LMFBR Thermal-Striping Evaluation

EPRI

Keywords:

LMFBR
Thermal Striping
Materials
Thermal Hydraulics

EPRI NP-2672
Project 1704-11
Interim Report
October 1982

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Prepared by
Rockwell International
Canoga Park, California

DO NOT MICROFILM
COVER

ELECTRIC POWER RESEARCH INSTITUTE

DISCLAIMER

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

DISCLAIMER

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

LMFBR Thermal-Striping Evaluation

EPRI NP-2672
Research Project 1704-11

Interim Report, October 1982

Prepared by

250 9479 / ROCKWELL INTERNATIONAL
✓ Energy Systems Group
8900 De Soto Avenue
Canoga Park, California 91304

Principal Investigator
J. E. Brunings

Prepared for

Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, California 94304

EPRI Project Manager
J. Matte III

Developing Applications and Technology Program
Nuclear Power Division

JHM
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

ORDERING INFORMATION

Requests for copies of this report should be directed to Research Reports Center (RRC), Box 50490, Palo Alto, CA 94303, (415) 965-4081. There is no charge for reports requested by EPRI member utilities and affiliates, contributing nonmembers, U.S. utility associations, U.S. government agencies (federal, state, and local), media, and foreign organizations with which EPRI has an information exchange agreement. On request, RRC will send a catalog of EPRI reports.

~~Copyright © 1987 Electric Power Research Institute, Inc. All rights reserved.~~

NOTICE

This report was prepared by the organization(s) named below as an account of work sponsored by the Electric Power Research Institute, Inc. (EPRI). Neither EPRI, members of EPRI, the organization(s) named below, nor any person acting on behalf of any of them: (a) makes any warranty, express or implied, with respect to the use of any information, apparatus, method, or process disclosed in this report or that such use may not infringe privately owned rights; or (b) assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information, apparatus, method, or process disclosed in this report.

Prepared by
Rockwell International
Canoga Park, California

EPRI PERSPECTIVE

PROJECT DESCRIPTION

Beginning in the mid-1970s, serious concern arose in several countries engaged in sodium-cooled breeder reactor design over the possibility of severe adverse effects on conventional construction materials caused by "thermal striping" (defined as rapid and continuing temperature fluctuations in the sodium that washes over metal surfaces). The surfaces of the upper internal structure immediately above the mixed-temperature flow exiting from the fuel, blanket, and control elements of the reactor core appeared to be the most obvious case of interest. Based on conservative assumptions regarding the phenomenon, design solutions utilizing high-strength but difficult-to-fabricate alloys were being adopted to cope with the concern.

On the other hand, the possibility that the severity of the thermal-striping problem was being overestimated was suggested by the remarkably few instances of observed failures or damage that had been attributed to the phenomenon, even in the upper internal structures of operating fast reactors. This suggested the desirability of a test program that would explore the threshold of striping damage; tests to create such damage would be conducted in a realistic thermal-striping environment with sodium.

PROJECT OBJECTIVES

The objectives of this project (RP1704-11) were:

- To define an empirically based program that would characterize the conditions under which thermal striping would cause structural damage to various metals and configurations
- To provide in an existing sodium test loop an apparatus that furnishes a realistic simulation of a thermal-striping environment over a wide range of parameter variations
- To begin the testing defined in the program plan to the extent initially funded

Since this test program was interrupted during the current reorganization of this large liquid metal fast breeder reactor (LMFBR) design project, this is an interim report covering the program planning and initial test operations.

PROJECT RESULTS

Definition of a rational program of research leading to realistic, empirically based guidelines for the design of LMFBR components has been completed and published in this report. The program addresses the existing uncertainties in four areas: (1) dynamics of the temperature field in the bulk fluid, (2) dynamics of the temperature field in the metal structures, (3) structural response of the metal, and (4) failure mode characterization. The first phase of the program tests the assumption that the severity of the striping problem was overstated, while the follow-on phase will explore alternative materials, configurations, etc., should the problem be found to warrant such approaches.

The test apparatus was commissioned, and calibration tests were performed and analyzed. Some of the calibration data appear to support the assumption that the striping problem may have been overemphasized:

1. Comparison of oscilloscope trace photos of two adjacent thermocouples, one protruding 0.04 inch from the specimen into the temperature mixing stream and the other covered by 0.01 inch of the metal, indicated a dramatic reduction in amplitude of temperature fluctuation at the metal surface.
2. With hot and cold sodium nozzles separated 0.25 inch apart and with equal flow rates of hot and cold sodium, the full difference in sodium temperatures was measured between points 0.25 inch above the nozzles. But when the cold flow rate was reduced to half the hot flow rate, only two-thirds of the incoming temperature difference existed at any points 0.25 inch above the nozzles.

From the limited data obtained thus far, the investigators concluded that large differences may be attainable between the temperature fluctuation amplitudes of incoming sodium streams and nearby metal surfaces. Implementation of the program proposed in this report should prove to be a key element in the ongoing development of the LMFBR.

Joseph Matte III, Project Manager
Nuclear Power Division

ABSTRACT

LMFBR Thermal Striping Evaluation

Thermal striping is defined as the fluctuating temperature field that is imposed on a structure when fluid streams at different temperatures mix in the vicinity of the structure surface. Because of the uncertainty in structural damage in LMFBR structures subject to thermal striping, EPRI has funded an effort for the Rockwell International Energy Systems Group to evaluate this problem. This interim report presents the following information:

- 1) A Thermal Striping Program Plan which identifies areas of analytic and experimental needs and presents a program of specific tasks to define damage experienced by ordinary materials of construction and to evaluate conservatism in the existing approach.
- 2) A description of the Thermal Striping Test Facility and its operation.
- 3) Results from the preliminary phase of testing to characterize the fluid environment to be applied in subsequent thermal striping damage experiments.

CONTENTS

<u>Section</u>	<u>Page</u>
1.0 Introduction.....	1-1
2.0 Thermal Striping Program Plan.....	2-1
2.1 Objectives.....	2-1
2.2 Program Plan.....	2-1
3.0 Thermal Striping Test Facility Description.....	3-1
3.1 Basic Sodium Loop.....	3-1
3.2 Thermal Striping Test Vessel.....	3-3
3.3 Striping Test Mechanism.....	3-8
4.0 Test Operations.....	4-1
4.1 Test Specimens.....	4-1
4.2 Installation of Calibration Test Specimen.....	4-1
4.3 System Checkout, Sodium Fill, Flow/Temperature Adjustments.....	4-5
4.4 Instrumentation.....	4-5
4.5 Testing and Data Acquisition.....	4-6
Reference.....	4-21
5.0 Test Data Analysis.....	5-1
5.1 Static Traverse Tests.....	5-1
5.2 Pendulum Oscillation Tests.....	5-7
5.3 Mixing Zone Temperature Fluctuations.....	5-11
5.4 Metal Temperature Response.....	5-12
5.5 Conclusions.....	5-14
References.....	5-18
Appendix — Thermal Striping Program Plan.....	A-1

FIGURES

<u>Figure</u>	<u>Page</u>
2-1 Thermal Striping Program Schedule.....	2-3
3-1 High-Temperature Sodium Supply System.....	3-2
3-2 Sodium Test Vessel — Striping Test.....	3-4
3-3 Test Pot and Test Fixture Layout.....	3-5
3-4 Sodium Vessel Inner Tank Assembly.....	3-6
3-5 Sodium Supply Nozzles.....	3-7
3-6 Air Blast Heat Exchanger.....	3-9
3-7 High-Temperature Sodium Loop.....	3-11
3-8 Striping Test Installation in High-Temperature Loop.....	3-13
4-1 Test Specimen.....	4-1
4-2 Thermocouple Locations on the Calibration Test Specimen.....	4-2
4-3 Specimen Thermocouple Assignments.....	4-3
4-4 Instrumented Calibration Bar.....	4-4
4-5 Test Record Offsets — Test 84 at 1 Hz.....	4-17
4-6 Thermocouple Trace Signatures — Test 59 at 0.2 Hz.....	4-19
4-7 Thermocouple 11 Traces at Various Frequencies	4-20
4-8 Oscilloscope Photographs of Thermocouple Trace in Fluid Adjacent to Specimen.....	4-22
5-1 Static Temperature Traverse at Balanced Full Flow.....	5-2
5-2 Fluid ΔT_f Measured at Static Positions with Natural Oscillation at Stream Mixing Boundary.....	5-3
5-3 Static Temperature Traverse at 50% Cold Flow.....	5-5
5-4 Pen Recorder Traces.....	5-8
5-5 Thermocouple 13 Magnetic Tape Temperature Traces.....	5-9
5-6 Temperature Wave Shape Variation with Position — Test 58.....	5-10
5-7 Oscilloscope Photographs of Thermal Striping Behavior.....	5-13
5-8 Fractional Temperature Response.....	5-15
5-9 Comparison of Metal Thermocouple and Fluid Thermocouple Response Behavior When Positioned in the Interface Mixing Zone.....	5-16

TABLES

<u>Table</u>	<u>Page</u>
4-1 Thermal Environment Calibration Test Matrix.....	4-7
4-2 Data Channel Assignments.....	4-16

SUMMARY

S.1 THERMAL STRIPING PROGRAM PLAN

Because of the uncertainty regarding the severity of thermal striping damage, a Thermal Striping Program Plan was prepared to describe the activities that should be accomplished to establish a design technology to guard against the consequences of severe thermal striping damage in LMFBR structures. The Thermal Striping Program Plan identifies areas where additional analytic and experimental activities are needed and presents a program of specific tasks to define the damage experienced by ordinary materials of construction under thermal striping environments and to evaluate the degree of conservatism that exists in the current methodology for predicting thermal striping damage.

The program plan is divided into an initial scoping phase and a follow-on testing phase. The initial scoping phase provides a test of the basic assumption underlying the program, namely that the current methodology for predicting thermal striping damage is unduly conservative. Assuming the basic assumption of the plan is confirmed, the initial scoping phase effect may prove to be sufficient to define satisfactory design guidelines for accommodating thermal striping with ordinary materials of construction. The duration of the initial scoping phase is 18 months.

If the results of the initial scoping phase do not confirm the adequacy of using stainless steel in practical configurations, further testing would be indicated. Therefore, a follow-on testing phase has been defined that would extend the knowledge of thermal striping and investigate design features that could mitigate thermal striping loads.

The results of the testing program will provide a more accurate prediction of the thermal striping loads and thermal striping damage that can occur in LMFBR structures. A more accurate prediction of these loads and the resulting damage will improve the ability of the designer to: (1) select appropriate materials of construction, (2) eliminate conservatism, and (3) characterize and quantify the margin against thermal striping damage. This improved ability will enhance the operational reliability of LMFBR components and should lead to more economical component designs.

A summary of the Thermal Striping Program Plan is presented in Section 2.0. The complete plan is presented in the Appendix.

S.2 THERMAL STRIPING TEST FACILITY AND OPERATIONS

The Thermal Striping Test Facility consists of a sodium test vessel that is installed in one of the five test stations in the high-temperature (1200⁰F) sodium loop located at the ESG Nuclear Development Field Laboratory. As shown in a simplified sketch (Figure S-1), flow is taken from the test vessel's outer reservoir (weir overflow) at some nominal mean temperature and then split into the "hot" and "cold" legs with the flow in each leg proportioned as required by a selection of valve settings and sodium pump output. Flow introduced into the hot leg is heated to the required maximum temperature by in-line immersion heaters, and flow into the cold leg is reduced in temperature by an air blast heat exchanger. The striping environment is created by the interaction of the flows impacting the test specimen which is positioned directly above the nozzles so that at rest its longitudinal centerline is parallel with a centerline passing through the centers of the two inlet nozzles. Actuation of the test specimen (at amplitudes of ± 2 in. and frequencies up to 2 Hz) is provided by a variable-speed drive that imparts a pendulum-type motion to the test article.

Figure S-1. Test Facility Schematic

From a group of test specimens (nominally 0.5 x 0.5 x 12.0 in.) that were machined from Type 316L stainless steel, a single Type 316L specimen was randomly selected for use as a calibration test article. The specimen was instrumented with 40-mil thermocouples positioned at several depths through the thickness and along the length of its lower face and then mounted on the lower end of the pendulum rod in the sodium test pot. The specimen-to-nozzle gap was set at 0.25 in.

The sodium test vessel was sealed and the test vessel and loop were filled with sodium and put on a closed loop operation. Appropriate instruments were utilized to record pertinent test parameters (temperatures, flow, cyclic frequencies, and displacements).

Testing followed a prescribed matrix and consisted of conducting a series of calibration tests to define the thermal environment existing on a test specimen under various conditions or combinations of flow, temperature, and specimen position and/or motion. As the test progressed, a region of "striping turbulence" was observed in a narrow zone in the mixing region between the hot and cold inlet nozzles. Detailed temperature surveys were conducted with approximately 0.05-in. incremental movements of the test specimen over a full pendulum excursion of approximately ± 2.5 in. from center (vertical) position. These tests accurately defined the regions where thermal striping environment existed as well as the width of the "thermal wash" on the specimen.

During the testing activities, it became evident that the response time of the thermocouples and multipoint pen recorder was too slow to capture the complete temperature amplitude of the thermal events. Consequently, an FM magnetic tape recorder was incorporated into the instrumentation setup to enhance the recording of the thermocouples.

After the thermal calibration survey was completed, further testing was put on hold pending EPRI approval of a contract extension to continue the testing program.

S.3 TEST RESULTS

The primary objective of the preliminary phase of testing was to characterize the fluid temperature environment that is to be applied in subsequent thermal striping damage experiments. A natural fluctuation due to stream mixing

dynamics was observed in conjunction with the temperature variation imposed by the pendulum oscillation as was expected. The relative amplitudes of the stream mixing and of the pendulum oscillation temperature components as well as the stability of the fluid temperature distribution were observed. Preliminary results suggest that the temperature distribution is quite stable (at the 1/4-in. separation distance) and that the hot-to-cold-stream interaction is localized. The temperature change in the mixing region is more rapid for the balanced full-flow case (i.e., maximum flow rate in both hot and cold inlet nozzles) than for the unbalanced flow case (cold flow reduced to 50%). Thus, a small amount of lateral shifting or turbulence in the hot-to-cold-stream mixing or interface region could account for the greater amplitude of apparent temperature fluctuation that was observed in the mixing region for the balanced full-flow case. Superficial examination of the mixing zone fluctuation shows characteristics similar to those reported for water experiments on thermal striping.

The temperature distribution stability is reflected in the repeatability of temperature cycles obtained in the pendulum oscillation testing mode. This repeatability will permit exclusion of cycle ordering complications from evaluations of the equivalence of cyclic strains induced by temperature loading with those induced by mechanical loading. If equivalence of induced cyclic strains can be demonstrated, a great potential exists for reducing the scope of thermal striping damage correlations and for decoupling thermal-hydraulics considerations from metal failure considerations.

An unexpected development from the preliminary testings was the observed reductions in the temperature range of the fluid film (as measured by specimen-mounted thermocouples which extend 0.04 in. into the fluid) for the unbalanced flow case (50% cold inlet flow). The maximum film temperature reached the hot inlet temperature (T_H) as would be expected if the hot inlet stream penetrated to the specimen surface. If little or no mixing occurred and the cold inlet stream penetrated to the specimen surface, then the minimum film temperature would drop to the cold inlet temperature (T_C) and the film temperature range would approach a value equal to the full inlet temperature differential ($T_H - T_C$). This is what occurred in the balanced flow tests. When a 400°F ΔT was set as the temperature differential at the inlet nozzles, a 400°F ΔT was imposed on the test specimen above the nozzles. However, the test data for the unbalanced flow case (50% of cold inlet flow) indicate a film temperature range of about 2/3 the ($T_H - T_C$) value that would be expected. This reduction is especially notable when the

small separation distance of 0.25 in. between the nozzles and the specimen is considered. The reduction apparently reflects either enhanced mixing or flow blanketing effects due to the preponderance of flow from the hot inlet nozzle.

In addition to the one-third reduction in the maximum fluid temperature range that occurred under the unbalanced flow conditions, the fluid temperature fluctuations at the hot-to-cold stream interface were also reduced. Under static test conditions with balanced flow at a 400°F ΔT , the fluctuating fluid ΔT at the interface was estimated at 130 to 210°F . When the cold flow was reduced to 50%, the fluctuating fluid ΔT reduced to about 70°F , or less than one-fifth of the original sodium fluid temperature gradient.

Only limited data were obtained from thermocouples at the metal surface after the magnetic tape recorder was installed. However, the maximum range of the metal temperature response was found to be approximately 34% of the temperature range in the adjacent fluid film when the response occurred with a 1.0-Hz frequency range.

The results of the Thermal Striping Facility thermal calibration testing program has provided new insight into the thermal-hydraulics of the sodium thermal striping problem. Preliminary characterization of structural material response under some thermal striping environments indicates that large temperature gradient attenuations may be achievable under certain design conditions allowing the use of ordinary materials of construction in potentially severe thermal striping environments.

1.0 INTRODUCTION

Thermal striping is defined as the fluctuating temperature field that is imposed on a structure when fluid streams at different temperatures mix in the vicinity of the structure surface. Thermal striping damage is the damage experienced by the structure subjected to thermal striping. Thermal striping damage is a problem in LMFBR design because of the potentially large temperature oscillations that can occur in the sodium coolant at locations where they can be imposed on components and structures.

Within the past several years, serious concern has arisen in the United States and the United Kingdom over the possible consequences of thermal striping on reactor internal structures. The current methodology employed for evaluating the effects of thermal striping leads to the prediction of significant structural damage to ordinary materials of construction in local regions where structures are subjected to large thermal striping loadings. This has led to the use of expensive, high-strength alloys that are difficult to fabricate and unsuitable for welding to avoid the potential problem.

The current methodology for predicting thermal striping damage, however, is based on the use of geometry-specific test correlations in unrepresentative environments and conservative simplifying analysis assumptions. If the methodology was applied to existing liquid metal systems, it would have predicted that a significant number of failures should have already occurred in these systems. There has been, however, very few actual failures observed in liquid metal systems that are attributable to thermal striping. Therefore, considerable uncertainty exists regarding the severity of thermal striping as a threat to sodium system structures. Because of this uncertainty, EPRI has funded this effort for the Rockwell International Energy Systems Group (ESG) to:

- 1) Define a program of testing and test data evaluation to characterize the conditions under which thermal striping causes structural damage to materials
- 2) Modify an existing sodium test loop to provide a testing capability to test material specimens in sodium under conditions that provide a realistic simulation of thermal striping environments
- 3) Initiate testing operations to demonstrate the capability of the thermal striping test facility and obtain thermal hydraulic environmental data on the test specimens prior to the initiation of thermal striping damage testing.

The work described herein summarizes the initial work that has been performed by ESG as part of a continuing program to evaluate thermal striping in LMFBRs.

2.0 THERMAL STRIPING PROGRAM PLAN

It has been recognized that considerable uncertainty exists regarding the severity of thermal striping damage in LMFBRs. Therefore, the basis of the Thermal Striping Program Plan is the need to establish a more accurate method for predicting thermal striping environments and assessing the structural damage that results from these environments.

2.1 OBJECTIVES

The goal of the Thermal Striping Program Plan is to develop an empirically based design methodology for fast breeder reactor components that operate in a thermal striping environment. This goal would be obtained through accomplishment of the following objectives:

- 1) Develop an empirical data base that provides correlation between observed damage and imposed striping environment, by experimental demonstration and characterization of thermal striping damage resulting from realistic simulations of reactor thermal striping environments
- 2) Develop an empirical data base that provides correlation between the fluid temperature field dynamics and field input (causative) parameters and dimensions
- 3) Develop an improved thermal striping design methodology that is consistent with the empirical data base, provides appropriate known margins of conservatism, and is related to physical principles and available analytical methods to the extent found beneficial.

2.2 PROGRAM PLAN

The Thermal Striping Program Plan is divided into an initial scoping phase and a follow-on testing phase. The initial scoping phase provides a test of the basic assumption underlying the program, namely that the current methodology for predicting thermal striping damage is unduly conservative. Assuming that the basic assumption of the plan is confirmed, the initial scoping phase effort may prove to be sufficient to define satisfactory design guidelines for accommodating thermal striping with ordinary materials of construction.

The initial scoping phase is oriented to define conditions under which thermal striping damage occurs, to characterize damage progression under continued thermal striping loading, and to determine the significance of thermal striping and thermal striping damage on the design of components in sodium. The initial materials testing will test conventional LMFBFR construction materials (i.e., Type 316L stainless steel) in severe thermal striping environments to create accelerated thermal striping damage. It is possible that although this testing may cause thermal striping surface cracks (crazing), it may also show that crack propagation, under some thermal striping conditions, is self-limiting. If this occurs, it may be possible to use ordinary materials of construction in thermal striping environments, especially in low-stressed applications, and still retain adequate structural capability to perform the intended function during the design life of the plant even though experiencing superficial surface damage.

The activities under the initial scoping phase include:

- 1) Experimental evaluation of the thermal striping fluid temperature field dynamics with sodium and water tests
- 2) Experimental evaluation of metal temperature and metal response dynamics of boundary materials in sodium thermal striping environments
- 3) Experimental determination of thermal striping damage and failure characterization of ordinary construction materials in sodium thermal striping environments
- 4) Development of thermal striping damage criteria and design guidelines.

If the results of the initial scoping phase do not confirm the adequacy of using stainless steel in practical configurations, further testing would be indicated. Therefore, a follow-on testing phase has been defined that would extend the knowledge of thermal striping and investigate design features that could mitigate thermal striping loads.

The effort under the follow-on testing phase of the program depends on the outcome of the initial scoping phase. Although it may be that the initial scoping phase will show that, with appropriate design features, thermal striping damage need not be a concern in the design of LMFBFRs, follow-on tests are described that would provide additional data to ameliorate thermal striping concerns if they really do exist. The follow-on tests could include:

- 1) Testing material specimens with special surface features or configurations
- 2) Testing alternative materials
- 3) Conducting extended thermal-hydraulic tests to better understand sodium mixing, heat transfer, and boundary layer film characteristics.

A summary of tasks in the program plan and a proposed schedule (prepared in October 1981) of testing are presented in Figure 2-1. Six tasks are identified under the initial scoping phase with four additional tasks described under the follow-on phase. Concurrent with the testing and data correlation work, a task is defined in each phase for the purpose of establishing thermal striping design criteria. The program is scheduled over a 3-1/2-year period, with the initial scoping phase lasting 18 months. The initial experimental work, under Task 4, has already been initiated, and the results of this testing are presented in Section 5.0. The complete Thermal Striping Program Plan is presented in the Appendix.

Figure 2-1. Thermal Striping Program Schedule

3.0 THERMAL STRIPING TEST FACILITY DESCRIPTION

3.1 BASIC SODIUM LOOP

The Energy Systems Group's (ESG) High-Temperature Sodium Supply System, which is located at the ESG Nuclear Development Field Laboratory at Santa Susana, California, was designed to provide a facility for testing components and materials intended for in-sodium service. The basic functions of the system are to supply high-temperature (up to 1200°F), high-purity sodium at rates up to 25 gpm to each of five interconnected test systems. Figure 3-1 is a photograph of the system. The specific functions of the supply system are as follows:

- 1) Deliver sodium to the appropriate test vessel(s) at the required flow and pressure conditions at temperatures up to 1200°F.
- 2) Provide sufficient storage volume to hold all sodium in the system including that contained in the test vessels.
- 3) Provide the means to remove oxides from the sodium and the means for determining the sodium oxide concentration.
- 4) Provide the means for transferring the sodium from the drain tank to the test vessel.

The supply system consists of a fill and drain tank, two filters, two pumps, a cold trap, a plugging meter, two sodium sampling stations, piping and valves, and an argon supply system. Provisions are made in the sodium, argon, and vent piping to enable connecting five tests stands in parallel.

The system may be divided into two sections, a test section and a cleanup section. Eight manual blocking valves (four located upstream and four located downstream of the sodium pumps) provide the means for the following combinations of operations: (1) both pumps may be connected in parallel to supply only the tests, (2) one pump may supply only the tests while the other supplies the cleanup system, (3) both pumps may supply only the cleanup system. The two filters are used to remove particles from the sodium supply prior to operation of the test vessels as well as during testing operations. The filters are arranged with manual blocking valves to allow continuous filtering of sodium by one filter while the other is being serviced. A bypass line around both filters with a manual blocking valve is also provided.

Figure 3-1. High-Temperature Sodium Supply System

The cleanup system, consisting of the plugging meter, cold trap, and sampling station, facilitates the determination of sodium oxide concentration in the system and the removal of the oxides. The plugging meter determines the precipitation temperature of sodium oxide (which is directly related to oxide content) by measuring the temperature at a built-in valve orifice at the onset of a flow decrease due to orifice plugging. The cold trap, equipped with an economizer, first cools the sodium to promote oxide precipitation and then reheats the cleaned sodium prior to its reentrance into the system. The flow-through-type sampler provided in the sampling station allows withdrawal of sodium samples for chemical analysis. Sodium samples analyzed per ANL/ST-6 are used to determine oxygen content in the sodium with the plugging meter technique used as a periodic check for oxygen at intermediate temperatures.

An argon system is used to purge the supply system of oxygen content prior to startup and also to provide an inert cover gas for the drain tank and test vessels.

3.2 THERMAL STRIPING TEST VESSEL

A test vessel, Figure 3-2, was designed to accommodate the striping test components and was installed in Station 3 of the high-temperature loop. Figure 3-3 shows the configuration details of the pot and the striping test actuation mechanism. The basic features of the vessel are (1) the inner tank, which maintains sodium level by means of overflow weirs (Figure 3-4), (2) the thermal baffles, which serve both to protect the lid's elastomer seals from excessive temperatures and to minimize the deposition of sodium on the underside of the lid (Figure 3-2), (3) a water-cooled lid that serves as the support for the striping test actuation mechanisms (Figure 3-2), (4) two nozzles for applying the impingement of "hot" and "cold" sodium on the test specimen (Figure 3-5), (5) heaters for maintaining sodium temperatures, and (6) thermocouples for monitoring vessel temperatures.

The test vessel was incorporated into the high-temperature sodium loop as shown in a simplified schematic in Figure S-1. This sketch shows that flow is taken from the pot's outer reservoir (weir overflow) at some nominal mean temperature and then splits into the hot and cold legs with the flow in each leg proportioned as required by a selection of valve settings and sodium pump output. Flow introduced into the hot leg is heated to the required maximum desired temperature

Figure 3-2. Sodium Test Vessel — Striping Test

Figure 3-3. Test Pot and Test Fixture Layout

Figure 3-4. Sodium Vessel Inner Tank Assembly

Figure 3-5. Sodium Supply Nozzles

by in-line immersion heaters. The flow into the cold leg is cooled from the existing mean temperature to the required cold inlet temperature by means of an air blast heat exchanger (Figure 3-6).

A diagram of the high-temperature sodium loop is shown in Figure 3-7 and denotes (by closed valve designations) the portion of the loop utilized and the valving technique employed to provide the required ΔT impingement on the test article. An overall view of the sodium loop with the completed striping test system installed is shown in Figure 3-8.

3.3 STRIPING TEST MECHANISM

The striping test mechanism (Figure 3-3) was designed to provide a pendulum-type motion to the test bar (specimen) with the test bar positioned so that at rest its longitudinal centerline is parallel with a centerline passing through the centers of the two inlet nozzles. Actuation of the load arm is accomplished by a variable-speed drive that can be adjusted (within limits) to provide the required displacement of the test article (for this test, ± 2.0 in.) at frequencies up to 2 Hz. A metal bellows between the actuation rod and the top lid structure precluded leakage.

The initial placement of the test bar in the center position of travel was 0.25 in. above the nozzle openings. Removable 1/4-in. spacers on top of the test bar are provided for subsequent resetting (increase) of the gap opening.

Penetrations in the vessel's lid and the passage down through the actuation rod ID are used for thermocouple entry to the pot. Appropriate fittings were used which sealed these penetrations against leakage.

Figure 3-6. Air Blast Heat Exchanger

Figure 3-7. High-Temperature Sodium Loop

Figure 3-8. Stripping Test Installation in High-Temperature Loop

4.0 TEST OPERATIONS

4.1 TEST SPECIMENS

Fifteen tests specimens (nominally 0.5 by 0.5 by 12.0 in.) (Figure 4-1) were machined from Type 316L and 9 Cr - 1 Mo materials. All test articles were machined to a 32 RMS or better surface finish on the test face (no grinding was permitted). The finish on the other faces was not considered critical to the test, but it was specified that the specimen surfaces must be orthogonal. Certified material was used for all specimens so as to establish test material validity.

Figure 4-1. Test Specimen

A single Type 316L test specimen was randomly selected from the group for use as a calibration test article. This bar was instrumented with thermocouples located at the positions noted in Figure 4-2. The sensors were positioned at several depths through the thickness and along the length of its lower face as shown on Figure 4-3.

The thermocouples selected for this test were 40-mil Inconel-sheathed Chromel/Alumel grounded junction sensors manufactured by Thermoelectric Co. This size and type of thermocouple was selected to ensure a sufficiently rapid response time — estimated at less than 25 ms in liquid sodium.

4.2 INSTALLATION OF CALIBRATION TEST SPECIMEN

The instrumented calibration test specimen was installed on the lower end of the pendulum fixture as noted on Figure 4-4. Tiedown straps, spot welded to the top of the specimen, were used to position and hold the thermocouples in place.

Figure 4-2. Thermocouple Locations on the Calibration Test Specimen

Figure 4-3. Specimen Thermocouple Assignments

Figure 4-4. Instrumented Calibration Bar

Sixteen thermocouple wires were passed through the inside of the pendulum rod and exited at the opposite end via a sixteen-hole Conax fitting. The remaining thermocouple wires were routed out of the sodium pot with single hole Conax fittings in the pot's top cover plate.

A flow deflection shield was installed on the test specimen as shown in Figure 4-4. This device was incorporated to eliminate edge effects and thus ensure a uniform flow over the face of the specimen.

Some additional thermocouples were installed in the sodium test pot to measure the test environment. Two thermocouples were installed in the hot and cold inlet nozzles to monitor the temperature of the incoming sodium. Other thermocouples were put in the vessel to measure the bulk sodium and cover gas temperatures.

4.3 SYSTEM CHECKOUT, SODIUM FILL, FLOW/TEMPERATURE ADJUSTMENTS

With the instrumented calibration test specimen mounted on the lower end of the pendulum, the pot lid was positioned and sealed on the sodium vessel. The actuation mechanism to drive the pendulum arm was attached, and the motor controller was hooked up in preparation for subsequent cyclic testing.

Following the detailed procedural steps outlined in the test procedure,⁽¹⁾ the sodium loop components associated with the striping test were filled with sodium, and the system was activated. Once the test vessel was filled to the required depth and all lines were filled, the sodium supply tank was valved off, and the striping test was put on "closed loop" operation.

An operational checkout of the sodium system was made prior to conducting any striping tests. It was found that variations of test parameters (temperature and flow) were easily attained by the fine tuning of in-line heater outputs, sodium valve adjustments, sodium pump settings, and air blast heat exchanger air flow. Once set, the test conditions remained stable.

4.4 INSTRUMENTATION

Appropriate instruments were used to record the data, which consisted of sodium temperature (basic loop, hot nozzle, cold nozzle), specimen and test

pot temperature variations, sodium flow (loop, hot nozzle, cold nozzle), and specimen cyclic frequencies and/or displacements. The basic instruments employed were:

Instrument	Manufacturer	Model/Type
1. Data Recorder	Doric	Model 240
2. Multipen Recorder	YEW	Type 3061
3. Temperature Recorder	Electronik	Model 64
4. Temp/Flow Recorder	Bristol	66A
5. Thermocouples	Thermocouple Co.	0.040 Inconel-sheathed Cromel/Alumel Model 561
6. Flow Recorder (2)	Leeds-Northrup	Speedomax
7. Oscilloscope	Hewlett-Packard	Model 175A
8. Real Time Analyzer	Rockwell	Model 1510
9. Magnetic Tape Recorder	Bell & Howell	VR 3360
10. DC Amplifier	Ectron	Model 561

Thermocouple test data for all tests were recorded on both the Doric and YEW recorders (Items 1 and 2) with loop performance data being recorded on the other recorders (Items 3, 4, and 6). During the latter part of the testing activities, some data were also recorded on an oscilloscope, a real time analyzer, and a magnetic tape recorder. These specially instrumented tests, defined in Table 4-1, were conducted to explore the merits of improving the quality of data by reducing the response time of the YEW direct-write pen recorder. The results of the supplemental tests are discussed in Section 5.0.

4.5 TESTING AND DATA ACQUISITION

The testing performed in this program consisted of conducting a series of calibration tests intended to define the thermal environment existing on the specimen under various conditions of flow, temperature, and specimen position and/or motion. With the test specimen positioned 0.25 in. above the two inlet nozzles (with the pendulum vertical), the series of tests shown in Table 4-1 was run. All the tests were conducted with a 0.25-in. specimen-to-nozzle spacing.

TABLE 4-1
THERMAL ENVIRONMENT CALIBRATION TEST MATRIX
(Sheet 1 of 9)

Test No.	Purpose	Specimen Orientation			Sodium				Measurement
		Horizontal		Gap to Nozzle	Temp. Hot	Temp. Cold	Flow Hot	Flow Cold	
		Movement	Location*						
1	Check uniformity of temperatures	Static	At center	1/4 in.	950	950	100%	100%	Pen Recorder
2	Check uniformity of temperatures	2 Hz	+2 in. to -2 in.	1/4 in.	950	950	100%	100%	Pen Recorder
3	Calibration of thermal profiles	Static	At center	1/4 in.	1000	900	Min.	Min.	Pen Recorder
4	Assessment of velocity on temp.	Static	At center	1/4 in.	1000	900	25%	25%	Pen Recorder
5	Assessment of velocity on temp.	Static	At center	1/4 in.	1000	900	50%	50%	Pen Recorder
6	Assessment of velocity on temp.	Static	At center	1/4 in.	1000	900	75%	75%	Pen Recorder
7	Assessment of velocity on temp.	Static	At center	1/4 in.	1000	900	100%	100%	Pen Recorder
8	Assessment of ef- fects on fluid temp.	Static	At center	1/4 in.	1050	850	100%	100%	Pen Recorder
9	Assessment of effects of specimen position	Static	+1/4 in.	1/4 in.	1050	850	100%	100%	Pen Recorder
10	Assessment of effects of specimen position	Static	+1/2 in.	1/4 in.	1050	850	100%	100%	Pen Recorder
11	Assessment of effects of specimen position	Static	+3/4 in.	1/4 in.	1050	850	100%	100%	Pen Recorder

TABLE 4-1
THERMAL ENVIRONMENT CALIBRATION TEST MATRIX
(Sheet 2 of 9)

Test No.	Purpose	Specimen Orientation			Sodium				Measurement
		Horizontal		Gap to Nozzle	Temp. Hot	Temp. Cold	Flow Hot	Flow Cold	
		Movement	Location*						
12	Assessment of effects of specimen position	Static	+1 in.	1/4 in.	1050	850	100%	100%	Pen Recorder
13	Assessment of effects of specimen position	Static	+1-1/2 in.	1/4 in.	1050	850	100%	100%	Pen Recorder
14	Assessment of effects of specimen position	Static	+2 in.	1/4 in.	1050	850	100%	100%	Pen Recorder
15	Assessment of effects of specimen position	Static	+2-1/2 in.	1/4 in.	1050	850	100%	100%	Pen Recorder
16	Assessment of effects of specimen position	Static	-1/4 in.	1/4 in.	1050	850	100%	100%	Pen Recorder
17	Assessment of effects of specimen position	Static	-1/2 in.	1/4 in.	1050	850	100%	100%	Pen Recorder
18	Assessment of effects of specimen position	Static	-3/4 in.	1/4 in.	1050	850	100%	100%	Pen Recorder
19	Assessment of effects of specimen position	Static	-1 in.	1/4 in.	1050	850	100%	100%	Pen Recorder
20	Assessment of effects of position	Static	-1-1/2 in.	1/4 in.	1050	850	100%	100%	Pen Recorder

TABLE 4-1
THERMAL ENVIRONMENT CALIBRATION TEST MATRIX
(Sheet 3 of 9)

Test No.	Purpose	Specimen Orientation			Sodium				Measurement
		Horizontal		Gap to Nozzle	Temp. Hot	Temp. Cold	Flow Hot	Flow Cold	
		Movement	Location*						
21	Assessment of effects of position	Static	-2 in.	1/4 in.	1050	850	100%	100%	Pen Recorder
22	Assessment of effects of position	Static	-2-1/2 in.	1/4 in.	1050	850	100%	100%	Pen Recorder
23	Assessment of frequency on specimen temp.	0.1 Hz	+2 in. to -2 in.	1/4 in.	1050	850	100%	100%	Pen Recorder
24	Assessment of frequency on specimen temp.	0.2 Hz	+2 in. to -2 in.	1/4 in.	1050	850	100%	100%	Pen Recorder
25	Assessment of frequency on specimen temp.	0.5 Hz	+2 in. to -2 in.	1/4 in.	1050	850	100%	100%	Pen Recorder
26	Assessment of frequency on specimen temp.	1 Hz	+2 in. to -2 in.	1/4 in.	1050	850	100%	100%	Pen Recorder
27	Assessment of frequency on specimen temp.	2 Hz	+2 in. to -2 in.	1/4 in.	1050	850	100%	100%	Pen Recorder
28	Effect of stroke length	1 Hz	+1 in. to -1 in.	1/4 in.	1050	850	100%	100%	Pen Recorder
29	Effect of fluid temp.	Static	At center	1/4 in.	1100	800	100%	100%	Pen Recorder

TABLE 4-1
THERMAL ENVIRONMENT CALIBRATION TEST MATRIX
(Sheet 4 of 9)

Test No.	Purpose	Specimen Orientation			Sodium				Measurement
		Horizontal		Gap to Nozzle	Temp. Hot	Temp. Cold	Flow Hot	Flow Cold	
		Movement	Location*						
30	Effect of specimen position	Static	+1/2 in. from center	1/4 in.	1100	800	100%	100%	Pen Recorder
31	Effect of specimen position	Static	+ 1 in.	1/4 in.	1100	800	100%	100%	Pen Recorder
32	Effect of specimen position	Static	+1-1/2 in.	1/4 in.	1100	800	100%	100%	Pen Recorder
33	Effect of specimen position	Static	+2 in.	1/4 in.	1100	800	100%	100%	Pen Recorder
34	Effect of specimen position	Static	+2-1/2 in.	1/4 in.	1100	800	100%	100%	Pen Recorder
35	Effect of specimen position	Static	-1/2 in.	1/4 in.	1100	800	100%	100%	Pen Recorder
36	Effect of specimen position	Static	-1 in.	1/4 in.	1100	800	100%	100%	Pen Recorder
37	Effect of specimen position	Static	-1-1/2 in.	1/4 in.	1100	800	100%	100%	Pen Recorder
38	Effect of specimen position	Static	-2 in.	1/4 in.	1100	800	100%	100%	Pen Recorder
39	Effect of specimen position	Static	-2-1/2 in.	1/4 in.	1100	800	100%	100%	Pen Recorder
40	Effect of specimen frequency	0.1 Hz	+2 in. to -2 in.	1/4 in.	1100	800	100%	100%	Pen Recorder
41	Effect of specimen frequency	0.5 Hz	+2 in. to -2 in.	1/4 in.	1100	800	100%	100%	Pen Recorder

TABLE 4-1
THERMAL ENVIRONMENT CALIBRATION TEST MATRIX
(Sheet 5 of 9)

Test No.	Purpose	Specimen Orientation			Sodium				Measurement
		Horizontal		Gap to Nozzle	Temp. Hot	Temp. Cold	Flow Hot	Flow Cold	
		Movement	Location*						
42	Effect of specimen frequency	1 Hz	+2 in. to -2 in.	1/4 in.	1100	800	100%	100%	Pen Recorder
43	Effect of specimen frequency	2 Hz	+2 in. to -2 in.	1/4 in.	1100	800	100%	100%	Pen Recorder
44	Effect of stroke length	1 Hz	+1 in. to -1 in.	1/4 in.	1100	800	100%	100%	Pen Recorder
45	Effect of fluid temp.	Static**	At center	1/4 in.	1150	750	100%	100%	Pen Recorder
46	Effect of specimen position	Static**	+1/4 in.	1/4 in.	1150	750	100%	100%	Pen Recorder and Magnetic Tape
47	Effect of specimen position	Static**	+1/2 in.	1/4 in.	1150	750	100%	100%	Pen Recorder and Magnetic Tape
48	Effect of specimen position	Static**	+3/4 in.	1/4 in.	1150	750	100%	100%	Pen Recorder and Magnetic Tape
49	Effect of specimen position	Static**	+1 in.	1/4 in.	1150	750	100%	100%	Pen Recorder and Magnetic Tape
50	Effect of specimen position	Static**	+1-1/2 in.	1/4 in.	1150	750	100%	100%	Pen Recorder and Magnetic Tape
51	Effect of specimen position	Static**	+2 in.	1/4 in.	1150	750	100%	100%	Pen Recorder and Magnetic Tape
52	Effect of specimen position	Static**	+2-1/2 in.	1/4 in.	1150	750	100%	100%	Pen Recorder and Magnetic Tape
53	Effect of specimen position	Static**	-1/2 in.	1/4 in.	1150	750	100%	100%	Pen Recorder and Magnetic Tape

TABLE 4-1
THERMAL ENVIRONMENT CALIBRATION TEST MATRIX
(Sheet 6 of 9)

Test No.	Purpose	Specimen Orientation			Sodium				Measurement
		Horizontal		Gap to Nozzle	Temp. Hot	Temp. Cold	Flow Hot	Flow Cold	
		Movement	Location*						
54	Effect of specimen position	Static**	-1 in.	1/4 in.	1150	750	100%	100%	Pen Recorder and Magnetic Tape
55	Effect of specimen position	Static**	-1-1/2 in.	1/4 in.	1150	750	100%	100%	Pen Recorder and Magnetic Tape
56	Effect of specimen position	Static**	-2 in.	1/4 in.	1150	750	100%	100%	Pen Recorder and Magnetic Tape
57	Effect of specimen position	Static**	-2-1/2 in.	1/4 in.	1150	750	100%	100%	Pen Recorder and Magnetic Tape
58	Effect of specimen frequency	0.1 Hz	+2 in. to -2 in.	1/4 in.	1150	750	100%	100%	Pen Recorder, Magnetic Tape, and Oscilloscope
59	Effect of specimen frequency	0.2 Hz	+2 in. to -2 in.	1/4 in.	1150	750	100%	100%	Pen Recorder, Magnetic Tape, and Oscilloscope
60	Effect of specimen frequency	0.5 Hz	+2 in. to -2 in.	1/4 in.	1150	750	100%	100%	Pen Recorder, Magnetic Tape, and Oscilloscope
61	Effect of specimen frequency	1 Hz	+2 in. to -2 in.	1/4 in.	1150	750	100%	100%	Pen Recorder, Magnetic Tape, and Oscilloscope
62	Effect of specimen frequency	2 Hz	+2 in. to -2 in.	1/4 in.	1150	750	100%	100%	Pen Recorder, Magnetic Tape, and Oscilloscope
63	Effect of stroke length	1 Hz	+1 in. to -1 in.	1/4 in.	1150	750	100%	100%	Pen Recorder and Magnetic Tape

TABLE 4-1
THERMAL ENVIRONMENT CALIBRATION TEST MATRIX
(Sheet 7 of 9)

Test No.	Purpose	Specimen Orientation			Sodium				Measurement
		Horizontal		Gap to Nozzle	Temp. Hot	Temp. Cold	Flow Hot	Flow Cold	
		Movement	Location*						
64	Effect of velocity	Static**	At center	1/4 in.	1150	750	50%	50%	Pen Recorder and Magnetic Tape
65	Effect of velocity and position	Static**	+1/2 in.	1/4 in.	1150	750	50%	50%	Pen Recorder and Magnetic Tape
66	Effect of velocity and position	Static**	+1 in.	1/4 in.	1150	750	50%	50%	Pen Recorder and Magnetic Tape
67	Effect of velocity and position	Static**	+1-1/2 in.	1/4 in.	1150	750	50%	50%	Pen Recorder and Magnetic Tape
68	Effect of velocity and position	Static**	+2 in.	1/4 in.	1150	750	50%	50%	Pen Recorder and Magnetic Tape
69	Effect of velocity and position	Static**	+2-1/2 in.	1/4 in.	1150	750	50%	50%	Pen Recorder and Magnetic Tape
70	Effect of velocity and position	Static**	-1/2 in.	1/4 in.	1150	750	50%	50%	Pen Recorder and Magnetic Tape
71	Effect of velocity and position	Static**	-1 in.	1/4 in.	1150	750	50%	50%	Pen Recorder and Magnetic Tape
72	Effect of velocity and position	Static**	-2 in.	1/4 in.	1150	750	50%	50%	Pen Recorder and Magnetic Tape
73	Effect of velocity and specimen frequency	0.2 Hz	+2 in. to -2 in.	1/4 in.	1150	750	50%	50%	Pen Recorder and Magnetic Tape
74	Effect of velocity and specimen frequency	0.5 Hz	+2 in. to -2 in.	1/4 in.	1150	750	50%	50%	Pen Recorder and Magnetic Tape

TABLE 4-1
THERMAL ENVIRONMENT CALIBRATION TEST MATRIX
(Sheet 8 of 9)

Test No.	Purpose	Specimen Orientation			Sodium				Measurement
		Horizontal		Gap to Nozzle	Temp. Hot	Temp. Cold	Flow Hot	Flow Cold	
		Movement	Location*						
75	Effect of velocity and specimen frequency	1 Hz	+2 in. to -2 in.	1/4 in.	1150	750	50%	50%	Pen Recorder and Magnetic Tape
76	Effect of velocity and specimen frequency	2 Hz	+2 in. to -2 in.	1/4 in.	1150	750	50%	50%	Pen Recorder and Magnetic Tape
77	Effect of stroke length	1 Hz	+1 in. to -1 in.	1/4 in.	1150	750	50%	50%	Pen Recorder and Magnetic Tape
78	Assessment of mixing	Static**	At center	1/4 in.	1150	750	50%	Min.	Pen Recorder and Magnetic Tape
†79	Assessment of mixing	Static**	At center	1/4 in.	1150	750	50%	25%	Pen Recorder and Magnetic Tape
80	Assessment of mixing	Static**	At center	1/4 in.	1150	750	50%	75%	Pen Recorder and Magnetic Tape
81	Assessment of mixing	Static**	At center	1/4 in.	1150	750	50%	100%	Pen Recorder and Magnetic Tape
82	Assessment of mixing	Static**	At center	1/4 in.	1150	750	Min.	50%	Pen Recorder and Magnetic Tape
†83	Assessment of mixing	Static**	At center	1/4 in.	1150	750	25%	50%	Pen Recorder and Magnetic Tape
†84	Assessment of mixing	Static**	At center	1/4 in.	1150	750	75%	50%	Pen Recorder and Magnetic Tape

TABLE 4-1
THERMAL ENVIRONMENT CALIBRATION TEST MATRIX
(Sheet 9 of 9)

Test No.	Purpose	Specimen Orientation			Sodium				Measurement
		Horizontal		Gap to Nozzle	Temp. Hot	Temp. Cold	Flow Hot	Flow Cold	
		Movement	Location*						
†85	Assessment of mixing	Static**	At center	1/4 in.	1150	750	100%	50%	Pen Recorder and Magnetic Tape

*"+" indicates movement toward hot nozzle

"-" indicates movement toward cold nozzle

**Static tests performed by moving the test specimen in 50 mil increments through the hot/cold fluid interface

†Tests also conducted at 0.1 and 1.0 Hz cyclic tests

At each test condition, it was necessary to make three separate runs because of a lack of sufficient data channels to record all data channels simultaneously. Key data channels, however, were repeated for each run so that comparative analyses could be made utilizing the common channels. The response data from the specimen's thermocouples were recorded on a direct-wire YEW nine-channel recorder. This instrument has a pen response time of 800 mm/s, and initially it was felt that this recording speed would be suitable for this test. Data channel assignments for the three runs (A, B, and C) of each condition are noted in Table 4-2 (refer to Figure 4-3 for test specimen thermocouple location).

TABLE 4-2
DATA CHANNEL ASSIGNMENTS
(YEW Direct-Write Recorder)

YEW Channel Number (Color)	Thermocouple Identification		
	Test Phase A	Test Phase B	Test Phase C
1. (red)	24	24	24
2. (green)	26	26	26
3. (dark blue)	11	11	11
4. (brown)	1	9	18
5. (black)	4	10	19
6. (purple)	5	13	20
7. (orange)	6	14	21
8. (light violet)	7	16	12
9. (light blue)	8	17	15

During initial stages of system checkouts, it became obvious that the recorder traces would be difficult, if not impossible, to read because of the pens being superimposed on each other with a narrow temperature range. To alleviate this problem, the nine channels were divided into groups of three simply by offsetting the zeros, and all tests were run following this recording procedure. The use of the offset on a typical test record (Test 84) is illustrated in Figure 4-5. Accordingly, curve corrections are required to interpret the raw data.

Based on the location on the test article, each thermocouple described its own particular trace signature because each traversed a slightly different course during the pendulum excursion.

Figure 4-5. Test Record Offsets — Test 84 at 1 Hz
(Nominal 400°F ΔT , 75% hot flow and 50% cold flow)

Examples of these trace variations are illustrated in Figure 4-6. General features presented here for background will be discussed in greater detail in the data analysis section. Consider first the thermocouples that penetrate into the fluid (Thermocouples 1, 3,* 5, 7, 9, 11, 13, and 17) which, due to their different location on the specimen, will spend different proportions of the stroke in the hot and cold streams. Except for fluid Thermocouples 1 and 17, which are positioned near the ends of the stroke, the fluid thermocouples on the cold stream side of the specimen (5 and 7) show longer periods near the cold stream temperature, while the fluid thermocouples on the hot stream side of the specimen (9, 11, and 13) show longer periods near the hot stream temperature.

Thermocouples 19, 20, and 21 are embedded in the specimen at depths of 0.07, 0.15, and 0.26 in., respectively, from the exposed surface of the test specimen. The remaining thermocouples (4, 8, 10, 14, 16, and 18) are embedded at a depth of 0.01 in. from the exposed surface. Due to the added thermal inertia of the metal, the embedded thermocouples are slower to respond than the fluid thermocouples. With increased inertia, a sharp ramp becomes more gradual so that a square wave shape tends toward a saw-tooth pattern. This trend is very obvious in most thermocouple traces but is somewhat less apparent in Thermocouples 14 and 16. The distortion of the temperature response traces is due not only to the thermal inertia of the embedment metal but also to the dynamic inertia of the total recording system and, to a lesser degree, to the thermal inertia in the thermocouple bead. Comparison of temperature response traces at various oscillation frequencies will provide an indication of the total system inertia.

Various test conditions required testing under pendulum oscillations of 0.1, 0.2, 0.5, 1.0, and 2.0 Hz. The typical response of a single thermocouple at these frequencies while under the same flow and temperature environment is shown in Figure 4-7. In addition to moderating the apparent rate of temperature response, recording system inertia attenuates the apparent range of response fluctuation. The degree of attenuation increases as both the excitation frequency and recording system inertia increase. The apparent response amplitude at the 2-Hz oscillation frequency is seen in Figure 4-7 to drop to less than one-third the amplitude at the 0.2-Hz oscillation frequency.

Interpreting the shape of the curves in Figure 4-7, it became evident during the testing that the response time of the thermocouples and/or recorder was too slow to capture the complete temperature amplitude of the thermal events.

*Thermocouple 3 inoperative

Figure 4-6. Thermocouple Trace Signatures —
Test 59 at 0.2 Hz

Figure 4-7. Thermocouple 11 Traces at Various Frequencies (see Figure 4-3 for Sensor Location)

This was confirmed when the output of thermocouples was put on an oscilloscope. The scope captured the high-frequency response of the sensors (approximately 15% attenuation in Figure 4-8) that the YEW direct-write recorder failed to record (approximately 65% attenuation in Figure 4-7).

To eliminate the response problems associated with the YEW direct-write recorder, a 14-channel FM magnetic tape recorder was installed and utilized to record the temperature response information for all tests following Test No. 45. Additional attention was also given to the region of "thermal striping turbulence" that was observed in a narrow zone in the mixing region between the hot and cold inlet streams. The discrete 1/4-in. and 1/2-in. steps specified in the test matrix were found to be too coarse to map the extent and effect of this turbulent region accurately. Consequently, following Test No. 45, the static-type measurements called for in the matrix were superseded by detailed static surveys conducted with ~0.05-in. incremental movements of the test specimen over a full pendulum excursion of approximately ± 2.5 in. from center (vertical) position. These tests were useful in accurately defining the regions where a striping environment existed as well as the width of the "thermal wash" on the specimen.

Upon completion of the test series, testing activities were terminated, and the test facility was put into a standby condition pending direction to proceed with testing work in accordance with the Thermal Striping Program Plan. All test data have been placed in storage under the control of the Rockwell International Energy Systems Group Component Test and Development Unit.

REFERENCE

1. 039DTP000001, "Sodium Thermal Striping Evaluation Detailed Test Procedure," R. M. Oliva, April 22, 1981

Figure 4-8. Oscilloscope Photographs of Thermocouple Trace in Fluid Adjacent to Specimen

5.0 TEST DATA ANALYSIS

The calibration testing performed in this program was designed to check out the operational characteristics of the testing and data acquisition system and to define the thermal environment on a test specimen under various conditions of flow, temperature, and specimen position and/or motion prior to actually conducting materials damage tests. As a result of the calibration testing, specific thermal/hydraulic observations were made, and preliminary conclusions were reached regarding the thermal striping environment at a typical LMFBF core outlet. These observations and conclusions are discussed in the following sections.

5.1 STATIC TRAVERSE TESTS

The static traverse tests (Test Nos. 8-22, 29-39, 46-57, and 64-69 of Table 4-1) consist of incrementally positioning the specimen (i.e., pendulum assembly) through the full stroke and recording temperatures at each incremental position. Each thermocouple in the thermal calibration test specimen recorded a rapid fluid temperature fluctuation about a steady temperature component (mean value) that varied with specimen position. The rapid fluctuation component was greatest in the hot to cold stream mixing interface and showed characteristics similar to those reported for water experiments^(1,2) on thermal striping.

The steady temperature component, as measured by the fluid temperature thermocouples (those that protrude 0.04 in. into the fluid), are plotted in Figure 5-1 for the balanced full flow condition. A typical temperature trace, from Test 45, shows that as a thermocouple is moved from a position over the cold nozzle ("-" positions) to a position over the hot nozzle ("+" positions), the steady temperature component changes, as expected, from the cold stream temperature of 680°F to the hot stream temperature of 1100°F. The fluid temperature fluctuation range about the steady temperature component, however, also varies with position. As shown in Figure 5-2, the measured fluid temperature fluctuation range is only about 10°F when a thermocouple is ± 0.10 in. from the midpoint ("0" position) between the two nozzles. At ± 0.05 in. from the midpoint, the measured temperature range is about 50°F. At the midpoint, the measured temperature range is about 100°F.

Figure 5-1. Static Temperature Traverse at Balanced Full Flow
(Test Nos. 45-57)

Figure 5-2. Fluid ΔT_f Measured at Static Positions with Natural Oscillation at Stream Mixing Boundary (Test 45)

The steady temperature component is independent of system response capability since the steady component is essentially constant at each incremental position. However, the rapidly fluctuating component can be quite sensitive to the instrumentation system response capability. Since the pendulum oscillation tests provide a measure of instrumentation system response capability, discussion of the instrumentation system time constant corrections will be deferred to the section covering the pendulum oscillation tests.

The comparable steady temperature component for an unbalanced condition of full hot flow and 50% cold flow is presented in Figure 5-3. The temperature patterns are similar to the balanced full flow temperature patterns, but there are some significant differences. In the balanced full flow condition, the patterns over the hot and cold nozzles are of similar shape with a maximum temperature range that is approximately equal to the differential between the hot and cold inlet temperatures as would be expected. The lower temperature extremes of the specimen thermocouples (except for Thermocouple 9) correlate very well with the cold inlet nozzle temperature (Thermocouple 24); but, due to an apparent calibration problem, the upper temperature extremes are consistently higher than the hot inlet nozzle temperature (Thermocouple 26). Recorder channel calibration was later identified to be the cause of low temperature correlation problem on Thermocouple 9. It is also noted that the change from hot to cold temperature extremes occurs quite rapidly, which implies a narrow mixing zone.

In the unbalanced 50% cold flow, 100% hot flow condition, the film temperature change in the transition region between the hot and cold nozzles is more gradual, and the similarity in the shape of the temperature pattern between the hot and cold regions disappears. For this unbalanced flow condition, one-third of the flow is supplied by the cold inlet with two-thirds of the flow supplied by the hot inlet, which results in a bulk mixing temperature of 990°F. The bulk mixing temperature falls midway between the extremes of the pattern of film temperature traverse. The range of the steady temperature component drops to two-thirds of the hot to cold inlet temperature differential, which suggests that enhanced mixing may occur during unbalanced flow. Alternatively, it has been suggested that the higher velocity hot stream may inhibit the approach of the cold stream to the specimen surface, which has been termed flow blanketing. Regardless of the cause, the one-third reduction in the film temperature range due to the flow unbalance significantly reduces the thermal striping environment on the specimen surface.

Figure 5-3. Static Temperature Traverse at 50% Cold Flow (Test 85)

5.2 PENDULUM OSCILLATION TESTS

As mentioned earlier, the pendulum oscillation tests (Test Nos. 23-28, 40-44, 58-63, and 73-77) provide a measure of the instrumentation system response capability. When subjected to a repetitive periodic excitation, the indicated (measured) fluid temperature will closely follow the actual temperatures at a nearly equal amplitude for very slow (long period) excitation signals. But the indicated temperature lags the actual temperature more and more and shows a reduced hot to cold temperature amplitude for faster (short period) excitation. The instrumentation system response capability (or time constant) has an inverse effect, i.e., the indicated hot to cold temperature amplitude is attenuated only slightly for a short instrumentation system time constant while attenuation increases for longer time constants. Substantial attenuation as evidenced in Figure 5-4 with the pen recorder implying a long instrumentation system time constant for that total system. Since the pen recorder response was suspected to be a major factor, a quick check test series (Tests 60-62) was made using an oscilloscope. The results shown in Figure 4-8 indicated considerable improvement. To improve the data definition and to increase flexibility of data reduction, a tape recorder was incorporated into the data system. The traces in Figure 5-5 show the improved definition of wave shapes and the reduced attenuation due to the improved response.

The primary purpose of the pendulum oscillation tests was to characterize the thermal environment for subsequent thermal stripping material damage tests. Pretest analysis⁽³⁾ suggested that the stroke length and the position on the specimen relative to the midstroke position would have a significant effect on the amplitude and on the wave shape of the temperature variation at the metal surface. The fluid temperature pattern from the static traverse test data was used to estimate temperature wave shapes for specific thermocouple positions. The data from the pen recorder test runs were used for this comparison since the instrumentation system response was adequate at the slower oscillation frequency under consideration. Estimates of temperature wave shapes are compared to the respective thermocouple data for a frequency of 0.1 Hz in Figure 5-6. The agreement is good. Therefore, for the 1/4-in. spacing between the inlet nozzles and the specimen, it is concluded that the pattern of the steady temperature component from static tests is quite stable and permits a reasonable prediction of temperature wave shape in the film boundary.

Figure 5-4. Pen Recorder Traces

Figure 5-5. Thermocouple 13 Magnetic Tape Temperature Traces

Figure 5-6. Temperature Wave Shape Variation with Position — Test 58

5.3 MIXING ZONE TEMPERATURE FLUCTUATIONS

As mentioned previously, the interface mixing zone is characterized by rapid temperature fluctuations. The mixing zone was found to be narrow and sharply defined with the largest amplitude of temperature fluctuation for the balanced full-flow condition. For the unbalanced condition of 50% cold flow with full hot flow, a wider and more gradual transition with lower amplitude temperature fluctuations was shown.

To determine the actual range of the temperature fluctuations, the apparent range has to be adjusted for the response lag of the recording system. For this adjustment, the measured film temperature range from the 0.1-Hz oscillation test was used as a reference level since response lag is minimal at this slow oscillation rate. Because the steady temperature pattern is stable, the attenuation at the higher frequencies is a measure of the response lag. Although the temperature fluctuation data were quite irregular, the larger amplitude excursions seemed to show a period of approximately 1 sec. At the 1-Hz frequency, instrumentation attenuation factors of 0.760 and 0.878 were obtained from the oscillation test data for the pen recorder system and the magnetic tape system, respectively. The measured fluctuation data were adjusted by dividing by the attenuation factors.

For a nominal 400°F ΔT test, the limited magnetic tape data shows an adjusted maximum temperature fluctuation of 384°F . The corresponding pen recorder data shows an apparent adjusted maximum fluctuation of 408°F for the comparable balanced full flow case. For the unbalanced, 100% hot flow, 50% cold flow case, pen recorder data shows an adjusted fluctuation range of only 70°F .

For the balanced flow case, the adjusted data show that there is no attenuation of the nozzle outlet temperature difference at the surface of the instrumented test specimen. However, the fluctuating temperature at the interface between the hot and cold streams in the static test with a nozzle to nozzle ΔT of 400°F is estimated at 130 to 210°F , as shown in Figure 5-2. This fluctuating temperature is further reduced to about 70°F , or about 17% of the balanced flow maximum temperature range, when the cold flow is reduced by 50%, indicating that the dominant hot sodium flow is blanketing the surface of the test specimen. This preliminary result indicates that the thermal striping environment at the core outlet of an LMFBR may be significantly reduced by flow blanketing under typical core operating conditions with the coolant flow from the colder blanket assemblies usually being less than the coolant flow from the hotter fuel assemblies.

5.4 METAL TEMPERATURE RESPONSE

Thermal stripping damage at the specimen surface is expected to be related to the temperature variation at the metal surface. The metal surface temperature variation is expected to be less than that in the fluid due to film boundary layer effects. The oscilloscope traces of Figure 5-7 show that the metal temperature variation is substantially less than that of the fluid for the rapid temperature fluctuation due to stream mixing.

During oscillating tests, each thermocouple sweeps back and forth through a different portion of the flow stream. Thermocouples located on the cold nozzle side of the specimen (Thermocouples 1 through 8) spend more time in the colder portion of the flow stream, and thermocouples on the hot nozzle side (Thermocouples 11 through 17) spend more time in the hotter portion of the flow stream. The fluid film thermocouples (odd numbered thermocouples) reflect this directly, as was shown in Figure 5-6. Thermocouple 9 at the midstroke position shows slightly more time in the hot region rather than equal time, which suggests that the specimen may be shifted slightly toward the hot side. This suggestion is reinforced by the comparison of traces for Thermocouples 1 through 17, which should be mirror images about a 900°F temperature level. Thermocouple 1 is seen to pass through the cold stream and just into the hot stream before moving back, while Thermocouple 17 moves through the hot stream but never makes it into the cold stream. This is consistent with a specimen shift toward the hot side of the stream. While the fluid temperature thermocouples are able to follow the stream temperature at the 0.1-Hz oscillation frequency, as shown in Figure 5-6, the metal thermocouples lag farther behind due to the added thermal inertia of the film boundary layer and (to a lesser degree) of the 0.01-in. embedment thickness.

As the hold period following a step change in fluid temperature is lengthened, the metal temperature is able to attain a greater percentage of the applied temperature change; conversely, as the hold period is shortened, the metal temperature attains a smaller percentage of the applied temperature change. Therefore, the metal temperature response (i.e., percentage of applied temperature change) is expected to decrease for positions farther from the midstroke position. Similarly, as the oscillation period is increased, the metal temperature response is expected to increase. To verify these expectations, the range of the surface temperature (as measured by thermocouples 0.01 in. beneath the metal surface)

Figure 5-7. Oscilloscope Photographs of Thermal Striping Behavior
(Exploratory test — unnumbered)

from the pendulum oscillation tests was expressed as a percentage of the fluid film temperature range and then plotted against oscillation period (and frequency) in Figure 5-8. The general trend of reduced metal temperature response at shorter periods (higher frequencies) and increased metal temperature response at longer periods (lower frequencies) is confirmed except for Thermocouple 10. Furthermore, Thermocouple 10 should show greater metal temperature response than the other thermocouples, since it is located at the most severe midstroke position. The responses of the other metal temperature thermocouples appear to be consistent with expectations for their relative locations except for Thermocouple 14, which would be expected to fall between Thermocouple 8 and Thermocouples 4 and 16 based on distance from the midstroke position.

The temperature traverse sequence (Test Nos. 46-57) and the pendulum oscillation sequence (Test Nos. 58-62) at balanced full flow were rerun with a magnetic tape recorder for improved system response. A portion of the recording showing the response of fluid temperature Thermocouple 13 and its companion metal temperature Thermocouple 14 when positioned in the interface mixing zone is reproduced in Figure 5-9. Letters are used to identify corresponding major fluctuations of interest in Figure 5-9. The added attenuation in the higher frequencies due to the fluid film and metal embedment is apparent when the metal and fluid thermocouple responses are compared. The longer period, lower frequency excursions such as D, H, K, and O exhibit a higher ratio of metal temperature to fluid temperature than do the shorter period, higher frequency excursions such as A, B, C, F, I, J, L, P, T, and V. The maximum temperature fluctuation is observed at point O.

Applying the 1-Hz attenuation factor (0.878) to the data, an adjusted maximum fluid temperature fluctuation of 385°F and an adjusted maximum metal temperature fluctuation of 129°F are obtained. Thus, the maximum metal temperature fluctuation is approximately 34% of the fluid temperature fluctuation. For the higher frequency peaks, the metal temperature excursions were approximately 25% of the fluid temperature excursions.

5.5 CONCLUSIONS

Checkout of the Thermal Striping Test Facility and the preliminary phase of testing to characterize the fluid temperature environment were successfully completed. Facility checkout resulted in the substitution of an FM tape recorder for the pen recorder system to improve the system instrumentation response time.

Figure 5-8. Fractional Temperature Response

THERMOCOUPLE 14 METAL TEMPERATURE AT +1.0 in FROM SPECIMEN MID LENGTH

THERMOCOUPLE 13 FLUID TEMPERATURE AT +1.0 in FROM SPECIMEN MID LENGTH

Figure 5-9. Comparison of Metal Thermocouple and Fluid Thermocouple Response When Positioned in the Interface Mixing Zone

During initial preliminary testing, it was determined that the temperature distribution along the stroke axis of the specimen could be characterized by rapid fluctuations superposed on a steady temperature pattern. The rapid fluctuation was most intense in the hot to cold stream mixing interface and showed the characteristics of a random variation of mixed frequencies. The amplitude of the rapid fluctuation component was greatest for the balanced full-flow condition.

The static traverse at the 50% cold flow, 100% hot flow condition shows that the thermocouples above the cold stream nozzle remain well above the cold inlet fluid temperature and that the range of the rapid temperature fluctuation is significantly reduced. As a result, the total thermal striping fluid temperature range was less than one-fifth of the hot to cold stream temperature differential. This suggests that flow unbalance between the hot and cold streams is likely to be very beneficial in mitigating thermal striping conditions.

The pendulum oscillation tests produce repeatable temperature traces that appear to be consistent with predictions based on the steady temperature pattern obtained from the static traverse tests.

Only a limited amount of data was obtained from thermocouples at the metal surface after the magnetic tape recorder was added. The maximum range of the metal temperature response was found to be approximately 34% of the temperature range in the adjacent fluid film when maximum response occurred with a 1.0-Hz frequency range. Further testing is recommended to confirm the magnitude of the attenuation.

The thermal calibration testing of the thermal striping test facility provided new insight into the thermal/hydraulics of the sodium thermal striping problem. Preliminary characterization of structural material response under some thermal striping environments indicates that large temperature gradient attenuations may be achievable under certain design conditions, allowing the use of ordinary materials of construction in potentially severe thermal striping environments.

REFERENCES

1. C. W. Sayles, "Thermal Striping Task Force, Meeting and Handouts," N254TI122004, p 155 (March 16, 1978)
2. J. T. Madell, "ANL 1/10 Scale Study of LMFBR Outlet Plenum Mixing Reported to Task Force"
3. C. W. Sayles, F. V. Naugle, and E. M. Mouradian, "Program Summary and Pretest Evaluation," 039TI000002 (held for incorporation of review comments)

APPENDIX
THERMAL STRIPING PROGRAM PLAN

CONTENTS

<u>Section</u>	<u>Page</u>
1.0 Introduction.....	A-5
2.0 Program Objectives.....	A-6
3.0 Background.....	A-8
3.1 Uncertainties in Current Design Methodology.....	A-9
3.1.1 Fluid Temperature Field Dynamics.....	A-10
3.1.2 Metal Temperature Field Dynamics.....	A-12
3.1.3 Metal Response to Cyclic Thermal Gradients.....	A-13
3.1.4 Damage Prediction and Failure Mode Characterization.....	A-14
3.2 Needed Development.....	A-15
4.0 Thermal Striping Program Plan.....	A-16
4.1 Initial Scoping Phase.....	A-19
4.1.1 Fluid Temperature Field Dynamics.....	A-21
4.1.2 Metal Temperature and Metal Response Dynamics.....	A-22
4.1.3 Thermal Striping Damage and Failure Characterization.....	A-23
4.1.4 Thermal Striping Damage Criteria and Design Guidelines.....	A-24
4.2 Follow-On Testing Phase.....	A-25
4.2.1 Fluid Temperature Field Dynamics.....	A-25
4.2.2 Metal Temperature and Metal Response Dynamics.....	A-26
4.2.3 Thermal Striping Damage and Failure Characterization.....	A-26
4.2.4 Thermal Striping Damage Criteria and Design Guidelines.....	A-27
5.0 Thermal Striping Programs in the U.S. and the U.K.....	A-28
5.1 U.K. Thermal Striping Program.....	A-28
5.1.1 Thermal Fatigue Studies.....	A-29
5.1.2 Model Tests to Measure Field Characteristics.....	A-29
5.1.3 Studies of Modeling Criteria.....	A-32
5.1.4 Studies of Relationship of Surface Temperature and Stress....	A-32
5.1.5 Studies of Relationship of Fluid Temperature and Metal Surface Temperature.....	A-32
5.2 U.S. Thermal Striping Program.....	A-32
5.2.1 Argonne National Laboratory Water Tests.....	A-33
5.2.2 In-Sodium Materials Testing.....	A-33
References.....	A-35

FIGURES

<u>Figure</u>	<u>Page</u>
A-1 Thermal Striping Program Schedule.....	A-18
A-2 Test Facility Schematic.....	A-20
A-3 Random Thermal Fluctuation Fatigue Test Section.....	A-30

1.0 INTRODUCTION

This Thermal Striping Program Plan was prepared to describe the activities that should be accomplished to establish a design technology to guard against the consequences of severe thermal striping damage in LMFBR structures. The main purpose of this plan is to identify the scope of work to be performed, including the work already initiated by Rockwell International Energy Systems Group (ESG) under EPRI sponsorship. Related activities being performed by other agencies and organizations, both in the United States and abroad, are also described briefly.

The objective of this program plan is to define an overall design methodology to prevent the loss of structural integrity due to thermal striping in LMFBR components. The plan identifies areas where additional analytic and experimental R&D activities are needed and presents a program of specific tasks to address these areas.

This plan was formulated in October 1981 as a part of the "Review of Large LMFBR Design--Thermal Striping Evaluation" being conducted under EPRI contract.* The proposed work scope of the identified tasks should be considered as preliminary. As initial results are obtained, new developments occur, and needs and priorities change, the plan will require change. Therefore, it is anticipated that this document may need to be updated periodically.

*EPRI Contract RP1704-11

2.0 PROGRAM OBJECTIVES

The goal of the thermal striping program is to develop an empirically based design methodology for fast breeder reactor components that operate in a thermal striping environment. This goal would be obtained through accomplishment of the following objectives:

- 1) Develop an empirical data base that provides correlation between observed damage and imposed striping environment, by experimental demonstration and characterization of thermal striping damage resulting from realistic simulations of reactor thermal striping environments.
- 2) Develop an empirical data base that provides correlation between the fluid temperature field dynamics and field input (causative) parameters and dimensions.
- 3) Develop an improved thermal striping design methodology that is consistent with the empirical data bases, provides appropriate known margins of conservatism, and is related to physical principles and available analytical methods to the extent found beneficial.

Proposed work scope and priorities for accomplishing the needed studies are also included in this plan.

Current design methodologies are based on the use of geometry-specific test correlations in unrepresentative environments and conservative simplifying analysis assumptions. This has led to the use of expensive high-strength alloys that are difficult to fabricate and unsuitable for welding.

Therefore, the basis for this thermal striping program is the need to establish a more accurate and realistic method for the assessment of structural damage caused by hydrodynamically induced temporal and spatial variation of thermal stresses. More accurate predictions of the loads and resulting stresses will improve the ability to: (1) select appropriate materials of construction, (2) eliminate excessive conservatism, and (3) characterize and quantify the margin against thermal

striping damage. This improved ability will enhance the design integrity and operational reliability of LMFBR components and should lead to more economical component designs.

3.0 BACKGROUND

Certain localized areas of the internal structural components of liquid metal fast breeder reactors (LMFBRs) are subject to oscillating temperatures due to temporal and spatial thermal variations of the adjacent liquid metal coolant. An important example of this type of thermal loading occurs in the structures located above the exit plane of the reactor core. Due to the impingement and mixing of the sodium streams exiting from core subassemblies at different temperatures, complex fluctuating thermal fields are imposed on the reactor internal components such as the upper internals structure. This phenomenon, referred to as "thermal striping," results in cyclic straining of the surface of the metal structure which, if sufficiently severe, may cause crack initiation and growth due to metal fatigue.

Within the past several years, serious concern has arisen in the LMFBR programs of the United States and the United Kingdom over the possible consequences of thermal striping on reactor internal structures. Consequently, various investigations and studies have been undertaken. The UK Atomic Energy Authority has initiated a development program⁽¹⁾ to study the thermal fatigue properties of austenitic stainless steels through analytic and experimental studies of fluid mixing characteristics, theoretical studies of fatigue crack propagation and arrest, and experimental and theoretical studies to interrelate the fluid and stress fluctuations. Meanwhile, in the United States, the Department of Energy has funded tests⁽²⁾ to establish the resistance of stainless steel and Inconel 718 to certain thermal striping environments. A summary of these investigations is contained in Section 5.0.

While the possible extent and severity of this potential problem has been recognized, it has been difficult to quantify the specific parameters relevant to thermal striping structural failure modes. Therefore, designers of LMFBR internal structures have chosen to:

- Adopt conservative design assumptions, and/or
- Use fatigue-resistant materials that are expensive and difficult to fabricate.

To help define the uncertainty that exists in the current methodology used in treating this problem, a brief review of this methodology is presented below.

3.1 UNCERTAINTIES IN CURRENT DESIGN METHODOLOGY

In sodium-cooled fast reactors, streams of sodium flow from the core at different temperatures and velocities. Since the streams are not completely mixed in the region of the reactor upper internal structures, local regions of the structure suffer rapid temperature fluctuations on their surfaces. These temperature fluctuations lead to oscillating temperature gradients, which cause repeated straining of the surface of the metal. If sufficiently severe, crack initiation and growth may occur due to metal fatigue. This represents the area of perhaps the greatest concern with thermal striping in LMFBRs. Other areas where conditions may exist that require evaluation for thermal striping effects include mixing tees, certain "leakage paths" within the reactor vessel, and the heat transfer equipment.

In the current design approach, it is assumed that the total exposed surface of the affected structure is subjected to oscillations of hot and cold sodium. The amplitude and frequency of this fluid oscillation are estimated based on an assumed, or experimentally observed, fluid mixing behavior at the component. The expected number of strain cycles is then determined from the total service life of the affected structure. Fluid velocity and velocity distribution estimates are then made from which a film coefficient at the fluid-structure interface is determined. With these parameters, a simplified model of the fluid dynamic behavior is established and used as thermal input to a structural model. Estimates of peak strain ranges in the metal are then computed and damage is predicted based on uniaxial, isothermal, mechanical fatigue test data. The numerous uncertainties and assumptions inherent in this design approach has, in many cases, resulted in a cascade of conservatisms, which probably leads to underpredicted structural capability.

From the above description, it can be seen that the thermal striping problem involves four areas of uncertainty that must be addressed in the design methodology:

- 1) The dynamics of the temperature field in the bulk fluid
- 2) The dynamics of the temperature field in the metal structure including the fluid boundary layer
- 3) The structural response of the metal to cyclic temperature gradients
- 4) Damage prediction and failure mode characterization.

In a rational design process, each of these areas must be characterized. A reliable basis for the design of structures to prevent the consequences of thermal striping damage requires an adequate understanding of all four of these areas. In the following, discussions of the areas of uncertainty or lack of knowledge in the current design methodology are presented.

3.1.1 Fluid Temperature Field Dynamics

The mixing of the reactor outlet fluid streams and the dynamics of the resulting temperature field are the initiating mechanisms of the thermal striping phenomenon. The ability to predict the temperature field depends on an ability to predict the mixing characteristics of multiple parallel jets issuing from the upper face of the core. Based on the available analytical and experimental data on the mixing of turbulent jets summarized by Schlichting,⁽³⁾ it appears that the information required for predicting of multiple jet mixing does not exist. Conclusions drawn from the available data show that analytical solutions of the mixing of a single cylindrical jet in free turbulent flow are in good agreement with measurements of temperature distributions from various experimental sources. The parameters that govern the mixing of coaxial turbulent jets issuing with different velocities and temperatures in a pipe have been well established. The conditions required for the breakup of a single turbulent liquid jet have been established, and extensive experimental and analytical data have been developed for jets exhausting into a deflecting stream. It is not possible, however, to characterize the dynamics of the temperature field of multiple cylindrical turbulent jets, such as issue from the upper core nozzles, on the basis of the available information.

It can be expected that the temperature field dynamics will be influenced by several fluid behavioral characteristics acting simultaneously. For example, under the action of turbulent eddies, the reactor outlet fluid streams might be expected to flicker like a candle flame. Also, parallel streams can interact with each other, both in a turbulent mixing behavior and in heat transfer that reduces the temperature difference between the two streams. Hence, an experimental program to obtain basic mixing data on multiple turbulent jets is needed. The parameters of interest are the following:

- The amplitude of the fluid temperature fluctuations
- The frequency spectrum of the temperature fluctuations
- The shape and motion of isothermal profiles of the jets

- The decay, with distance, of the stream-to-stream temperature differentials caused by the heat transfer from the hot fluid plume to the cold fluid plume.

Since the temperature field dynamics are dependent on the flow field, the dynamics of the fluid velocity field should also be characterized at locations of interest, as follows:

- The amplitude of the velocity fluctuations
- The degree of regularity of the velocity fluctuations
- The frequency or period of the fluid velocity variation
- The correlation between the fluid velocity variation and the fluid temperature variation.

The approach taken on the CRBR program to estimate the temperature field on the CRBR upper internal structure (UIS) is based on ANL^(4,5,6) water testing one-tenth scale model of the UIS. Fast response thermocouples were located about 1/8 in. from the UIS surface above the core discharge. Although the location of the maximum thermal striping temperature differences was not known, the measured water temperature oscillations were considered representative of the maximum sodium temperature conditions. Water temperature differences were scaled to sodium temperature difference. Based on spectrum analysis, the greatest temperature amplitude occurred at about 1/4 Hz.

It is concluded that the greatest uncertainties in the thermal striping phenomenon are in this area of fluid temperature dynamics. There is no current analytic theory with which to accurately predict the mass and heat transfer behavior that occurs during the mixing of sodium streams.⁽⁷⁾ Explicit analytic solutions are relatively intractable due to the large number of parameters, and recourse is made to empirical factors based on tests and experiments for specific design configurations.^(4,8) The determination of appropriate values for these fluid field parameters have been based on meager data and/or simplifying conservative assumptions. The basic hydrodynamic behavior in unobstructed fluid fields, as well as the fluid interactions with a structural obstruction, are therefore areas of great uncertainty in the current technology.

3.1.2 Metal Temperature Field Dynamics

The flow of heat into (and out of) the metal depends on the bulk fluid boundary conditions of temperature and the fluid boundary layer characteristics, both of which vary with time. The interior metal temperature depends on the metal properties and geometry as well as the thermal boundary conditions at the other boundaries. Only after the dynamic temperature field within the metal structure has been established can the structural response of the metal, in particular the cyclic straining of its surface, be determined.

Methods for analyzing the temperature and stress/strain distribution within metal structures are well established. However, because of the 3-dimensional and transient nature of the problem, implementation of the solutions are complex and simplifying assumptions are often made in the modeling and analysis.

The current methodology generally applies a 1-dimensional modeling of the problem. The fluid field temperature oscillations are assumed to occur over the total area of an exposed surface of the affected structure, and the fluid boundary layer is modeled by a conventional heat transfer coefficient.

The film coefficient is an empirically based factor used to describe the heat transfer rate at a fluid-solid interface under a steady-state ΔT . It is used to determine the quantity of heat transferred across a unit area of interface per unit of time for a ΔT that is steady state and presumed to exist uniformly in the directions normal to the interface.

In actual practice, empirical heat transfer correlations are usually determined from average temperatures and flows measured over a specified surface area. However, pronounced variable temperatures and flows are observed on surfaces heated or cooled by impinging jets, and differences in heat transfer at the axis and the peripheral regions of the jet can differ by an order of magnitude. Under thermal striping conditions, a number of additional differences can arise because of the fluctuating nature of the flow. For example, the following deviations from an assumed steady condition generally prevail at a fluid-solid interface in a thermal striping environment:

- 1) The ΔT is not steady state
- 2) The boundary layer thickness is not uniform

- 3) The surface area subjected to a specific ΔT at any instant is limited in extent (and may be very small).

Because of these differences, it is clear that the use of conventional average film coefficients in striping calculations is applicable only for short moments of time and for very small elements of surface area; the possibility of integrating these microelements into some average continuum appears to be a very difficult task.

Experimental methods to determine fluid boundary layer and metal surface temperature behavior under thermal striping conditions are also not well developed. Temperature transducers with the size and response characteristics necessary to accurately define the fluctuating temperature behavior at the fluid-surface interface in an environment with rapid, large, spatial variations in temperature are beyond the current state of the art.

Therefore, a key area where the current technology is weak is in the determination of the effect of the fluid boundary layer at the fluid-structure interface on the transient temperature response in the metal.

3.1.3 Metal Response to Cyclic Thermal Gradients

Although complete 3-dimensional analytical methods exist to evaluate the cyclic stress/strain history at critical locations in the structure, it is rare that sufficient definition of the 3-dimensional temperature history is available to enable a complete 3-dimensional analysis of the thermal response in the metal structure to be made. Therefore, the current design methodology utilizes simplified 1-D and 2-D thermal/structural models of the metal structure, in combination with a simplified representation of the fluid thermal condition.

It is not presently known how these simplifications affect the predicted structural response. A specific unknown is the extent to which spatial variations in the thermal gradients within the structure will affect the structural response at critical locations and sections. If it can be determined to what extent adjacent location response affects the response at critical locations, only the critical location would need to be evaluated thermally and structurally. This would permit a considerable reduction in analytic effort. Also unknown is the degree to which local geometric discontinuities concentrate the strain under thermal striping conditions; i.e., peak thermal strain concentration factors are not well established.

3.1.4 Damage Prediction and Failure Mode Characterization

The rapid temperature fluctuations in a thermal striping environment lead to repeated straining at the surface of the metal which, if severe enough, can cause crack initiation and growth. Present design methodologies are based on the use of standard linear damage assessments utilizing design curves derived from existing strain-controlled fatigue data.

Although the methodology is relatively straightforward, there exist areas of uncertainty and a lack of knowledge relative to damage prediction and failure mode characterization. The first of these is the lack of a sufficient base of empirical material failure data in the sodium thermal striping environment. Current thermal striping fatigue design criteria are based on uniaxial specimen failure data obtained from mechanically applied strain cycles often in an isothermal atmosphere other than sodium and often at strain rates considerably different from those occurring in service. Since the stress gradients imposed by thermal striping are likely to be quite different both spatially and temporally from those imposed by mechanically cycling, the needed empirical fatigue data are best determined by testing in an actual thermal striping environment. Detailed knowledge of the metal failure mode under thermal striping conditions is not available. The effect of surface conditions and the crack formation and propagation morphology are not well understood, and thermal striping damage may exhibit significantly different behavior than mechanical fatigue damage.

Since the fatigue design data currently used is based predominantly on cyclic testing to complete failure of a relatively small specimen cross section, it is generally assumed that the number of cycles from "crack initiation" to "complete failure" is not significant compared to the number of cycles required to initiate a crack. For thermal striping, it may be that the crack propagation phase is significant. Material failure data from tests in a realistic thermal striping environment are needed to address this concern. The need for crack growth tests can then be addressed when these data are available.

Ratcheting damage has been observed in tests⁽⁹⁾ of cylinders subjected to oscillatory movement of an axial temperature distribution. This damage mode is a concern associated with the reactor vessel wall structures located at the sodium surface, where there are level and temperature changes during operation. Although less likely in plate and bar structures, it is conceivable that a similar damage mechanism could occur at boundaries between hot and cold regions in a thermal

striping environment. Some analytic investigations are needed to resolve the uncertainty of ratcheting as a possible failure mode due to thermal striping. However, tests to characterize ratcheting are not proposed in this program plan.

3.2 NEEDED DEVELOPMENT

Instances of inservice failures attributed to thermal striping have been limited to a scant few.⁽¹⁰⁾ Those that have occurred were in mixing tees in piping systems that were simultaneously subjected to sustained loads as well as fluctuating thermal gradients. LMFBR internal structures normally have very low sustained loads and have apparently operated without evident damage. On the other hand, current conservative analytical evaluations of the problem have suggested that striping damage should have been detectable in at least some of these applications. The proposed program will explore whether past successes were due to good fortune or because the "problem" has been exaggerated.

Recent design concepts proposed for the upper internal structures (UIS) for large LMFBR reactors have been based on conservative analytical predictions of high-cycle fatigue damage caused by thermal striping as described in Section 3.1. The designs are based on the estimation that stainless steel can withstand high-cycle temperature oscillations of only 100°F without failure.⁽¹¹⁾ This has resulted in the use of high-strength alloys that are difficult to fabricate and unsuitable for welding. Such design concepts are very complex and, therefore, particularly unattractive for the UIS, which is one of the most difficult of the reactor components to maintain.

These considerations indicate a need for developing an improved understanding of thermal striping damage and an improved design methodology for protection against thermal striping. The goal is to establish the methodology based on an empirical data base from tests that simulate, as closely as possible, the thermal striping environment. The tests should include an experimental demonstration of striping damage of several appropriate materials (particularly alternatives to the high-alloy steels) and quantitative identification of the various parameters under which the damage occurs, including characterization of the damage and its rate of progress. This approach will reduce the design conservatism required by current lack of knowledge and permit the use of appropriate materials with confidence in their performance under known conditions of thermal cycling.

4.0 THERMAL STRIPING PROGRAM PLAN

The Thermal Striping Program Plan has been prepared emphasizing the need to obtain basic test data on thermal striping recognizing the fact that neither current design practice nor current theory of thermal striping has been adequately based on empirical data and actual damage experience. Therefore, an experimental demonstration of thermal striping, and the pertinent parameters under which damage is caused, is required.

The goal of this thermal striping program is to develop an empirically based methodology for the design of LMFBR components that operate in a thermal striping environment. This goal would be obtained through accomplishment of the following objectives:

- 1) Develop an empirical data base that provides correlation between observed damage and imposed striping environment, by experimental demonstration and characterization of thermal striping damage resulting from various experimentally defined, realistic simulations of reactor thermal striping environments. These tests will also characterize the sensitivity of time to onset of damage for variations in the imposed striping environment and for variations in the metal being tested (e.g., thickness, welds, and superimposed stress).
- 2) Develop an empirical data base that provides correlations between the fluid temperature field dynamics and field input (causative) parameters and dimensions.
- 3) Develop an improved thermal striping design methodology that is consistent with the empirical data bases, provides appropriate, known margins of conservatism, and is related to physical principles and available analytical methods to the extent found beneficial.

An improved thermal striping design methodology, which more accurately predicts the loads and resulting stresses from thermal striping environments, will improve the ability to:

- 1) Select appropriate materials of construction
- 2) Eliminate excessive conservatism
- 3) Characterize and quantify the margin against unacceptable thermal striping damage.

This improved ability will enhance the fabricability and operational reliability of LMFBFR components and should lead to more economical component designs.

The Thermal Striping Program Plan is organized into two phases: an initial scoping phase and a follow-on testing phase. The initial scoping phase is oriented to define conditions under which thermal striping damage occurs, to characterize damage progression under continued thermal striping loading, and to determine the significance of thermal striping and thermal striping damage on the structural design of components in sodium. The initial materials testing will test conventional LMFBFR construction materials in severe thermal striping environments to create accelerated thermal striping damage. It is possible that although this testing may cause thermal striping surface cracks (crazing), it may also show that crack propagation, under some thermal striping conditions, is self-limiting. If this occurs, it may be possible to use ordinary materials of construction in thermal striping environments, especially in low-stressed applications, and still retain adequate structural capability to perform the intended function during the design life of the plant even though experiencing superficial surface damage.

The effort under the follow-on testing phase of the program depends on the outcome of the initial scoping phase. Although it may be that the initial scoping phase will show that, with appropriate design features, thermal striping damage need not be a concern in the design of LMFBFRs, follow-on tests are described which would provide additional data to ameliorate thermal striping concerns if they really do exist. The follow-on tests could include:

- 1) Testing material specimens with special surface features or configurations
- 2) Testing alternative materials
- 3) Conducting extended thermal-hydraulic tests to better understand sodium mixing, heat transfer, and boundary layer film characteristics.

The effort described for each phase of the plan is subdivided into the following three areas:

- 1) Fluid temperature field dynamics
- 2) Metal temperature and metal response dynamics
- 3) Thermal striping damage and failure characterization.

A proposed schedule of testing is presented in Figure A-1. Six tasks are identified under the initial scoping phase with four additional tasks described under the follow-on phase. Concurrent with the testing and data correlation work, a task is defined in each phase for the purpose of establishing thermal striping design criteria. The program is scheduled over a 3-1/2 year period with the initial scoping phase lasting 18 months. The initial experimental work, under Task 4, has already been initiated.

Figure A-1. Thermal Striping Program Schedule

The tasks described in the plan should be considered preliminary. It is expected that, as initial results are obtained and a new understanding of the thermal striping phenomena is developed, the needs, priorities, and scheduling of the test program may change.

4.1 INITIAL SCOPING PHASE

The initial effort of this phase of the thermal striping program provides a test of the basic assumption underlying this program, namely that the current methodology for predicting thermal striping damage is unduly conservative. The first task, described below, provides an experimental demonstration of the time required to create detectable striping damage to ordinary LMFB materials of construction. If the test results show that the time predicted by current design methodology is unrealistically conservative, the initial scoping phase of the program should proceed as described herein. If, however, the test results confirm the current methodology, the scope of the proposed test program should be reconsidered.

Assuming that the basic assumption of the plan is confirmed by Task 1, the remaining tasks of the initial scoping phase may prove to be sufficient to define a satisfactory design approach, particularly if the problem proves to have been overstated.

Task 1 — Thermal Striping Damage Demonstration

The objective of this task is to determine the time to create damage in Type 316L stainless steel due to a realistic set of thermal striping conditions. Two test specimens will be tested in a sodium-filled vessel, under simulated core exit conditions, sufficiently increased in severity (ΔT) as to create striping damage in a reasonable period of time. After initial surface damage is observed, testing will be continued to characterize the nature of the damage and the rate of its propagation.

The test rig, designed specifically to perform these tests, is illustrated in Figure A-2. The test rig consists of a sodium-filled test chamber with the capability to inject hot and cold sodium jets onto the bottom surface of an oscillating test specimen. The sodium jets streams can be maintained at temperatures ranging between 700 and 1100°F with a flow rate capability in each jet of 10 gpm (10 ft/sec).

Figure A-2. Test Facility Schematic

This test rig* is installed in the ESG High-Temperature Sodium Supply System at Santa Susana, California.

The test specimens will be solid Type 316L stainless steel bars of 1/2 in. x 1/2 in. x 12 in. nominal dimensions. One bar will contain a single-sided transverse weld. Thermal shielding will be located over the top and side surfaces of the specimens to maintain relatively uniform temperature boundary conditions on these surfaces. To simulate thermal striping, each test specimen will be mounted on the articulating arm of the test rig and moved laterally through the two sodium jet plumes. The rate of cyclic motion can be varied, and sustained strain levels can be applied to the test specimen by the imposition of fixed displacements.

The test results will be compared with predictions using the current design methodology. The results of this task will establish the rationale for the subsequent tasks in the Program.

*Test rig designed and built by ESG under EPRI Contract RP-1704-11.

4.1.1 Fluid Temperature Field Dynamics

The extent and severity of thermal striping damage is a function of the magnitude and frequency of the temperature oscillations in the fluid flowing across the surfaces of the structures. For given nozzle discharge conditions, the oscillatory behavior of flow and temperature depends on the degree of thermalhydraulic mixing that is experienced by the fluid as it travels from the nozzle to the structure. It is important, therefore, to enhance mixing and mixing data should be obtained as a function of jet penetration distance for a number of nozzle configurations, discharge velocities, and fluid temperature differences. The intent of these tests is not only to measure basic jet mixing data, but also, in conjunction with the other tasks of the initial phase, to furnish tentative guidelines for LMFBR conceptual design work.

An additional objective of this effort is to determine whether water is a suitable alternative test fluid. Water has obvious advantages with respect to cost and operating ease. A water test facility is relatively inexpensive, velocity measurements are generally simple, flow visualization techniques can be used, and test article changes and modifications can be made easily. The hydrodynamic mixing of sodium and water is comparable under forced flow conditions. If it can be demonstrated that under reactor flow conditions the thermal mixing of sodium and water is also comparable, then it may be economically feasible to perform mixing experiments in water using prototypic size equipment. The mixing test program therefore includes an initial series of sodium and water mixing tests on small-scale equipment to determine whether mixing correlations between sodium and water are possible and whether subsequent mixing experiments using larger scale water test facilities are feasible.

Task 2 — Experimental Evaluation of Mixing in Sodium

The objective of this task is to obtain experimental data on basic mixing behavior in sodium for a number of nozzle diameters, fluid velocities, and hot-to-cold ΔT s. The fluid dynamic properties during the heat and mass mixing of two sodium jets will be measured in a sodium test rig consisting of a simple cylindrical sodium-filled vessel into which parallel streams of sodium at different temperatures can be injected into an unobstructed sodium plenum (i.e., no structural impingement surfaces will be placed in the vessel).

Data of interest are characterization of the mixing jets, particularly the frequency spectrum of the temperature fluctuations and the decay with distance of the amplitude of the temperature oscillations, due to mass and thermal mixing of the sodium streams.

Initial testing can be performed in the ESG Striping Test Facility described in Task 1. It is anticipated that additional testing will be required using a longer tank than is currently available in the ESG facility to explore jet phaseout in the region of complete thermal mixing. (The need for a longer tank can be determined by the near-surface observations during the calibration runs of Task 4.)

Task 3 — Experimental Evaluation of Mixing in Water

The objective of this task is to obtain experimental fluid thermal mixing data in water to provide a basis for developing mixing correlations with the sodium test data of Task 2 to see if water can be a suitable alternative test fluid. Initially, the water tests will be conducted for the simple fluid mixing configuration used in Task 2. Appropriate instrumentation, such as thermocouples and dye cells, will be used to observe and measure the dynamic fluid mixing behavior. The water test tank, however, should be sufficiently high to permit essentially complete thermal mixing of the two water jets so as to permit additional tests with variable mixing height.

Following these unobstructed fluid field tests, additional tests with simple geometric obstructions in the flow stream will be conducted. These tests will provide a better understanding of thermal-hydraulic fluid behavior, including flow blanketing characteristics, in representative LMFBR geometries. The sodium-water correlations developed under this task will be used to evaluate the data from available design-specific UIS water tests to determine the suitability of using Type 316L stainless steel in current LMFBR UIS designs.

4.1.2 Metal Temperature and Metal Response Dynamics

Task 4 — Experimental Evaluation of Effects of Velocity and Oscillation

The objective of this test is to obtain direct temperature measurements in the fluid and in the structure of a metal specimen immersed in a thermal striping environment to enable the direct observation of metal temperature response dynamics. A series of in-sodium tests will be conducted utilizing the sodium test rig described in Task 1 and thermocouple instrumented metal test specimens.

Sodium jets of different temperatures will be injected into the tank at controlled flow rates and will impinge on the instrumented specimen in a manner simulating a thermal striping environment. Recorded measurements of the response of the specimen and corresponding measurements of the fluid field temperature will be used to determine the effects of fluid jet velocity and separation distance and to observe the effects of the fluid boundary layer at the fluid-metal interface.

Tests will be conducted utilizing different flow rates, temperature differences, separation distances, and oscillation frequencies. Additional tests to establish the effect on specimen temperature dynamics due to specimen geometry and orientation may also be performed.

This testing has already been initiated in the ESG Thermal Striping Test Facility to define the thermal environment for the Task 1 test series.

4.1.3 Thermal Striping Damage and Failure Characterization

Task 5 — Thermal Striping Damage Test

This task is an extension of the thermal striping damage demonstration test conducted under Task 1 with the objectives of obtaining data on the threshold parametric values relating to damage and of characterizing the damage. Once a set of conditions that cause damage have been found from Task 1, further tests of Type 316L stainless steel will be made, in which the test parameters (i.e., frequency, temperature difference, and flow rate) will be varied to determine the sensitivity of the damage phenomenon to these parameters. When Type 316L bar material is characterized, a selected set of tests will be conducted on Type 316L weldments to identify any differences in thermal striping damage to the weld material. Testing will then be conducted on specimens that are preloaded to induce mechanical stress in the test specimens. Preloading is accomplished with a preloading rod in the test fixture which can exert a vertical load on center of the specimen. Stress levels can be set by setting specimen end fixity and the loading conditions. Additional testing will also be done for specimens of varying thickness to determine the relationship between thickness and thermal striping damage. Thin members may show reduced thermal striping damage, and this testing may be significant in establishing the feasibility and usefulness of thermal baffles.

The initial tests, under each test series, will attempt to establish the conditions that establish the onset of thermal striping damage. However, the

characterization of thermal striping damage progression is also a major objective of the test. Therefore, once damage appears, such as initial surface crazing, selected test specimens will be subjected to continued thermal striping to quantitatively characterize the progress of the damage.

Post-test metallographic examination and testing of the test specimens after removal from the striping test rig are required to quantify damage progression in the specimen and to determine the effects of damage on the specimens' ability to sustain loads. The results of the tests will provide an empirical data base from which to establish design information applicable to structures subjected to thermal striping. If crack formation and growth is found to be self-limiting, the data will be evaluated to determine the suitability of the materials for use in LMFBRs in a partially damaged condition.

The testing under this task will be performed in the ESG Thermal Striping Test Facility described in Task 1.

4.1.4 Thermal Striping Damage Criteria and Design Guidelines

Task 6 — Interim Thermal Striping Damage Correlations and Design Guidelines

The objective of this task is to obtain a correlation of the thermal striping damage observations. The results obtained from the thermal striping damage tests (Tasks 1 and 5) will be analyzed, evaluated, and compared to correlate the observed damage to the imposed environment and loading parameters. The data obtained from each test series will be examined, and an attempt will be made to correlate the results on a common basis. A comparison and correlation of the test data will also be made with thermal striping damage data, where available, from thermal striping testing conducted in the United Kingdom and in the United States.

The test data and correlations for Type 316L stainless steel will be extrapolated to assess the thermal striping damage potential of Type 316L stainless steel under representative LMFBR UIS operating conditions. This effort will attempt to evaluate the acceptability of Type 316L stainless steel for application to the UIS in LMFBR design.

The results of the various tests and analytic investigations will be summarized, evaluated, and synthesized into recommended damage criteria and design guidelines for protection against thermal striping. The effort will be initiated early

in the initial scoping phase to provide interim damage criteria and design guidelines for LMFBR design.

The results of this task, in combination with the results from Tasks 1 through 5, will show whether or not any additional follow-on testing work is required before an overall thermal striping damage criteria and design guidelines document for LMFBRs, as described in Task 10, can be formulated.

4.2 FOLLOW-ON TESTING PHASE

If the results of the initial scoping phase does not confirm the adequacy of using Type 316L stainless steel in a practical UIS configuration, further testing involving other materials and other configurations would be indicated. Therefore, the following sections outline three follow-on tasks that would extend the knowledge of thermal striping damage in materials, provide a more complete understanding of the thermal-hydraulic parameters influencing thermal striping damage, and investigate design features that could mitigate thermal striping loads.

The results of the tests and analysis conducted during the initial scoping phase of the program may show the need for additional experimental and analytical tasks. Any decision to modify the proposed follow-on testing phase should, therefore, be considered at the completion of the scoping phase.

4.2.1 Fluid Temperature Field Dynamics

Task 7 — Experimental Investigation of Mixing Behavior

The objective of this task is to identify, by testing, design features and configurations that will enhance fluid jet mixing to mitigate thermal striping environments. A test will be conducted, which could be with sodium or water, depending on the results of the sodium and water tests from Tasks 2 and 3. Special reactor outlet nozzle configurations, with diameters up to 6 in., could be tested. Following the unobstructed fluid field tests, additional tests with alternative mixing plenum configurations could be conducted.

4.2.2 Metal Temperature and Metal Response Dynamics

Task 8 — Experimental Investigation of Surface Geometry

The objective of this task is to determine experimentally the effect of surface geometry on the resistance to thermal striping damage. A series of metal samples with different surface geometry conditions will be tested in a sodium thermal striping environment. The samples will be identical, except for surface geometry, to those used for the thermal striping damage tests in Tasks 1 and 5.

It is recognized that the thermal striping conditions in the bulk sodium fluid field can be mitigated by the fluid boundary layer at the fluid-metal interface. It should be possible, therefore, to design surface geometries that enhance the boundary layer capability to perform this function. Providing special surface geometries, however, may create locations of thermal strain concentration that could aggravate thermal striping damage. The testing of special surface geometries will show if this approach to mitigating thermal striping damage is feasible.

4.2.3 Thermal Striping Damage and Failure Characterization

Task 9 — Thermal Striping Damage Characterization

The objective of this task is to extend the thermal striping damage tests initiated under Task 5. Depending on the outcome of the initial scoping tests, additional testing may be required under the testing conditions of Task 5, or alternative testing conditions, to further characterize material damage and test alternative materials.

Additional materials with potential for LMFBR application in thermal striping environments, such as Type 347 stainless steel, 2-1/4 Cr - 1 Mo steel, 9 Cr - 1 Mo steel, and their weldments, may also be tested in this test series. The effect of sustained strains on the test specimens could also be investigated. Resistance to thermal striping damage would then be correlated to pertinent material parameters in order to form a basis for selection of alternative materials for design.

Specimens with alternative overall geometries and surface condition may also be considered. If the testing under Task 8 shows that the use of special surface geometries enhances the fluid boundary effect and mitigates the thermal striping condition, the testing of these specimens for damage characterization will be undertaken.

The ESG High-Temperature Sodium Supply System, mentioned in Task 1, has the capability of adding a second thermal striping test rig to double the facility testing capability. This option could be exercised if the results of the initial scoping tests warrant an expanded testing effort.

4.2.4 Thermal Striping Damage Criteria and Design Guidelines

Task 10 — Thermal Striping Damage Criteria and Design Guidelines

The objective of this task is to provide a document containing guidelines and criteria for the designer of components subjected to thermal striping. This task will consist of synthesizing the results of the various elements of this thermal striping program into a recommended thermal striping design guideline. The damage mechanisms to which metal structures are subjected in thermal striping environments will be identified. Recommended limits will be established for various metals to limit damage to acceptable levels, based on considerations of safety, function, and consequence of failure. Guidelines will also be presented for a design methodology to provide protection against the consequences of thermal striping damage in LMFBR internal structures. Summaries of the significant results from the tasks investigating fluid mixing dynamics, boundary layer behavior, and metal temperature response will be included to enable the designer to understand the effect and significance of the various parameters. Interim guidelines will be documented as the guidelines are being developed.

5.0 THERMAL STRIPING PROGRAMS IN THE U.S. AND THE U.K.

Within the past several years, serious concern has arisen in the LMFBR programs of the United States and the United Kingdom over the possibility of fatigue damage caused by the thermal striping phenomena. Since 1976, the United Kingdom Atomic Energy Agency (UKAEA) has conducted a combined experimental and analytic program to study thermal striping of the above core structure in support of the Prototype Fast Reactor (PFR) project. In 1978, the U.S. Department of Energy (DOE) convened an LMFBR industry task force to recommend R&D programs to address the thermal striping question. The resulting program of experimental specimen tests has been aimed at evaluating the thermal striping resistance of materials specified for the upper internal structures of the Clinch River Breeder Reactor Plant (CRBRP). A description of some of these activities is presented here.

5.1 U.K. THERMAL STRIPING PROGRAM

The UKAEA development program to study the potential for thermal striping damage to the above core structures includes the following activities:

- Material thermal fatigue studies using a mixing tee geometry to generate a representative temperature field
- Air and water studies on flow models of the reactor region or representative sections thereof
- Reactor measurements with specially inserted instrumentation
- Theoretical study of the modeling criteria between air or water and sodium
- Theoretical studies to relate component temperature fluctuations to stress fluctuations
- Experiments to relate component surface temperature fluctuations to fluid temperature fluctuations.

Pertinent highlights from published results of these studies are discussed below.

5.1.1 Thermal Fatigue Studies

Thermal fatigue tests on tubular specimens (12-mm diameter, 3-mm wall thickness) have been conducted using the sodium mixing tee test rig shown in Figure A-3. For comparison of the results with conventionally obtained fatigue data, the fluid temperature fluctuations were measured and assumed to exist at the surface of the component. The temperature fluctuation was analyzed for relevant thermal shocks and then converted to a stress fluctuation. Fatigue was assessed using a linear damage law (Miner's Law). Some test results conducted for Type 316 stainless steel are tabulated below:

Test	Specimen	Input ΔT ($^{\circ}\text{C}$)	Peak ΔT Shock ($^{\circ}\text{C}$)	Duration (h)	Specimen Damage
1	1	200	160	313	Not cracked
2	2	300	160	311	Cracks initiated
3a	3	230	200	300	Not apparently cracked
3b	3	230	200	+300	Cracks generated from starter cracks only

These data trends were concluded to be reasonably consistent with conventionally acquired fatigue data obtained in sodium, and, on the basis of this, a conservative material temperature fluctuation limit of 145 $^{\circ}\text{F}$ (63 $^{\circ}\text{C}$) was specified as acceptable for Type 316 stainless steel in the PFR.

5.1.2 Model Tests to Measure Fluid Characteristics

A series of air and water tests have also been conducted in the UKAEA program. The tests were performed using models of portions of the reactor internal structures that are subjected to thermal striping in PFR. These components included the control rod shroud tubes (CRST), the antivibration grid (AVG), and the charge hole instrument plug (CHIP).

The methodology was to use these air and water tests of the model systems to obtain data on the surface temperature fluctuations and amplitudes under simulated thermal striping conditions. These results were then used to assess potential thermal striping damage by utilizing limits obtained from the sodium tee thermal fatigue tests described above.

Figure A-3. Random Thermal Fluctuation
Fatigue Test Section

In their PFR modeling studies, the UKAEA ran two water tests and two air test as follows:

- Control Rod Shroud Tube Model (Water): This was a water test of a full-size, single-control rod absorber assembly surrounded by six fuel assemblies. The measurements, made with bare wire thermocouples inserted at fixed positions, showed that the peak-to-peak temperature fluctuation amplitude could approach the inlet temperature difference.
- Thirty-Two Subassembly One-Half-Scale Lozenge Model (Air): This was an air test that considered different heating rates in simulated fuel, blanket, and control rod absorber assemblies (one-half-scale geometric model of the above core structure). Measurements of air flow were taken with hot wire anemometers used as dynamic thermometers. These tests indicated that the amplitude of the temperature fluctuations apparently reach a peak of 80 to 90 percent of the input temperature difference during the first meter (reactor scale) of flow, and then diminish.
- One-Fifth-Scale Model of the Outlet Pool (Water): In this water test, the above core components were modeled in one-fifth scale. Temperature differences were simulated by tracing the breeder subassembly flows, and buoyancy effects were simulated by using brine for these flows. Dye cells (response approximately 20 Hz) were used to detect concentration fluctuations. This highly geometry-dependent test indicated that, depending on location, the peak-to-peak fluctuations in the water at the above core structures ranged from 65 percent down to 30 percent of the test assembly inlet temperature difference.
- One-Ninth-Scale Model of the outlet Pool (Air): This test was similar to the 1/5-scale model test, except that it was fitted with individual temperature control flow jets over a 120° sector of the reactor cross section. Hot wire anemometers were again used as dynamic temperature sensors. The results of these tests have not been published.

5.1.3 Studies of Modeling Criteria

Theoretical studies of the fluid dynamics problem associated with thermal striping have been conducted by the UKAEA. The simplification of the fluid problem to that of a series of temperature steps generated in a plane and moving downstream has been investigated. Their degradation with time and, hence distance, was treated as a transient heat transfer calculation with the turbulent Prandtl number considered as the relevant parameter. The study concluded that for sodium Reynolds numbers of approximately 10^6 , air and water models with equivalent Reynolds numbers of approximately 10^5 will provide adequate fluid dynamic representations.

5.1.4 Studies of Relationship of Surface Temperature and Stress

Analytic investigations of the behavior of the stress field in a metal structure due to a fluctuating temperature field applied at its surface were conducted. To simplify the problem, only 1-dimensional heat flow and stress distributions were considered. Parameters investigated were material geometry (thickness from input surface) and frequency of oscillation of surface temperature. The surface temperature time sequence was assumed to vary sinusoidally. Some work was also performed to study response to random surface temperature variation.

5.1.5 Studies of Relationship of Fluid Temperature and Metal Surface Temperature

In all of the analyses of the data discussed above, it has been assumed that the temperatures measured in the fluid were fully applied to the surface of the component. This conservative assumption disregarded any mitigating effect of the boundary layer. Experiments were to be planned in sodium and in the reactor to obtain data related to this factor. No published reports have been found on the results of these tests. Tasks proposed in this program plan are intended to investigate these boundary layer effects.

5.2 U.S. THERMAL STRIPING PROGRAM

The DOE-sponsored activities relating to thermal striping investigations consist of water tests of a model LMFBR reactor vessel at the Argonne National Laboratory (ANL) and an in-sodium thermal striping material test program at Westinghouse Advanced Reactor Division (WARD). These activities are briefly described below.

5.2.1 Argonne National Laboratory Water Tests

Water tests have been conducted at the Argonne National Laboratory hydraulic test facility on a scale model CRBRP reactor vessel and upper internal structure. Fluid temperature fluctuations and amplitudes have been studied by dye injection and measurement of dye concentration and thermocouples. The initial tests focused on upper plenum mixing, the reactor vessel outlet nozzle transients, and the fluctuating axial thermal gradient on the vessel wall that occurs as the hot-cold sodium interface moves during transient reactor operation.* Subsequent tests have studied the core outlet fluid mixing characteristics and established the thermal striping environment on the CRBRP upper internal structure.

5.2.2 In-Sodium Materials Testing

The Westinghouse Advanced Reactors Division has run tests wherein a heated block of stainless steel, instrumented with three thermocouples, was dunked alternately into baths of different temperature liquid sodium. Although this simple test produced results for crack propagation studies, the experimental data are only of limited value because the heat transfer and fluid dynamics characteristics differ significantly from those in the thermal striping environment.

WARD has also performed sodium jet thermal striping fatigue tests in support of the design of the upper internals structures for CRBRP. In this test setup, the specimen is a vertical hollow cylinder that is spun, in an argon atmosphere, between two sodium streams, one hotter than the other. This experiment is designed to study thermal striping induced failures. By adjustments of the fluid stream temperatures and cylinder spinning speed, the amplitude and frequency of the imposed fluid temperature fluctuations can be controlled.

This test program has been underway since 1978. To date, comparative tests of Inconel 718 and austenetic stainless steel have been made, and approximately seven tests using Type 316 stainless steel specimen have been performed. The current tests are being performed with sodium stream temperatures of 500 and 900°F (400°F

*Studies of this problem have been, or are being, conducted by the UKAEA in England, EdF in France, and PNC in Japan. The fluctuating sodium level problem (analysis and experimental results) has been adopted as a benchmark problem for the International Benchmark Project on Simplified Methods for Elevated Temperature Design and Analysis by the PVRC (Pressure Vessel Research Committee) of the Welding Research Council.

stream temperature differential). Previous tests have shown cracking in Type 316 stainless steel with sodium stream temperature differentials of 500 and 600°F. A serious shortcoming of the test setup is the poor simulation of the fluid dynamic and heat transfer characteristics of the thermal striping environment. The tests proposed in this program plan are intended to provide more realistic representations of the thermal striping environment.

REFERENCES

1. C. Boorman, "Thermal Striping of the PFR Above Core Structure," (November 1977) transmitted by W-ARD Letter TM-78-024 dated January 31, 1978, R. F. Ranellone to Distribution
2. "Report of the National Task Force on Thermal Striping in LMFBRs," ANL-CT-78-46, P. R. Huebotter, Ed., p 3.29-3.31 (September 1978)
3. Herman Schlichting, "Boundary Layer Theory," 7th Ed.; McGraw-Hill Book Co., New York, (1979)
4. J. J. Lorenz and P. A. Howard, "A Study of CRBR Outlet Plenum Thermal Oscillations During Steady-State Conditions," ANL-CT-76-36 (July 1976)
5. P. A. Howard, "Steady-State CRBR Outlet Plenum Mixing with an AFMS Core," ANL-CT-77-14 (April 1977)
6. P. A. Howard, "Influence of Heterogeneous Core Geometry Upon Outlet Plenum Mixing," ANL-CT-78-8 (November 1977)
7. "Report of the National Task Force on Thermal Striping in LMFBRs," ANL-CT-78-46, P. R. Huebotter, Ed., p 5.1 (September 1978)
8. K. E. Kasza and W. S. Colwell, "Characterization of the Temperature Fluctuations Generated in a Thermal Mixing Tee (Sodium vs Water Behavior)," ANL-CT-78-1 (November 1977)
9. R. T. Bell, "Ratchetting Experiments on Thin Cylinders Subject to Axially Moving Temperature Fronts," UKAEA Report ND-M-1325(R) (October 1980)
10. "Report on US/UK Information Interchange Meetings of May 8-9, 1978" Section 3.2, transmitted by W-ARD Letter TM-78-167 dated June 8, 1978, P. J. Angeline to Distribution
11. "Report of the National Task Force on Thermal Striping in LMFBRs," ANL-CT-78-46, P. R. Huebotter, Ed., p 2.2 (September 1978)