.

2.5.2 Background

Some simplified methods are provided in Code Case 1592 and RDT Standards F9-4T and F9-5T. However, their range of applicability is severely limited – generally to axisymmetric structures subjected to axisymmetric loadings and away from local structural discontinuities. To use these methods the designer has generally had to devise some sort of justification.

Prior to the adoption of these existing methods, analytical parameter studies under this subtask were undertaken to demonstrate their conservatism over their limited range of applicability. Scores of inelastic analyses were carried out on simple cylinders and on a nozzle-to-sphere geometry to provide the basis for this demonstration.

Subsequent to the adoption of the existing methods, a much larger effort was undertaken to extend the range of applicability of the methods. Phase 1 of this analytical effort was completed in FY 1977. It consisted in performing a number of detailed inelastic analyses on geometries ranging from axisymmetric cylinders to nozzle-to-sphere and nozzle-to-cylinder configurations and in using the results of these analyses as a basis for assessing the applicability of simplified methods. The existing ratchetting and creep-fatigue evaluation procedures based on elastic analyses were found to be conservative relative to detailed inelastic analysis predictions for this set of problems except for a few minor cases. Thus, the designer has some justification for applying these procedures to a broader range of applications than previously permitted. Conversely, although one-dimensional cyclic inelastic simulations of the two-dimensional and three-dimensional problems gave insight into the behavior, a method was not found for ensuring reasonably conservative predictions.

All of the verification efforts on simplified methods for ratchetting and creep-fatigue damage thus far have been restricted to a consideration of type 304 stainless steel, and, generally, extremely severe loading conditions were examined at just a few temperatures.

2.5.3 Plan of action

Phase 2 studies will include additional detailed inelastic analyses of axisymmetric nozzle-to-sphere geometries and an investigation of the applicability of simplified methods to less severe loadings than were considered in the phase 1 studies. Additional temperatures will also be investigated. Phase 2 will also include improvements in the O'Donnell-Porowski method such as temperature-dependent yield strength, loading into the plastic ratchetting regimes, primary bending, and biaxiality. Bounds will be derived for the strain range (for elastic fatigue evaluations) during plastic cycling in the presence of creep, and their validity will be tested by comparisons with detailed inelastic analysis results. Finally, a sizable effort in phase 2 will be devoted toward developing guidance for the designer as to how simplified inelastic analyses can best be used for screening analyses and when they can be used for final design assessments. These phase 2 efforts will include subcontracts with O'Donnell and Associates and Foster-Wheeler Energy Corporation.

All of the past studies, as well as the phase 2 effort, are based on type 304 stainless steel. The relative behavior of other materials, in terms of their propensity for ratchetting, fatigue damage, and creep-rupture damage, could affect conclusions reached on the basis of type 304 stainless steel alone. Thus, other materials must be checked and any necessary modification to the procedures made. The milestone schedule shows anticipated efforts on materials of current LMFBR interest. Any additional materials will necessarily increase the scope of the subtask.

Certain bounding techniques provide a different avenue of approach to simplified methods than that generally pursued. Considerable work has been done, principally by the group at Leicester University in England, for example, A. R. S. Ponter and F. Leckie, on bounding techniques that incorporate inelastic constitutive laws which include creep and plasticity. The form of constitutive relations most suitable for use in these bounding principles (variational principles) is that which incorporates a potential function, just as in the "flow potential" theory being developed under subtask A. One of the major drawbacks of these bounding techniques is that, so far, it has been possible to apply them only to rather simple structures and loadings. A thorough study is planned of whether or not these techniques can be applied to realistic structures and of how the information one obtains can be used in predicting bounds on component life, etc. Hopefully these activities will lead to a new collection of simplified procedures for design use.

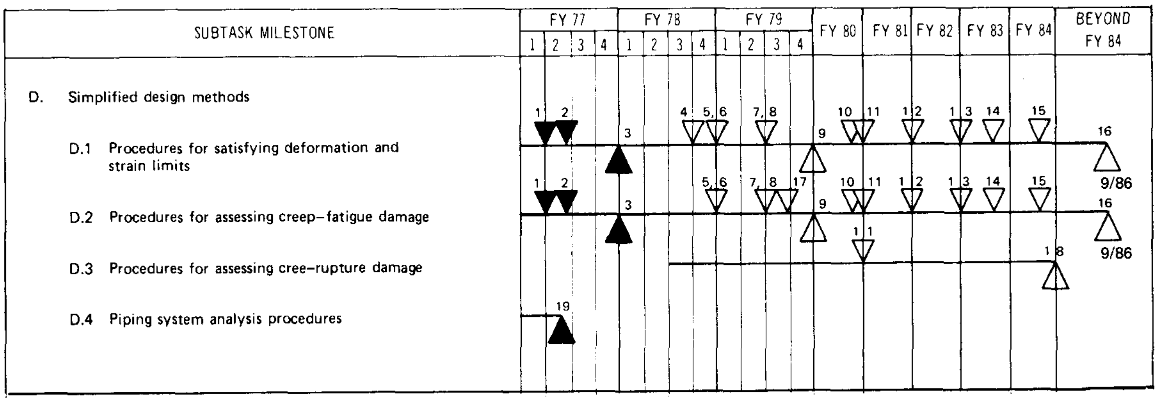
Procedures such as those based on the reference stress method represent yet another category of simplified methods. Applicability of the reference stress procedure to situations involving cyclic thermal loadings will be assessed, particularly for predicting creep-rupture failures.

The emphasis in this subtask is on simplified methods for satisfying deformation and strain limits, for assessing creep-fatigue damage, and for assessing creep-rupture damage. However, some work was done previously on developing a simplified piping analysis computer program (PIRAX2). This work will be pursued further under the HTSD Piping task at Atomics International.

Creep buckling is also an area where simplified methods are needed. Such methods are being developed under the HTSD Application task at Westinghouse Advanced Reactors Division.

Finally, as the high-temperature structural design technology matures, simplified design methods will be developed for recurrent elements such as nozzle reinforcement regions, bellows, elbow, and weldments. Efforts to develop simplified methods for weldments are included under subtask F (structural design methods for weldments).

2.5.4 Subtask/milestone schedule



Milestones

1. Publish report on investigations of simplified methods, using axisymmetric shell models (phase 1 studies).
2. Hold special information transfer meeting (with designers) on phase 1 studies.
3. Publish report summarizing all phase 1 studies.
4. Publish report (O'Donnell and Associates) on generalized O'Donnell-Porowski approach.
5. Complete investigation of simplified methods, using axisymmetric nozzle-to-sphere geometries.

6. Provide recommended screening rules based on one-dimensional inelastic analysis.
7. Complete investigations of effects of loadings and temperatures on applicability of simplified methods, using axisymmetric shell models.
8. Publish report (Foster-Wheeler) on use of special-purpose efficient computer programs to assess inelastic structural response.
9. Publish report (phase 2) on recommended simplified methods (milestones 4 through 8).
10. Complete assessment of applicability of simplified methods to type 316 stainless steel.
11. Complete evaluation of other bounding techniques, etc., for screening rules.
12. Complete assessment of applicability of simplified methods to 2¼ Cr–1 Mo steel.
13. Complete assessment of applicability of simplified methods to alloy 800.
14. Complete assessment of applicability of simplified methods to alloy 718.
15. Complete assessment of applicability of simplified methods to advanced ferritic steel.
16. Complete development and verification of advanced simplified methods (for materials of interest).
17. Publish report (O'Donnell and Associates) on simplified creep-fatigue procedures.
18. Publish report recommending improved simplified procedures for assessing creep rupture.
19. Transfer PIRAX2 code (simplified piping system analysis) to Argonne Code Center.

2.6 Subtask E – Thermal Ratchetting Tests

2.6.1 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 and failure criteria used to predict, or assess, these effects are particularly pertinent. Thus, the objective of this subtask is to provide carefully obtained ratchetting and failure test data for evaluating basic design analysis methods and design failure criteria and for verification and qualification of inelastic analysis computer codes by benchmark problem calculations.

2.6.2 Background

Thermal ratchetting of a structure is an outwardly visible and measurable behavior that results from the basic inelastic response of a structure to cyclic thermal loadings. Ratchetting is a manifestation of the process of residual stresses being set up by changing thermal gradients and of these residual stresses relaxing with time. This basic process is repeated over and over in high-temperature reactor system components, regardless of whether or not ratchetting actually occurs. Even in gas-cooled reactor systems where transient temperature effects are transmitted to components more slowly than in an LMFBR, large cyclic thermal gradients can occur in thick sections, and the basic mechanisms for ratchetting and creep-fatigue damage are present.

Thermal ratchetting tests are thus aimed not so much at ratchetting per se, although this is important, but at the basic underlying inelastic response to cyclic thermal loadings, which is extremely important in assessing creep-fatigue damage at high temperature. Thus the thermal ratchetting tests described in this subtask are considered to be particularly pertinent simple structural tests wherein our ability to predict the very complex material and structural response to cyclic thermal loadings can be assessed simply by comparing analysis predictions with a readily measurable quantity – the incremental strain per cycle.

This subtask began in 1971 with the design and construction of a sodium test facility (TTTF)[20] to be used specifically for subjecting 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). Four pipe thermal ratchetting tests have been undertaken to date. The first two tests (designated TTT-1 and TTT-2) were on straight sections of type 304 stainless steel pipe. The specimen for the third test consisted of a section of 2¼ Cr–1 Mo steel pipe welded, using Inconel 82 filler metal, to a section of type 316 stainless steel pipe. The fourth test specimen consisted of a section of seamless type 316 stainless steel pipe welded to a section of seam-welded type 316 stainless steel pipe. The weld filler metal was 16-8-2 stainless steel, and there were two axial seam welds located 180° apart – one made using the gas-tungsten-arc process and the other made using the submerged-arc process.

The duration of each test has been several months, and roughly one test has been completed every 18 months or so.

2.6.3 Plan of action

Temperature distributions and outside surface strains are recorded during each test, and the measured response is compared with analysis predictions to assess the current constitutive equations and analysis methods under cyclic thermal loading conditions. Thus, 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.[21]

Although the first three tests were completed prior to FY 1977 and typifying results were published, computer processing of many of the detailed measurements made during the thermal transients and subsequent hold periods was not completed until early in FY 1977. Final topical reports on these tests will be published at the end of FY 1977 and at mid FY 1978. With the completion of these topical reports, documented thermal ratchetting data will be available for type 304 stainless steel, type 316 stainless steel, and 2¼ Cr–1 Mo steel pipes.

The fourth test will provide substantiating data on the ratchetting response of type 316 stainless steel seamless pipe and comparative data on type 316 stainless steel seam-welded pipe.

The fifth test (TTT-5), which is being planned, will utilize a pipe specimen consisting of a section of type 304 stainless steel pipe welded, using 16-8-2 filler metal, to a section of alloy 800 pipe which, in turn, is welded to a section of 2¼ Cr–1 Mo steel pipe, using Inconel 82 as the filler metal. A notch in the form of a circumferential groove in the outer surface of the pipe will be included to induce failure of the specimen in a reasonable testing period. Purposes of this test include providing ratchetting test data for alloy 800, providing confirmatory ratchetting test data for type 304 stainless steel and 2¼ Cr–1 Mo steel, providing carefully obtained ratchetting data for dissimilar metal weld joints typical of those which are being considered for use in LMFBRs, and providing failure data under ratchetting-type loading conditions.

The matter of confirmatory test data is particularly important in ratchetting tests. Because the behavior is complex and sensitive to material variations and to testing variables, confidence is gained by having data from two or more tests. As an example, although the test conditions for TTT-1 and TTT-2 differed, both specimens were from the same heat of type 304 stainless steel. Yet, analysis predictions compared very well

20. Thermal Transient Test Facility (TTTF), *Liquid-Metal Fast Breeder Reactor Program Facility Profiles,* ERDA-68, pp. 163–65 (December 1975).

21. The requirement that appropriate mechanical properties data be generated on the materials of each specimen is a significant one, particularly since several base and weld metals may be involved.

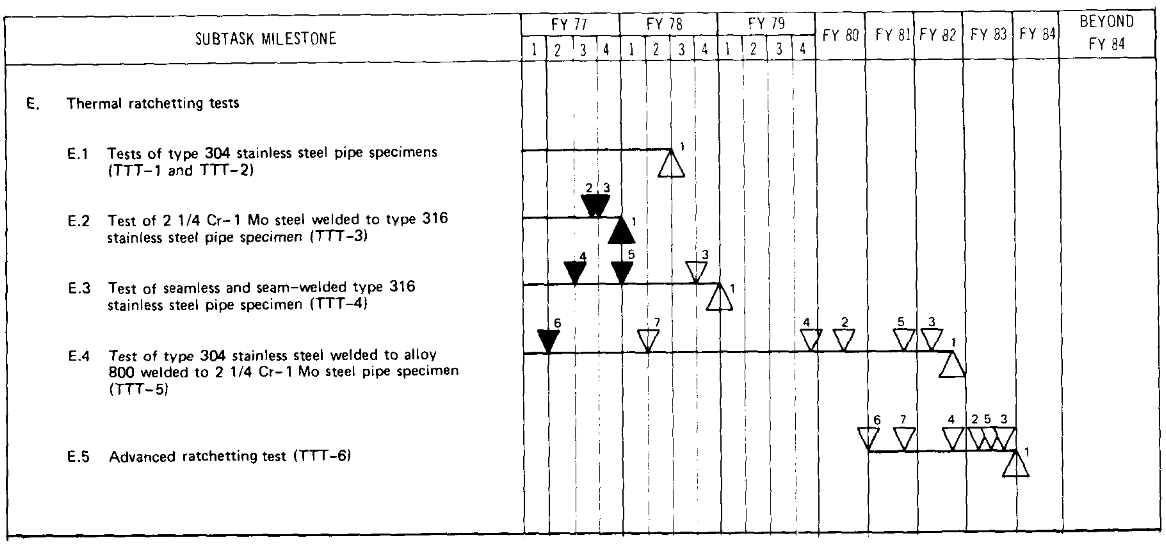
with the results of TTT-1 but not nearly so well with the results of TTT-2. Thus, the degree to which we can predict ratchetting in type 304 stainless steel components is still somewhat questionable. The TTT-5 test, which will again utilize a length of type 304 stainless steel, will hopefully help to answer this question.

Test TTT-5 will be the first of the TTT series to be designed as a test to failure. It is intended to meet the need for failure test data on a structure involving significant deviations from a homogeneous stress state and subjected to realistic complex loading conditions.

Only one future test (TTT-6) is shown in the milestone schedule, and it has not been specifically identified as to type. Although the TTTF 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. Thus, the specimen for TTT-6 might conceivably be a small nozzle-to-spherical-shell model or it might be an advanced ferritic steel pipe specimen. In any event, this sixth test will be continued to failure under ratchetting conditions.

The choice of a test specimen for TTT-6 and a decision on whether or not there is a need for one or more additional tests beyond TTT-6 must await further developments. If additional new materials are introduced into considerations for advanced reactor systems, then additional pipe thermal ratchetting tests on those materials may be required.

2.6.4 Subtask/milestone schedule



Milestones

1. Publish report of test results, including comparisons with one-dimensional inelastic analysis predictions.
2. Complete minimum mechanical properties test effort on specimen materials (base and weld metal).
3. Complete inelastic analyses.
4. Initiate test.
5. Complete test.
6. Complete preliminary test plan.
7. Procure necessary material.

2.7 Subtask F – Structural Design Methods for Weldments

2.7.1 Objective

Current design methods do not explicitly account for the behavior characteristics and properties of structural weldments, neither in performing design analyses nor in establishing failure criteria. Yet, structural failures often do occur in weld regions. Thus, weldments in a sense represent a gap in the current high-temperature structural design technology. The primary objective of this subtask is to develop and verify more suitable high-temperature design methods for structural weldments by explicitly accounting for the weldment characteristics and properties. The end goal is, of course, to provide methods for ensuring that failures do not occur in weldment regions. To be effective, these methods must be based not only upon proven failure criteria but also upon a reasonable understanding of weldment behavior and a capability to predict that behavior, at least approximately.

Thus, this subtask, which considers both similar and dissimilar metal welds, has a number of subordinate objectives:

- to identify and evaluate methods for approximately predicting stresses and deformations in unflawed structural weldments,
- to assess the role of preexisting flaws in weldment behavior,
- to assess the influence of residual stresses on weldment behavior,
- to establish appropriate criteria (commensurate with the level of analysis) to guard against excessive deformation and failure,
- to identify and evaluate simplified design procedures for assessing deformation and failure in structural weldments.

2.7.2 Background

There are several reasons why development of a completely adequate and verified design technology for weldments has not kept pace with that for base-metal structures. First, and most basic, is the recognized diversity and complexity of weldments. 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. Structural weldments are metallurgically, and often structurally, complex, and there is a scarcity of data delineating the various causes and effects. A second reason for the lack of an adequate technology stems from the number of different weldments to be considered. Each combination of weld metal, base metal, and welding process produces, in effect, a different weldment material whose behavior must be investigated and understood. The final hindrance to the development of a technology for weldments has, in the past, been the lack of an in-place technology for base metal upon which to build.

There now exists a basic high-temperature structural design technology, at least for types 304 and 316 stainless steels and 2¼ Cr–1 Mo steel. Also, a relatively small number of weld metal–weld process combinations are considered to be the leading contenders for welding these alloys, and several materials programs are generating information on both the elastic and inelastic behavioral characteristics of these basic weldments. Thus, the time has arrived when the development of a design technology for weldments can be aggressively pursued by concentrating on a relatively small number of key weldments and by taking advantage of the existing technology for base metals.

Activities under this subtask were expanded significantly in FY 1977. In prior years, an interpretive report on the behavior of weldments at high temperatures was published.[22] Also, a series of long-term tests to rupture was conducted on type 304 stainless steel shell structures (circular cylinders with flat heads) with type 308 stainless steel weldments located in various positions on the different specimens. The purpose of that test series was to determine the comparative deformation and failure behavior of the specific 304/308 weldment. Activities in prior years also were related to two pipe thermal ratchetting tests of specimens containing weldments (tests TTT-3 and TTT-4 of subtask E). Finally, plans were developed in FY 1977, and both deformation and failure tests of additional simple weldment specimens were initiated.

2.7.3 Plan of action

The total effort in this combined analytical and experimental subtask will consist of structural tests of both flawed and unflawed joints, and the development and assessment of analysis methods, of deformation and failure criteria, and of simplified design procedures. Thus, these activities will parallel the activities for base metal in subtasks A through D and will draw significantly on the procedures and test equipment available under those subtasks, as well as on the technical accomplishments.

Initial efforts will center on 304/308 weldments. Simple structure tests (flat plates, beams, and cylinders) will be performed both at room temperature (elastic-plastic) and at high temperature (elastic-plastic-creep). Although these tests will extend to failure, initial emphasis will be on stress and deformation behavior and on the ability to approximately predict the response, using detailed inelastic analyses in which the weldment properties are approximately accounted for on a zone basis.

An accurate experimental assessment of weldment behavior dictates that whole-field strain distributions be accurately measured. The Moire technique of strain measurement seems to be best suited to this purpose. An initial effort to extend the Moire method to high temperatures was only partially successful.[23] As a result of this experience, several promising modifications to the basic technique have been identified which should result in a usable high-temperature methodology. These modifications will be the subject of development work during FY 1977 and 1978.

The development and assessment of constitutive equations and analysis methods will require that uniaxial, and perhaps a minimum of multiaxial, test data be obtained both as a basis for constitutive equation development and assessment and as input to inelastic analyses of the structural tests. *Each* key weld metal–weld process combination will be examined to determine whether or not existing constitutive equations for the base metal can be adapted to describing the weld metal as well. If not, efforts will be undertaken to modify the basic base-metal procedures so that they do adequately apply to the weldments.

A key question in the high-temperature analysis of weldments regards the extent to which residual stress effects must be taken into account. Are the effects mitigated by a moderate period of high-temperature operation? This question will be resolved through a small, carefully chosen, series of tests and companion analyses, wherein the magnitude and distribution of residual stresses in fabricated joints will be assessed after periods of high-temperature exposure.

Flaws are more likely to preexist in weldments than in base-metal structures; consequently, flaws and flaw growth are likely to play a key role in design assessment procedures for weldments. Both notches and characterized flaws will be considered in structural tests and analysis. For notches, the goal will be to

---

22. R. G. Gilliland, *The Behavior of Welded Joints in Stainless and Alloy Steels at Elevated Temperatures,* ORNL-4781 (August 1972).

23. A. J. Durelli and J. Buitrago, *Experimental Determination of Strains at High Temperature,* prepared by The Catholic University of America, October 1975, for Oak Ridge National Laboratory under UCND P. O. Contract 11Y-92204V.

determine if a particular weldment is notch weakening or notch strengthening. If notch weakening, the design criteria must reflect that fact. In tests of preflawed joints, our ability to monitor and account for the effects of the flaw will be assessed. Ultimately, guidelines for judging the acceptability of flaw sizes must be established.

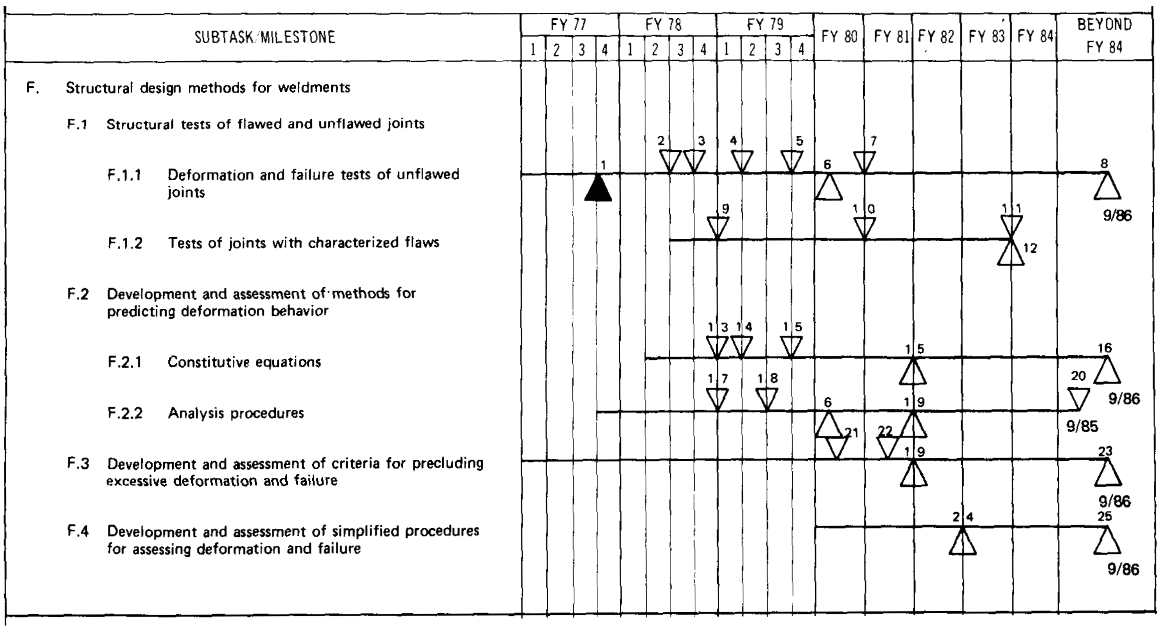
Deformation and failure criteria for weldments must be commensurate with the level of analysis that is practicable (the more approximate the analysis, the more conservative the criteria) and with the propensity for preexisting flaws and flaw growth. The approach to be taken in developing and assessing criteria will again be to look first at existing base-metal criteria and to recommend changes where deficiencies are identified.

Just as is the case for base-metal structures, it is envisioned that two levels of sophistication of design procedures will be required. The first, which has been discussed in the preceding paragraphs, consists of relatively detailed analyses and associated criteria and will be applied only in a few critical regions. The second, which will be based in part on the first, will consist of simplified procedures for screening assessments and for use in many noncritical areas. The development of these procedures will make use of the results of subtask D, but will, in addition, include the use of special stress concentration, strain concentration, and life reduction factors for weldments.

Once detailed analysis procedures and criteria, as well as simplified procedures, are recommended, their final applicability must be verified. This is to be done through tests of a series of prototypical structural joints (cyclic bending of welded pipes to failure, thermal ratchetting, etc.).

In conclusion, it should be emphasized that although the framework for a design technology for weldments will hopefully be the same for the various base metal–weld metal–weld process combinations, the details will vary and must be developed for each through an experimental and theoretical effort. As stated earlier, initial efforts will concentrate on 304/308 weldments. Later, 316/16-8-2 stainless steel weldments [using both the gas-tungsten-arc (GTA) process and the submerged-arc (SA) process] will be introduced as will alloy 800/Inconel 82/2¼ Cr–1 Mo steel dissimilar metal weldments. As new materials are added, the magnitude of this subtask will necessarily increase.

2.7.4 Subtask/milestone schedule



Milestones

1. Publish report on weldment creep-rupture tests of type 304 stainless-steel-capped cylinders.
2. Complete room-temperature elastic-plastic strain gage and Moire tests on in-plane-loaded plate weldment specimens.
3. Adapt shear-lag specimen test frame to high-temperature weldment tests; initiate testing.
4. Complete first creep-rupture test of restrained cylinder under cyclic thermal loading.
5. Complete assessment of special Moire technique for in-place photographing of fringes at high temperature.
6. Publish report on plate weldment specimen tests and analyses.
7. Complete beam weldment tests.
8. Complete verification tests on prototypical structural joints (using materials of interest).
9. Complete literature survey of notch effects in weldments.
10. Complete notch effects tests for commonly used weldments.
11. Complete tests of preflawed joints.
12. Publish summary report on effects of notches and flaws on failure behavior of commonly used weldments.
13. Assess the applicability of interim (RDT Standard F9-5T) constitutive equations on basis of existing data for commonly used weld metals.
14. Define and initiate exploratory (yield, creep, relaxation, etc.) tests (using loadings ranging from sustained to cyclic) as required to improve behavioral representations of commonly used weld metals.
15. Complete modifications to interim equations on basis of existing test data as required.
16. Adapt unified constitutive equations to commonly used weld metals.
17. Complete preliminary assessment (analytical and experimental) of residual stresses in as-welded structures and their implications with respect to high-temperature behavior.
18. Complete analysis of plate specimens.
19. Recommend relatively detailed (but practicable) inelastic analysis procedures and commensurate design criteria.
20. Complete relatively detailed analyses of all structural tests.
21. Complete assessment of adequacy of existing deformation and failure criteria (for base metals) using existing all-weld-metal data.
22. Propose modifications to existing criteria as required for commonly used weld metals.
23. Recommend final criteria based on all available materials test data and structural test (flawed and unflawed) results.
24. Recommend scoping analysis procedures.
25. Propose simplified assessment procedures and commensurate deformation and failure criteria.

3. HIGH-TEMPERATURE STRUCTURAL DESIGN – VALIDATION

(Westinghouse ARD 189a CW063)

3.1 Introduction and Scope

3.1.1 Objective

The overall objective of this program is to experimentally validate high-temperature structural design methods and criteria used in the design of LMFBR components operating in the thermal creep range. The validation program is based on testing and analysis of specimens ranging from simple configurations, used to separate out the effects of specific assumptions, to full-size components and prototypical conditions, used to validate the total analysis procedure. These data are used in conjunction with the data from complementary programs to achieve the following specific objectives:

- Determine the validity and evaluate implementation of the ORNL proposed constitutive relations for time-dependent material response with multiaxial states of stress under constant and stepped load conditions.
- Determine the factors affecting strain at failure in base metal, welds, and at geometrical discontinuities.
- Determine the time-dependent strain and deformation response of piping components under LMFBR loading conditions, investigate creep buckling and ratchetting, and validate detailed and simplified methods for predicting deformation and buckling of piping components.
- Perform a prototypic worst-case creep ratchetting test on an FFTF-IHX inlet nozzle under combined pressure and transient loading, investigate ratchetting in axisymmetric and nonaxisymmetric nozzle configurations, and experimentally validate detailed and simplified analysis procedures for ratchetting in two- and three-dimensional configurations.
- Characterize crack initiation and propagation in LMFBR materials and components to determine crack morphology and validate methods for predicting crack propagation under cyclic loading conditions and steady creep at elevated temperatures.

3.1.2 Background

To assure safe and reliable operation of components, design criteria and standards must be established to define the margin of safety between operating conditions and failure. The designer must demonstrate that the structural analyses, which are performed to confirm the existence of that margin, truly provide a conservative approximation of real component behavior and typical complex loading conditions. Design criteria and standards are being prepared for structural design of components operating in the thermal creep range. These include: ASME Boiler and Pressure Vessel Section III, Elevated-Temperature Code Cases, RDT Standard F9-4T, and RDT Standard F9-5T, which place a high reliance on design by analysis.

Many structural analysis computer programs have been developed and have been validated by comparison of results with experimental component tests in the linear elastic range. However, very few validation tests have been performed for nonlinear problems typical of those encountered in high-temperature design where material response is time-dependent. The validity of proposed constitutive relations to represent time-dependent material response also must be established for conditions of multiaxial stress. This can only be accomplished by comparison of calculated results with actual test results for representative geometries, loads, and environmental conditions.

The validation program at WARD was started in 1971 as an integral part of the national program on development of high-temperature structural design methods and criteria for LMFBR components. Testing and analysis have been concentrated on creep behavior of types 304 and 316 stainless steels at 1100°F (593°C). Creep-rupture tests have been performed on plate and bar specimens to determine the effects of plane stress vs plane strain, holes, notches, welds, and eccentric loading. Uniform and stepped loads have been applied with test durations ranging from 138 to 16,892 hr. Creep tests have also been performed on tubular specimens under both uniaxial and multiaxial loading conditions to evaluate the application of constitutive relations.

The Multiloading Test Facility (MLTF) has been designed and constructed to perform structural tests on piping components up to 28 in. (0.711 m) in diameter with temperatures up to 1200°F (649°C), internal pressure up to 600 psi (4.14 MPa), and external force applied by load- or displacement-controlled load actuators. Initial emphasis has been on testing of 16-in.-diam (0.406-m) type 304 stainless steel FFTF elbows.

The Creep Ratchetting Test Facility (CRTF) has been designed and constructed to provide the capability for thermal transient ratchetting tests on full-scale FFTF-IHX nozzles. A shell test section has been fabricated which contains three prototypic FFTF-IHX inlet nozzles and one axisymmetric outlet nozzle in one of the two end closure heads.

The work on crack propagation has been focused on providing data to support FFTF and CRBRP safety analysis on piping integrity with fatigue and burst tests on quarter- and full-scale reactor inlet downcomer elbows containing hypothetical defects.

3.1.3 Plan of action

The program is organized into five subtasks. The overall plan of action for each of these subtasks is outlined below and detailed in subsequent sections. The overall program schedule is shown in the chart presented in Sect. 3.1.4, with more detailed schedules shown after each of the subtask descriptions.

Subtask A – basic specimens. Perform testing and analysis of 304 SS, welded 304 SS, and 316 SS creep specimens made from plate and notched bar to evaluate damage theories, investigate strain limit criteria, and validate analytical methods to predict creep behavior.

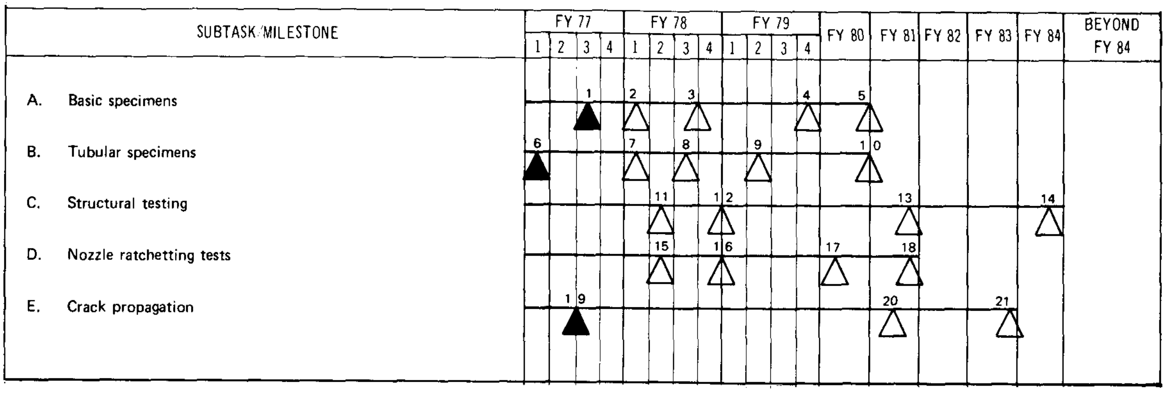
Subtask B – tubular specimens. Perform testing and analysis of 304 SS and 316 SS tubular specimens to verify constitutive relations and design criteria for time-dependent material response of shells under uniaxial and multiaxial loading conditions.

Subtask C – structural testing. Using the MLTF, a series of full-scale piping component deformation, creep, and fatigue tests will be performed at temperatures up to 1200°F (649°C). The components to be investigated will include elbows, tees, straight pipe, and reducers made from types 304 and 316 stainless steels. Initial testing and analysis will be on 16-in.-diam elbows to determine short-term elastic-plastic buckling behavior. Subsequent elbow tests will determine creep deformation and buckling during test durations up to 2000 hr and ratchetting under cyclic loading conditions. All test results will be compared with analytical results to validate simplified and detailed analysis procedures.

Subtask D – nozzle ratchetting tests. Ratchetting tests will be performed in the CRTF, using programmed flow rates of inert gas and controlled-flow annuli to provide thermal transients with hold temperatures up to 1100°F (593°C) and internal pressure up to 600 psi (4.14 MPa). Thermal and strain histories will be determined at critical nozzle locations. A parallel effort will provide uniaxial test data on the nozzle material to characterize material behavior for nozzle test results interpretation. Initial results will be used as a proof test of the FFTF-IHX inlet nozzle design. Subsequent tests will be compared with analysis results to provide validation of simplified and detailed analysis methods for ratchetting in nozzles.

Subtask E – crack propagation. Additional testing and analysis are needed to characterize crack propagation in LMFBR materials and components. Analysis methods for prediction of crack propagation in the thermal creep range need to be developed and validated by comparison with experimental data on crack propagation in scale-model and full-scale piping components with prototypic loading conditions. Test data are also needed on fatigue cracking resulting from thermal striping where fluid streams of different temperature alternately impinge on the surface of components.

3.1.4 Subtask/milestone schedule



Milestones

1. Topical report on testing of nonuniform section 304 SS specimens.
2. Topical report on analysis of uniform section 304 SS specimens.
3. Topical reports on testing of 304 SS welds and analysis of nonuniform section 304 SS specimens.
4. Final report on 304 SS testing and analysis.
5. Final report on 316 SS testing and analysis.
6. Initiate 316 SS testing.
7. Topical report on 304 SS testing.
8. Topical report on constant-load 316 SS tests.
9. Topical report on stepped-load 316 SS tests.
10. Final report on tubular specimen testing, including tests with geometric discontinuities.
11. Topical reports on plastic collapse elbow test.
12. Topical report on creep deformation elbow test.
13. Complete elbow testing and analysis.
14. Complete testing and analysis of additional piping components.
15. Complete checkout testing.
16. Complete worst-case FFTF transient tests.
17. Complete shell nozzle testing.

18. Complete final report on FFTF-IHX nozzle testing and analysis.
19. Complete final report on fracture mechanics testing in support of FFTF and breeder reactor safety analysis for reactor vessel inlet downcomer.
20. Complete crack growth tests on cyclically loaded components.
21. Complete tests on initially flawed components to confirm proposed design criteria.

3.2 Subtask A – Basic Specimens

3.2.1 Objective

The objective of this subtask is to test and analyze types 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:

- Evaluate damage theories for steady-state loading and interspersed creep during step loadings.
- Investigate the factors which influence ductility and upgrade the damage and strain limit criteria.
- Validate analytical methods to predict creep behavior.

3.2.2 Background

The six basic specimen types are shown in Fig. 3.1, with the specimen sizes and weld configurations described in Table 3.1. Specimens have been made from 304 and 316 SS base material and 304 SS weldments, using 308 SS filler metal with controlled residual elements.

Type A. This test section is long, uniform, and rectangular. The ends of this gage length have fillets, and the area at the heads is more than five times that of the gage section. The state of stress is essentially plane

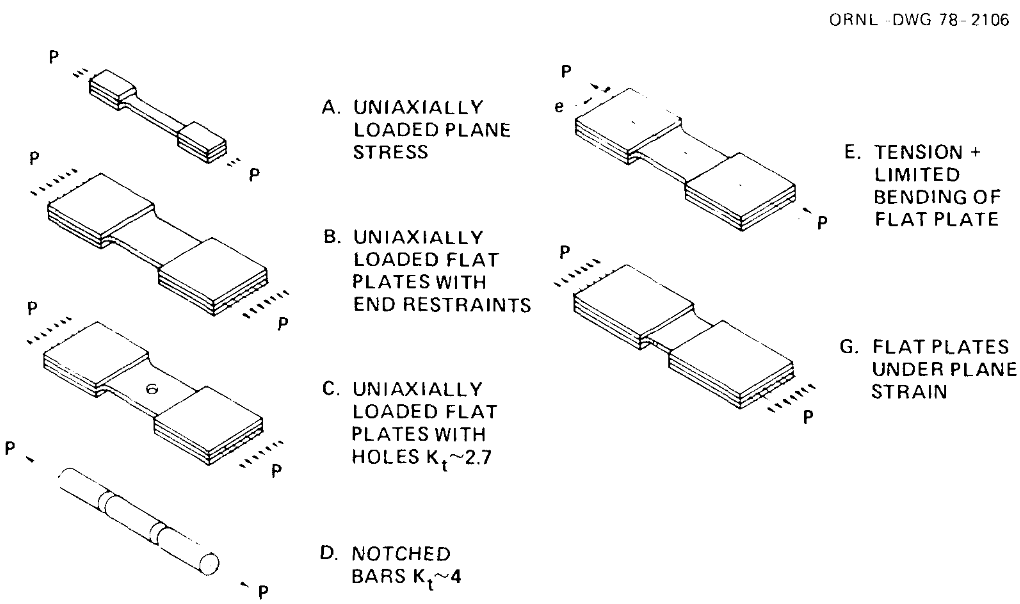


Fig. 3.1. Basic specimen types.

Table 3.1. Model types

Code designation	Description[a]
	Specimens from base material[b]
A	Plane stress specimen 1/3 × 2/3 × 3 in. (8.5 × 17 × 76.2 mm) gage section
B	Plate specimen 1/3 × 10/3 × 3 in. (8.5 × 85 × 76.2 mm) gage section
C	Plate specimen with central hole of 1/3 in. (8.5 mm) diameter, 1/3 × 10/3 × 3 in. (8.5 × 85 × 76.2 mm) plate section
D	Round circumferentially notched specimen, major diameter = 0.96 in. (24.4 mm), minor diameter = 0.64 in. (16.2 mm), K_t = 4, root radius = 0.018 in. (0.46 mm), two nearly identical notches in specimen
E	Plate specimen in bending and tension, 1/3 × 10/3 × 2 in. (8.5 × 85 × 50.8 mm) plates section, eccentric load
F	Designation generally refers to failure or fracture; therefore, it is not used to identify a type of model
G	Plane strain specimen 1/3 × 10/3 × 1 in. (8.5 × 85 × 25.4 mm) gage section; ends constrained in transverse direction
	Specimen with welds
BTW	B-type plate specimen with transverse weld at midlength of gage section
BAW	B-type plate specimen with axial weld at center of gage section
CTW	C-type specimen with hole through transverse weld
CAW	C-type specimen with hole through axial weld
DTW	D-type specimen with notch root in transverse weld
DZTW	D-type specimen with notch root at weld fusion line of heat-affected zone
GTW	G-type specimen with transverse weld at midgage length
GAW	G-type specimen with axial weld at center of gage section

[a]Reference Fig. 3.1.
[b]Type 304 SS (HT9T2796) annealed at 2000°F.

over much of the gage section. The creep-rupture data for this specimen are directly comparable with the smooth-bar data obtained by the ORNL program and serve as baseline data for this size plate made from the reference heat.

Type B. This plate specimen, with a width-to-thickness ratio of 10 and a uniform gage length approximately equal to the width, has a high degree of plane strain that is generated at the ends of the gage length by restricting the lateral motion and having little restraint in the thickness direction. The transverse stresses are the largest at the ends and diminish toward the center of the gage length. The stress at the center increases with increasing plastic flow.

Type G. This plane strain specimen is a shorter gage length version of the type B specimen, having a high degree of plane strain over the gage sections. With increasing plastic strain, the ratio of the biaxial stress (transverse to axial) approaches one-half, and the ratio of the Mises effective stress to the maximum principal stress approaches 0.86. Therefore, the relative damage for the biaxial stress state caused by the stress and strain patterns is being evaluated by comparing the flow and rupture characteristics of specimens A, B, and G (all have uniform-width gage sections).

Type C. The configuration of this finite-width plate specimen with a central hole combines the biaxiality of the type B specimen with the stress and strain concentration of a central hole. The elastic stress concentration factor is 2.7 at the sides of the hole on the central transverse axis. The magnitude of the strain concentration, which is developed when the yield stress is exceeded or when creep occurs, will be evaluated for this geometry. The damage around the hole that is influenced by the rate of stress and strain states will be determined.

Type D. This round circumferentially notched specimen has an elastic stress concentration factor of 4 at the base of the notch and a triaxial state of stress below the surface. The degree of triaxiality and the ratio of the maximum principal stress to the Mises effective stress are functions of the plastic flow. These stresses and the maximum rate of damage vary with time for critical volumes around the notch root. In tests of the notched specimens, the initiation and propagation of damage will be determined at several fractions of rupture life, and the influence of stress and strain concentrations on rupture time and strain under triaxial stress will be evaluated.

Type E. This type of specimen has a bending moment applied by a tensile load offset from the longitudinal axis, as shown in Fig. 3.1. The load is sufficiently large to obtain approximately 5% more strain on one edge than on the other. Since a fillet radius larger than that for the type B specimen is used to minimize the strain concentration and still maintain the same length of specimen between the loading points, the uniform gage length has been reduced.

Specimens with welds. The creep and rupture characteristics of welds are being investigated. Welds of critical volumes are incorporated in the various types of specimens described in Table 3.1. In general, the purpose of each type of test is the same, but the material response is more complex.

The first series of tests utilizes a type 308 stainless steel weld with controlled residual elements to join type 304 stainless steel base metal plates made from RRT reference heat 9T2796. The welds are tested in the transverse and longitudinal (axial) directions. ORNL tests of all-weld-metal specimens indicate that the strength of the weld is higher and the ductility is lower than for the base-plate material.

The specimens are being tested at 1100°F (593°C) with stress levels systematically varied and both monotonic and stepped loading conditions. Strain measurements are made using extensometers, strain gages, and plated surface grids with interim photographic measurements. Crack initiation and propagation are also being monitored by interim photography and metallographic examination of the test specimens. Pretest analyses have been completed to guide selection of test conditions, and posttest analyses have been completed on the type A and B 304 SS specimens. The test matrix of 18 type 304 SS base-metal specimens has been completed, and 11 of the 14 type 304 SS welded specimens have been completed. The 316 SS test matrix has been started on type A and D specimens. Topical reports have been prepared on all the test results obtained from the 304 SS base-metal specimens.

3.2.3 Plan of action

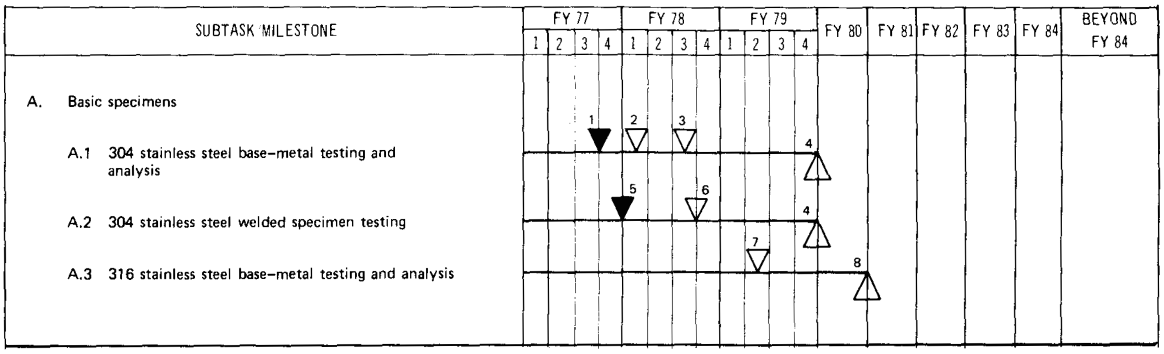
The remaining 304 SS welded specimen and 316 SS base material creep tests will be completed. The 316 SS test matrix will be limited to base material tests with a total of approximately 15 specimens. The test data will be compiled to provide:

1. Stress-strain curves for monotonic loading conditions.
2. Stress-strain curves for creep-interspersed step-loading conditions.
3. Comparison of strain and time hardening from monotonic and step-loading conditions.

4. Mapping of strain contours for a variety of geometries.
5. Determination of creep rates as a function of stresses.
6. Magnitude of transitional and rupture strains for a variety of stress states.
7. Transitional and rupture time as a function of stress.
8. Determination of the stress state from strain measurements.
9. Evaluation of the characteristics of weldable strain gages and surface grids at elevated temperature.
10. Measurement of crack initiation and propagation at strain concentrations.
11. Comparison of the test strain distributions with those of computer calculations for the various specimen geometries and stress states.
12. Evaluation of damage criteria and strain limits for steady-state and interspersed creep loading.

A series of topical reports will be issued on the testing and analysis performed in this subtask, with the current work scope defined in the milestone chart (Sect. 3.2.4).

3.2.4 Subtask/milestone schedule



Milestones

1. Complete topical report on nonuniform gage section base-metal 304 SS specimen testing.
2. Complete topical report on uniform gage section base-metal 304 SS specimen analysis.
3. Complete topical report on nonuniform gage section base-metal 304 SS specimen analysis.
4. Complete final report on 304 SS specimen testing and analysis.
5. Complete topical report on uniform gage section welded 304 SS specimen testing.
6. Complete topical report on nonuniform gage section welded 304 SS specimen testing.
7. Complete topical report on plane stress plate and notched bar 316 SS specimen testing.
8. Complete final report on 316 SS specimen testing and analysis.

3.3 Subtask B – Tubular Specimens

3.3.1 Objective

The objectives of this task are to provide creep data for reference heats of 304 and 316 SS to verify constitutive relations and design criteria for time-dependent material response of shells under multiaxial loading and to investigate the effect of geometric discontinuities in shells.

3.3.2 Background

Creep deformation tests at 1100°F (593°C) are being conducted on specimens approximately 9 in. (22.9 cm) in length with 0.05- to 0.1-in. (0.13- to 0.25-cm) walls and 1.8 in. (4.57 cm) in diameter. Initial tests were under uniaxial loading to provide a comparison with results from other product forms made from the same reference heat. 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. Selected tests are being continued to rupture after determination of creep deformation rates in the first 2000 hr.

The test matrix on specimens from a reference heat of type 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 with constitutive equations developed by ORNL. Testing of type 316 stainless steel has been started with a test matrix of 13 specimens including both uniaxial and biaxial loading.

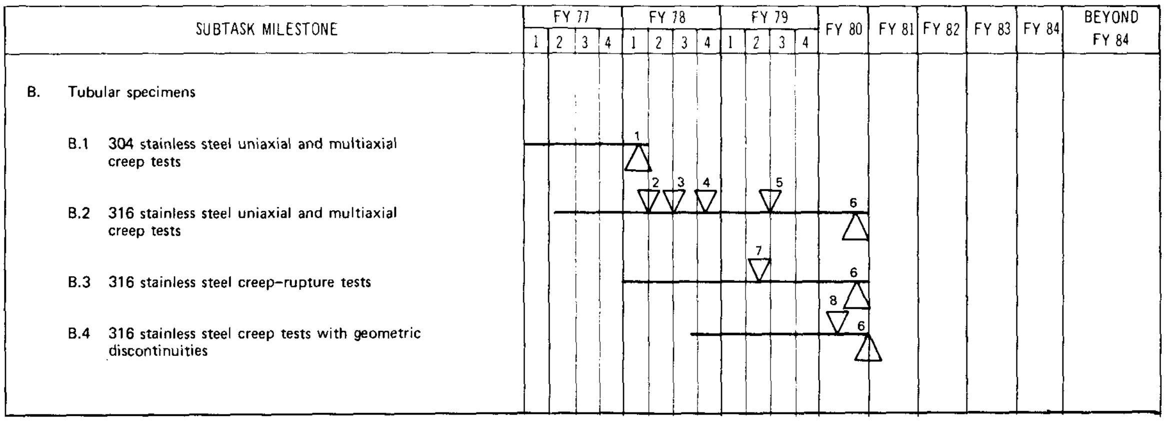
Detailed inelastic analyses of a typical tubular specimen test have been performed to examine the nonuniformity in the stress and strain behavior and to guide the definition of equivalent uniform values. A data-reduction computer program package, TUBE DATARED, has been developed for the tubular specimen data.

3.3.3 Plan of action

The 304 SS data from uniaxial and multiaxial tests will be used to evaluate the applicability of proposed ORNL constitutive relations developed from tests on specimens from other product forms of the same reference heat. These data will also be analyzed to evaluate damage criteria and inelastic methods of analysis for cylindrical shells. The reference heat 316 SS uniaxial and multiaxial test matrices will be completed to obtain creep deformation behavior up to 2000 hr. Selected specimens will also be tested to rupture. These data will be analyzed in a manner similar to those from the 304 SS specimens. Subsequent tests will be aimed at determining the effect of geometric discontinuities on the creep behavior of cylindrical shells.

The current work scope for this subtask is shown in the milestone chart (Sect. 3.3.4).

3.3.4 Subtask/milestone schedule



Milestones

1. Complete topical report on 304 SS uniaxial and multiaxial test data.
2. Complete fixed-load 316 SS uniaxial and multiaxial testing.
3. Complete topical report on fixed-load 316 SS uniaxial and multiaxial testing.
4. Complete stepped-load 316 SS multiaxial testing.
5. Complete topical report on stepped-load 316 SS multiaxial testing.
6. Complete final report on 316 SS creep testing and analysis.
7. Complete testing and topical report on 316 SS rupture testing.
8. Complete testing and topical report on 316 SS creep with geometric discontinuities.

3.4 Subtask C – Structural Testing

3.4.1 Objective

The objectives of this subtask are as follows:

- Investigate inelastic and creep collapse and ratchetting of piping components under various combinations of load.
- Investigate time-dependent strain and deformation response of piping components under LMFBR loading conditions.
- Validate detailed and simplified methods for predicting deformation and collapse of piping components.

3.4.2 Background

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 principal piping components of interest are: straight pipe, tees, reducers, and elbows. The major stresses and deformations experienced by an LMFBR piping system are due to seismic and dead-weight loads and thermal expansions. The thermal forces are transmitted to the plant pressure vessels and supporting structures connected to the piping. It is highly desirable to keep these forces as small as possible or, equivalently, to accommodate most of the straight pipe section expansion by a relatively flexible piping layout. Typically, the expansion is accommodated by the piping elbows, which, for low-pressure LMFBR systems, have a high degree of flexibility in comparison with that of the straight components. The MLTF has been specially designed for this subtask to perform structural tests on this type of component with initial emphasis on full-scale LMFBR piping elbows. Six 16-in.-diam (0.406-m) 304 SS FFTF seamless elbows have been procured for the initial test program.

Checkout testing of the MLTF has been completed using a commercial specification 304 SS 16-in.-diam (0.406-m) elbow test section. The checkout testing included operation of temperature, pressure, displacement, and strain control and instrumentation equipment. A collapse test on an FFTF 16-in.-diam (0.406-m) elbow has also been completed to determine the limit load and displacement modes. A number of analyses have been performed for use in design of the MLTF and test planning. These analyses have also served to establish the basis and procedures for the analysis in correlating predicted and measured data. A simplified MARC pipe bend finite-element model has been used to investigate several elbow loading conditions, and good comparison was obtained between the predicted and measured load at which buckling occurred in the FFTF elbow buckling test.

3.4.3 Plan of action

The piping components to be investigated include elbows, tees, straight pipe, and reducers made from 304 and 316 SS. The first six tests are being made on 16-in.-diam (0.406-m) 304 SS FFTF seamless elbows. The following types of tests have been identified for elbow test sections with test durations up to 2000 hr:

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 deformation under in-plane and out-of-plane bending moments.
4. Creep buckling under in-plane bending moment.
5. Strain accumulation due to ratchetting.

Test data from the elbow test sections include measurements of temperature distribution, external surface strain using both resistance and capacitance strain gages, ovalization deformation at the central cross section, rotational and linear displacement in three directions, and loading history. Samples of material are also cut from the test sections to determine mechanical properties for input to the analysis of the tests and test planning.

A topical report is being prepared on the first FFTF elbow collapse test with completion scheduled before the end of FY 77. The second FFTF elbow test is under way to determine creep deformation response under an in-plane bending moment at 1100°F (593°C) for 2000 hr. Test conditions and priorities for additional tests will be detailed as data are analyzed from the initial tests.

A scale-model piping component test program at room temperature is planned to supplement the data obtained from the full-scale tests in the MLTF. Examples of where this type of testing would be particularly cost effective are as follows:

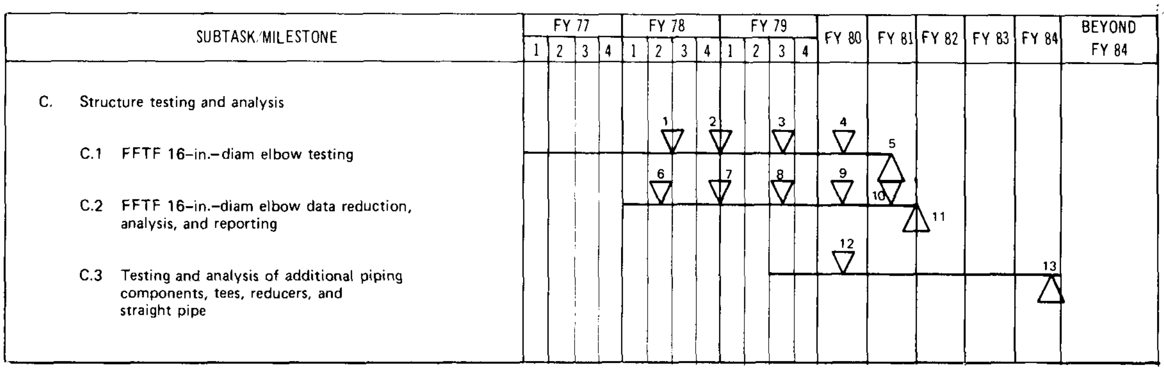
1. duplication testing to evaluate the data scatter at nominally similar test conditions,
2. determination of out-of-plane vs in-plane loading effects,

3. determination of buckling behavior of cylinders in bending as opposed to axial compression,
4. evaluation of welded vs seamless piping component structural response.

All of the test results will be compared with analytical results to validate the analytical methods. In a typical bending situation, the cross section of an elbow becomes oval, causing a major redistribution of stress around the cross section, whereas a straight pipe behaves according to simple bending theory. Special analysis techniques are required to account for the ovalization and geometric nonlinear effects for large displacements. Other factors to be considered during analysis include the stiffening effect of straight sections attached to the elbow, initial cross-sectional ovality, and nonuniform wall thickness. Both detailed and simplified methods of analysis will be investigated in this subtask, with the end result of providing specific methods and guidelines for plant component design.

The current work scope for this subtask is shown in the milestone chart (Sect. 3.4.4).

3.4.4 Subtask/milestone schedule



Milestones

1. Complete second FFTF elbow creep deformation test.
2. Complete third FFTF elbow test.
3. Complete fourth FFTF elbow test.
4. Complete fifth FFTF elbow test.
5. Complete FFTF elbow testing.
6. Issue topical report on first FFTF elbow collapse test.
7. Issue topical report on second FFTF elbow creep deformation test.
8. Issue topical report on third FFTF elbow test.
9. Issue topical report on fourth FFTF elbow test.
10. Issue topical report on fifth FFTF elbow test.
11. Issue final report on FFTF elbow testing and analysis.
12. Procure additional piping components.
13. Complete testing and analysis of additional piping components.

3.5 Subtask D – Nozzle Ratchetting Tests

3.5.1 Objective

The primary objective of the test program is to provide a proof test of the FFTF-IHX inlet nozzle under worst-case thermal transient conditions experienced by the nozzle. A secondary objective is to obtain and analyze experimental data to validate analytical techniques for design of components in which creep ratchetting may produce strains in excess of ASME code allowables.

3.5.2 Background

Creep ratchetting is the monotonic accumulation of inelastic strain from load cycle to load cycle and tends to occur at locations of peak thermal gradients, such as nozzles and mixing tees, which are also geometrically complex. There are some experimental data to confirm analytical predictions of ratchetting in simple geometries such as beams and cylindrical shells. No experimental data are available for more complex two- and three-dimensional geometries typical of LMFBR nozzles. This subtask was initiated to provide data on creep ratchetting of FFTF-IHX nozzles which represent typically complex geometries in which ratchetting is most likely to cause a problem during design.

Fabrication of a nozzle ratchetting test section has been completed to provide a shell structure containing four test nozzles: three FFTF-IHX inlet nozzles and one FFTF-IHX outlet nozzle. The test nozzles are all designed for 16-in.-diam (0.406-m) piping and are made from type 304 H stainless steel by the same manufacturer as used for the FFTF plant hardware. Preliminary analysis of the FFTF-IHX inlet nozzle predicted over 3% strain, using a conservative Bree diagram technique. Subsequent elastic and inelastic analysis, using the programs CHERN and MARC, indicated that the maximum strain would be approximately 0.5% and would occur just upstream of the thickest cross section of the nozzle.

The thermal transients will be achieved by high-flow-rate argon passing through controlled annuli on the inner surface region of the test nozzle. The tests will be performed in the CRTF at ARD. The test facility consists of a reinforced concrete test cell, 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 adjacent control room for remote test operation provides for visual observation of the test section. An inert-gas test fluid was chosen over sodium to reduce test facility cost and to facilitate internal surface strain measurement. No strain gages are available for reliable measurements in high-temperature sodium for this type of test, and since the internal surface is of primary interest during the test, this instrumentation problem was an important factor in facility design.

3.5.3 Plan of action

During FY 77, the FFTF-IHX test section will be instrumented and prepared for testing in the CRTF. Temperature and pressure control systems will be installed, and checkout testing will be performed to evaluate and test facility performance, temperature distribution during transients and hold periods, strain measurement techniques, and gas flow control used to produce the transients.

The initial test conditions will be similar to the worst-case transients expected in the FFTF-IHX with cooling rates of up to 4°F/sec (2.2°C/sec). The hold temperature between transients will be ∿1050°F (566°C), and the internal pressure will be ∿200 psi (1.38 MPa). Current information on reference plant operating conditions indicates that the hold time should be at least 150 hr. The reference number of transients applied to the proof test nozzle is 20. If shakedown occurs early in the test, only five to ten transients may be justified. The actual number of transients to be performed will be based on strain data obtained during the testing.

It is anticipated that the ratchetting strain obtained in the FFTF proof test will not be sufficiently large to quantitatively evaluate the analysis techniques or design code limits. Consequently, more severe follow-on tests are planned to meet the secondary objectives of this program. Larger ratchetting strains can be obtained in the follow-on tests by increasing test pressure, thermal transient gradient, and hold temperatures between transients. By increasing the test pressure, the nozzle membrane stresses are increased. Thermal stresses can be increased by maximizing the thermal gradient. Increasing the hold temperature primarily increases the creep rate and, therefore, the rate of stress relaxation between transients. Specific test conditions for the follow-on tests will be determined after evaluation of the proof test results. Tentatively, the thermal transient ramp rate will be similar to that used for the proof test with an increase in pressure to 450 psi (3.1 MPa) and an option to increase the hold temperature to 1200°F (649°C). In addition, the cylindrical portion of the test section can be removed and the hemispherical heads welded together. This would allow for tests with a further increase of pressure to 600 psi (4.14 MPa) on the axisymmetric outlet nozzle.

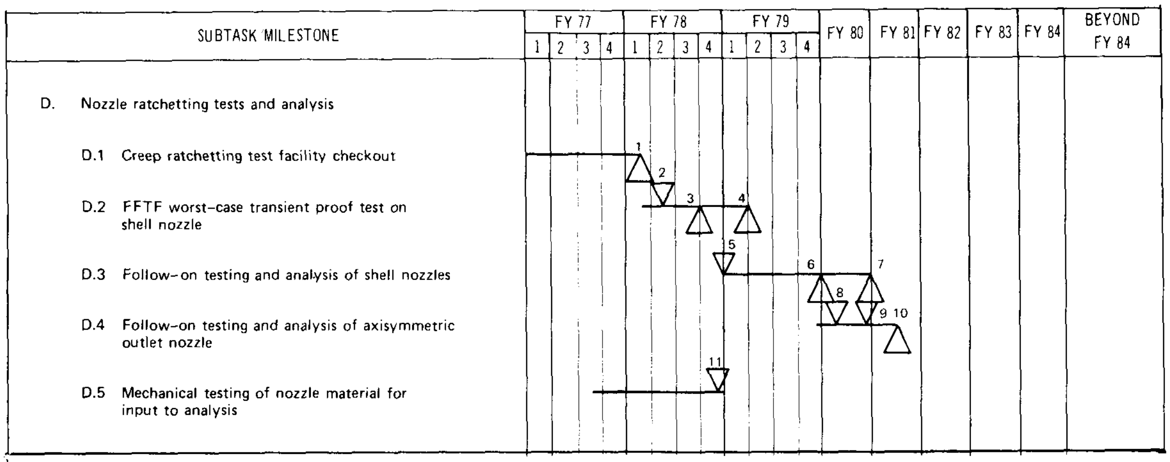
Overall strain measurements of the test nozzles will be performed with an LVDT system and/or with conventional metrology equipment. Strain measurements at specific locations on the test nozzles will be made with strain gages and a replication technique. This technique provides only measurements of residual strain at room temperature, but these measurements can be realistically compared with both ASME code strain limits and analytical results. Replicas will be made to provide an image of target scribe marks at specific locations before testing. The distance between the scribe marks on the replica will be measured very accurately using optical techniques. After selected transients, the test article will be cooled to ambient temperatures, and replicas of the same specific locations will be made and measured to determine the residual strain that exists between the target scribe marks.

High-temperature capacitance and resistance strain gages will also be used to measure strain at selected locations throughout the test. A three-gage rosette will be used at each measurement location. Temperature distribution will be measured using fast-response Chromel-Alumel thermocouples attached to critical positions on the test nozzles and adjacent shells. The test data will be recorded on a high-speed digital data acquisition system which automatically transmits the data to a central computer for data reduction and processing.

In parallel to the nozzle test program, uniaxial mechanical test data will be obtained for specimens machined from a nozzle from the same batch as for the test nozzles. The material property data will be used as input to the structural analysis and for test planning.

The test data obtained from this program will be compared with analytical results to validate analysis methods for predicting the incremental strain during creep ratchetting. The current work scope for this subtask is shown in the milestone chart (Sect. 3.5.4).

3.5.4 Subtask/milestone schedule



Milestones

1. Complete checkout testing of CRTF.
2. Start FFTF worst-case transient proof test.
3. Complete FFTF worst-case transient proof test.
4. Issue topical report on FFTF worst-case transient proof testing and comparison with analytical results.
5. Start follow-on testing and analysis of shell nozzles.
6. Complete follow-on testing of shell nozzles.
7. Issue topical report on ratchetting tests and analysis of shell nozzle.
8. Complete conversion of test section to spherical configuration for outlet nozzle testing.
9. Complete outlet nozzle testing.
10. Complete final report on nozzle ratchetting testing and analysis.
11. Complete mechanical tests (tensile, creep, relaxation) on nozzle material for input to analysis.

3.6 Subtask E – Crack Propagation

3.6.1 Objective

The objective of this subtask is to characterize crack initiation and propagation in LMFBR materials and components to determine crack morphology and validate methods for predicting crack propagation under cyclic loading conditions and steady creep at elevated temperatures.

3.6.2 Background

The initial testing and analysis on this subtask were aimed at characterizing crack propagation in piping elbows for input to safety analyses on the reactor inlet downcomer piping in the FFTF and the CRBRP. The inlet downcomer region is critical because a large rupture could cause hot-channel boiling in the core. Tests were performed to demonstrate that growing cracks would 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. Burst tests were performed on model and full-scale elbows to determine the critical crack size at which the crack bulges open under plant operating internal pressure. Fatigue tests on flawed elbows demonstrated that the crack always grew through the wall to leak before the critical crack size was reached and confirmed the leak before break argument used in the safety analyses. Creep efforts could be sensibly ignored in this program because of the relatively low operating temperature of the inlet downcomer region. The requested work for the FFTF and the CRBRP safety analyses has been completed.

While the ASME Boiler and Pressure Vessel Code provides fatigue and creep-fatigue limits to guard against failure by cyclic crack growth, these limits are based on test data from smooth-surface uniform-section specimens. Because of the difficulty in extrapolating these data to typical cracklike flaws in actual components, the fatigue limits tend to be excessively conservative. Actual components invariably contain cracklike flaws; however, no significant crack growth may occur under service loads even though the as-fabricated components do not meet fatigue design criteria.

Improved methods are needed to predict crack initiation and propagation behavior in LMFBR components, particularly in the thermal creep range. As these methods are developed, it will be necessary to experimentally validate the ability to predict crack growth behavior in typical components. The effort will be complementary to the analytical development presented in Sect. 4.5 of this program plan.

3.6.3 Plan of action

The test program on crack growth will emphasize validation of methods to predict crack growth rates to assure piping integrity. To avoid the limitations of predicting component performance from small simply loaded specimens, results will be obtained from actual component configurations under actual loading conditions. Environmental conditions also will be simulated because they may have a major effect on crack growth rates.

Primary emphasis will be placed on pipe, elbow, tee, and nozzle test sections. Both small- and full-scale components will be tested to validate analytical developments in the following areas:

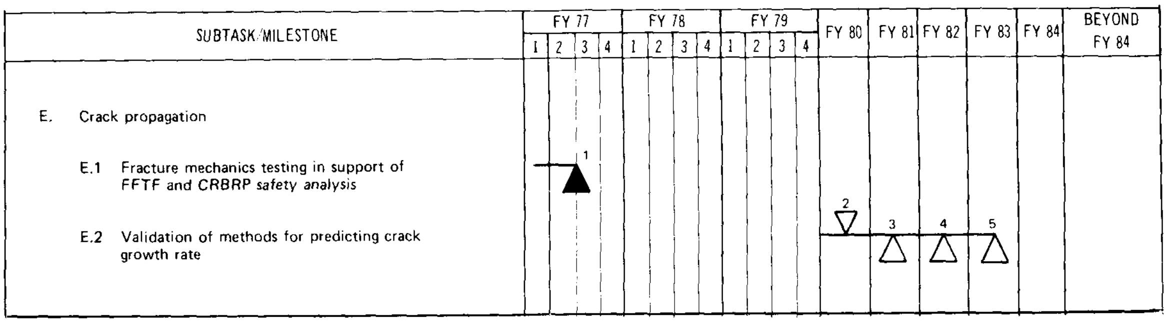
- Analytical determination of stress intensity factors for cracked components.
- Methods for predicting crack growth under inelastic conditions.
- Models for predicting crack morphology in complex stress fields.
- Methods for predicting crack growth under conditions of varying load amplitudes, cyclic frequencies, and temperatures.

A test facility similar to the MLTF (previously discussed in Sect. 3.4) will be required with modifications to provide alternating loads under a controlled environment. It may also be desirable to investigate the effect of repeated thermal transients, applied in conjunction with steady mechanical loads, using an experimental facility similar to the CRTF (previously discussed in Sect. 3.5).

Thermal-striping fatigue is a specific loading mechanism that merits further investigation. Thermal striping occurs where fluid streams of differing temperature alternately impinge upon a component to cause local straining. There are no known experimental programs in this country aimed at characterizing thermal-striping resistance of LMFBR structural materials. Direct experimental data are needed to (1) validate the thermal-hydraulic film coefficient calculations by which the designer determines how much of the fluid stream temperature differential is delivered to the surface of the component and (2) validate the structural integrity calculations of the design, using the metal surface temperature differentials. Initial tests would emphasize fatigue of a 316 SS pipe specimen with alternating hot and cold sodium flows on the inside wall with a temperature differential estimated to cause cracking in 1 X 10^6 cycles.

Current funding limitations preclude the start of any further work on this subtask through FY 78. However, in anticipation of additional funding in subsequent fiscal years, an overall schedule has been prepared as shown on the milestone chart (Sect. 3.6.4).

3.6.4 Subtask/milestone schedule



Milestones

1. Complete final report on fracture mechanics testing in support of FFTF and CRBRP safety analysis for reactor vessel inlet downcomer.
2. Complete exploratory testing in support of analysis of flawed components.
3. Complete crack growth tests on cyclically loaded components.
4. Complete crack growth tests on components under steady creep.
5. Complete crack growth tests to confirm proposed design criteria.

4. HIGH-TEMPERATURE STRUCTURAL DESIGN – APPLICATION
(Westinghouse ARD 189a CW138)

4.1 Introduction and Scope

4.1.1 Objective

The objectives of this program are to develop qualified analysis methods, design procedures, design limits and criteria, and the guidance required to assure their proper application. This work is necessary to translate the results of basic development programs into procedures and guidelines which provide a basis for structural design and for assurance of safety and reliability.

4.1.2 Background

The structural design of LMFBR components to perform reliably at elevated temperatures for long periods of time requires consideration of the time-dependent response of the structure to steady, varying, and cyclic mechanical and thermal loads as well as environmental conditions. In addition to the failure modes considered for low-temperature service, it is necessary to guard against failure by creep rupture, creep-fatigue interaction, ratchetting, creep buckling, and environmental enhancement of low-temperature failure modes. Special attention must be paid to material behavior, elastic follow-up, strain concentrations, and geometrical stability. Although design procedures are well established for low-temperature service by a long history of tests and operational experience, elevated-temperature design procedures are still under development and will be for some time to come. Whereas a high level of assurance can be demonstrated for the reliability and safety of LWR structures, it is not possible to demonstrate the same level of assurance for LMFBR structures operating at elevated temperatures.

This problem was recognized early in the LMFBR development, and programs were initiated by the AEC, ASME code committees, and PVRC to produce the necessary technology to support elevated-temperature structural design. Under these programs, basic material tests have been performed to investigate time-dependent material failure modes and to determine the time-dependent response of LMFBR structural materials. Constitutive relations have been developed to describe the inelastic behavior of structural materials under multiaxial and time-varying loading conditions. Advanced methods of structural analysis have been adapted to predict the nonlinear, time-dependent response of complex geometrical structures under steady and time-varying loading conditions. Simplified analysis procedures have been developed to apply these methods economically to practical design situations. Design limits and criteria have been developed and implemented in national codes and standards to avoid time-dependent failure modes, and component tests have been initiated to validate the analysis techniques, design procedures, and design limits.

Preliminary results of these programs have been reported and used in design. However, the translation of these developments into accepted design procedures is not yet complete. Many of the development programs are ongoing with critical results yet to be obtained. The design criteria are incomplete and will have to be modified based on experience gained in their application to actual LMFBR structures. Validation of analysis methods and design limits is ongoing. Although sophisticated analysis techniques are generally available, procedures must be developed for their practical application to actual design problems. Methods must be devised for providing the same level of assurance for elevated-temperature structural design as we now have for low-temperature applications.

In summary, development of an elevated-temperature structural design technology is well under way. The basic physical phenomena have been identified and are sufficiently well understood to allow safe design. However, a design-oriented effort is needed to translate the basic knowledge into accepted design practice.

4.1.3 Plan of action

Work required to meet the objectives of this program includes development of design criteria and standards to provide design limits; development and validation of simplified methods of inelastic analysis to provide practical methods for design evaluation; implementation and validation of computer programs to provide standardized analysis tools; and development of guidelines for the application of codes, standards, and analysis methods. It also includes development of methods that are unique to the assurance and assessment of piping integrity. The specific tasks to be performed are thus grouped under the four subtask headings: Design Criteria and Standards, Simplified Inelastic Analysis, Computer Programs, and Piping Integrity.

The subtask on Design Criteria and Standards is concerned with the development of standards to assure safe and reliable performance of LMFBR components and provide guidance for their application in design. Emphasis is placed on development of national concensus standards to minimize the need for supplementary RDT standards and NRC guidelines. Work includes continued development of ASME Boiler and Pressure Vessel Code Section III code cases for elevated-temperature design of class 1 components, class 2 and 3 components, and core support structures; modification and expansion of RDT Standard F9-4T, which provides supplementary requirements to Code Case 1592, and to RDT Standard F9-5T, which provides interpretations, guidelines, and analysis procedures for meeting the requirements of F9-4T; assessment and modification of design rules for core components; and development of new rules for the design of low-temperature class 2 components.

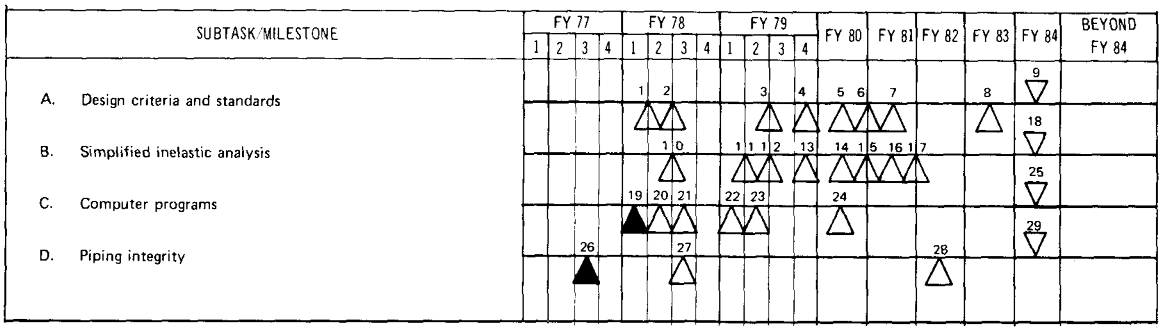
The subtask on Simplified Inelastic Analysis is concerned with the development of cost- and time-saving methods for predicting the inelastic response of LMFBR structures and of guidelines for their use in structural design. Work is concentrated in three areas: simplified analysis methods for specific components, methods for approximating complex time-dependent response by time-independent analysis, and techniques for bounding creep strains and deformation by elastic analysis. Work on specific components includes development of simplified methods for the analysis of plastic and creep buckling of cylinders under axial compression and bending, plastic and creep buckling of piping elbows, and strain concentration in piping elbows.

The subtask on Computer Programs is concerned with the validation, distribution, and maintenance of computer programs for the structural evaluation of LMFBR components, and with the development of auxiliary programs that make computer solutions more reliable and efficient. Emphasis is on the adaptation of public-domain programs for use in LMFBR design and on the development of pre- and postprocessors to simplify input-output and minimize user errors. Validation will be concentrated in the areas of greatest uncertainty: constitutive relations, nonlinear and time-dependent response, and cyclic response. Specific programs under development include the MATLIB library of material property subroutines; MATUS for three-dimensional thermal-structural analysis; STAGS for large-deflection, inelastic-shell analysis; TMHIST seismic preprocessor; and a finite-element stress analysis postprocessor for ASME Code Section III Code Case 1592 evaluation. Maintenance and/or minor modifications continue on reference versions of MATLIB, MATUS, EURCYL, SEAL-SHELL, GAPL-3, CREEP-PLAST, CHERN, and STAGS.

The subtask on Piping Integrity is concerned with development and monitoring of a national plan to assure piping integrity, development of design procedures that account for growth of cracklike flaws in

LMFBR components, and development of design limits that assure an adequate margin of safety against pipe rupture. Current effort is focused on development of a Piping Integrity Plan (PIPLAN) to organize and implement tasks required for the assurance of piping integrity, and on the quantitative assessment of the effects of geometrical and material nonuniformities on piping design. The purpose of the latter effort is to provide a basis for assessment of alternate piping manufacturing processes and to aid in the selection of fabrication techniques. Future work will be focused on the extension of linear elastic fracture mechanics to predict crack growth behavior in LMFBR components operating at elevated temperatures. This will remove excess conservatism from design and at the same time allow quantitative assessment of piping integrity.

4.1.4 Subtask/milestone schedule



Milestones

1. Complete code case for elevated-temperature class 2 and 3 components.
2. Complete interim code case for core support structures.
3. Complete elevated-temperature code case for core support structures.
4. Complete a significant expansion of RDT Standard F9-5T to provide guidance in buckling analysis, inelastic analysis, and experimental validation.
5. Complete design rules for low-temperature class 2 and 3 components.
6. Complete significant revisions to the creep-fatigue and buckling rules of Code Case 1592.
7. Complete contribution to design criteria for core components.
8. Complete development of design rules for flawed components.
9. Continue development, modification, and correction of RDT Standard F9-4T, RDT Standard F9-5T, and Code Case 1592.
10. Complete development of simplified analysis for plastic buckling of cylinders under axial compression.
11. Complete development of simplified analysis for plastic deformation and buckling of piping elbows.
12. Complete development of simplified analysis for plastic buckling of cylinders in bending.
13. Complete development of simplified analysis for creep deformation and buckling of piping elbows.
14. Complete development of simplified analysis for creep buckling of cylinders under axial compression and bending.

15. Complete analysis of ratchetting of piping elbows.
16. Complete development and validation of isochronous σ-ϵ material model for creep deformation and buckling.
17. Complete development and validation of reference stress method for simplified inelastic analysis.
18. Continue development of simplified methods for inelastic analysis.
19. Complete documentation of EURCYL-1 cylinder-cylinder mesh generator and transmit to the Argonne Code Center.
20. Complete development of the MATLIB library of material property subroutines and transmit to the Argonne Code Center.
21. Complete validation of MATUS 3D structural analysis programs and transmit to the Argonne Code Center.
22. Complete development of the TMHIST seismic analysis preprocessor and transmit to the Argonne Code Center.
23. Install postprocessing plotting package and creep version of the STAGS large deformation shell and buckling analysis program.
24. Complete Code Case 1592 inelastic analysis postprocessor and transmit to the Argonne Code Center.
25. Obtain, modify, and maintain a library of reference versions of computer programs for elevated-temperature structural analysis.
26. Complete initial version of a piping integrity plan to identify tasks required to achieve and demonstrate adequate piping integrity.
27. Complete analysis of the effects of nonuniform geometry and welding on piping elbow design.
28. Complete development of a crack-growth-based design procedure for creep-fatigue and creep rupture.
29. Continue revision, update, and monitoring implementation of PIPLAN.

4.2 Subtask A – Design Criteria and Standards

4.2.1 Objective

The objectives of this subtask are to develop design criteria, RDT standards, and industry standards for the structural design of LMFBR components, and to develop guidelines and procedures for their application to assure structural safety and reliability of reactor core and plant components. This activity is the culmination of development of an elevated-temperature structural design technology and has the most direct influence on design.

4.2.2 Background

Criteria and standards required for LMFBR structural design include the ASME Boiler and Pressure Vessel Code Section III, Code Case 1592, RDT Standard F9-4T, and RDT Standard F9-5T.

Section III of the ASME Boiler and Pressure Vessel Code provides rules and criteria for the structural design of nuclear power plant components. Code Case 1592 provides rules for the design of class 1 nuclear components when metal temperatures exceed those for which allowable stress values are given in Sect. III (700°F for carbon steels and 800°F for austenitic steels). Although Sect. III is well established, Code Case 1592 is still under development. New concepts, such as strain limits, have been introduced to avoid failure by mechanisms associated with the time-dependent behavior of material which are not included in Sect. III. The current limits are tentative in nature, and considerable development is required to put them on a firm basis. The design of components to operate at elevated temperatures requires a relatively greater dependence on analysis, with design limits that take account of current and anticipated analytical capability. As the characterization of material behavior becomes more precise, and analysis procedures more firmly established, design limits must be modified to take advantage of increased prediction capability.

RDT Standard F9-4T, Requirements for Design of Nuclear System Components at Elevated Temperatures, contains supplementary requirements to Code Case 1592. Although it would be desirable to avoid two sets of standards, it is recognized that there are requirements unique to the LMFBR application that have not been addressed by the code. The most expeditious way to impose these requirements is by incorporation into an RDT standard as supplementary design limits and criteria. As the criteria mature to the point of industry acceptance, they should be transferred to the industry code and eliminated from the RDT standard. The objective here is to identify areas where additional requirements are needed to assure LMFBR structural integrity, develop appropriate design limits and criteria, incorporate them into the RDT standard, and work for their ultimate adoption by the industry standard. Although RDT Standard F9-4T may contain requirements that are never incorporated into the industry code, its major role in developing an LMFBR industry is to lead development of requirements unique to the LMFBR application.

RDT Standard F9-5T, Guidelines and Procedures for Design of Nuclear System Components at Elevated Temperatures, is inherently different from F9-4T and Code Case 1592 in that it provides interpretation and guidance in application of the design code. The design code provides only limits and criteria which must be met to avoid failure of components in any of the anticipated failure modes. It does not assure that all possible failure modes are included, nor does it give guidance as to how the limits and criteria shall be met. To assure uniformity and efficiency in application of the code, the designer must be provided with interpretations of the design criteria, guidance in use of the code, proven methods of analysis, guidance in planning and control of design analysis, alternate analysis procedures, a check list of design considerations, and a format for documentation of design analysis. As experience is gained in the design, fabrication, and service of nuclear system components at elevated temperatures, the lessons of service should be included in the RDT standard (guidelines and procedures) to assure maximum availability to future design of LMFBR components.

4.2.3 Plan of action

The overall plan is to promote development of design criteria and standards to assure safe and reliable performance of LMFBR components and to provide guidance for their application to design. Emphasis will be placed on development of national consensus standards to minimize the need for supplementary RDT standards, and on the development of guidelines for the application and interpretation of standards. Areas of work include revisions to RDT Standard F9-4T, expansion of RDT Standard F9-5T, modification to Code Case 1592, completion of rules for class 2 and 3 components, development of rules for core support structures, assessment and modification of rules for core components, and development of rules for low-temperature class 2 and 3 components.

Work on RDT Standard F9-4T will be limited primarily to revisions to accommodate changes in Code Cases 1592, 1593, 1594, 1595, and 1596. However, modifications may be made to provide timely implementation of significant changes under consideration for Code Case 1592 or to add additional requirements if needed.

RDT Standard F9-5T will be expanded to provide guidance in areas not yet included, to update guidance in areas where the code has been modified, and to provide design procedures for specific components. Additional areas which need to be covered by RDT Standard F9-5T include:

1. Friction and wear – a draft of a section was written but no action taken relative to inclusion in F9-5T.
2. Buckling and instability – a draft of a section was written but not included in F9-5T.
3. Environmental effects – a description of how the effects of sodium, nitrogen, air, water vapor, and fluence are properly accounted for in the structural design process.
4. Thermal screening analysis – a draft of a section was written but not included.
5. Simplified methods of analysis – reference stress method, isochronous representation of time-dependent behavior, etc.
6. Improved and expanded guidance for analysis of bolts.
7. Effects of variations in material properties.
8. A brief description of the MATLIB library of material property computer subroutines.
9. Weldments and weld metal properties.
10. Structural discontinuities.
11. Elastic follow-up.
12. Design procedures for piping system – detailed and simplified.
13. Design procedures for components – pumps, valves, nozzles, piping, components.
14. Crack propagation and brittle fracture.
15. Guidelines on how to utilize experimental evaluation of structural integrity in lieu of analytical evaluations.
16. Guidance on the validity of one-, two-, and three-dimensional approximations of real structures.
17. Fabrication effects – cold working, prestressing, welding, etc.
18. Dynamics.
19. Aging.
20. Inclusion of thermal and thermofluid computer program abstracts.

Work on rules for core support structures will focus on completion of an interim limited-temperature code case and then on development of an advanced elevated-temperature code case.

Work on design limits for core components will focus on incorporation of improvements in the proposed design criteria that have already been identified, and in assessing the use of the proposed criteria in actual practice.

Work in support of Code Case 1592 will focus on the elevated-temperature failure limits, compressive hold-time effects, stress rupture, and creep fatigue.

The objective of the work on compressive hold time is to obtain a modification to Code Case 1592 to reduce creep damage associated with compressive stress states. The materials of interest are austenitic stainless steels types 304 and 316. There are several competing creep-fatigue damage assessment procedures. For each one the data needed to evaluate the criterion used to distinguish between tensile and compressive stress states will be identified. The available creep-fatigue data will then be compared with the data needed to validate the tensile vs compressive criterion of each procedure to determine if further experimental data are needed. When sufficient data are available, a complete justification will be prepared for a change to the ASME Code Case 1592 creep-fatigue interaction rule to properly account for the lower potential for damage of compressive stresses as compared with tensile stresses. The proposal will then be actively supported within the code's technical committee structure.

Work on creep rupture is directed toward assuring that the appropriate multiaxial stress-rupture damage criterion is utilized in the ASME Code Case 1592. Four major areas require evaluation: (1) the criterion used to assess damage due to multiaxial stress states, (2) the damage assessment method for nonsteady stress and temperature values, (3) the damage criterion for stress gradient applications, and (4) the significance of secondary stresses on stress rupture. The initial efforts will be focused upon types 304 and 316 austenitic stainless steels.

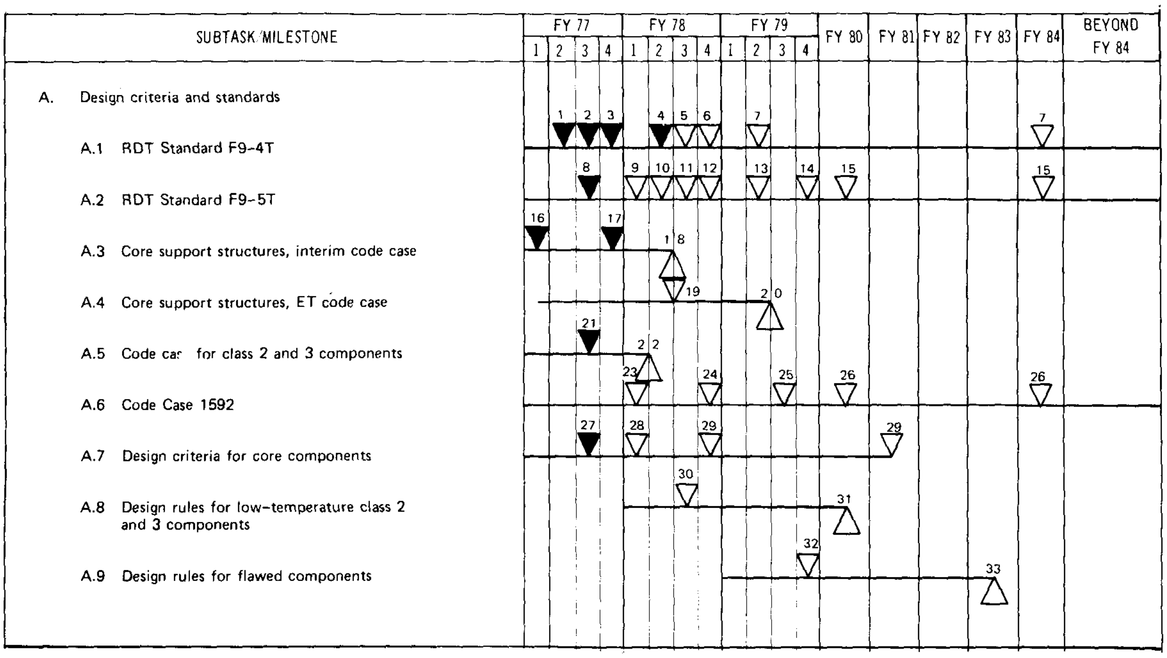
Significant experimental creep-rupture data already exist for stress gradient applications and for nonsteady stress values. Several competing damage hypotheses exist. Systematic evaluation of each hypothesis is required with identification of key verification experiments if necessary. The existing multiaxial stress-state damage criterion (Von Mises) will need to be verified by direct experiments in the second and fourth quadrants of two-dimensional stress space. The United Kingdom is believed to possess such data. Work under this subtask includes evaluation of the effects of notches on stress rupture and a proposed modification to structural design limits if required.

The effects of secondary stress states need to be examined from two viewpoints: potential for initiating creep instability and potential for contributing to structure failure. The potential for creep instability needs to be resolved. Existing experimental data need to be reviewed. The theoretical bases for creep instability should be documented. Conclusive experiments will be defined where necessary. The effects of secondary stresses in multiaxial stress gradient applications will be evaluated to bound their potential for contributing to structural failure.

The result of these evaluations will be either a major relaxation of Code Case 1592 stress-rupture limits or a comprehensively documented technical basis for the existing limits.

The objective of the work on creep-fatigue limits is to assure that the design rules which protect against creep-fatigue failure have an adequate published technical basis on a material-by-material basis. Specifically, the effects of notches, hold time, saturation of hold-time effect, stress and strain gradient, mean stress, ratchetting, and nonradial prior history must be treated in a realistic but conservative manner. The design rules must also be practical to apply and must be phrased in a manner which will maximize the frequency of correct applications by practicing structural analysts. The rules should reflect the current knowledge of heat-to-heat variations and their effects on the creep-failure lifetime. Generally, this work item is a continuing one without an itemized schedule, because the progress depends to a large degree on the evaluations produced by others (Oak Ridge, Argonne, and other investigators). As new experimental data become available, as new correlations are published, or as new design rules are proposed, the information will be evaluated, and an appropriate response will be prepared. However, all 304 and 316 stainless steel notched creep-fatigue data will be collected and utilized in preparing responses to the proposals of others. Generally, the effects of notches are either ignored by investigators or are treated in the most conservative manner. The development of creep-fatigue design rules which treat notches in a rational fashion will require that all proposals be evaluated against the available experimental data from notched creep-fatigue tests.

4.2.4 Subtask/milestone schedule



Milestones

1. Issue revision to cover Code Case 1592-4.
2. Draft amendment to DOE to cover Code Case 1592-5.
3. Draft amendment to DOE to cover Code Case 1592-6.
4. Draft amendment to DOE to cover Code Case 1592-7 and deletion of $P_L + P_b/K_t$ requirement.
5. Provide separate coverage of Code Cases 1593 through 1596 in RDT standards.
6. Draft amendment to DOE to cover Code Case 1592-8.
7. Update as required to supplement and accommodate changes in ASME code.
8. Task force approval of constitutive equations for 2¼ Cr–1 Mo steel and new options for 304 and 316 SS.
9. Constitutive equation amendment to DOE.
10. Draft update (revision) to task force.
11. Draft guidance on application of buckling rules to task force.
12. Draft guidance on use of one-dimensional inelastic analysis to task force.
13. Add guidance on experimental validation of structural integrity.
14. Add guidance on the calculation of buckling loads for specific component configurations.
15. Add guidance on:
    (a) Bolting design
    (b) Environmental effects
    (c) Analysis of flawed components

(d) Application of simplified methods for inelastic analysis
(e) Design scoping and screening procedures
(f) Effects of material aging
(g) Fabrication effects

16. Submit proposed code case to elevated-temperature design subgroup.
17. Continuing support and revision in response to committee comments. Prepare addition for 20% CW SS and other high-strength bolting materials.
18. Approval by subcommittee, Sect. III.
19. Submit draft of code case to subgroup for elevated-temperature design.
20. Approval by subcommittee, Sect. III.
21. Submit proposed code case to subcommittee on properties.
22. Approval by subgroup, elevated-temperature design.
23. Complete preliminary assessment of effects of notches on creep rupture.
24. Identify work required to modify rules for treatment of compressive hold time.
25. Propose reduced plastic buckling design factors.
26. Continued modification and development.
27. Submit proposal for alternate strain limits to DOE working group on core components.
28. Submit alternate event categorization scheme to DOE working group on core components.
29. Continue working group participation.
30. Complete draft of rules for design by analysis.
31. Complete draft of rules for design by formula.
32. Draft proposal of rules for flawed components.
33. Code approval of rules for flawed components.

4.3 Subtask B – Simplified Inelastic Analysis

4.3.1 Objective

The objectives of this subtask are to develop simplified methods, verified experimentally or analytically, for predicting the inelastic response of complex LMFBR components, and to provide guidelines for their use in structural design. Motivation is not only to reduce the cost of analysis, but more importantly to reduce calendar time requirements so that analysis can influence design in the formative stage.

4.3.2 Background

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 needed, especially in the preliminary stages of design, for scoping the effects of design parameters and assessing alternate design configurations. Detailed analysis can be used most effectively in (1) the development of simplified methods, (2) the development of design charts and tables, (3) prediction of response for the most critical conditions, and (4) evaluation of fabricated components that do not meet design specifications. There is a definite need for detailed inelastic analysis, but simplified methods should serve the designer's need for the bulk of design decisions.

Simplification may take the form of simplified geometry, simplified material model, simplified load history, or some combination of these. There is nothing new about the use of simplified methods in design. In fact, it is the use of detailed methods of analysis that is new. ASME Code Sect. III design limits are based on classical beam, plate, and shell theories to represent two- and three-dimensional geometries; elastic theory to represent inelastic behavior; and neglect of temporal effects. However, lacking proven simplified methods of analysis, the new elevated-temperature design Code Case 1592 generally requires a more detailed analysis of component behavior, including nonlinear material and geometrical effects and time-dependent response to transient loads. What is needed are methods that approximate complex structural behavior adequately to ensure integrity but avoid complex modeling of nonessential detail.

Recent work on this program has been focused on inelastic, time-dependent buckling of vessels and piping components. Due to the relative thinness of LMFBR structures, this failure mode has been found to be design limiting for many LMFBR components under combined thermal and seismic loading conditions.

4.3.3 Plan of action

Work on simplified methods will be concentrated on development in three areas: simplified methods for specific components, methods for approximating complicated time-dependent response by time-independent analysis, and techniques for bounding creep strains and deformations without doing a complete inelastic analysis.

Work on specific components includes simplified methods for the analysis of plastic and creep buckling of cylinders under axial compression and bending, plastic and creep buckling of piping elbows, and creep ratchetting of piping elbows.

Work on the time-independent (plastic) buckling of cylinders in axial compression has resulted in recommendation of a simplified method of analysis and will be completed during FY 77. Work on the plastic buckling of cylinders in bending has resulted in a preliminary recommendation for simplified analysis and should be completed in FY 78. Work remaining to be done includes a detailed analysis using the STAGS finite-difference computer program, a detailed MARC analysis to check the Brazier mode of buckling, and confirmation of the simplified method by comparison with the results of detailed analysis and experimental data. The results of this work will be summarized in a topical report and prepared for inclusion in RDT Standard F9-5T.

Work on plastic buckling of piping elbows should be completed in FY 78. Preliminary comparisons between the simplified MARC 17 pipe bend element, a detailed MARC analysis using a shell model of double curvature, and MLTF test data show a divergence of results. Additional work is required to confirm the MLTF test data and to confirm the detailed inelastic analysis. The latter confirmation will be carried out using the STAGS computer program. If results to date cannot be reconciled, it may be that the simplified MARC pipe bend element will not be adequate for use in design, and a more accurate method will have to be developed.

The time-dependent (creep) deformation and buckling of elbows will also be investigated. Simplified methods of analysis will be developed, validated by comparison with detailed analysis methods and experimental results obtained from the MLTF tests, and a solution method proposed for use in design analysis.

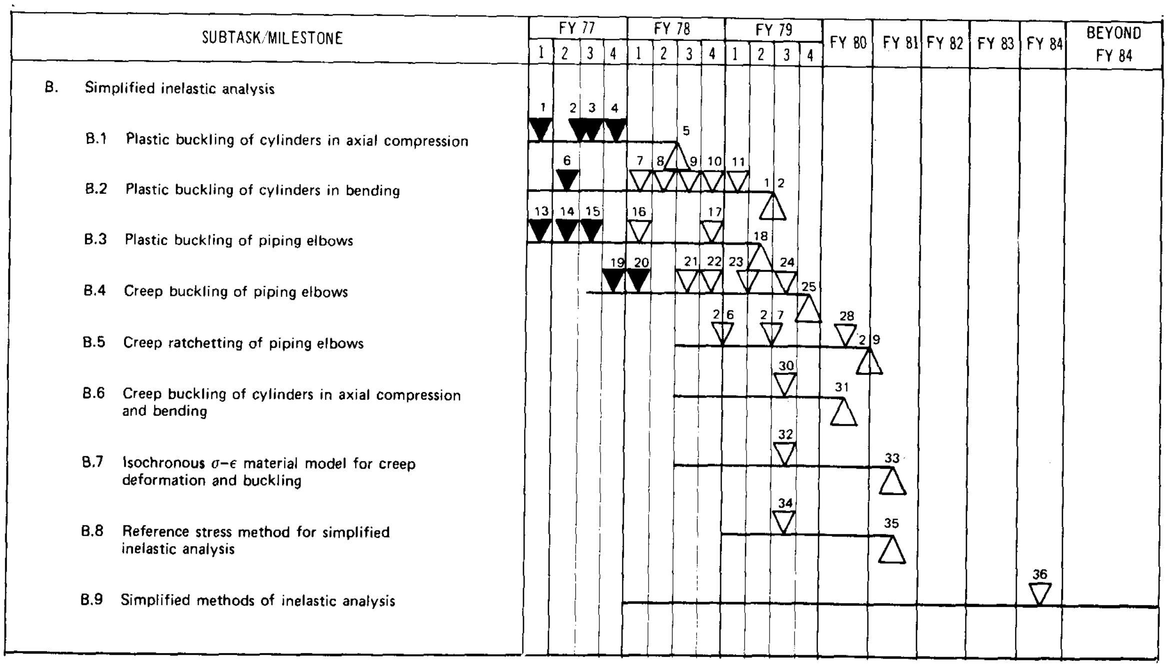
Another possible failure mode for piping elbows is strain accumulation due to ratchetting. The magnitude of this problem will be scoped and tests planned for the MLTF. A solution method will be developed and guidelines for its use prepared for RDT Standard F9-5T.

Methods for bounding creep strains and for approximating complicated time-dependent response by time-independent analysis will be developed. Techniques for bounding creep deformations due to varying loads have been developed by Ponter and Leckie. An example for a simple structure under cycle loading indicates the bounds can be very accurate. These techniques will be reviewed and investigated for application to more complex structures and loading histories.

Calculations using the isochronous approach will be compared with detailed time-dependent analyses for cyclic loading of simple structures. Relaxation as well as creep response will be considered. Comparisons will then be made for more complex structures such as nozzles, piping elbows, and tees. Geometrical buckling as well as creep deformations will be considered in piping components. Ultimately, comparisons will be made between the simplified method of analysis and experimental results obtained from the TTTF and the MLTF. The end product will be a verified quasi time-independent method for approximating time-dependent creep stresses and deformations in structural components.

A recent survey of the reference stress method carried out by the PVRC Subcommittee on Elevated-Temperature Design indicates the method has potential for predicting creep deformation under steady and variable loads, creep rupture, creep buckling, and relaxation. Applicability of the method to LMFBR structures will be investigated by comparison with detailed inelastic results for specific LMFBR components that have already been analyzed. It is expected that applicable experimental data will be obtained from tests scheduled in the MLTF, CRTF, and ORNL TTTF as well as other facilities operated under the National LMFBR HTSD Program. The end product will be a clear statement of the reference stress method, guidance on how it may be applied to practical design problems, and its range of applicability for inclusion in RDT Standard F9-5T.

4.3.4 Subtask/milestone schedule



Milestones

1. Complete STAGS solution.
2. Develop reduced buckling design factors – design chart concept.
3. Complete analysis of axial buckling test results.
4. Complete draft of topical report on simplified analysis of plastic buckling of cylinders in axial compression.
5. Prepare proposal for RDT Standard F9-5T guidance.
6. Complete preliminary simplified analysis.
7. Report review of simplified methods of analysis.
8. Complete STAGS analysis.
9. Complete matched cylinder buckling tests.
10. Complete draft of topical report of test results.
11. Complete draft of topical report on simplified analysis of plastic buckling of cylinders in bending.
12. Prepare proposal for RDT Standard F9-5T guidance.
13. Investigate effect of residual stress on buckling.
14. Complete topical report – simplified analysis, MARC 17 model.
15. Investigate limit load analysis approach.
16. Complete draft of topical report on detailed analysis MARC model.
17. Complete draft of topical report on simplified analysis of plastic buckling of piping elbows.
18. Prepare proposal for RDT Standard F9-5T guidance.
19. Complete MARC 17 isochronous σ-ϵ material model analysis.
20. Complete MARC 17 creep equation for material model analysis.
21. Complete draft of topical report on MARC 17 simplified analysis.
22. Complete MARC 4 creep equation material model analysis.
23. Complete MARC 4 isochronous σ-ϵ material model analysis.
24. Complete draft of topical report on MARC 4 detailed analysis.
25. Prepare proposal for RDT Standard F9-5T guidance.
26. Complete scoping analysis – plastic ratchetting.
27. Complete MARC 17 creep equation material model analysis.
28. Complete MARC 17 isochronous σ-ϵ material model analysis.
29. Complete topical report on creep ratchetting of piping elbows.
30. Develop simplified methods of analysis.
31. Prepare proposal for RDT Standard F9-5T guidance.
32. Complete analysis for monotonic loading conditions.
33. Complete analysis for cyclic loading conditions.

34. Complete preliminary assessment of reference stress method.
35. Prepare guidelines for application of reference stress method.
36. Investigate and develop new methods for simplified inelastic analysis – Southwell plot, etc.

4.4 Subtask C – Computer Programs

4.4.1 Objective

The objectives of this subtask are to validate, distribute, and maintain reference versions of structural analysis computer programs required in the design, analysis, and safety evaluation of LMFBR components, and to develop auxiliary programs that make computer solutions more efficient and reliable.

4.4.2 Background

The design of LMFBR components to function safely for long periods of time in an elevated-temperature environment places high reliance on analysis. In fact, the ASME high-temperature design Code Case 1592 virtually requires design by analysis. Over the past 15 years, a great many computer programs have been developed, many at government expense, 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. Absolute verification is not possible. Instead, it is necessary to compare the results of one program with another and with experimental results. Since the material constitutive relations for multiaxial states of stress are conjectural at this point, and the mathematical formulation of the solution is inseparable from the material representation for complex structures, it is necessary to validate the combination of inputs and computer solutions for specific classes of problems, that is, the combination of geometrical approximation, load representation, material constitutive relations, mathematical model, and solution technique. This can only be accomplished by comparison of calculated results with test results for representative geometries, loads, and environmental conditions. Comparisons are needed with test data for relatively simple geometries and loads to isolate effects of various assumptions, and for prototypical conditions to establish validity for actual designs and loading conditions.

Modification of programs is required to incorporate new constitutive relations as they are developed, to represent the behavior of new materials, and to account for load history in time-dependent analysis. Although general-purpose inelastic programs exist, new programs will be required to implement simplified methods of analysis.

One major problem is the transferability, portability, and usability of complex computer programs. Even those developed specifically for use in the LMFBR program must be modified for use on the various types of computers used by LMFBR contractors. Pre- and postprocessors are required to utilize programs efficiently in design and to assure adequate validation of results. These may include compatible heat conduction programs, mesh generating routines, mesh plotting routines, input checking routines, output plotting routines, calculation of quantities needed for comparison with design criteria, and comparison of calculated results with design criteria.

There are a number of nonproprietary programs already in use in the LMFBR program. As they are converted from one major computer system (IBM, UNIVAC, CDC) to another, errors are inevitably introduced. Individual users correct, modify, and add additional capacity to the programs, producing multiple versions of the same program with little or no interchange of information among contractors. The duplication of effort is particularly insidious because of the compounding effect on validation, which must be provided for each new version of the program.

To avoid undue duplication of effort by the proliferation of multiple versions and to facilitate a high level of program validation, it would be desirable to establish a central library of reference versions of programs in use with the LMFBR. The function of the library is to provide a central source of programs in a usable form, assure and provide adequate documentation, assure some reasonable level of validation, and provide for orderly development by inclusion of properly checked-out modifications in reference versions.

Recent work on this subtask has been focused on adaptation of public-domain programs for use in LMFBR design, and on development of pre- and postprocessors to simplify input-output and to avoid errors.

4.4.3 Plan of action

Work will continue with emphasis on adaptation of public-domain programs for use in LMFBR design, and on the development of pre- and postprocessors to simplify input-output and to avoid errors. Validation will be concentrated on the areas of greatest uncertainty: the constitutive relations, nonlinear and time-dependent response, and cyclic response.

Further work on the MATLIB library of material property subroutines will be devoted to modification and additions to accommodate new and revised material property representations.

The STAGS finite-difference program for the large-deflection, inelastic analysis of shells is being used for the large-deflection analysis of plastic buckling of cylinders and piping elbows, and for analysis of the effects of nonuniformities on piping elbow performance. When validation is completed, the program will be documented and distributed for use with the LMFBR.

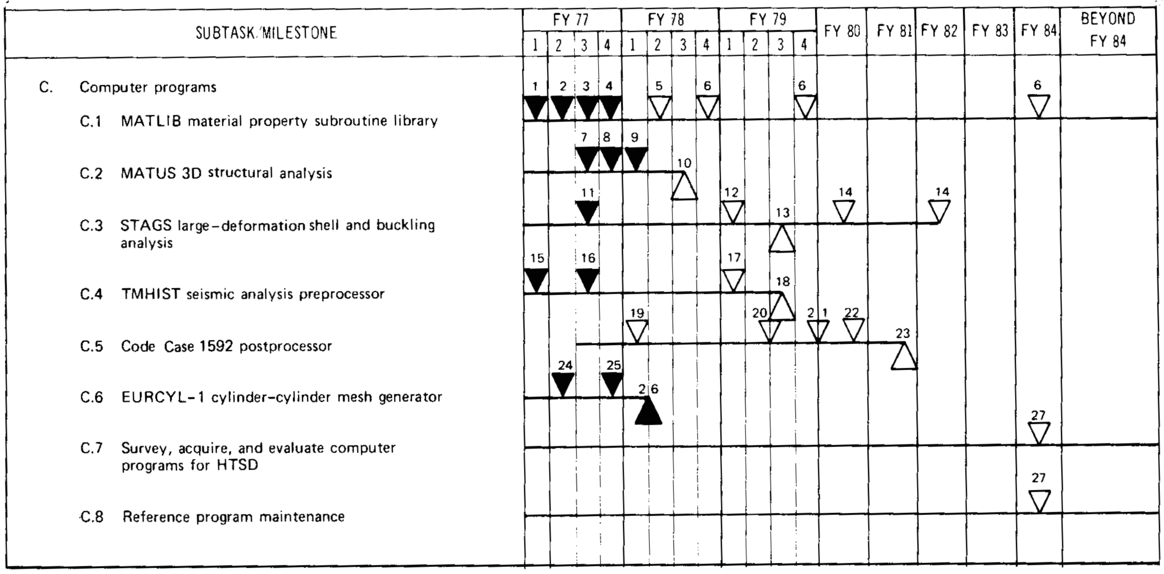
Work on pre- and postprocessors will continue on the development of a seismic preprocessor, TMHIST, and on a finite-element stress analysis postprocessor for stress and strain evaluation against ASME Code Sect. III and Code Case 1592 criteria. Programming of TMHIST is essentially completed and the program is being tested. It will be validated, documented, and made available for distribution. Specifications are being developed for the finite-element analysis postprocessor. Future work includes programming, verification, documentation, and preparation for distribution.

The CHERN program was developed by the Foster Wheeler Energy Corporation under the FFTF program for the efficient inelastic analysis of cylinders. It is very useful in design and should be made available to LMFBR contractors. The program will be formatted for general use, documented, and transmitted to the Argonne Code Center.

Maintenance and/or modification of the following structural analysis computer programs will continue in an attempt to establish relatively hardened reference versions for use in LMFBR design: MATLIB, MATUS, EURCYL, SEAL-SHELL, GAPL-3, CREEP-PLAST, CHERN, and STAGS.

Survey of nonproprietary structural analysis computer programs will continue. Those that appear to be useful for LMFBR structural design will be obtained, implemented on the computer, and evaluated.

4.4.4 Subtask/milestone schedule



Milestones

1. Modify creep relaxation subroutine for 2¼ Cr–1 Mo steel and alloy 800H materials for use with ELTEMP.
2. Write program to calculate Code Case 1592 stress limit S_{RH}.
3. Write creep property subroutines for ORNL reference heat of type 304 SS.
4. Complete draft of MATLIB user's manual.
5. Transmit MATLIB to Argonne Code Center.
6. Incorporate new creep equations and continue maintenance.
7. Complete verification problem.
8. Complete draft of user's guides for MAT3D and APACHE.
9. Complete draft of user's guide for MATUS.
10. Transmit MATUS package to Argonne Code Center.
11. Complete validation.
12. Install postprocessing plotting package.
13. Install creep version of STAGS.
14. Install periodic updates to STAGS.
15. Complete initial programming.
16. Complete verification.
17. Complete drafts of user's, programmer's, theoretical, and verification manuals.
18. Transmit TMHIST program to Argonne Code Center.

19. Complete program specifications.
20. Complete programming.
21. Complete verification.
22. Complete documentation.
23. Transmit Code Case 1592 postprocessor to Argonne Code Center.
24. Complete modification and verification.
25. Complete draft of EURCYL-1 user's manual.
26. Transmit EURCYL-1 to Argonne Code Center.
27. Continue.

4.5 Subtask D – Piping Integrity

4.5.1 Objective

The objectives of this subtask are to develop and monitor a national program to assure piping integrity, to develop design procedures that account for growth of cracklike flaws in LMFBR components, and to develop design limits for crack growth that assure an adequate margin of safety against pipe rupture. Motivation for this work is based partially upon the fact that ASME code limits are excessively restrictive while at the same time insufficient to allow a quantitative assessment of piping integrity.

4.5.2 Background

Aside from failure to meet functional requirements due to excessive deformation, the ultimate failure mode for piping systems is loss of integrity due to rupture. Rupture may occur suddenly, apparently without warning, or by slow growth of a crack until final separation. Stress limits are provided in the ASME Boiler and Pressure Vessel Code to guard against sudden rupture and creep rupture due to long-term loads. Fatigue and creep-fatigue limits are provided to guard against failure by cyclic crack growth.

Fatigue limits are based on the observed behavior of cyclically loaded, carefully machined, uniform test specimens. The data are not readily extrapolated to account for the effects of sharp discontinuities or cracklike flaws, and design limits tend to be excessively conservative for these conditions. However, while actual components invariably contain flaws or cracks, the cracks may not grow significantly under service loads even though the as-fabricated components do not meet fatigue design criteria. The empirical nature of the fatigue design approach makes it virtually impossible to predict margins against failure for actual components.

A more fundamental approach to fatigue is to consider the various stages of the process – crack initiation in structures can be related to plastic strain at crack initiation in test specimens. Crack growth can be related to the range of stress intensity factor ΔK based on the linear elastic fracture mechanics approach. Rupture ultimately occurs when the critical crack size is reached. At elevated temperatures, where material behavior is time-dependent, it is not likely that such simple relations exist. But by considering the separate stages of fracture, it should be possible to include the effect of significant factors – creep, environment, range of load, geometry, etc. – more precisely than in the current creep-fatigue approach based on the simple addition of creep damage (expressed either as the sum of time or strain fractions) and fatigue damage.

Although assurance of piping integrity is achieved primarily through design of piping components to meet ASME code structural limits, there are many other factors that influence piping integrity either directly or indirectly. These include fabrication processes, handling, inspection, installation, plant operating procedures, and in-service monitoring and inspection. Each of these various aspects must be considered in the design and construction of LMFBR piping to perform reliably at elevated temperatures.

Past work on this subtask has been focused on development of an overall plan for assurance of piping integrity, investigation of crack propagation in specific components, and assessment of effects of geometrical and material nonuniformities on piping design.

4.5.3 Plan of action

Work will be focused on development of a Piping Integrity Plan (PIPLAN) for organizing and implementing the tasks required to assure piping integrity, determination of fabrication effects on piping design, and development and implementation of crack-growth-rate-oriented methods for assuring piping integrity.

A second draft of the Piping Integrity Plan will be submitted to RRT in July 1977. This draft will reflect a significant change in philosophy and technical content and will, therefore, require additional review. Future work will depend upon comments received, but will at least require resolution of the comments and issue of a final draft. An ongoing effort will be required for implementation, monitoring of results, and modification to reflect changing goals and objectives.

Work will continue on the determination of sensitivity of piping elbows to geometrical and material nonuniformities. The results will provide a technical basis for assessment of alternate piping manufacturing procedures and aid in the selection of fabrication technique. The four main tasks are to determine the effects of:

1. circumferential thickness variation,
2. initial ovality of cross section,
3. wrinkling along the intrados,
4. shrinkage effects of longitudinal welds.

Work on crack growth will be directed toward development of crack-growth-rate-oriented methods for assuring piping integrity. Current methods of predicting crack growth will be reviewed relative to their applicability to LMFBR design conditions. Where linear elastic fracture mechanics applies, it will be necessary to develop stress intensity factors (K) for specific component geometries – elbows, tees, nozzles, etc. It is unlikely that closed-form expressions can be obtained, as for simple geometries, but a variety of procedures based on the finite-element technique have been developed for calculating K values for cracks in bodies of arbitrary shape subjected to arbitrary loads. Special crack-tip elements have been developed and energy methods applied to avoid use of a great many finite elements to approximate the crack-tip geometry. These methods will be applied to obtain K values for geometries of interest in design.

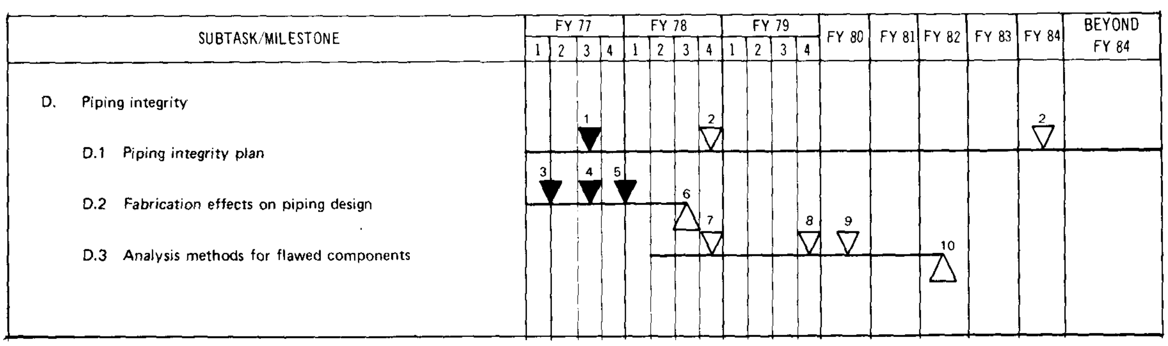
For cases where linear elastic fracture mechanics does not apply, as, for example, when plastic flow at the crack tip is not contained locally or at temperatures where creep occurs, both of which are conditions encountered in LMFBR design, it will be necessary to develop methods for predicting crack propagation rates. Work has been initiated in both of these areas, but it is highly theoretical in nature and must be adapted for use in analysis of real structures. The J-integral technique will be investigated for gross plastic flow, and extension of the linear elastic fracture mechanics approach will be considered for application at elevated temperatures.

If the enhancement of crack growth rate at elevated temperatures is due primarily to environmental effects, as some speculate, then alternate methods of crack growth analysis may be required. Analytical work in this area will depend upon experimental results being obtained at HEDL.

The application of test data obtained using compact test specimens to predict crack growth rates in real structures requires numerous assumptions as to crack growth behavior under complex loading conditions in complex geometrical shapes. The use of simple test specimens to predict behavior in real structures is analogous to the generalization of uniaxial stress-strain curves to predict component response under multi-axial loading conditions. Experimental results are required for actual component configurations under actual loading conditions to validate generalization of results on compact test specimens. In the case of crack growth, environmental effects play a relatively more important role, so they must be included in the validation program. A test program will be developed to test crack growth analysis methods for actual component configuration, environmental, and loading conditions. Primary emphasis will be placed on pipe, elbow, tee, and nozzle configurations to verify analytical techniques and assure integrity of the primary coolant boundary. A test facility similar to the MLTF, modified to apply alternating loads under a controlled environment, will be required. Both small-scale and full-sized components should be tested. It may also be desirable to investigate the effect of repeated thermal transients, applied in conjunction with steady mechanical loads, using an experimental facility similar to the CRTF.

The end result will be a validated method for predicting crack growth rates in structures with crack-type flaws operating in an elevated-temperature environment. This will not only be useful in design to replace the more empirical fatigue and creep-fatigue approach to analysis, but will provide a method for evaluating fabricated structures with cracks detected during inspection which are larger than those anticipated in design. This latter capability becomes most significant in the construction stage when tight schedules discourage the scrapping of components which may be slightly out of specification, but may nevertheless be acceptable if the cracks are located in noncritical regions.

4.5.4 Subtask/milestone schedule



Milestones

1. Revise PIPLAN to take account of reviewer comments and submit to RRT.
2. Continue revision, update, and monitoring implementation of PIPLAN.
3. Complete draft preliminary report: Effects of Nonuniform Geometry and Welding on Piping Elbow Design.

4. Complete preliminary analysis of effects of thickness variation, initial ovality, wrinkling, and weld shrinkage on piping elbow performance.
5. Complete draft interim report on effects of nonuniformities on piping elbow assessment.
6. Complete final report.
7. First interim report: Evaluation of LEFM for Predicting Crack Growth at Elevated Temperatures.
8. Develop J-integral approach for predicting crack growth due to cyclic loading.
9. Develop C* approach for predicting crack growth due to creep.
10. Complete development of crack-growth-based design procedures for creep fatigue and creep rupture.

5. HIGH-TEMPERATURE STRUCTURAL DESIGN – PIPING

(Atomics International 189a SA020)

5.1 Introduction and Scope

5.1.1 Objective

The objectives of this program are (1) to provide design methodology for elevated-temperature piping systems based on experiences in FFTF, Liquid Metals Engineering Center (LMEC) and CRBRP designs, and in operating other high-temperature piping systems; (2) to assess the validity of using current high-temperature Code Case 1592 design rules for piping systems; (3) to investigate critical piping system design problems from the design criteria viewpoint; (4) to increase the confidence level in high-temperature design rules for piping by demonstrating the conservativeness of these rules.

5.1.2 Background

The design of high-temperature metal piping requires the incorporation of several factors which were either negligible or nonexistent in the earlier light-water reactors. The major new design considerations are as follows:

1. The LMFBR piping operates at elevated temperatures. Thus, operating conditions are within the creep range of the structural alloys used, and materials are subject to both creep and relaxation behavior.
2. Rapid temperature drops of 250 and 350°F associated with FBR scrams represent severe thermal transients. The transients, coupled with high-temperature operation, can lead to significant inelastic response involving creep, relaxation, and plastic behavior.
3. Main-loop sodium piping for a commercially feasible plant size can be characterized by very large radius-to-thickness ratios, and in the presence of large external loads may pose design problems and require design considerations not usually associated with piping design.
4. Although experience with sodium systems is gaining rapidly, there is concern that all of the variables or mechanisms that affect the systems' integrity or reliability may not have been identified or perhaps given proper emphasis.

5.2 Subtask A – PIPLAN Development

5.2.1 Objective

The objective of this subtask is to prepare and maintain a Piping Integrity Plan. The purpose of PIPLAN is to provide a framework for identifying and coordinating those tasks which will improve or verify the structural integrity of LMFBR piping systems.

5.2.2 Background

Piping integrity must be built into the design initially and monitored during operation to assure it is not lost. It requires a coordinated effort of specification, design, analysis, fabrication, installation, inspection, maintenance, and monitoring. Basically, piping integrity is achieved by following "good" design, construction, and operating practices.

The ASME Boiler and Pressure Vessel Code provides rules for design and construction. It has evolved over a period of some 70 years and is based on experience with pressure vessel and piping systems that have operated over a wide range of service conditions. The code, in essence, establishes "good" design and construction practice by defining responsibilities, identifying service conditions that must be considered, establishing design margins relative to anticipated modes of failure, providing methods for calculating design margins, providing acceptable design configurations and fabrication techniques, prohibiting design configurations and fabrication techniques that have led to failure, establishing installation and inspection requirements, and providing means for assuring the requirements and rules have been met. The code approach is deterministic, and in a sense somewhat qualitative, but has proven to be highly successful in providing reliability and protecting the public safety. Achievement of piping integrity is, therefore, based primarily upon design to code-type concepts, interpreted and applied for the operating conditions of the LMFBR.

Although the ASME code as described provides a reliable basis for achieving piping integrity, there are areas in which regulatory bodies require additional verification beyond that normally covered by the ASME code. For example, Code Case 1592 provides rules for design of elevated-temperature piping systems, but the design methodologies and their verification do not have the same degree of demonstrated conservatism as the more conventional piping systems which operate below the temperature range where creep effects are significant. An additional example is the ASME code philosophy with respect to environmental effects. The code considers the identification of design procedures and/or allowances to account for environmental effects as part of the plant owner's responsibility and does not provide specific code rules for environmental considerations. Thus, one purpose of PIPLAN is to identify tasks which are required to supplement and/or verify the provisions of the ASME code.

Another aspect of PIPLAN is to identify methods and procedures to more accurately define the design margins in current procedures so that excessive conservatism can be minimized. Examples of this are the rules for design of piping systems, using elastic analysis, which, because of the complexity of the structure behavior of elevated-temperature piping, currently require very conservative assumptions with respect to load distribution and damage accumulation.

Finally, PIPLAN can be used as a vehicle for establishing priorities and planning and coordinating base technology programs which directly support the achievement of high-integrity piping and also identify those portions of other program areas, for example, high-temperature design technology, which contribute to piping integrity even though they are justified by other considerations.

PIPLAN objectives address some needs that are design specific, but are primarily concerned with the general development needs of LMFBR piping design and construction. They take account of the proven LWR piping design technology, knowledge accumulated to date on elevated-temperature design, and theoretical and experimental work in progress on LMFBR programs. PIPLAN consists essentially of a definition of tasks required to meet the preceding objectives in terms of need (justification), scope, and schedule. For the sake of completeness, tasks are included that contribute to piping design and construction but which are also necessary for the design and construction of nonpiping components. Estimates of man-hours required to completion are given only for subtasks unique to piping systems.

5.2.3 Plan of action

In June 1975, a PIPLAN Working Group was established to prepare PIPLAN. The basic steps required to achieve piping integrity were identified. These steps were then translated into eight general program areas such as design rules, material behavior, etc. Within these program areas, specific tasks were identified along with scope and schedule. The resulting draft of PIPLAN was transmitted to ERDA in March 1976. The draft version of PIPLAN was sent out for review and comment to reactor manufacturers, architect-engineering firms, laboratories, and utility representatives. These comments were received in February 1977, were reviewed with ERDA, and changes were identified.

PIPLAN has been revised and will be reissued in accordance with the suggested changes. It will be subsequently revised and reissued periodically to reflect programmatic developments and technology improvements.

5.3 Subtask B – Assess and Catalog Failure Data

5.3.1 Objective

The objective of this subtask is to collect and compile data on the cause and frequency of sodium piping system deficiencies. This will focus development effort on means to avoid operational problems and will provide data to evaluate successful operating experience relative to design rules. Where sufficient data are available, the degree of conservatism in current design rules will be assessed relative to observed piping performance.

5.3.2 Background

A number of sodium systems of various types and sizes (at AI, ANL, EG&G, GE-NED, HEDL, LASL, LMEC, ORNL, and WARD) have accumulated significant operating experience. However, it was recognized that the incident data on sodium piping failures had not been well documented or widely disseminated. In addition, the ACRS expressed the desire to be informed of the collective experience with stainless steel in sodium piping systems.

This subtask responds to the need for better documentation and distribution of incident data on sodium piping failures. Published data[1,2] were expanded and supplemented by data from other U.S. and foreign sources, transcribed to a standard format, and published in an interim report.[3] Although elevated-temperature piping systems in fossil-fueled plants generally operate at much higher pressure with correspondingly thicker walls than sodium systems, a brief survey of more widely used piping support designs and their respective failure experience is planned.

The interim report[3] has been updated to July 1977, and the sodium piping service experience data have been supplemented and extended in a recently issued summary report.[4] Facilities were also surveyed[4] to collect available data on the incidence and characterization of construction defects. Due to the limited extent of quality assurance records at the time of construction, the only construction defects noted have occurred in welds which failed to pass quality assurance provisions.

As part of the effort to assess the conservatism of current design rules, an elastic analysis in accordance with Code Case 1592 was performed on the SNAP 8-ER outlet piping which had functioned satisfactorily for more than 10,000 hr, including more than a year of service at temperatures above 1300°F. Dependent upon the restraint condition assumed at the intermediate support, negative margins from –1300 to –7000 were calculated and reported.[5]

---

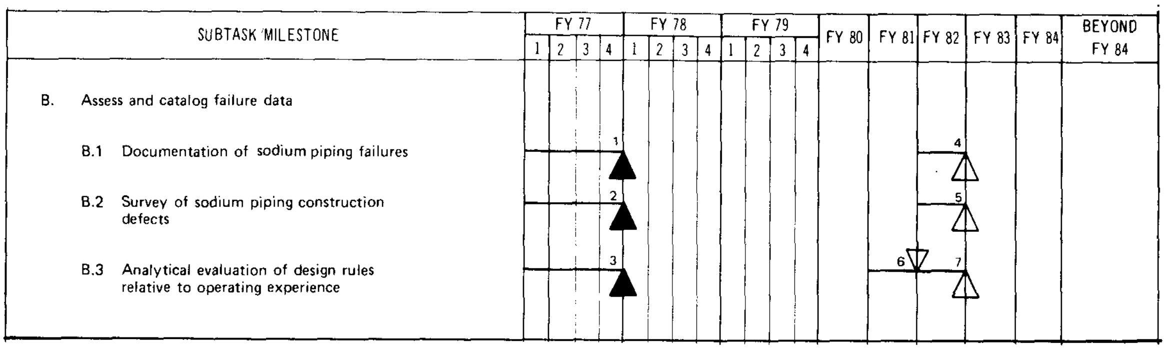
1. *Failure Data Handbook for Nuclear Power Facilities,* LMEC-MEMO-69-7, vols. I and II (August 1969).
2. P. Novacek and J. Lynn, *Sodium to Gas Leakage – Incident Survey and Analysis,* RAR-707-530-001 (September 1972).
3. P. F. Novacek and A. C. Karkau, *Interim Report; Sodium Piping Leaks,* N146T1350004 (September 1976).
4. P. F. Novacek, R. M. Ohlenkamp, L. Humphries, T. Woytowich, and W. Vaughn, *Sodium Piping Survey – to July 1977,* N146T1350005 (September 1977).
5. K. R. Jaquay, *Evaluation of a Piping Line with Successful Operating History Using the Elastic Rules of ASME Code Case 1592,* N146SR250001 (August 1976).

Analysis of the same pipe run, using the MARC computer program to assess the conservatism of current inelastic analysis methods, has been completed.[6] The results of the analysis indicated that conventional analysis assumptions would result in a failure to satisfy the code strain limit criteria.

5.3.3 Plan of action

Sodium piping failure and construction defect experience up to July 1977 has been collected and reported.[4] These data show a mean exposure time of approximately seven years, which is much shorter than projected plant lifetimes, and are based on smaller pipe sizes to a large extent. Since plants which are coming on line have a larger proportion of larger pipe sizes, an update after five years is planned to extend the mean exposure time and to provide more significant data for larger pipe sizes. Also, as increased quality assurance requirements should provide more quantitative data, an update of the construction defect report is planned. In addition, more detailed documentation of operating conditions and performance is expected to provide better data for further evaluation of design rules.

5.3.4 Subtask/milestone schedule



Milestones

1. Submit summary report on failure data in sodium piping systems.
2. Submit survey report on construction defects in sodium piping systems.
3. Complete inelastic analysis of SNAP 8-ER loop.
4. Update failure data in sodium piping systems and submit report.
5. Update construction defect survey and submit report.
6. Select additional piping systems for Code Case 1592 evaluation and report progress.
7. Complete report on assessment of conservatism of design rules for Code Case 1592.

---

6. K. R. Jaquay, *Evaluation of a Piping Line with Successful Operating History Using the Inelastic Rules of ASME Code Case 1592,* N146SR250002 (December 1977).

5.4 Subtask C – Evaluation of Sensitivity of Piping Design Margins to Variability in Material and Geometry

5.4.1 Objective

The objectives of this subtask are to evaluate the effect of variations between actual and design values for material, geometry, and loading characterization upon predicted design margins; and by determining those design parameters which have the greatest impact on design margins, methods, and material properties, to define critical tests, areas for further study, and analytical development to obtain maximum benefit from available funds. Sensitivity evaluations will provide guidance for preparing design specifications, selecting fabrication processes, and establishing dimensional tolerances. Sensitivity evaluations will provide the groundwork for future reliability evaluations of piping systems.

5.4.2 Background

The variability of material properties has always been a matter of concern for designers and analysts. The most widely used approach has been to conservatively base design allowables on "minimum specification" values of material properties. The degree of conservatism inherent in the "minimum specification" design allowable is uncertain, but comparison with "nominal" or "expected" values is sometimes used to assess the effect of material properties variability upon design margins. For elevated-temperature design, the problem is compounded, since most material specifications require only short-time, room-temperature tensile testing; and due to the cost and time-consuming nature of elevated-temperature creep and fatigue testing, it becomes even more essential to assess the sensitivity of calculated design margins to variability of material data prior to testing. The variability of loading conditions is often treated by specifying a design load combination which envelopes the maximum expected operating load combinations. In some sections of the ASME code, operating conditions are categorized as normal, upset, emergency, and faulted on the basis of expected frequency of occurrence, and allowables are specified for each category.

Generally, a conservative frequency of occurrence is estimated (i.e., once a day, four times a week, etc.) for a simplified loading history which tends to envelope a group of similar loading events. While these simplified load histories lead to higher predicted values for fatigue damage, the conservatism appears to be acceptable for low-temperature piping in most instances. The tendency has been to reduce the conservatism of the loading history or frequency estimates where difficulties are encountered rather than to seek out operating history data. The problem is compounded for elevated-temperature piping, where creep strain accumulates as well as interacts with cyclic fatigue damage. Due to creep and fatigue interaction, in addition to enhanced potential for sequential effects, sensitivity analysis of design margins relative to loading history variability becomes the only practical method for defining critical tests to evaluate the relative validity of competing models of material behavior under complex loading histories.

The variability of piping-component geometry, as for material and loading variability, is a two-part problem. One part of the problem is data collection to determine the degree of variability which exists, and the other part of the problem is to determine the sensitivity of design margins to variability in the piping-component geometry.

Studies of the existing variability indicate that except for straight pipe and flanged joints, dimensional control of piping components is limited. Generally, the minimum wall thickness and the component fit-up dimensions and tolerances are controlled, but maximum thickness and other structurally significant dimensional parameters are not specified. Work to develop dimensional data is under way, but the adequacy of the dimensional control of piping components fabricated by conventional processes must be assessed relative to the effects upon design margins.

The degree of conservatism in analytical methods also contributes to variability in design margins. Low-temperature piping design analysis is generally based upon modeling of the pipeline as an assemblage of beam-type elements with modifying factors applied to cover flexibility and stress intensification effects. A topical report[7] has been prepared which discusses the basis for extending code primary stress indices for low-temperature piping to elevated-temperature piping. The allowables for elastic analysis of elevated-temperature piping have been selected to be quite conservative to cover the attendant uncertainties of the analysis. Less restrictive allowables are permitted for detailed inelastic analysis, which is more costly and time-consuming. Sensitivity analysis of design margins would also provide a basis for selecting the appropriate analysis method.

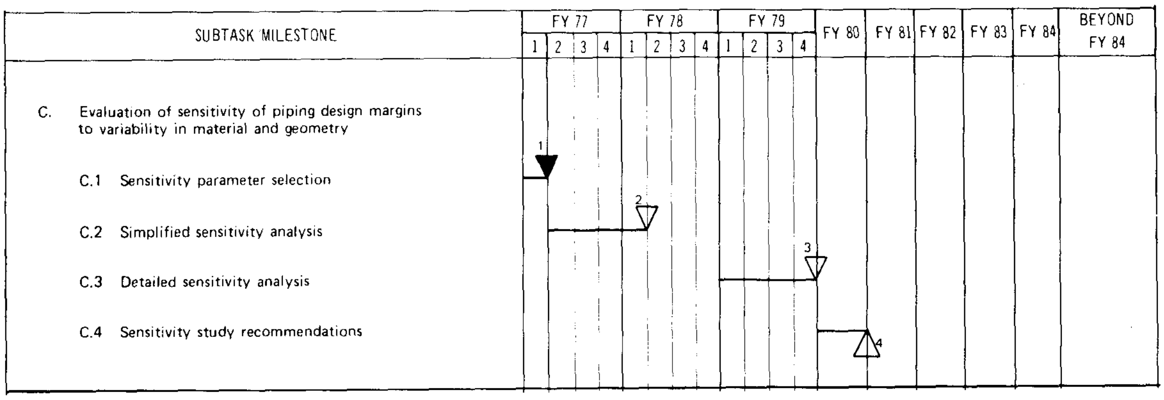
5.4.3 Plan of action

Initial design margin sensitivity evaluations will be based on elastic analysis of variations in piping-component geometry (i.e., wall thickness, ovality, weld mismatch) for four sets of loading conditions with material allowables which vary from the code-specified values. Variations in code stress indices will also be considered. The changes in design margin which result from variations in material properties, component geometry, and loading parameters will provide insight into the limitations of elastic analysis methods and indication of the potential for improvement through further refinement of code stress indices.

The next phase of sensitivity evaluation will investigate the benefit obtained by inelastic analyses of the same cases. In addition, the sensitivity of design margins to geometry variations will be evaluated for the same four sets of loading conditions. Where feasible, more than one analytical approach will be pursued to develop critical tests for assessing the validity of computing methods.

Later phases will involve verification testing and reliability assessments of current design procedures.

5.4.4 Subtask/milestone schedule



Milestones

1. Sensitivity evaluation matrix submitted.
2. Submit interim report on simplified sensitivity evaluations.

7. E. C. Rodabaugh, *Appropriate B Indices for Evaluating Load-Controlled Stresses in Piping Products at Elevated Temperature,* AI-ERDA-13202 (March 1977).

3. Submit report on detailed sensitivity evaluations based on detailed inelastic analyses.
4. Submit final report on sensitivity evaluations with definition of safety margin in design codes and quantification of design range parameters.

5.5 Subtask D – High-Cycle Fatigue Behavior at Elevated Temperature

5.5.1 Objective

The objectives of this subtask are to extend the fully reversed fatigue data at elevated temperature from the 10^6 cycle range of current design curves to 10^8 cycles and to evaluate the fatigue damage produced by high-cycle, small-amplitude cyclic loadings superimposed on a substantial level of sustained stress in the creep temperature range. Other objectives include investigation of variable-amplitude loading effects on fatigue damage, notch effects, and the evaluation of creep-fatigue interaction and mean stress effects under multiaxial straining conditions at elevated temperatures.

5.5.2 Background

A Brookhaven[8] report on the integrity of LMFBR primary piping stated that "The combination of these small-amplitude vibrations superimposed on long time-hold creep fatigue cycles at high strain ranges is very deleterious for fatigue endurance and may require a reduction in the allowable strain ranges at 10^6 cycles by a factor of two or more." The postulated sources of these small-amplitude vibrations are high-frequency mechanical equipment vibration, high-frequency thermal cycling due to mixing of hot and cold streams of sodium, acoustical vibration, and seismic excitation. Three cases of thermal fatigue failure in sodium systems are cited to support the thermal mixing conditions as a high-cycle fatigue source, but evidence of enhanced failure rates near high-frequency rotating equipment or acoustic sources is not mentioned. In addition, concern has been expressed about the validity of theoretical extrapolation of constant-amplitude, uniaxial test data to variable-amplitude loading of a multiaxial strain field at elevated temperature.

5.5.3 Plan of action

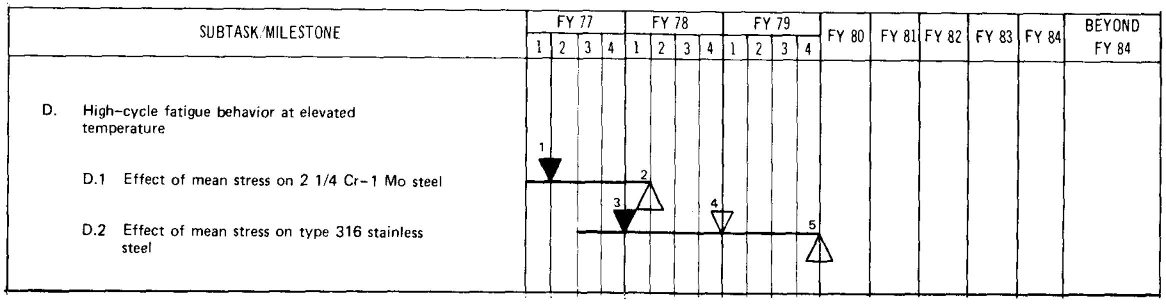
Mean stress fatigue testing in the range of 10^6 to 10^8 cycles is under way to resolve the concern about high-cycle fatigue combined with substantial mean stress at elevated temperature. In addition, fully reversed, high-cycle fatigue data at elevated temperature has been developed for correlation with mean stress interaction theory.

Preliminary data do not indicate reductions as severe as those postulated. Later phases of the subtask are planned to address the concerns about variable-amplitude loading history at elevated temperature, correlation of thermal cycling data (i.e., hot and cold stream mixing conditions) with mechanical cycling data in the high-cycle range, and the validation of theoretical procedures for relating multiaxial strain fatigue data with uniaxial data for elevated temperature.

---

8. J. G. Y. Chow, J. R. Weeks, D. H. Gurinsky, M. Reich, and E. P. Esztergar, *Integrity of LMFBR Piping, a Preliminary Evaluation,* BNL-FRS 74-2 (September 1974).

5.5.4 Subtask/milestone schedule



Milestones

1. Submit interim report on high-cycle fatigue of 2¼ Cr–1 Mo steel.
2. Submit final report on high-cycle fatigue of 2¼ Cr–1 Mo steel.
3. Submit interim report on high-cycle fatigue of type 316 SS.
4. Submit final report on high-cycle fatigue of type 316 SS.
5. Submit final report on high-cycle fatigue studies.

5.6 Subtask E – Simplified High-Temperature Piping Analysis

5.6.1 Objective

The objective of this subtask is the development of simplified analysis methods for elevated-temperature piping and, eventually, incorporation of these methods into the applicable design codes for LMFBR piping. Primary emphasis will be placed on the development of appropriate elevated-temperature stress indices for piping products having low-temperature stress indices. Other activities will include development of stress indices for additional piping products and joints commonly employed in sodium piping systems, and development of a simplified method to evaluate and control the effects of local overstrain (elastic follow-up).

5.6.2 Background

Analytical methods for piping systems are based upon modeling the piping as an assemblage of beam elements to determine the internal moments (loads) when the system is subjected to specified loading conditions. The internal moments (loads) are applied to the pipe cross-sectional properties to determine a basic stress level which is then multiplied by a stress index to determine the stress in the piping component.

Since the ASME code is based upon failure mode analysis, specific allowables are specified: primary stress allowables for limit load failure, primary-plus-secondary stress allowables for shakedown failure, and peak stress allowables for fatigue failure. Similarly, B, C, and K stress indices are specified for primary, primary-plus-secondary, and peak stresses respectively. Due to the three-dimensional nature of many piping components, theoretical treatment is more difficult than for the typically axisymmetric pressure vessel component. Due to theoretical complexity and the overwhelming number of pipelines to be designed, simplified methods are virtually a necessity. Indices have been developed for the more widely used piping components under low-temperature operation and are generally based upon a mixture of theory and test data.

To extend the stress index approach to elevated-temperature piping analysis, as a minimum, it will be necessary to review the basis for determining the low-temperature indices. Modification of equations for stress indices or additional indices may be required. Review of existing test data for the respective failure modes on piping components at elevated temperature is the essential first step in developing simplified methods.

Stress indices provided for branch connections in piping generally do not consider thermal stresses induced by increased wall thickness used for compensation of the opening. The effect could be severe for a small but heavily compensated branch connection in a thin, large-diameter run pipe. Thermowell failures have often been attributed to flow-induced vibration, and supporting analyses are needed to establish flow velocity limits for standardized thermowell configurations. Design guidelines are also needed for transition joints between piping and equipment and for pipe supports.

The code cautions the designer to avoid piping configurations that concentrate strain in local regions, since, during unloading, the elastic portions of the piping can further extend the strain range in the locally concentrated region. Elastic follow-up is of even greater concern in the elevated-temperature range, where creep effects would aggravate the strain concentration. However, while the code discusses elastic follow-up, specific criteria for evaluating elastic follow-up are not supplied, neither in or below the elevated-temperature range.

5.6.3 Plan of action

Primary emphasis will be placed on the development of appropriate elevated-temperature stress indices for piping products having low-temperature stress indices. A detailed evaluation of the primary stress indices (i.e., B indices) has been reported,[9] and the recommendations have been presented to the ASME Working Group on Piping.

The primary-plus-secondary (C) and peak (K) stress indices are complicated by creep-ratchetting and creep-fatigue interaction effects at elevated temperature. Existing data on time-to-failure tests of branch connections[10,11] and data from ORNL beam and elbow tests[12,13] have been reviewed[14,15] with respect to simplified analysis methods. This work is expected to provide further insight on appropriate C and K stress indices for piping products having low-temperature stress indices.

Other activities will include development of stress indices for additional piping products and joints commonly employed in sodium piping systems. Specific items considered for further development include peak stress indices for branch connections, classification guidelines for primary and secondary loads in piping components, and design guidelines for thermowells, transition joints, and pipe supports.

---

9. E. C. Rodabaugh, *Appropriate B Indices for Evaluating Load-Controlled Stresses in Piping Products at Elevated Temperatures,* AI-ERDA-13202 (March 1977).

10. T. E. Taylor, *High-Temperature Testing of Pressure Vessels,* Institution of Mechanical Engineers P3/60 (June 1968).

11. W. Sys, "Creep Rupture Testing of Pressure Vessels Containing a Nozzle," *Proceedings of the First International Conference on Pressure Vessel Technology* – Part II, 1969.

12. See sect. 2.3 of this document.

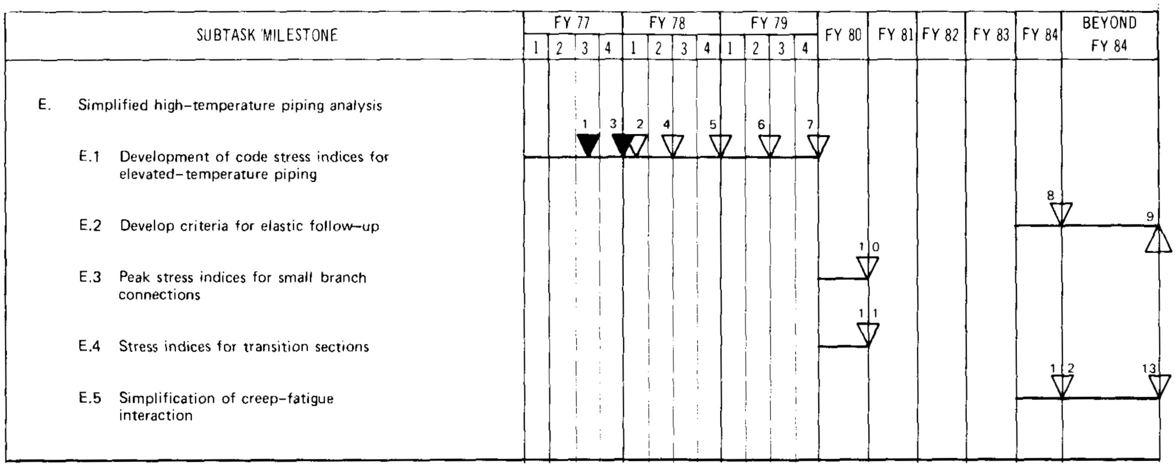
13. S. E. Bolt and W. L. Greenstreet, "Experimental Determinations of Plastic Collapse Loads for Pipe Elbows," ASME Paper 71-PVP-37, 1971.

14. E. C. Rodabaugh, *Evaluations of the Piping System Inelastic Analysis Computer Program, PIRAX2,* AI-DOE-13216 (October 24, 1977).

15. *Quarterly Technical Progress Report, High-Temperature Piping Design Technology, July–September 1977,* AI-DOE-13214.

The development of criteria to evaluate and control the effects of local overstrain (elastic follow-up) is planned. Specific criteria for elastic follow-up would avoid further consideration of piping designs with excessively unbalanced stiffness rather than eliminate such designs subsequent to detailed evaluation.

5.6.4 Subtask/milestone schedule



Milestones

1. Report on appropriate B indices for evaluating load-controlling stresses.
2. Report on evaluations of computer program PIRAX2.
3. Report on evaluation of branch connection time to failure.
4. Report on simplified equations for deformation control and creep-fatigue evaluation.
5. Report on strain concentration in piping systems.
6. Report on correlation of Code Case 1592 to elbow test data.
7. Report on simplified methods for estimating strains at welds.
8. Interim report on elastic follow-up.
9. Summary report on elastic follow-up.
10. Summary report on branch connection analyses methods.
11. Summary report on pipe-to-valve transitions.
12. Interim report on creep-fatigue interaction.
13. Interim report on creep-fatigue interaction.

5.7 Subtask F – Design Methods and Criteria for LMFBR Piping

5.7.1 Objective

The objective of this subtask is the preparation of interpretative reports presenting a methodology for the design of elevated-temperature sodium piping systems. Emphasis will be given to providing practical data in terms of analytical modeling methodologies and code evaluation techniques.

5.7.2 Background

Because the code design rules are presented in the form of design requirements without detailed explanation of the rationale behind the design rules or detailed recommendations on how the rules are to be implemented, an interpretative report presenting the methodology and rationale for elevated-temperature piping design would be of substantial benefit to the piping designer. It is hoped that the increased understanding by the practicing piping designer-analyst would result in better piping designs and, therefore, improved piping integrity.

With the increased use of finite-element analysis techniques for detailed stress analysis of piping components and because the code is not a "how to do it" document, there also exists a need for guidelines as to how the finite-element results should be related to the code requirements. Acceptable modeling simplifications and assumptions for typical piping components also need some standardization.

For elastic piping system analysis, compliance with code stress limits is most effectively evaluated by means of a postprocessor computer program, such as ELTEMP. Regular updating and verification of such a program is required to comply with changing code requirements.

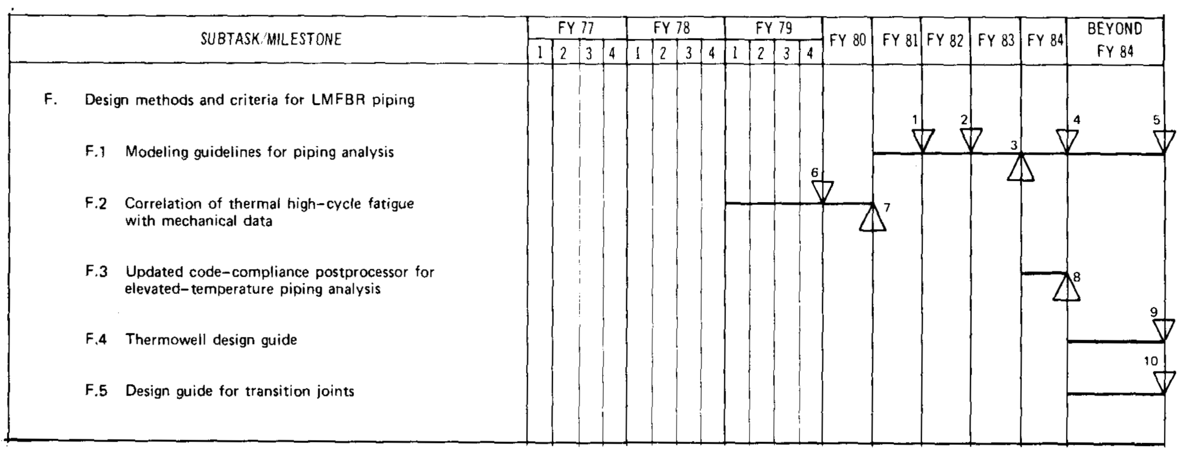
A computer program for simplified inelastic analysis of piping systems is urgently needed. The most widely accepted inelastic analysis programs have generally been limited to analysis of piping components due to the considerable expenditure of computer and manpower costs required for a complete solution. Several simplified approaches have been proposed, but evaluation of their capabilities and limitations is needed.

In addition, a simplification of evolving creep-fatigue interaction methods for application to piping systems is expected to be a future requirement.

5.7.3 Plan of action

Design methods are to be reviewed and studied to permit preparation of a recommended design methodology and criteria for high-temperature piping. Emphasis will be given to providing practical data in terms of analytical modeling methodologies and code evaluation techniques.

5.7.4 Subtask/milestone schedule



Milestones

1. Interim report on design guidelines.
2. Interim report on design guidelines for small branch connections.
3. Summary report on modeling guidelines.
4. Interim report on design guidelines for pipe clamps and supports.
5. Interim report.
6. Interim report on thermal and mechanical high-cycle fatigue correlation.
7. Summary report on thermal and mechanical high-cycle fatigue correlation.
8. Summary report.
9. Interim report.
10. Interim report.

5.8 Subtask G – Piping Component Testing

5.8.1 Objective

The objective of this subtask is to thermally and mechanically test piping components. Evaluation of the thermal transient limitations of pipe clamps and elbows is a near-term objective.

5.8.2 Background

Conventional pipe supports are generally attached to the pipe by means of a bolted clamp without intervening insulation. Concern has been expressed about the adequacy of such uninsulated or bare pipe clamps for high-temperature sodium service, and the complex, more expensive, insulated or standoff pipe clamp has been specified.

For pipe supports subject only to tensile loading radial to the pipe axis, the preload of the clamping bolts acts to bring the clamp and pipe into contact. However, if compressive loading can occur at even a slight skew angle, the frictional resistance imposed by the clamp preload is necessary to prevent clamp slippage and potential malfunction of the support. Differential expansion during transients and creep at high temperature could lead to clamp slippage. Increasing the clamp preload could result in excessive stress in the clamp or clamping bolts or in the supported piping. For thin-walled piping, buckling could also result from excessive clamping loads. Testing is required to verify the adequacy of analytical methods used to predict clamp contact pressure distribution and the corresponding temperature and stress distributions in the pipe and clamp.

Pipe bends and elbows are essential in the design of high-temperature piping systems due to the added flexibility they can provide. At the same time, elbows and bends are among the more highly stressed components in piping systems. Due to their critical application, verification of the current analytical assumption that radial thermal gradients do not influence the load deflection characteristics or the mechanical load carrying capacity of elbows and bends is required.

The code cautions the designer against piping configurations that concentrate strain in local regions but does not supply specific criteria for elastic follow-up. Such criteria are being developed under subtask E.

A number of piping failures have been attributed to rapid thermal cycling resulting from fluid oscillations. Where the branches of a pipe junction must operate at significantly different temperatures, a special branch connection termed a mixing tee should be designed to prevent fluid oscillations from subjecting the pressure boundary and primary structural members to excessive thermal cycling.

5.8.3 Plan of action

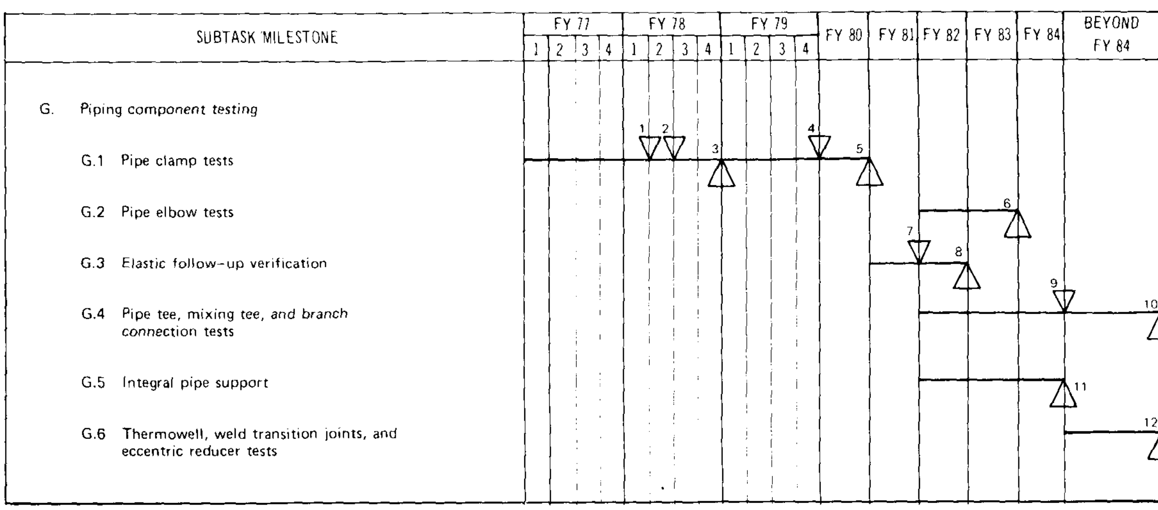
A request for transient testing of bare pipe clamps has been prepared that will provide benchmark data from which analytical modeling techniques can be developed for the clamp-pipe interaction. This and subsequent pipe support tests will provide data on the limiting mode of failure for basic pipe supports. The initial bare-clamp tests will also provide an indication of the potential for using conventional-type pipe clamps for the support of small-diameter, high-temperature piping, which is subject only to moderate thermal transients. A test plan for larger-diameter, insulated (standoff) pipe clamps will be submitted in fiscal year 1978.

Cyclic elevated-temperature testing of a simple piping loop of unbalanced stiffness is planned to validate criteria being developed for elastic follow-up.

Tests to confirm design guidelines for an integral pipe support, standardized thermowells, weld transition joints, and eccentric reducers are being considered. Verification tests for peak stress indices of small branch connections are also being considered.

Tests of conventional pipe tees and mixing tees are planned to determine temperature differential and cyclic limitations for verification of design guidelines for thermal cycling resulting from fluid oscillation.

5.8.4 Subtask/milestone schedule



Milestones

1. Interim report on first bare-clamp tests.
2. Interim report on second clamp tests.
3. Summary report on bare-clamp tests.
4. Interim report on tests of advanced clamps.
5. Summary report on tests of advanced clamps.

6. Final report on elbow tests.
7. Interim report on elastic follow-up criteria tests.
8. Summary report on elastic follow-up criteria tests.
9. Interim report on tee and branch connection tests.
10. Summary report on tee and branch connection tests.
11. Summary report on integral pipe support tests.
12. Summary report on thermowell, weld transition joint, and eccentric reducer tests.

5.9 Subtask H – Investigation of Improved High-Temperature Strain Gages

5.9.1 Objective

The objective of this subtask is to survey and recommend small, high-temperature strain gages for use in piping component tests.

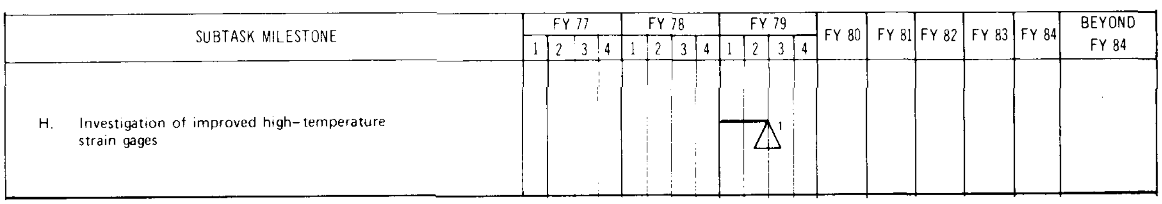
5.9.2 Background

Strain measurements in current high-temperature tests generally employ one of several types of capacitance gages. While these gages have performed satisfactorily in some instances, considerable care is required in mounting and calibration. In addition, while some reduction in gage length has been achieved, the overall size of current capacitance gages precludes their application in critical regions in many cases. The considerable expense of high-temperature testing would appear to justify a continuing effort to reduce the size and to improve the stability and accuracy of high-temperature strain gages.

5.9.3 Plan of action

The available high-temperature strain gage information will be surveyed to determine sources of suitable small, high-temperature strain gages which can be used on piping components undergoing high-temperature testing. Reports describing the use of various strain gages will be reviewed and contacts made with users of these strain gages to determine their experiences with each of the available types of gages. Based on these evaluations, sources will be recommended. If satisfactory gages are not available, a proposed development plan would be prepared.

5.9.4 Subtask/milestone schedule



Milestone

1. Summary report on recommended high-temperature strain gages.

5.10 Subtask I – Development of Piping Analysis Methods

5.10.1 Objective

The objective of this subtask is to develop piping analysis methods with emphasis on a simple inelastic piping analysis program which is intermediate to factored elastic and finite-element inelastic methods.

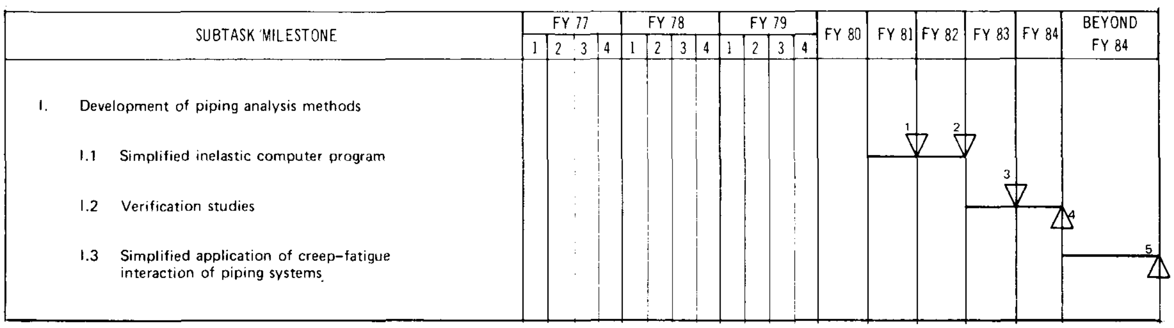
5.10.2 Background

Current inelastic analysis methods are too expensive and time-consuming for routine production analysis of high-temperature piping systems, while factored elastic analysis imposes a heavy burden of conservatism. A number of approaches have been proposed which include a computer program for inelastic piping analysis,[16] reference stress methods,[17] and enhanced flexibility at critical elbows.[18] These approaches are based on different analytical simplifications, and a comparative evaluation of the various assumptions and of computational techniques and limitations is needed to develop a simplified inelastic analysis method for piping that is generally acceptable.

5.10.3 Plan of action

Proposed methods will be applied to piping runs, for which detailed inelastic analyses are available, to obtain preliminary comparisons of solution time and accuracy. The results of this study will be the basis for development of a simplified inelastic computer program. A review of the underlying assumptions with respect to potentially limiting parameters will be made to select verification test cases. It is also expected that when the current creep-fatigue interaction questions are resolved, some simplification may be required for application to piping system analysis.

5.10.4 Subtask/milestone schedule



Milestones

1. Interim report on simplified inelastic computer program.
2. Summary report.

---

16. G. H. Workman and E. C. Rodabaugh, *Development of a Simplified Analytical Procedure for Determining the Inelastic Response of Piping Systems,* ORNL-Sub-3651-1 (September 1974).
17. J. Spence, "Creep Behavior of Smooth Curved Pipes under Bending," Proceedings of 1st Int. Conf. on Pressure Vessel Technology, 1968.
18. T. Yuhara, *Simplified Method of Design Analysis,* SA013 KWG77-10(15) (October 1977).

3. Interim report on verification studies.
4. Summary report on computer program with verification results.
5. Summary report.

ORNL-5369
Dist. Category UC-79,
-79e, -79h, -79k

INTERNAL DISTRIBUTION

1. C. R. Brinkman
2. W. E. Cooper
3–78. J. M. Corum
79. W. O. Harms
80. J. F. Harvey
81. R. F. Hibbs
82. Milton Levenson
83. B. S. Maskewitz
84. P. Patriarca
85. H. Postma
86. H. E. Trammell
87. D. B. Trauger
88. G. D. Whitman
89. Patent Office
90–92. Central Research Library
93. Y-12 Document Reference Section
94–96. Laboratory Records Department
97. Laboratory Records (RC)

EXTERNAL DISTRIBUTION

98–99. Director, Division of Reactor Research and Technology, Department of Energy, Washington, D.C. 20545
100. Director, Reactor Division, DOE, ORO
101. Research and Technical Support Division, DOE, ORO
102–355. Given distribution as shown in TID-4500 under categories UC-79, -79e, -79h, -79k