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MATERIALS AND STRUCTURES TECHNOLOGY

Program Plan for Advanced Reactors

Oak Ridge National Laboratory

Georgia Institute of Technology

Rockwell International Corporation

General Electric Company

University of Tennessee

Energy Technology Engineering Center

Westinghouse Electric Corporation

Program Plan: FY 1988–1993

September 1988

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U.S. Department of Energy
Nuclear Energy
Technology Support Programs

MATERIALS AND STRUCTURES TECHNOLOGY PROGRAM PLAN FOR ADVANCED REACTORS

Prepared by
Oak Ridge National Laboratory
with
Energy Technology Engineering Center
General Electric Company
Georgia Institute of Technology
Rockwell International Corporation
The University of Tennessee
Westinghouse Electric Corporation

November 1988

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PREFACE

This program plan was prepared by the staff of the Materials and Structures Technology Program at Oak Ridge National Laboratory on behalf of the Office of Technology Support Programs, Office of Nuclear Energy, U.S. Department of Energy. The activities described support the DOE Advanced Liquid-Metal Reactor Program as described in the draft Program Plan dated November 4, 1987.

Portions of this plan are based on contributions provided by the Advanced Energy Systems Division of Westinghouse Electric Corporation, the Energy Technology Engineering Center, Georgia Institute of Technology, and The University of Tennessee.

The plan was prepared with the assistance of advanced LMR designers at General Electric Company and Rockwell International Corporation. It reflects their identification of program needs, and it has their agreement. The assistance of these individuals, as well as the support of staff members of the DOE Office of Technology Support Programs, is gratefully acknowledged.

EXECUTIVE SUMMARY

To satisfy the long-term needs of the United States for electric power, the strategy of the Department of Energy (DOE) includes development of advanced liquid metal reactor (LMR) plants as a low-cost, low-risk, nuclear power option. These plants will have passive safety features, such as self-actuated shutdown and natural-convection decay heat removal, and will employ modular construction techniques. Compared to current light-water reactor (LWR) plants, the advanced LMR plants offer benefits including (1) enhanced safety and licensability, (2) increased reliability and availability, (3) improved economics, and (4) increased U.S. competitiveness in the international marketplace.

As part of the DOE Advanced LMR Program, conceptual design was completed for two plants, the Power Reactor Inherently Safe Module (PRISM) by the General Electric Company (GE), and the Sodium Advanced Fast Reactor (SAFR) by Rockwell International Corporation (RI). PRISM was selected as the reference concept, and advanced conceptual design by GE is scheduled for FY 1989-91.

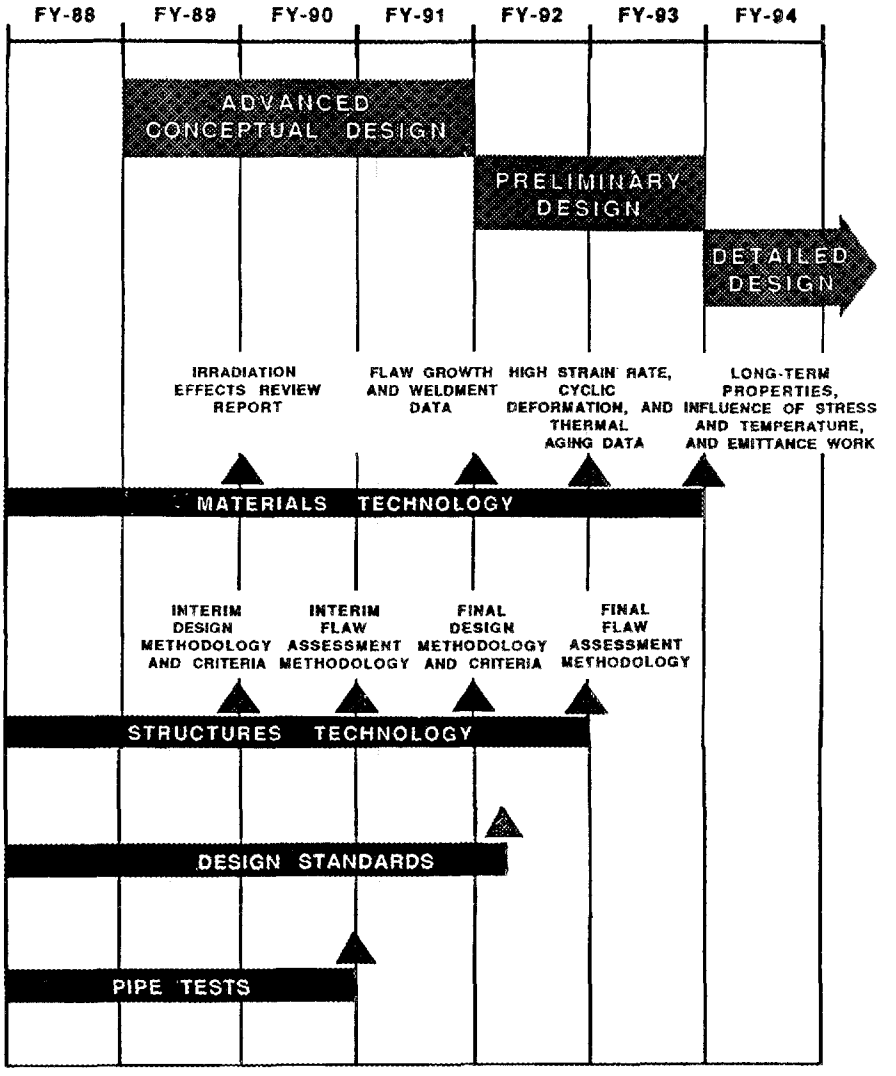
Advanced LMR plants will be designed for a service life of up to 60 years. Such long service presents significant challenges to the structural integrity of the reactor and the heat transport systems. These challenges arise not only from the relatively high service temperatures but also from the large, rapid temperature changes associated with the use of a liquid metal as the heat transport medium. An effective response to this unique set of challenges is required to ensure the success of the DOE Advanced LMR Program.

For this reason, the DOE Office of Technology Support Programs established a coordinated program to develop the specialized high-temperature materials and structural design technology necessary for safe and reliable, long-term operation of advanced LMR plants. This Program Plan describes the activities required to complete the development of this technology. The remaining tasks were identified as essential by advanced LMR designers at GE and RI.

Oak Ridge National Laboratory has played a leading role in the development of the materials and structures technology for advanced reactors and was responsible for preparation of this plan, in collaboration with DOE, GE, RI, Westinghouse, and the Energy Technology Engineering Center.

The plan is divided into two larger and two smaller parts, all of which are complementary. The first part, materials technology, focuses primarily on providing materials data needed for design and safety assessments. The second, structural design/life assurance technology, focuses on providing the design and safety assessment methodologies and criteria. Each of these two major parts of the plan is subdivided into a number of tasks, each of which addresses a specific designer-identified requirement. The third and fourth parts of the plan, design standards for components unrelated to nuclear safety and pipe thermal ratchetting tests to failure, each consist of a single task addressing a specific design need.

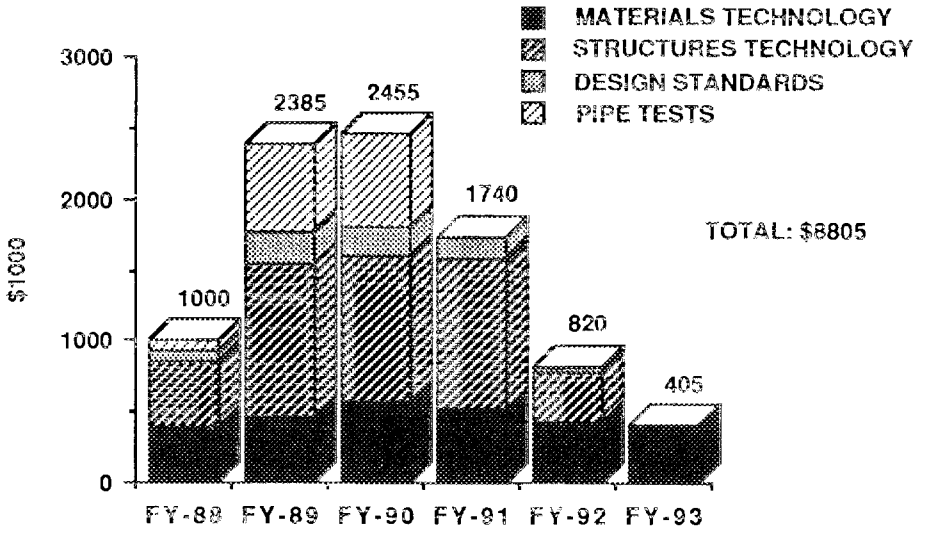
As shown in the following chart, the materials technology effort is projected to require five additional years to complete (FY-89 through -93). To meet designer-identified need dates, the structures technology effort is scheduled for



completion in four additional years (FY-89 through FY-92). Key deliverables are shown on the schedule. The dates for these deliverables are consistent with the draft DOE **Advanced Liquid Metal Reactor Program Plan** (November 4, 1987) and with designer-identified need dates. The design stages shown at the top of the chart are taken from the draft DOE plan.

The total cost of the effort described in this plan is estimated to be $8,805,000. The breakdown of this total is given in the chart on the following page.

A significant part of the overall remaining effort addressed by this plan is focused on the addition of a new alloy, modified 9 Cr—1 Mo steel, to the design methodology and data base so that advantage can be taken of its superior mechanical and physical properties in advanced LMR plants. Development of this alloy was carried out over a period of ten years, and it has gained broad worldwide acceptance for nonnuclear applications. The present emphasis is on supplying the specific



methods, criteria, and data needed for structural design and assessment by designers of advanced reactors. Elements of this present effort include the generation of design data, the identification of appropriate design analysis methods and failure criteria, and development of the high-temperature fracture assessment procedures needed for reactor safety and reliability assessments. Completion of these modified 9 Cr—1 Mo steel tasks will allow the use of the material for advanced reactors, with large attendant cost savings. For example, RI estimated that use of the material would result in a $150 million cost savings per plant.

In addition to modified 9 Cr—1 Mo steel, this plan addresses a small number of remaining critical materials and structural design issues involving traditional materials and design methods. For example, structural failures resulting from creep and fatigue damage accumulation have occurred in both fossil and earlier LMR plants. Current LMR design methods and criteria must be improved to preclude such failures in the future. In addition, special new data requirements have arisen that are associated with recent advanced reactor designs. These include data needs associated with a longer 60-year life and with passive safety features.

Although developed to address the materials and structures needs of LMRs, portions of this plan are applicable as well to the modular high-temperature gas-cooled reactor (MHTGR). This is particularly true of the materials technology tasks related to 2-1/4 Cr—1 Mo steel and the more generic structural design/life assurance technology tasks.

1. INTRODUCTION

Materials and structures technology development activities have been underway since the early 1970s in support of the Department of Energy's liquid-metal reactor (LMR) program. These activities have resulted in an established high-temperature structural design methodology and a significant base of mechanical properties design data. With the exception of efforts leading to the development of a new, improved structural alloy, modified 9 Cr—1 Mo steel, most of the past development efforts focused on types 304 and 316 stainless steels, and 2-1/4 Cr—1 Mo steel. The resulting technology was used in the design of the Fast Flux Test Facility, the Clinch River Breeder Reactor Plant, and various test facilities.

The purpose of this plan is to bring the materials and structures technology development effort to completion for application in the DOE Advanced LMR Program. To that end, the plan reflects extensive interactions with advanced reactor designers at General Electric and Rockwell International, as well as with DOE staff members in the Nuclear Energy Office of Technology Support Programs. The plan, as presented in this document, addresses specific needs identified by the advanced reactor designers, and it is supported by them.

The plan addresses four general areas of need:

- resolution of the few key remaining problem areas in the overall technology (deficiencies that have come to light primarily through application experience),
- qualification of the new alloy, modified 9 Cr—1 Mo steel, for nuclear applications, to take advantage of its superior mechanical and physical properties in the advanced LMR program,
- special data and design standard requirements associated with advanced reactor designs (e.g., longer 60-year life and passive safety features), and
- a flaw-growth-based safety and reliability assessment procedure, which has not previously been developed but is a necessary requirement for licensing.

A significant part of the overall effort is concerned with modified 9 Cr—1 Mo steel, whose superior mechanical and physical properties, including high strength, high thermal conductivity, and low thermal expansion, make it especially well suited for LMR applications.

The plan is divided into two larger and two smaller parts, all of which are complementary. The first part, materials technology, focuses primarily on providing materials data needed for design and safety assessments. The second, structural design/life assurance technology, focuses on providing the design and safety assessment methodologies and criteria. Each of these two major parts of the plan is divided into a number of tasks, as follows.

- Materials Technology
  1. Mean Stress and Creep-Fatigue Tests on Modified 9 Cr—1 Mo Steel Base and Weldment Material

2. Long-Term Creep-Rupture Tests on Modified 9 Cr—1 Mo Steel Base and Weldment Material
3. High Strain Rate Tensile and Low-Cycle Deformation Studies on Modified 9 Cr—1 Mo Steel
4. Development of Flaw Growth and Critical Crack Size Data for Modified 9 Cr—1 Mo and 2.25 Cr—1 Mo Steel
5. Defining of Long-Term Thermal Aging Effects on Tensile, Creep, and Toughness Properties of Modified 9 Cr—1 Mo Steel
6. Development of Carbon Steel to Modified 9 Cr—1 Mo Steel Joint Welding Procedures
7. Long-Term Creep-Rupture Behavior of Type 316 Stainless Steel
8. Influence of Prolonged Periods of Low Stress at Elevated Temperatures on the Short-Term Tensile Properties of Type 316 Stainless and Modified 9 Cr—1 Mo Steel
9. Influence of Irradiation on Mechanical Properties of Types 304 and 316 Stainless Steel and Modified 9 Cr—1 Mo Steel — A Status Report
10. Emittance of Passive Cooling System Materials
11. Mechanical Properties of Austenitic Stainless Steels After Exposure to Temperatures Above Operating Conditions

- Structural Design/Life Assurance Technology
  1. Inelastic Deformation Model for Modified 9 Cr—1 Mo Steel
  2. Creep-Rupture and Creep-Fatigue Failure Criteria
  3. Simplified Ratchetting and Creep-Fatigue Rules for Modified 9 Cr—1 Mo Steel
  4. Design Rules for Weldments
  5. Validation of Life Prediction Methodology at Geometric Discontinuities
  6. Confirmatory Structural Failure Tests
  7. Flaw Assessment Procedures for Predicting Leaks in Pressure Boundary Components
  8. Adaptation of Flaw Assessment Procedure to Initial Cracks Produced by Thermal Striping

The third and fourth parts of the plan each consist of a single task, as follows:

- Design Standards for Components Unrelated to Nuclear Safety
- Pipe Thermal Ratchetting Tests to Failure

A chart showing scheduled completion dates for each part of the plan is included in the Executive Summary. Detailed schedules for each task are given in the following chapters.

The total cost of the effort described in this plan is estimated to be $8,805,000. The breakdown of this total is given in the following table. A task by task cost breakdown is given in the following chapters.

The body of this plan is divided into four chapters. Chapter 2 describes the Materials Technology tasks, Chapter 3 the Structures Technology tasks, Chapter 4 the Design Standards task, and Chapter 5 the Pipe Tests task. For each task, the approach to be taken, the deliverables, the current status, a justification statement, and a cost and detailed milestone schedule are given.

Cost Summary ($1000)

	Fiscal Year						Totals
	88	89	90	91	92	93	
Materials Technology	390	470	585	530	420	405	2800
Structures Technology	470	1085	1020	1050	360		3985
Design Standards	70	210	200	160	40		680
Pipe Tests	70	620	650				1340
Totals	1000	2385	2455	1740	820	405	8805

2. MATERIALS TECHNOLOGY

2.1 Objective

An adequate mechanical and physical properties data base is required for the licensing, construction, and operation of advanced liquid-metal reactor (LMR) plants. Specifically, data are required for development of design methods, for application of design procedures, for extension of ASME Code cases to longer times, and to serve as bases for safety analyses, e.g., flaw assessment and defect behavior, and for licensing and regulatory decisions. The objective is to provide a mechanical and physical properties data base for advanced LMR plants that will safely and economically operate for 60 years. Although considerable data have been generated to date, there are a number of critical areas, identified herein as Tasks 1-11, that remain to be completed in an expected five-year effort.

The scope of the program ranges from completion of a number of ongoing tasks on modified 9 Cr—1 Mo steel to acquisition of additional data for type 316 stainless steel to define long-term stress allowables for 60-year design lives. Emphasis is on the completion of the data required for air environments; but some environmental data, including high vacuum to simulate sodium conditions, are included, and a state-of-the-art report on irradiation effects is planned.

Most of the work defined herein is in support of a mechanical properties data base, with the exception of Tasks 6 and 10 which are related to weld methods development and physical properties data acquisition, respectively. The tasks cover necessary work on wrought modified 9 Cr—1 Mo, 2-1/4 Cr—1 Mo, and the austenitic stainless steels as well as associated weldment materials.

Modified 9 Cr—1 Mo steel was developed under DOE sponsorship as a special new structural steel for heat exchanger applications. It has been recognized worldwide as having many superior properties in comparison to other alloys used for such applications. One foreign supplier has already manufactured over 1000 tons of this material in the form of heat exchanger components for the fossil-fired power generation industry. However, it is a new material and before it can be fully accepted for advanced LMR applications the work outlined herein must be completed. Accordingly, work on this material receives heavy emphasis as found in Tasks 1-6, 8, and 9.

2.2 Task 1. Mean Stress and Creep-Fatigue Tests on Modified 9 Cr-1 Mo Steel Base and Weldment Material

Approach: Complete key mean stress and hold-time creep-fatigue tests in air and high vacuum of base material and weldments needed to establish a data base in order to develop a reasonably accurate creep-fatigue interaction model for design.

Deliverables: (1) A data base (about 38 tests) on modified 9 Cr--1 Mo steel base and weldment material for model development of creep-fatigue interaction behavior.

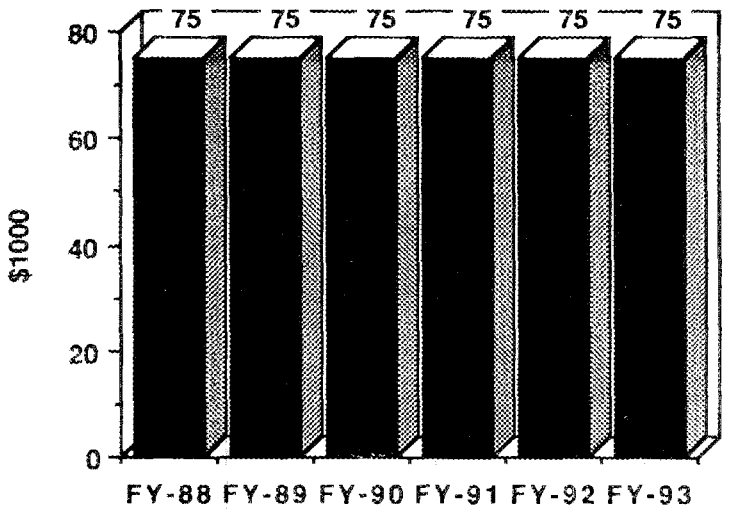
Status: The following briefly summarizes tests completed and planned for both base material and weldments.

	Base Material	Weldments
Completed:	13	0
Planned:	12	13

Tests have been conducted to date at temperatures of 538 and 593°C and strain ranges between 0.5 and 1%, using either tensile or compressive hold times, with test times of up to about one year, in both air and high vacuum environments. Remaining tests will be conducted at 538 or 593°C and low strain ranges, e.g., 0.5%, for test times of up to 3 or 4 years in both air and a high vacuum.

Justification: Failure by possible creep-fatigue interaction is one of the most important failure modes that must be taken into consideration in the design of liquid-metal reactor systems. Available data, while limited on base material, indicate that the method of linear damage summation is not appropriate and therefore sufficient data must be developed to justify development of a model for extrapolation purposes. Data on other materials suggest that failure by creep-fatigue interaction can be related to creep ductility (reduction of area) as measured from long-term creep tests, i.e., the lower the ductility the lower the cycles to failure under creep-fatigue loading conditions. Data from ongoing creep tests show that the ductility of this material begins to drop from high values after about 20,000 h of test time. Data on weldments are not available. Hence, data are required and will be generated to establish appropriate rules for prevention of failure by creep-fatigue interaction.

Cost and Schedule:



TOTAL:$450

TASK: Data Base on Mean Stress and Creep-Fatigue of Modified 9 Cr–1 Mo Steel						
SUBTASK/MILESTONE	FISCAL YEAR					
	1988	1989	1990	1991	1992	1993
1. Uniaxial creep-fatigue on base material	a		b	c	d	e
a. Complete up to 1-year-long test in air						
b. Complete up to 2-year-long test in air						
c. Complete mean stress tests in air						
d. Complete high vacuum tests						
e. Complete up to 3-year-long test in air and establish damage interaction diagram						
2. Uniaxial creep-fatigue tests on weldments					a	b
a. Complete up to 1-year-long test in air						
b. Complete up to 1-year-long test in vacuum						
3. Complete summary report						a
a. Complete final report						

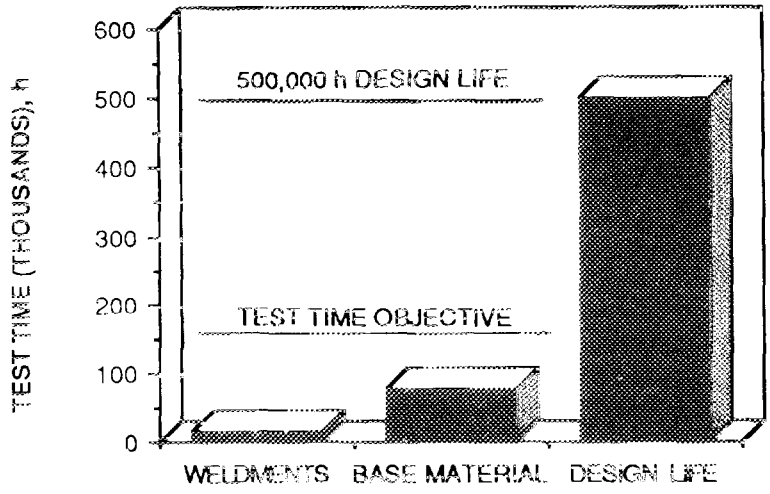
2.3 Task 2. Long-Term Creep-Rupture Tests on Modified 9 Cr-1 Mo Steel Base and Weldment Material

Approach: Continue long-term creep-rupture tests supporting extension of the property package to 500,000 h. Conduct ongoing tests to 166,000 h.

Deliverables: (1) Data will become available from approximately 30 ongoing tests on base and 13 ongoing tests on weldment material. (2) Stress-rupture models will be updated permitting confidence in extrapolation to 500,000 h.

Status:

STATUS AND OBJECTIVES OF ONGOING CREEP-RUPTURE TESTS

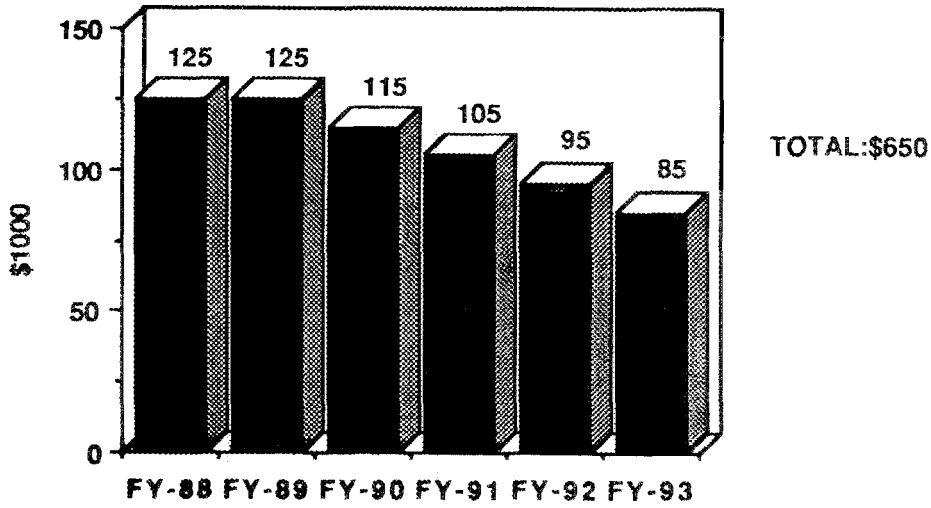


COMPARISON OF CURRENT STATUS & DESIGN LIFE

About 43 long-term creep tests on both base material and weldments are currently underway. Test temperatures range from 482 to 649°C with stress levels set to produce failure at increasing times. The longest ongoing test to date has accumulated 79,000 h and the longest test to failure lasted 56,908 h.

Justification: Current extrapolations of flow, rupture, and ductility data must be backed up with sufficient additional data to define behavioral trends and stress allowables for a 60-year design life. Both base material and weldments are included in this task. Rupture data from tests conducted on weldments are urgently needed to define stress-rupture reduction factors since some softening is known to occur in the heat-affected zone of high strength ferritic materials.

Cost and Schedule: Ten years of additional test time is required. The work is to be continued to FY-93 when detailed design of an advanced LMR begins. Work to be continued beyond this date will be funded as a surveillance program by plant owners.



TASK: Long Term Creep-Rupture Tests on Base and Weldment Material of Modified 9Cr-1Mo Steel						
SUBTASK/MILESTONE	FISCAL YEAR					
	1988	1989	1990	1991	1992	1993
1. Continue rupture tests on base and weldment material	a ▽	b ▽	c ▽	d ▽	e ▽	f △
a. Complete testing to 81,000 h on base and 23,000 h on weldment material						
b. Complete testing to about 90,000 h on base and 32,000 h on weldment material						
c. Complete testing to about 98,000 h on base and 40,000 h on weldment material						
d. Complete testing to about 107,000 h on base and 49,000 on weldment material						
e. Complete testing to about 116,000 h on base and 57,000 h on weldment material						
f. Complete testing to about 125,000 h on base and 65,000 h on weldment material and write summary report						

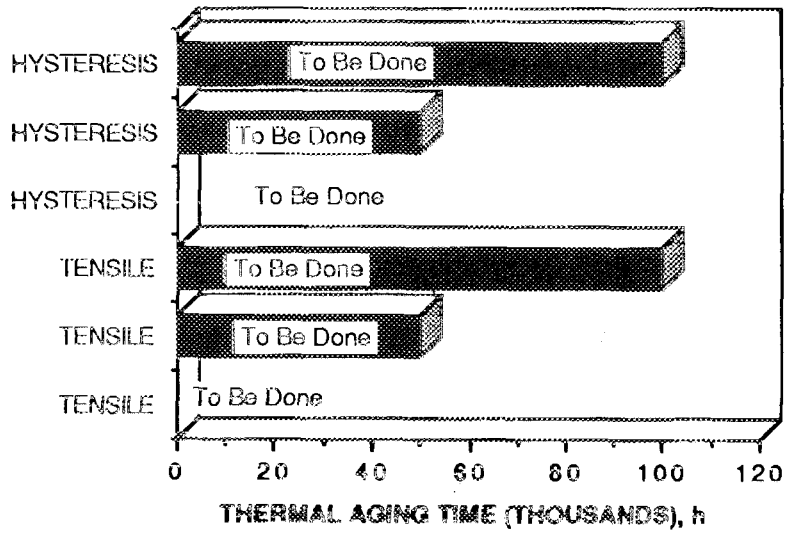
2.4 Task 3. High Strain Rate Tensile and Low-Cycle Deformation Studies on Modified 9 Cr-1 Mo Steel

Approach: Perform exploratory high strain rate tensile and low-cycle fatigue tests at ambient and elevated temperatures to provide hysteretic behavior under dynamic loading conditions.

Deliverables: (1) High strain rate (0.08/s) tensile data at ambient, 482, 538, and 593°C on two heats (194 and 30383) of virgin and aged (50,000 and 100,000 h) materials. Total specimens: 24. (2) Hysteresis loop information generated at ambient, 482, 538, and 593°C on two heats (194 and 30383) of virgin and aged (50,000 and 100,000 h) material. Total specimens: 24.

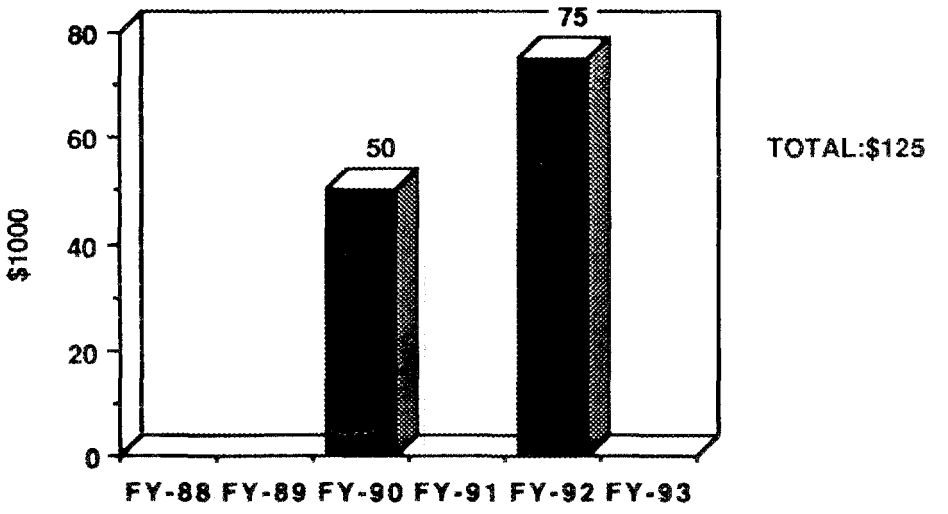
Status: Limited high strain rate testing has demonstrated that this material can be strain-rate sensitive in terms of tensile properties, depending upon test temperature. Further, the material undergoes cyclic softening when cyclic loads exceed the yield strength.

STATUS OF HIGH STRAIN RATE HYSTERESIS AND TENSILE TESTS



Justification: Seismic and sodium water reaction loads can produce high strain rate loading conditions. Therefore, both tensile (ongoing) and cyclic dynamic data must be generated in order to develop the inelastic dynamic design methodology being used for advanced LMR systems.

Cost and Schedule:



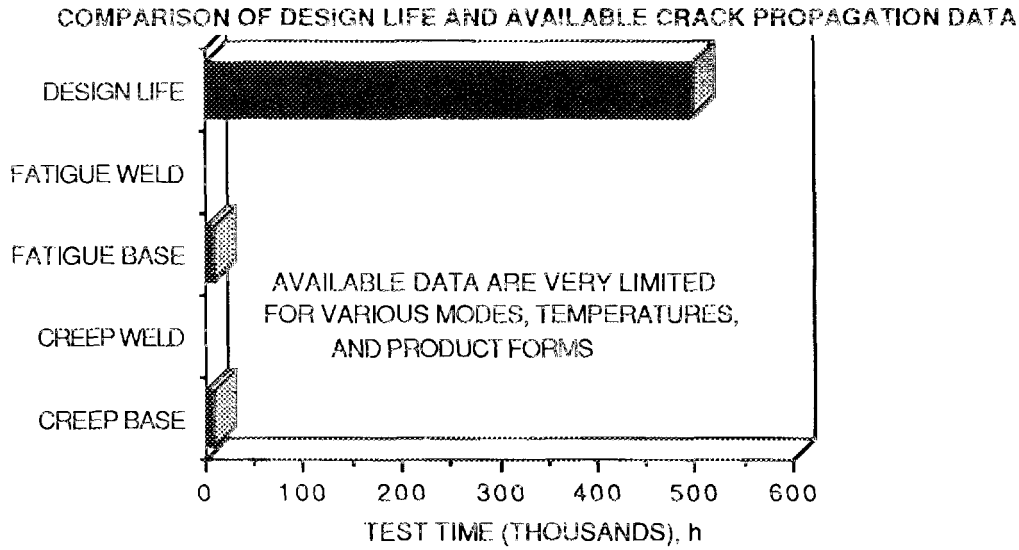
TASK: High Strain Rate Tensile and Low Cycle Deformation Studies on Modified 9Cr-1Mo Steel						
SUBTASK/MILESTONE	FISCAL YEAR					
	1988	1989	1990	1991	1992	1993
1. High strain rate tensile tests			a		b	
a. Complete high strain rate tensile tests on unaged and short term aged material						
b. Complete high strain rate tensile tests on long term aged material						
2. Hysteresis tests			a		b	
a. Complete uniaxial hysteresis tests on unaged and short term aged material						
b. Complete uniaxial hysteresis tests on long term aged material			a		b	
3. Reports						
a. Complete interim report						
b. Complete final report						

2.5 Task 4. Development of Flaw Growth and Critical Crack Size Data for Modified 9 Cr-1 Mo and 2.25 Cr-1 Mo Steel

Approach: Both creep crack and cyclic crack growth data will be generated.

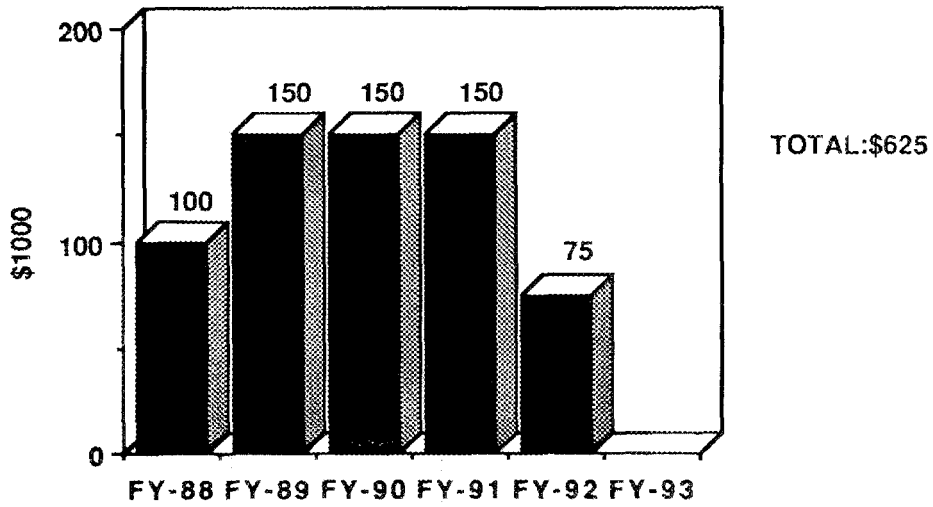
Deliverables: (1) An experimentally derived data base for creep crack propagation in 2.25 Cr—1 Mo and 9 Cr—1 Mo steel for both base and weldment material (about 25 specimens). (2) An experimentally derived data base for cyclic crack growth propagation in 2.25 Cr—1 Mo and 9 Cr—1 Mo steel for both base and weldment material (about 25 specimens).

Status: Limited creep crack growth and cyclic crack growth data have been generated to date on base material. Data are required on multiple product forms and weldments. A program plan was recently formulated in conjunction with the design method activity (see **Program Plan — Development of a Flaw Assessment Methodology for LMR Components of Modified 9 Cr—1 Mo Steel**, ORNL/CF-88/19, January 1988).



Justification: Crack propagation behavior is material sensitive and existing growth models need to be parameterized to fit data after an adequate data base has been generated. Experimental efforts will emphasize creep crack propagation since growth of cracks or flaws under this form of loading has not been determined. The resulting data, together with the methodology developed under Task 7 of Chapter 3, will be used for (1) leak assessments, (2) evaluating the stability of thermal striping-induced cracks in upper internals, and (3) assessing flaws found through inspections.

Cost and Schedule:



TASK: Development of Flaw Growth Data for 2.25Cr-1Mo and 9Cr-1Mo Steels

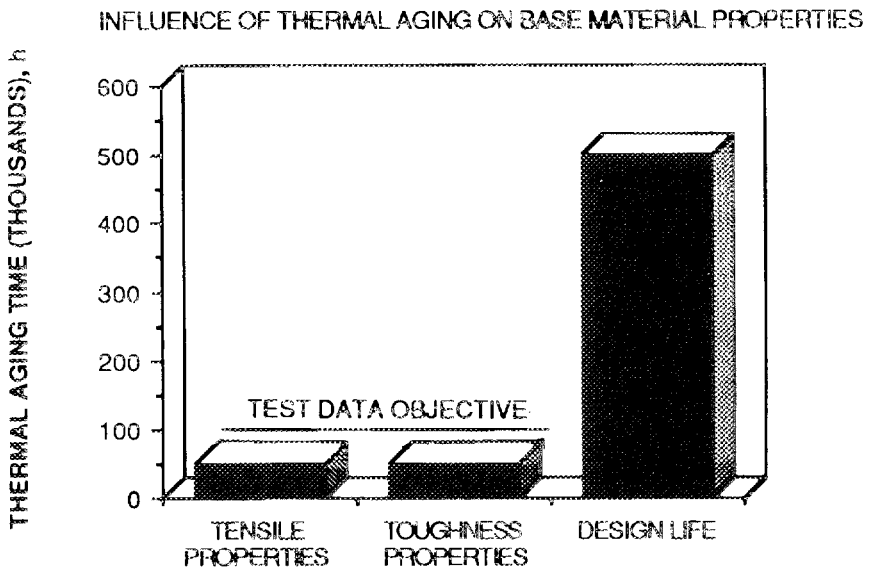
SUBTASK/MILESTONE	FISCAL YEAR					
	1988	1989	1990	1991	1992	1993
1. Conduct creep crack propogation tests on Modified 9Cr-1Mo steel			a		b,c	
a. Complete tests on base material						
b. Complete tests on weldments						
c. Report results						
2. Conduct cyclic crack propogation tests on Modified 9Cr-1Mo steel			a		b,c	
a. Complete tests on base material						
b. Complete tests on weldments						
c. Report results						
3. Conduct limited crack growth tests on 2.25Cr-1Mo steel					a,b	
a. Complete crack and cyclic tests						
b. Report results						

2.6 Task 5. Defining of Long-Term Thermal Aging Effects on Tensile, Creep, and Toughness Properties of Modified 9 Cr-1 Mo Steel

Approach: Material from three heats is currently undergoing thermal aging (no applied stress) at temperatures ranging from 482 to 704°C. Periodically material is removed from the furnaces and tensile (multiple strain rates), creep, and toughness tests are performed to determine the influence of long periods at elevated temperatures on properties.

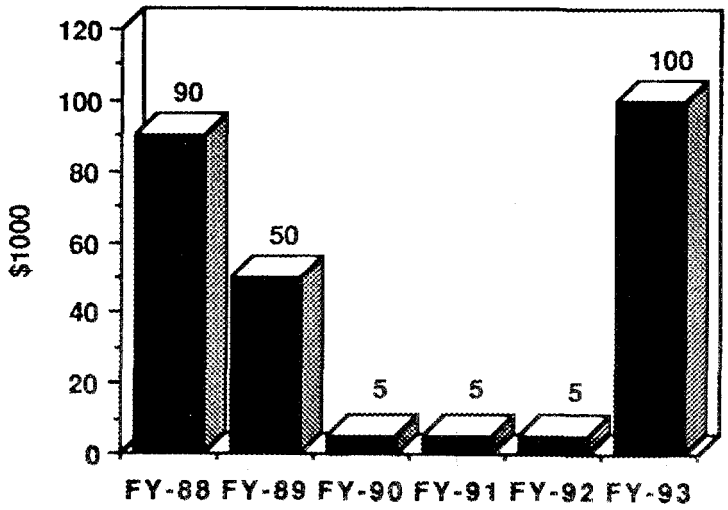
Deliverables: (1) Mechanical properties data base for several heats of base material aged at various temperatures for times up to 100,000 h. (2) Mechanical properties data base on weldments aged to 40,000 h. (3) Results from approximately 100 specimen tests will be obtained.

Status: Work is complete on base material to 50,000 h of aging as shown below. Aging of weldments to begin in FY-89. Approximately 100 specimens required for this effort.



Justification: The design codes do not explicitly provide for long-term aging effects and even if implicitly considered in selection of safety factors, it has not been done for 60-year design life. Exposure to elevated temperatures for prolonged periods of time is known to reduce tensile properties and decrease toughness. The magnitude of these changes needs to be quantified so that appropriate knock-down factors can be defined. Toughness data are necessary for component exchange work during winter maintenance of plants.

Cost and Schedule: Base material is currently aging and will reach 100,000 h of exposure in FY-93. FY-89 funding of $50K is required to prepare weldments and begin their thermal aging. Funding of $5K per year for FY-90, -91, and -92 is required to maintain the aging facilities.



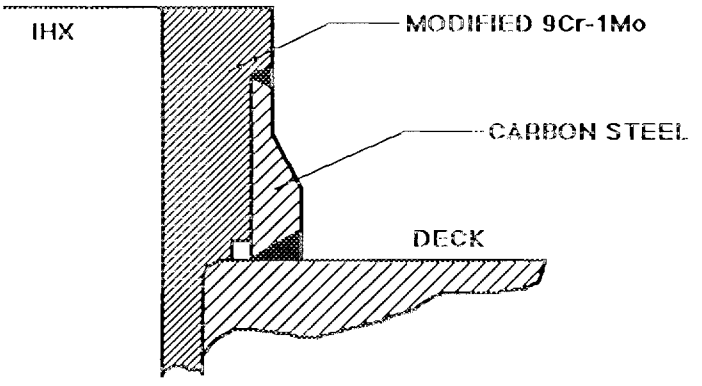
TOTAL:$255

TASK: Defining of Long Term Thermal Aging on Mech. Properties of 9Cr-1Mo Steel						
SUBTASK/MILESTONE	FISCAL YEAR					
	1988	1989	1990	1991	1992	1993
1. Thermal aging studies on base material	a ▽					b △
a. Complete aging studies to 50,000 h and report results						
b. Complete aging studies to 100,000 h and report results		a ▽				b △
2. Thermal aging studies on weldment material						
a. Prepare weldments and initiate aging						
b. Complete tests and report for material aged to about 40,000 h						

2.7 Task 6. Development of Carbon Steel to Modified 9 Cr-1 Mo Steel Joint Welding Procedures

Approach: Welding procedures will be developed for joining modified 9 Cr—1 Mo steel to low carbon steel.

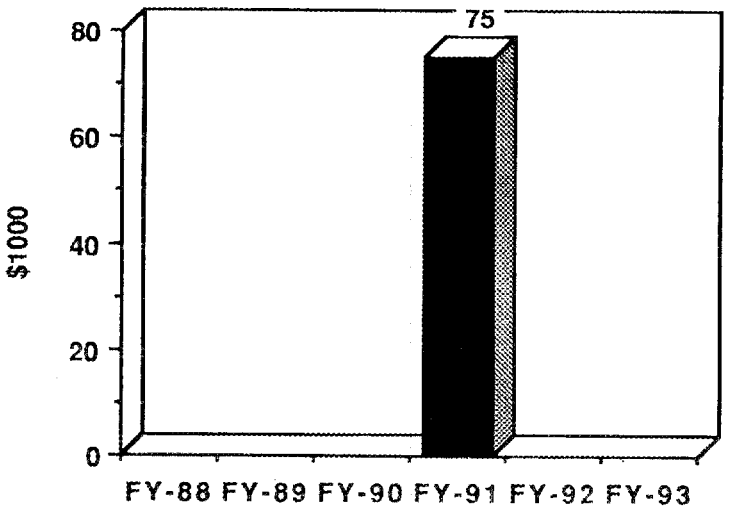
Deliverables: Welding procedures will be developed for applications like preparing support welds to be used in SAFR for joining both the intermediate heat exchanger (IHX) and the upper internal structure to the deck structure (see sketch). The IHX contains girth welds which will be prepared by hand. Both components will employ butt welds which will be about 2 in. thick. The welds in service will be exposed to low temperatures, i.e., about 200°F. A limited number of mechanical property tests (about 25 specimens) will be conducted to determine strength characteristics.



Status: A number of transition joint weldments between modified 9 Cr—1 Mo steel and austenitic material have been prepared. Work on ferritic transition joints is limited.

Justification: Defined by the advanced LMR project and needs to be a Section III Code-approved methodology. Also must be shown to meet strength requirements.

Cost and Schedule: A one-year effort in FY-91 includes methods development and mechanical property characterization.



TOTAL:$75

TASK: Develop Carbon Steel to Modified 9Cr-1Mo Steel Joint Welding Procedures						
SUBTASK/MILESTONE	FISCAL YEAR					
	1988	1989	1990	1991	1992	1993
1. Develop weldment procedure				a b c		
a. Prepare weldments						
b. Perform selected mechanical properties tests						
c. Complete report						

2.8 Task 7. Long-Term Creep-Rupture Behavior of Type 316 Stainless Steel

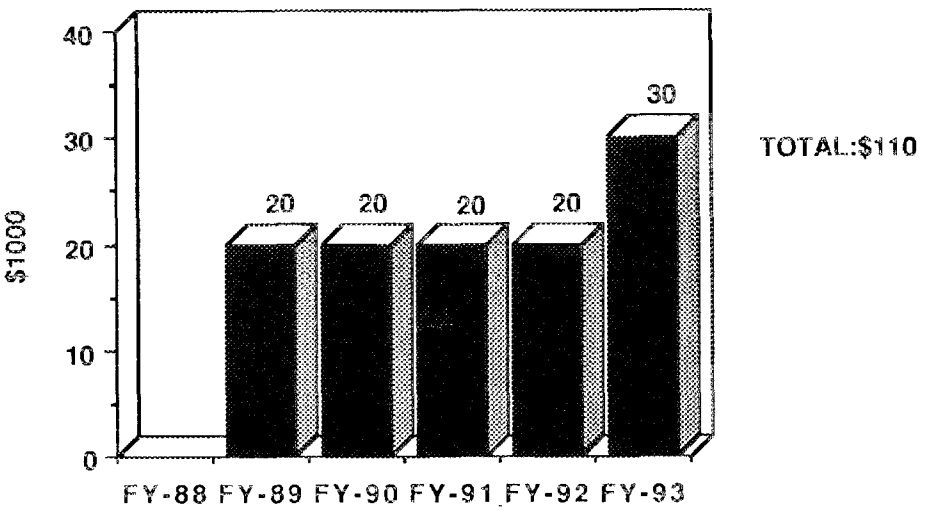
Approach: Eight specimens from the reference heat of type 316 stainless steel will be continued in long-term creep-rupture tests.

Deliverables: (1) Development of data base to substantiate the 60-year design life of the advanced LMR. (2) Long-term creep-rupture data from the ORNL reference heat to test times of about 120,000 h. Data will include rupture, ductilities, and creep-rate. (3) Tests not completed at the end of five years will either be stopped and specimens subjected to short-term tensile tests (see 2.9, Task 8) or continued as project surveillance tests.

Status: Eight creep-rupture tests will be started again and continued for up to five additional years. These tests were being tested at test temperatures of 482 to 593°C and have accumulated test times of 65,000 to 81,000 h. Additional details can be found in ORNL/TM-9896.

Justification: Design lives for advanced LMR projects have been set at 500,000 h while present design codes have allowables to only 300,000 h. Data need to be developed to justify extrapolation of time-dependent stress tables and isochronous stress-strain curves.

Cost and Schedule:



TASK: Long Term Creep-Rupture Behavior of Type 316 Stainless Steel

SUBTASK/MILESTONE	FISCAL YEAR					
	1988	1989	1990	1991	1992	1993
1. Continue long term rupture tests	a		b		c	d
a. Restart tests						
b. Reach test times of about 95,000 h						
c. Reach test times of about 112,000 h						
d. Conclude tests after about 120,000 h						
e. Write report documenting results						

2.9 Task 8. Influence of Prolonged Periods of Low Stress at Elevated Temperatures on the Short-Term Tensile Properties of Type 316 Stainless and Modified 9 Cr-1 Mo Steel

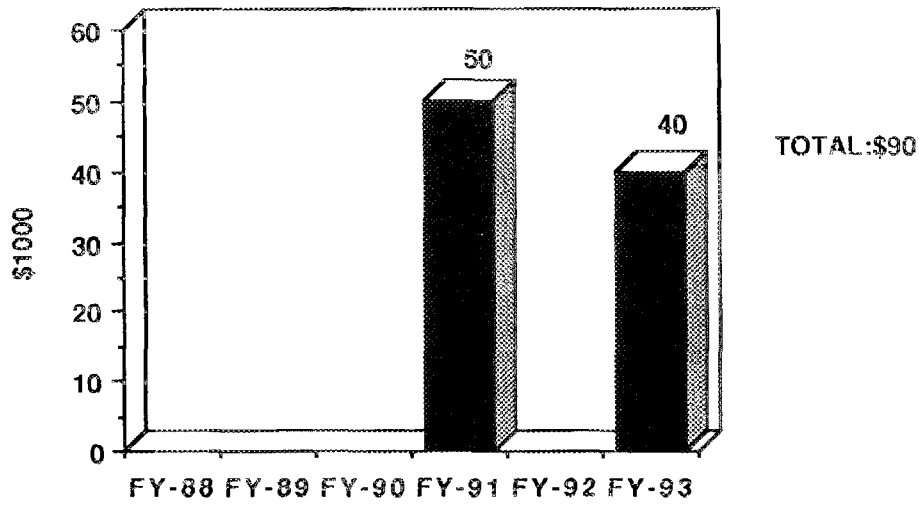
Approach: Material that has been thermally aged for prolonged periods of time at elevated temperatures at low stress levels will be subjected to short-term tensile and impact tests. Material is available from either ongoing creep-rupture tests (2.2, Task 1; or 2.8, Task 7) or from large diameter pipe aging studies (see ORNL/TM-8884). Also available is material (type 316) that has received thermal aging only from exposure to temperatures ranging from 427 to 565°C for 100,000 h (July 1989). All the type 316 stainless steel is from a single heat which will allow comparisons between properties of unaged, aged, and aged under stress material.

Deliverables: (1) A comparison of properties (short-term high strain rate tensile and toughness) will be made to determine the influence of prolonged thermal aging with and without exposure at low stress levels. Results from about 90 specimen tests will be available.

Status: Two segments of large diameter pipe containing welds of type 316 stainless steel are available. These pipes (reference heat and FFTF pipe) were aged for 32,500 and 48,455 h at 565°C with a hoop stress of 55 MPa. Other material from ongoing creep studies and laboratory furnace exposure is also available as indicated above.

Justification: Design analysis of advanced LMR systems requires that a knowledge of the short-term tensile and impact properties be known for structural materials that have seen prototypic plant operating conditions for prolonged periods of time. These properties are needed for analysis of behavior during accident conditions.

Cost and Schedule: Both tensile (30 specimens in FY-91 and 20 specimens in FY-93) and toughness (40 specimens in FY-91) of type 316 stainless steel will be tested. Work on modified 9 Cr—1 Mo steel will be done in FY-93.



TASK: Influence of Thermal Aging and Stress on Short Term Properties of Type 316 Stainless Steel and Modified 9Cr-1Mo Steel

SUBTASK/MILESTONE	FISCAL YEAR					
	1988	1989	1990	1991	1992	1993
1. Type 316 stainless steel characterization				a,b,c		d
a. Complete tensile testing of aged thin wall pipe base and weldment materials						
b. Complete impact testing of aged thin wall pipe base and weldment materials						
c. Write report						
d. Complete short term tensile tests on creep specimens (2.8 Task 7)						
2. Modified 9Cr-1Mo steel						a,b
a. Complete tensile tests from remaining creep tests (2.2 Task 1)						
b. Write report						

2.10 Task 9. Influence of Irradiation on Mechanical Properties of Types 304 and 316 Stainless Steel and Modified 9 Cr-1 Mo Steel - A Status Report

Approach: A report will be prepared covering the influence of irradiation on the mechanical properties of types 304 and 316 stainless steel and modified 9 Cr—1 Mo steel. Results from experimental efforts from both domestic and foreign sources will be included. The effort will cover fracture toughness and ductility at low (0.5-5.0 dpa) exposure levels as well as the effects of irradiation induced helium on strengths and ductilities of appropriate materials.*

Deliverables: (1) A status report will be prepared reviewing work done to date and defining any areas of uncertainty requiring future experimental effort.

Status: Whereas much experimental work has been accomplished to date, a general review of the state of the art is required.

Justification: (1) Establishment of a data base is needed to eliminate inspection/surveillance provisions for irradiated out-of-core structures which receive low doses (requested by NRC for CRBRP). (2) The effects of helium concentrations relevant to in-core structures (e.g., Core Former) must be determined in response to NRC's questions on similar applications for CRBRP. Elevated-temperature (T > 400°C) tensile, creep-rupture, and fracture toughness properties of types 304 and 316 stainless steel, including weldments, must be available. Data will be combined with that from the UKAEA and Energy Center of Netherlands (ECN) PETTEN. (3) Structural components in reactor systems exposed to irradiation damage must maintain a short-term tensile ductility in excess of 10% during their lifetime.

Cost and Schedule: A one-year effort in FY-90 is required to write a report providing a state-of-the-art assessment and defining any outstanding needs.

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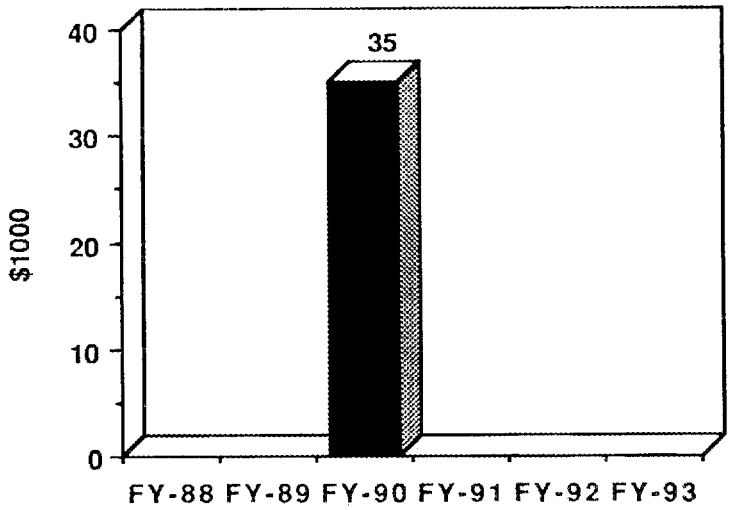
*Note: A typical advanced LMR is expected to have dpa exposure levels for a 60-year life of about 4×10^{-8} on the reactor vessel, 0.01 on the core support, 3.4 on the inlet modules, 0.5 on the shield barrel, and 5.4 on the core barrel, which are all 300 series stainless steels. The 9 Cr—1 Mo UIS has a 0.004 dpa.



TOTAL:$35

TASK. Influence of Irradiation on Mechanical Properties of Structural Materials						
SUBTASK/MILESTONE	FISCAL YEAR					
	1988	1989	1990	1991	1992	1993
1. Complete review report			△			

2.11 Task 10. Emittance Of Passive Cooling System Materials

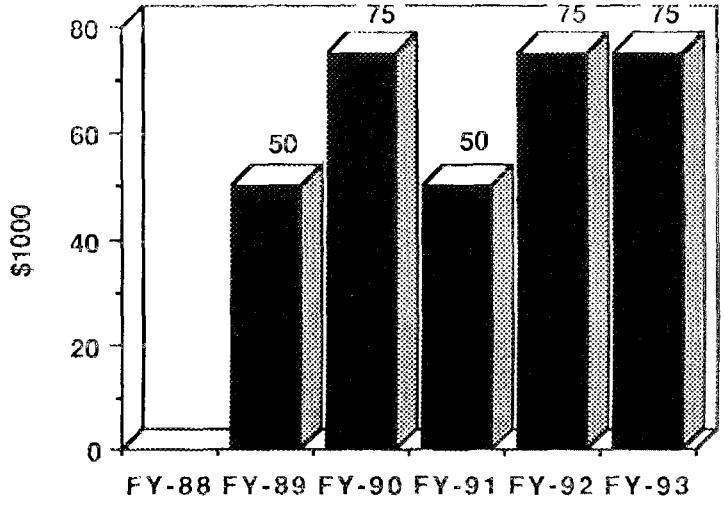
Approach: Confirm by experimental measurements and review of technology that the high emittance surfaces required for satisfactory removal of decay heat by the passive cooling systems of advanced LMRs are maintained over 60-year plant lifetimes and that the currently employed design correlation for emittance values is conservative.

Deliverables: (1) Detailed, in-depth survey of available information relative to emittance values and emittance changes for 2.25 Cr—1 Mo ferritic steel and 316 stainless steel, and (2) measurements of emittance for these materials after long-term exposures under appropriate conditions. Results from 36 tests will be reported.

Status: Design correlations have been developed based on emittance measurements performed on materials given specific pretreatments and on these same pretreated materials thermally cycled to full life but in a relatively short period.

Justification: The information needed is to evaluate different types of surfaces to define improvement of the present surface and to evaluate potential degradation due to thermal cycling and aging. Different surfaces would include grit blasting combined with oxidizing and grooved surfaces. Also there is a need to evaluate the effects of dust, dirt, and salt.

Cost and Schedule: The detailed survey of available information will be completed and reported in FY-89. Long-term exposures (5,000, 12,500, and 30,000 h with and without thermal cycles) and subsequent emittance measurements are to be done over a four-year period (FY 1990-1993) at three temperatures for both passive cooling system materials (36 total tests).



TOTAL:$325

TASK: Emittance of Passive Cooling System Materials

SUBTASK/MILESTONE	FISCAL YEAR					
	1988	1989	1990	1991	1992	1993
1. Complete survey report on emittance of advanced LMR materials						
2. Emittance behavior of 2.25Cr-1Mo and 316 stainless steel						
a. Report on 5,000 h emittance values of 2.25 Cr-1Mo and 316 SS (12/90)			a			
b. Report on 12,500 h emittance values of 2.25Cr-1Mo and 316 SS (2/92)					b	
c. Final report on emittance values including confirmation/modification of design correlations (9/93)						c

2.12 Task 11. Mechanical Properties of Austenitic Stainless Steels After Exposure to Temperatures Above Operating Conditions

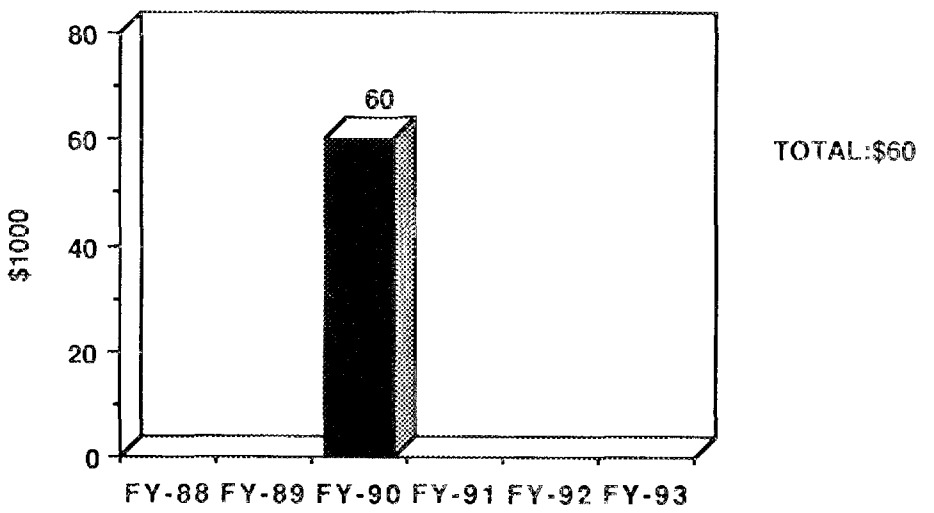
Approach: Base material will be available in FY-89 that has been exposed at 482 and 538°C for 100,000 h. This material will then be subjected to temperatures from 593 to 649°C for 100-200 h. Similarly, material available from a large diameter pipe aging (32,510 h at 565°C and 55 MPa hoop stress) will be subjected to temperatures from 593 to 649°C for 100-200 h. Short-term tensile, creep, impact, and creep-fatigue tests will then be conducted.

Deliverables: The influence of relatively short-term exposure to over-temperature conditions on subsequent mechanical properties will be determined. Results of about 60 specimen tests will be reported.

Status: Material as defined above is, or shortly will be, available for mechanical property characterization.

Justification: Advanced LMR components will be exposed to over-temperature excursions in the range 593 to 649°C for durations of up to one week at a time. A number of these events will occur over the plant lifetime. Data will be used to assess remaining service life of materials following over-temperature events.

Cost and Schedule: This is a one-year effort in FY-90. About 60 specimens of base and weldment material will be tested (tensile, creep, impact, and creep-fatigue).



TASK: Mechanical Properties of Stainless Steels After Extended Time Above Operating Temperatures						
SUBTASK/MILESTONE	FISCAL YEAR					
	1988	1989	1990	1991	1992	1993
1. Conduct mechanical properties tests and report results for materials exposed to over temperature conditions						

3. STRUCTURAL DESIGN/LIFE ASSURANCE TECHNOLOGY

3.1 Objective

The overall objective of these tasks is to provide the structural design and safety assessment methods, data, and criteria required to ensure safe and reliable operation of advanced liquid-metal reactors for a 60-year design life. The tasks described build on and complete the effort in the United States to establish a liquid-metal reactor design methodology. This effort has produced high-temperature design criteria and inelastic analysis methods that are used worldwide. However, the methodology is limited to stainless steels and 2-1/4 Cr—1 Mo steel (annealed), and it has a few remaining problems or shortcomings that will hinder licensing and acceptance. This planned effort will eliminate these deficiencies.

Tasks 1 through 6 have two specific objectives: (1) to add modified 9 Cr—1 Mo steel to the design methodology, and (2) to resolve three remaining problem areas (design rules for weldments, treatment of significant geometric discontinuities, and an inadequate creep-fatigue criteria for guarding against cracking due to repeated thermal transient loadings). Tasks 7 and 8 are new activities aimed at providing the high-temperature flaw assessment procedures needed to (1) establish leak rates for safety and licensing assessments, (2) assess flaws found through inspections, and (3) evaluate the stability of cracks that may be produced in upper internal structures due to thermal striping.

The majority of the planned activities, including the test work, is focused on modified 9 Cr—1 Mo steel. In some cases, activities also address the stainless steels, but this is true only where the work is generic and the stainless steels offer particular advantages.

Completion of the test and development efforts described here will contribute significantly to LMR safety and reliability, licensability, economics, and utility acceptance.

3.2 Task 1. Inelastic Deformation Model for Modified 9 Cr-1 Mo Steel

Approach: A unified model, which does not distinguish between rate-dependent plasticity and time-dependent creep, is required for modified 9 Cr—1 Mo steel. A two-step approach is being followed in which (1) a tentative model has been developed on the basis of uniaxial stress-strain and creep data (generated at temperatures ranging from 500 to 650°C) and (2) the deficiencies of the tentative model are removed and a final model recommended on the basis of a select few uniaxial and multiaxial exploratory tests (performed at 538°C).

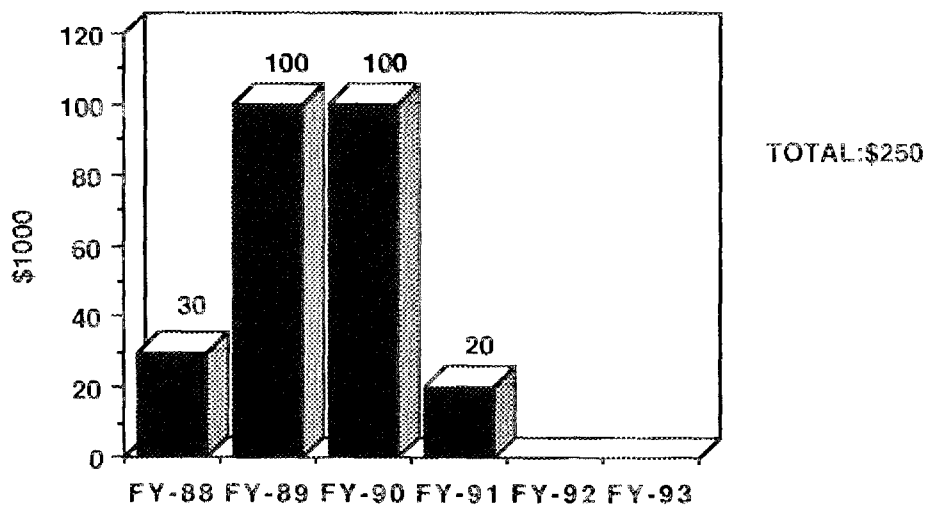
Deliverables: (1) An experimentally validated unified deformation model. (2) A calculated set of isochronous stress-strain curves and stress relaxation curves for simplified design analysis use.

Status: The tentative model has been completed, and comparisons have been made with the results of two-bar ratchetting tests. Deficiencies have been identified and special uniaxial and multiaxial tests planned to resolve them.

Justification: Inelastic analysis methods are required to (1) provide the basis for development and confirmation of simplified ratchetting and creep-fatigue rules, including the associated isochronous and relaxation curves, and (2) provide the basis for detailed inelastic design analyses, should they be required in a critical area.

Cost and Schedule:

- Provide tentative isochronous and relaxation curves FY-89
- Provide final model and isochronous and relaxation curves FY-91



TASK: Inelastic Deformation Model for Modified 9 Cr–1 Mo Steel

SUBTASK/MILESTONE	FISCAL YEAR					
	1988	1989	1990	1991	1992	1993
1. Provide final unified model			a ▽	b △		
a. Complete 6 to 10 special exploratory uniaxial and multiaxial tests to guide final model development						
i. Stress change uniaxial tests						
ii. Cyclic uniaxial tests with fixed stress hold						
iii. Nonproportional loading multi-axial tests						
b. Publish final report providing unified equations and their bases		a ▽		b △		
2. Provide isochronous stress-strain and stress relaxation curves for design use						
a. Curves calculated on basis of tentative model						
b. Final curves based on final unified model						

3.3 Task 2. Creep-Rupture and Creep-Fatigue Failure Criteria

Approach: A two-prong approach is being followed — one aimed at interim and final creep-rupture and creep-fatigue criteria for modified 9 Cr—1 Mo steel and one aimed at a generic improvement in the fundamental creep-fatigue criterion used in design rules for all materials. Special tests, including the mean stress and hold-time creep-fatigue tests being performed under materials technology Task 1, will guide the model development for modified 9 Cr—1 Mo. The tests performed under this task will be done at 538°C. The generic improvement effort will focus initially on use of existing 316 stainless steel data; then the improved model will be adapted to modified 9 Cr—1 Mo steel.

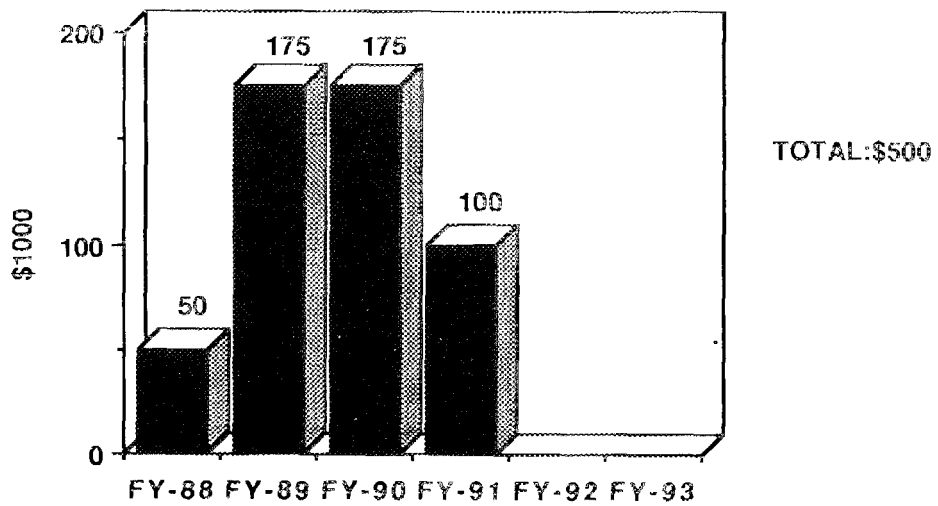
Deliverables: (1) Creep-rupture and creep-fatigue damage accumulation and multiaxial strength theory rules for modified 9 Cr—1 Mo steel, plus (2) an improved generic creep-fatigue damage accumulation rule framework for stainless steels and modified 9 Cr—1 Mo steel.

Status: Some few variable load and temperature creep-rupture tests and multiaxial creep-rupture tests are complete for 9 Cr—1 Mo steel (538-593°C), and potential failure criteria have been identified. Creep-fatigue tests including mean stress effects, are underway in materials technology Task 1. The United States has an excellent 316 stainless steel creep-fatigue data base that can be used to guide development of an improved creep-fatigue model. These data have been collected and are being used for assessing several proposed improved creep-fatigue approaches, including ductility exhaustion.

Justification: Creep-rupture and creep-fatigue criteria are required for design of modified 9 Cr—1 Mo steel LMR components. The current linear-damage creep-fatigue rule used as the basis for LMR design criteria is recognized to be seriously deficient for all materials and must be improved for defensible LMR designs. This is particularly true for 60-year design lives. Linear damage, without modification, cannot be used for modified 9 Cr—1 Mo steel.

Cost and Schedule:

- Interim creep rupture and creep-fatigue damage rules and multiaxial strength criteria for modified 9 Cr—1 Mo steel FY-89
- Improved generic creep-fatigue criterion identified for design use FY-90
- Final creep-rupture and creep-fatigue damage rules and strength criteria provided for modified 9 Cr—1 Mo steel FY-91



TASK: Creep-Rupture and Creep-Fatigue Failure Criteria

SUBTASK/MILESTONE	FISCAL YEAR					
	1988	1989	1990	1991	1992	1993
1. Provide verified multiaxial creep-rupture strength criterion for modified 9 Cr–1 Mo steel			a,b	c d		
a. Complete two multiaxial tests to establish interim criterion						
b. Provide interim criterion						
c. Complete two to four additional multiaxial tests to finalize criterion						
d. Publish report providing final criterion for design use						
2. Provide final verified creep-rupture damage accumulation criterion for modified 9 Cr–1 Mo steel			a b	c d		
a. Identify interim damage accumulation rules						
b. Complete four uniaxial variable load and temperature tests at temperatures of interest						
c. Complete two variable, nonproportional loading multiaxial tests						
3. Provide improved generic creep-fatigue damage accumulation rule on basis of 316 stainless steel data base			a b c			
a. Complete screening assessment of potential rules						
i. Ductility exhaustion						
ii. Damage rate						
iii. Strain-range partitioning						
b. Complete assessment of candidate models relative to available nonisothermal data, plant failure experience, etc.						
c. Publish report identifying improved rule and bases						
4. Provide creep-fatigue rules for modified 9 Cr–1 Mo steel			a,b	c d		
a. Provide interim creep-fatigue damage accumulation rule on basis of incorporating mean stress effects into linear damage						
b. Provide verification of conservatism of Mises effective strain criterion on basis of base metal multiaxial fatigue tests of Task 4						
c. Adapt generic framework to modified 9 Cr–1 Mo steel						
d. Publish report providing creep-fatigue criteria and their bases						

3.4 Task 3. Simplified Ratchetting and Creep-Fatigue Rules for Modified 9 Cr-1 Mo Steel

Approach: The approach is to adapt the recently developed simplified elastic analysis ratchetting procedure (Sartory-O'Donnell-Porowski) and creep-fatigue procedure (Severud) of N-47 to modified 9 Cr—1 Mo steel and to substantiate their applicability through comparisons with 1-D and 2-D inelastic analysis results. These rules are generally applicable, and they have been checked against 1-D, 2-D, and 3-D inelastic analysis results for other materials.*

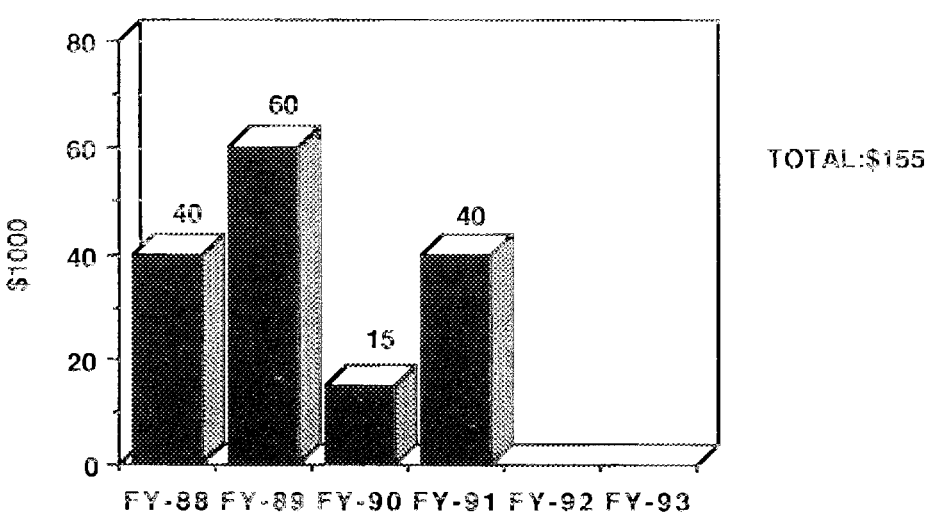
Deliverables: Procedures that are not overly conservative and that have been verified through comparisons with detailed inelastic deformation and failure analyses.

Status: The current inelastic deformation model (see Task 1) and the linear-damage creep-fatigue model have been used with some 1-D problems to demonstrate the adequacy of the current rules for modified 9 Cr—1 Mo steel. However, further 1-D and 2-D analyses are planned to verify the procedures for interim use. The final unified model (Task 1) and creep-fatigue rules (Task 2) will require that these analyses be repeated for verification of the final simplified rules and procedures.

Justification: Nonsafety-grade advanced LMR components of modified 9 Cr—1 Mo steel will be designed for LMR thermal transient loadings using these simplified procedures. The strain-softening behavior exhibited by modified 9 Cr—1 Mo steel makes it particularly important to thoroughly validate the rules against inelastic analysis results.

Cost and Schedule:

- Provide tentative confirmation of ratchetting rules FY-88
- Provide tentative creep-fatigue rules FY-89
- Provide final simplified creep-fatigue rules and confirmation of both creep-fatigue and ratchetting rules FY-91



*A more rigorous validation of simplified methods, needed for all materials, is not a part of the minimal planned program presented here.

TASK: **Simplified Ratchetting and Creep-Fatigue Rules for Modified 9 Cr-1 Mo Steel**

SUBTASK/MILESTONE	FISCAL YEAR					
	1988	1989	1990	1991	1992	1993
1. Complete confirmation of currently identified elastic analysis ratchetting and creep-fatigue rules on basis of comparison with results of two 2-D inelastic analyses						
2. Provide interim simplified creep-fatigue rules for conceptual design on basis of interim creep-fatigue criteria (see 4.a in Task 2)						
3. Provide final confirmed ratchetting and creep-fatigue rules						
a. Develop final elastic analysis creep-fatigue rule consistent with final criteria identified in Task 2				a		
b. Complete inelastic confirmation using final unified deformation model from Task 1					b	
c. Publish report on final rules and their bases						c

3.5 Task 4. Design Rules for Weldments

Approach: With the stainless steel weldments the design approach has been to use life reduction factors for creep rupture and fatigue and to confirm the adequacy of these factors through an understanding of weldment behavior provided by a few key structural weldment tests and inelastic failure analyses. Although modified 9 Cr—1 Mo steel weldments are of somewhat greater concern, it is believed that this same approach will prove adequate. The final proof will be provided by thermal shock failure tests of welded modified 9 Cr—1 Mo steel tubes in Task 6.

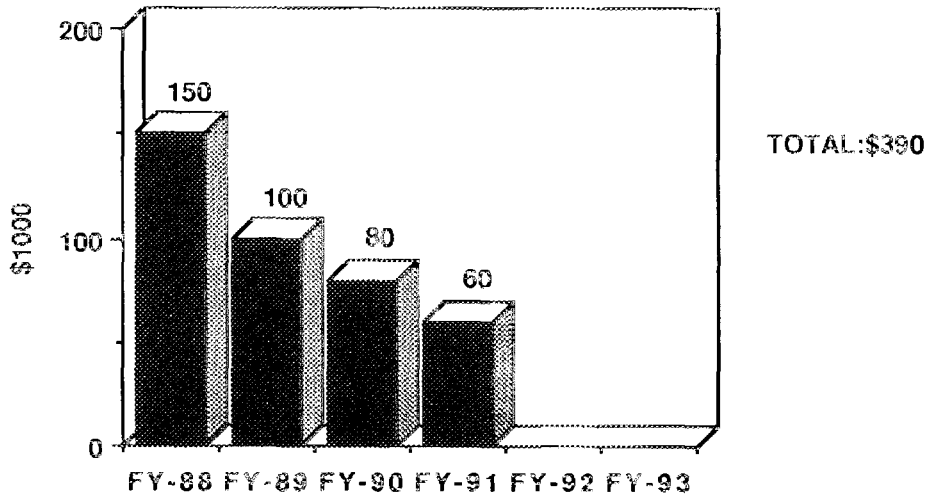
Deliverables: (1) A final report on creep-rupture tests and analyses of 316/16-8-2 plate and pipe weldments confirming reduction factors (a comparison report on fatigue tests of welded tubes has already been published). (2) A set of design factors for modified 9 Cr—1 Mo steel weldments (jointly with mechanical properties task), backed up by creep-rupture and fatigue tests and analyses of welded tubes.

Status: The 316/16-8-2 structural weldment creep-rupture and fatigue tests are complete, and they have confirmed the adequacy of previously established design factors. Analysis of the last two of these tests is underway, and a report is being prepared. Tubular modified 9 Cr—1 Mo steel weldment specimens for four creep-rupture tests and 30 fatigue tests are currently being fabricated. These tests will be conducted at 538°C.

Justification: Components generally fail in welds where a metallurgical notch exists, often along with a geometric discontinuity. This strength or life reduction must be accounted for in design. The lack of procedures for doing this was the number one unresolved structural issue in the CRBRP licensing hearings, and the project had committed to a five-year development program in this area.

Cost and Schedule:

- Publish report completing substantiation of strength reduction factors for 316/16-8-2 weldments FY-88
- Establish interim weldment strength reduction factors for modified 9 Cr—1 Mo FY-89
- Complete tests and analyses of structural weldments substantiating factors for modified 9 Cr—1 Mo steel FY-91



TASK: Design Rules for Weldments

SUBTASK/MILESTONE	FISCAL YEAR 1988	1989	1990	1991	1992	1993
1. Publish report on tests and analyses of 316/16-8-2 structural weldment creep-rupture tests	a ▽	△				
a. Complete final two inelastic failure analyses						
2. Specify weldment fatigue strength reduction factor for modified 9 Cr-1 Mo steel		a ▽	b ▽	c △		
a. Complete assessment of available uniaxial weldment fatigue data						
b. Complete 30 fatigue tests of tubular weldments						
i. Axial and torsional fatigue of base metal specimens						
ii. Axial and torsional fatigue of tubes with axial welds						
iii. Axial and torsional fatigue of tubes with circumferential welds						
c. Publish final report on reduction factor and its bases						
3. Assist in establishing weld metal creep rupture strength reduction factors for modified 9 Cr-1 Mo steel and provide structural confirmation		a ▽		b ▽	c ▽	d △
a. Tentative factors established						
b. Complete minimum set of four confirmatory creep-rupture tests of welded tubes						
i. Two tubes with axial welds						
ii. Two tubes with circumferential welds						
c. Complete analyses and assessment of factors						
d. Publish report providing confirmation of creep-rupture strength reduction factors						

3.6 Task 5. Validation of Life Prediction Methodology at Geometric Discontinuities

Approach: The goal here is to demonstrate that even when heat-to-heat variability of material properties and strain hardening are considered, the high-temperature design methodology, including design margins, is adequate to assure structural integrity of components containing gross geometric discontinuities. This is being done by (1) creep-rupture tests and analyses of two "notched" plates (one monotonically loaded and one cyclically loaded), and (2) a parametric study in which the effect of material variability on life will be determined for a notched structure. Since this is a generic issue, 304 stainless steel, for which the most heat-to-heat variability information exists, is being used for the initial tests and analyses. Once the case is made for stainless steel, the study will be extended to modified 9 Cr—1 Mo steel, where the tests will be performed at 538°C.

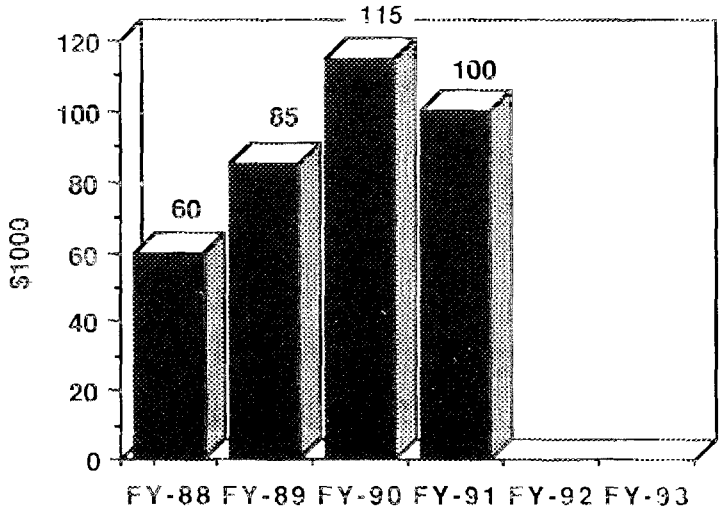
Deliverables: Two reports summarizing tests and analyses showing that geometric discontinuities are adequately handled by the structural design/life assurance methodology. The first report will cover stainless steel, while the second report addresses modified 9 Cr—1 Mo steel.

Status: The first of two stainless steel notched-plate tests has been underway for more than a year, and preparations for the stainless steel analytical parameter study are being made. The heat-to-heat variability correlations exist for 304 stainless steel.

Justification: Like metallurgical discontinuities (Task 4), geometric discontinuities are sources of component failure initiation. The adequacy of the methodology to handle such discontinuities is an LMR reliability and licensing issue, particularly when heat-to-heat variability, strain hardening, and bending loadings are considered. This was the number two unresolved structural issue (after weldments) in the CRBRP licensing hearings, and again a development program was required by NRC.

Cost and Schedule:

- Complete stainless steel study and publish report FY-89
- Complete modified 9 Cr—1 Mo steel study and publish report FY-91



TOTAL:$360

TASK: Validation of Life Prediction Methodology at Geometric Discontinuities

SUBTASK/MILESTONE	FISCAL YEAR					
	1988	1989	1990	1991	1992	1993
1. Complete stainless steel study and publish report	a	b c				
a. Complete monotonic creep-rupture bending test and analysis of notched plate						
b. Complete analytical parameter study of effect of heat-to-heat variability						
c. Complete cyclic creep-rupture bending test and analysis of notched plate						
2. Complete modified 9 Cr-1 Mo steel study and publish report			a	b c		
a. Develop heat-to-heat variability property correlations based on mechanical properties data						
b. Complete analytical parameter study of notched structure						
c. Complete two bending creep-rupture tests of notched plates						

3.7 Task 6. Confirmatory Structural Failure Tests

Approach: For the stainless steels and annealed 2-1/4 Cr—1 Mo steel, deformation and failure tests of a variety of structural models subject to various thermal and mechanical loadings have provided a base of data used to confirm the adequacy of LMR design analysis methods and failure criteria. For modified 9 Cr—1 Mo steel, tests of only one type — cylinders subjected to thermal and mechanical loadings — are planned for confirming the analysis methods and failure criteria. Two of these cylinder tests will be without a mechanical load. The ORNL cylinder thermal transient test rig will then be modified to provide an axial load for the last two tests. These thermal shock tests will be performed at a nominal temperature of 593°C.

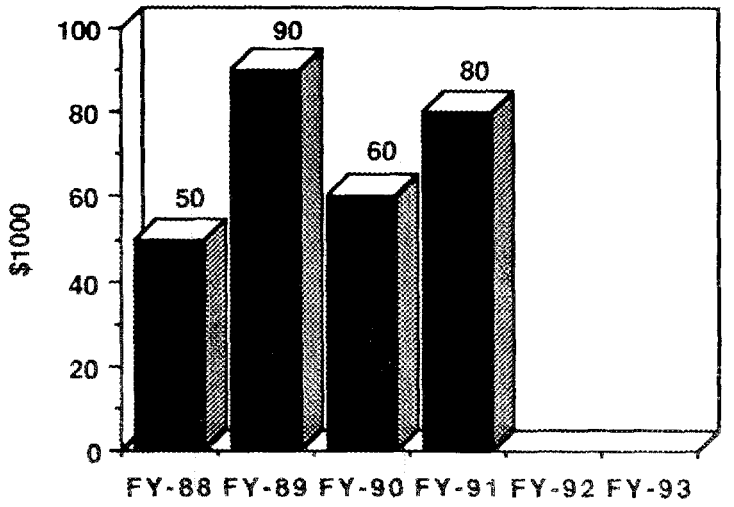
Deliverables: (1) Report on test and analysis of final stainless steel structure (long-term failure test of nozzle-to-sphere). (2) Two cyclic thermal transient tests and analyses of cylinders (one welded, one unwelded). (3) Two cyclic thermal transient tests and analyses of cylinders (one welded, one unwelded) with axial loads.

Status: The stainless steel nozzle-to-sphere test failed late in 1987 after more than two years under load, demonstrating the primary nature of mechanical discontinuity stresses in producing cracking and the nature of a long-term creep failure (the failure was by multiple pin-hole leaking rather than by well-defined cracking). The results of this test, along with analytical studies of the different effects of mechanical secondary stresses and thermal secondary stresses, have led to design rule changes. The nozzle-to-sphere specimen is currently being micrographically examined. The first of the four modified 9 Cr—1 Mo steel thermal transient cylinder tests is complete, and the welded specimen for the second test is being fabricated.

Justification: Structural tests to failure provide the only means of assessing the adequacy of LMR structural design methods and of quantifying design margins against failure. Since there is no applicable service experience for modified 9 Cr—1 Mo steel, the role of these tests is especially crucial.

Cost and Schedule:

- Report of nozzle-to-sphere failure test and analysis FY-89
- Complete thermal transient test and analysis of welded modified 9 Cr—1 Mo steel cylinder FY-89
- Complete two thermal transient tests and analyses of modified 9 Cr—1 Mo steel cylinders with axial loads FY-91



TOTAL:$280

TASK: Confirmatory Structural Tests

SUBTASK/MILESTONE	FISCAL YEAR 1988	1989	1990	1991	1992	1993
1. Publish report on long-term creep-rupture test of stainless steel nozzle-to-sphere specimen	a	b				
a. Complete microstructural assessment of failed structure						
b. Complete inelastic analysis to time of failure						
2. Complete two thermal shock tests of modified 9 Cr-1 Mo steel cylinders	a	b				
a. Complete test and analysis of unwelded cylinder						
b. Complete test and analysis of welded cylinder						
3. Complete two thermal shock tests of modified 9 Cr-1 Mo steel cylinders under "ratchetting" conditions (axial mechanical load)		a	b	c d	e	
a. Complete facility modification for axial load						
b. Complete test and analysis of unwelded cylinder						
c. Complete test and analysis of welded cylinder						
d. Redo analyses using final rules and procedures for modified 9 Cr-1 Mo steel						
e. Publish report providing structural test confirmation of modified 9 Cr-1 Mo steel methodology						

3.8 Task 7. Flaw Assessment Procedures for Predicting Leaks in Pressure Boundary Components

Approach: A four-part methodology for assessing flaws will be developed, with emphasis on modified 9 Cr—1 Mo steel: (1) characterization of initial defects, (2) inelastic analysis of flawed components, (3) characterization of subcritical crack growth, and (4) structural failure criterion. From these four parts a flaw assessment methodology, including the basis for assessing leak rates due to through-wall cracks, will be identified and confirmed through tests. All of the tests for this task will center around a temperature of 538°C.

Deliverables: An experimentally confirmed high-temperature flaw assessment methodology and leak rate assessment basis for modified 9 Cr—1 Mo steel. The methodology will have some applicability to other LMR alloys as well.

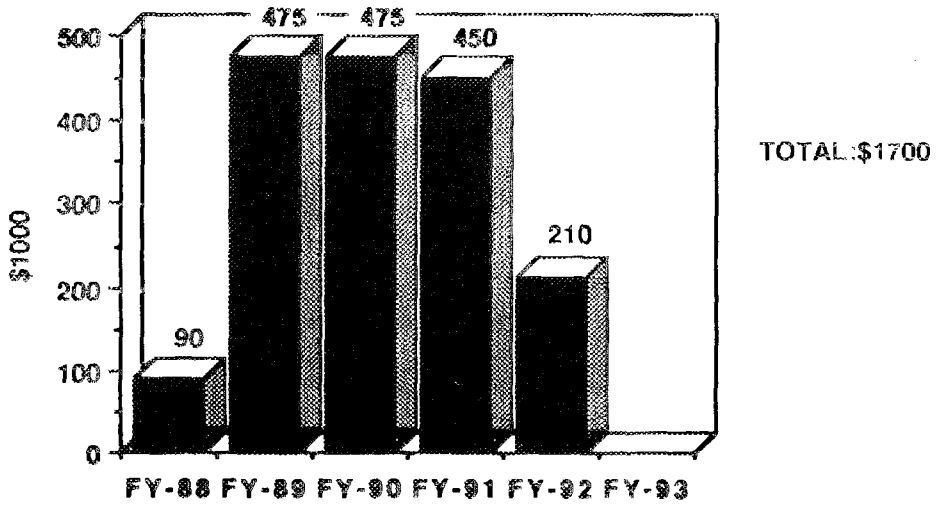
Status: A detailed program plan has been prepared for development of a flaw assessment methodology for LMR components of modified 9 Cr—1 Mo steel.* The plan was prepared with the help of a group of outside experts in the field of inelastic fracture mechanics.

Justification: A high-temperature flaw assessment procedure is a necessary and key part of reliability and safety assessments of liquid-metal reactors. Flaws, whether assumed to be initially present or found by inspections, must be assessed and an acceptance/repair criteria established. In addition, a licensing scenario must be based on a postulated leak. The goal in advanced LMRs is to show that leaks can be detected and corrective action taken before they exceed, at most, a size corresponding to the "moderate fluid system leak." This requires a flaw assessment procedure capable of reliably predicting crack induced failures as well as the size and growth of the resulting opening in the pressure boundary. Such a procedure does not currently exist.

Cost and Schedule:

- Interim methodology and basis for leak-before-break licensing scenario for use in advanced conceptual design FY-90
- Final methodology and basis for leak-before-break licensing scenario for use in preliminary design. FY-92

*Program Plan — Development of a Flaw Assessment Methodology for LMR Components of Modified 9 Cr—1 Mo Steel, Oak Ridge National Laboratory, ORNL/CF-88/19 (January 1988).



TASK: **Flaw Assessment Procedures for Predicting Leaks in Pressure Boundary Components**

SUBTASK/MILESTONE	FISCAL YEAR 1988	1989	1990	1991	1992	1993
1. Provide comprehensive plan for development of flaw assessment procedures	△					
2. Provide guidelines for characterizing the size and shape of initial flaws		a ▽ b ▽		c ▽	△	
a. Complete interim assessment of non-destructive inspection procedures						
b. Provide interim guidelines						
c. Complete final assessment of non-destructive inspection procedures						
3. Provide inelastic analysis guidelines for determining crack tip parameters for flawed components		a ▽	b ▽	c ▽	△	
a. Complete 6 to 10 inelastic analyses of specimens and components and four to eight specimen tests to tentatively establish parameters						
b. Provide interim guidelines						
c. Complete 6 to 10 inelastic analyses of specimens and components and four to eight specimen tests to firmly establish parameters						
4. Provide models to characterize subcritical crack growth		a ▽	b ▽	c ▽	△	
a. Complete 8 to 12 creep and fatigue crack growth tests to guide development of interim models						
b. Provide interim models						
c. Complete 8 to 12 creep and fatigue crack growth tests to guide development of final models						
5. Provide structural failure criterion and basis for leak rate assessment/determination of remaining life			a ▽ b ▽		c ▽	△
a. Complete 8 to 12 fracture toughness and tearing instability tests including effects of creep to establish interim criterion						
b. Provide interim structural failure criterion and basis for leak rate assessment						
c. Complete 8 to 12 fracture toughness and tearing instability tests with creep to establish final criterion						
6. Provide experimental confirmation of time-dependent fracture mechanics methodology				a ▽	b ▽	△
a. Complete 6 to 8 small scale model tests and analyses						
b. **Complete 4 to 6 large scale model tests and analyses**						

3.9 Task 8. Adaptation of Flaw Assessment Procedure to Initial Cracks Produced by Thermal Striping

Approach: Both Westinghouse and Rockwell International have, under DOE funding, conducted thermal striping tests of stainless steels and, to a lesser extent, modified 9 Cr—1 Mo steel. These tests produced "initial" cracking due to striping under typical reactor core outlet temperature variations. Rockwell International is continuing that effort, under Electric Power Research Institute (EPRI) funding, with an emphasis that includes crack growth. A few modified 9 Cr—1 Mo steel tests are a part of this continuing effort.* The approach of this task is to adapt the flaw assessment procedure developed in Task 7 for modified 9 Cr—1 Mo steel to an assessment of cracks induced by thermal striping. In other words, this task picks up with the existence of thermal striping induced cracks and is to answer what happens to these cracks under additional loadings. Specimens from the above mentioned thermal striping tests will be used as a basis for characterizing striping induced cracks (including the influence of "mud cracking") as initial flaws.** The ability to predict the growth/arrest of these cracks will then be examined through tests and analyses. Factors to be considered include the effects of mechanical loads, thermal shock loads, load ordering, and prior creep damage.

Deliverables: A demonstrated analysis procedure for predicting the growth/arrest of cracks induced by thermal striping, including many of the factors unique to upper internal structures.

Status: Thermal striping crack initiation data exist for modified 9 Cr—1 Mo steel. Some crack propagation data for simple beam specimens are being generated by Rockwell International. Finally, as explained in Task 7, a plan has been developed, and will be followed in principle, for establishing a high-temperature flaw assessment procedure for modified 9 Cr—1 Mo steel. This will form the starting point for initiation of this task in FY-91.

Justification: It is uncertain whether or not the upper internal structure of an advanced LMR can be designed to resist crack initiation due to thermal striping over a 60-year life. If it cannot, then the cracks must be shown to be benign. This requires a flaw assessment procedure demonstrated to be applicable to upper internal structures.

Cost and Schedule:

- Demonstrated flaw assessment methodology applicable to cracks induced in upper internal structures by thermal striping FY-92

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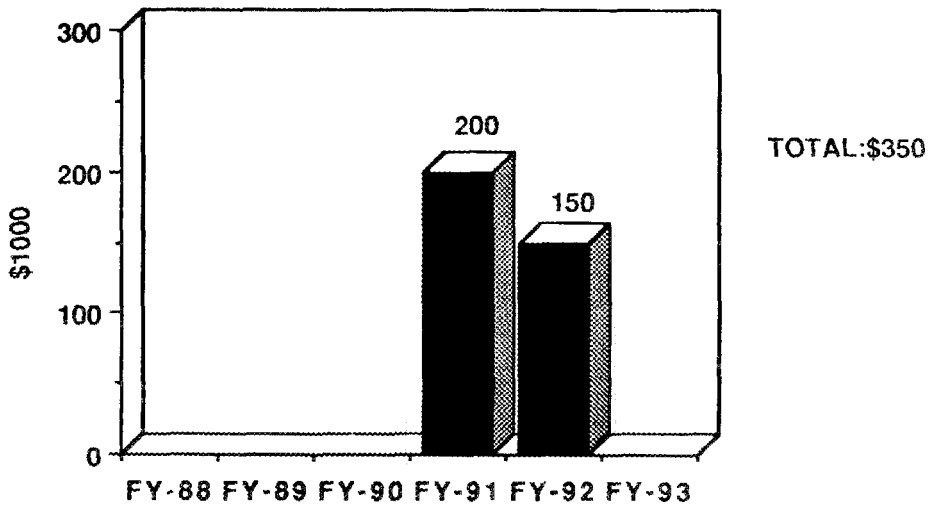
*The EPRI-funded task is a joint effort with the Central Research Institute for Electric Power Industry (CRIEPI) in Japan and is scheduled for completion in early 1990. In addition to striping tests, which are mostly on 304 stainless steel specimens, the joint effort includes thermal hydraulics work by CRIEPI. Note that neither the EPRI/CRIEPI work nor this plan address Alloy 718, which is also a candidate material for upper internal structures.

**This approach depends on the continuation and successful completion of the EPRI-sponsored effort.



TASK: Adaptation of Flaw Assessment Procedure to Initial Cracks Produced by Thermal Striping

SUBTASK/MILESTONE	FISCAL YEAR					
	1988	1989	1990	1991	1992	1993
1. Establish guidelines for characterizing the size and shape of thermal striping cracks (including method for accounting for influence of "mud cracking")				△		
2. Establish fatigue crack growth threshold values using compact tension specimens					△	
3. Complete minimum set of crack growth tests confirming characterization of:					△	
a. Thermal striping cracks						
b. Mean stress effects						
c. Thermal gradients						
d. Prior creep effects						
e. Effects of other superimposed cyclic loadings						
4. Complete analytical studies demonstrating applicability of flaw assessment methodology (from Task 7) to above crack growth tests and to predicted crack growth/arrest in thermal striping situations						△

4. DESIGN STANDARDS FOR COMPONENTS UNRELATED TO NUCLEAR SAFETY

Objective: The objective of this task is to develop, as consensus standards, structural design criteria which are simple to apply, for elevated-temperature (creep/stress-rupture) vessels and piping which are not related to nuclear safety. The design standards will provide a high level of assured structural integrity consistent with large capital investment and high cost of down time, but without nuclear safety implications.

Approach: The vessel criteria will be submitted for consideration as an elevated-temperature extension to Section VIII of the ASME Boiler and Pressure Vessel Code which could be referenced directly from Subsections NC and ND of Section III for Class 2 and Class 3 components as well. The piping criteria will be submitted to the ASME Code for Pressure Piping, B31. Initially the materials to be covered by the standards are stainless steels 304 and 316, and 2-1/4 Cr—1 Mo steel. Modified 9 Cr—1 Mo steel will be added later.

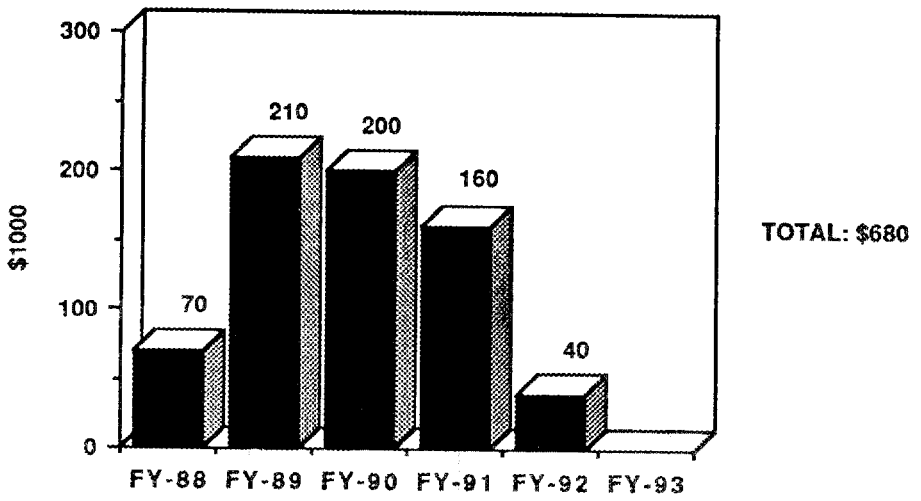
Deliverables: The initial products will be complete drafts of vessel design criteria and their technical bases. The criteria will be in the format, style, and nomenclature of Division 2 of Section VIII. They will be submitted to the ASME Boiler and Pressure Vessel Code for consideration as a supplement to Section VIII. Analogous criteria will be drafted for piping and will be submitted to the ASME Code for Pressure Piping, B31.

Status: This task was initiated in June 1988. The failure modes to be considered, the scope of the design rules, and the target consensus standards have been determined. Consideration has also been given to the inclusion of modified 9 Cr—1 Mo steel.

Justification: Advanced LMR design concepts greatly reduce the number of components that are safety related. Thus, much of the plant can be designed to nonnuclear safety standards, such as Sections I and VIII of the ASME Boiler and Pressure Vessel Code, which would significantly reduce plant design and construction costs. However, there are no nonnuclear criteria for high-temperature components that are adequate to provide the reliability needed for a high-cost system and long design life and minimal inspection. The high-temperature limits of Sections I and VIII do not address all of the failure modes that are significant for nuclear applications. Therefore, new criteria are needed that will provide high reliability without involving the regulatory overview required for nuclear safety.

Cost and Schedule:

- Issue draft standard for elevated-temperature vessel design FY-89
- Issue draft standard for elevated-temperature piping FY-90
- Add modified 9 Cr—1 Mo steel to vessel and piping standards FY-91
- Support ASME Code consideration of vessel and piping standards . . . . . FY-89 through -92



TASK: Design Standards for Nuclear Nonsafety High-Temperature Components

SUBTASK/MILESTONE	FISCAL YEAR 1988	1989	1990	1991	1992	1993
1. Issue draft standard for elevated-temperature vessel design						
2. Issue draft revision of Subsections NC and ND of Section III						
3. Issue draft standard for elevated-temperature piping						
4. Evaluate Japanese, British, and French criteria for possible adoption of best features						
5. Add modified 9 Cr-1 Mo steel to vessel and piping standards						
6. Provide interactive computer program for implementation of piping rules						
7. Support ASME Code consideration of vessel and piping standards						

5. PIPE THERMAL RATCHETTING TESTS TO FAILURE

Objective: The objective of this task is to provide key structural failure test results for modified 9 Cr—1 Mo steel that can be used to validate analysis methods and design criteria and to establish appropriate design margins. This will complement the Structural Design Technology effort at ORNL, and fulfill the need for realistic structural test data to support the evaluation and acceptance of modified 9 Cr—1 Mo steel as a usable structural alloy in advanced LMR plants.

Approach: At ETEC, two 9 Cr—1 Mo test articles will be subjected to repeated thermal downshocks and constant axial load until failure occurs. One test article, designated TT-10, will be a contoured unwelded pipe. The second, designated TT-11, will be a contoured pipe with three circumferential butt welds.

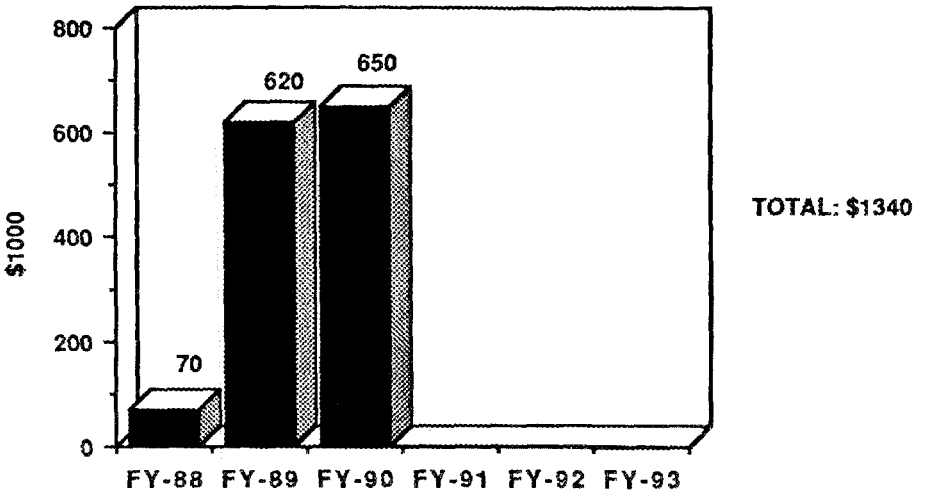
Deliverables: Test results will be provided on thermal ratchetting and on structural failure due to creep-fatigue damage accumulation, of modified 9 Cr—1 Mo steel pipe, with and without circumferential welds. These results will serve as a basis for assessing the applicability of current structural design methods and criteria to modified 9 Cr—1 Mo steel and will be used to compensate for lack of service experience with this material.

Status: The welded and unwelded blanks of 9 Cr—1 Mo for fabrication of the test articles are at ETEC. Modifications to and checks of the existing test fixture center bodies have been completed. Design and documentation for fabrication of the test articles is complete. Preparation of the load ring adapters, used for applying the axial load, is approximately 25% complete. The hydraulic load maintainer and nitrogen blowdown systems with instrumentation and controls are available.

Justification: Structural test data are particularly needed for modified 9 Cr—1 Mo steel, because it is a relatively new material for which comparatively little structural experience exists, especially for complex thermal ratchetting loadings. The results of the present tests will be used to validate the ASME Code procedures for evaluating creep-fatigue damage. The ratchetting data obtained before specimen failure will also be used to validate the inelastic analysis procedures for this material. The direct comparison of welded and unwelded pipes under the same loading conditions will provide a direct indication of weldment strength under thermal transient loading conditions — a key NRC concern in the LMR licensing process.

Cost and Schedule:

- Fabricate and install test articles FY-89
- Complete checkouts with "dummy" test articles FY-89
- Complete thermal creep ratchetting tests FY-90



TASK: ETEC Thermal Ratchetting Tests

SUBTASK/MILESTONE	FISCAL YEAR 1988	1989	1990	1991	1992	1993
1. Test TT-10, unwelded modified 9 Cr–1 Mo steel pipe	a, b	c d e	f g h			
a. Preparation of center body						
b. Delivery of stock						
c. Fabricate T.A. and assemble test rig						
d. Complete c/o with "dummy" T.A.						
e. Install T.A. and initiate tests						
f. Complete testing – predicted rupture						
g. Disassemble test rig – send T.A. to ORNL						
h. Complete test report						
2. Test TT-11, modified 9 Cr–1 Mo steel pipe with circumferential butt welds	a b	c d e	f g h			
a. Preparation of center body						
b. Delivery of stock						
c. Fabricate T.A. and assemble test rig						
d. Complete c/o with "dummy" T.A.						
e. Install T.A. and initiate tests						
f. Complete testing – predicted rupture						
g. Disassemble test rig – send T.A. to ORNL						
h. Complete test report						

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