QUARTERLY TECHNICAL PROGRESS REPORT
HIGH-TEMPERATURE
PIPING DESIGN
TECHNOLOGY
JULY – SEPTEMBER 1976

ERDA Research and Development Report

*Prepared for the United States
Energy Research and Development Administration,
Division of Reactor Research and Development,
under Contract Number E(04-3)-824*

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The preceding Progress Report was AI-ERDA-13177

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CONTRACT: E(04-3)-824
ISSUED: DECEMBER 15, 1976

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Program: High-Temperature Piping Design Technology

ERDA Task: 21 - High-Temperature Piping Design

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Reporting Period: July-September 1976

Category: KG-10-04-02.2

General Order: 09146

Subaccount: 13000

189a Number: SA020

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I. PROJECT OBJECTIVES

The overall objectives of the High-Temperature Piping Design Technology Program are:

- 1) To provide design methodology for elevated temperature piping systems based on experiences in FFTF, LMEC, and CRBRP designs and from operating high temperature piping systems.
- 2) To assess the validity of using current high temperature Code Case 1592 design rules on Piping Systems.
- 3) To investigate critical piping system design problems from the design criteria viewpoint.
- 4) To increase the confidence level in high temperature design rules for piping by demonstrating the conservativeness of these rules.

This project has several major tasks, each supportive of one or more of these overall objectives. One of these tasks is the development and updating of a long-range program plan (PIPLAN) to assure piping integrity for current and future LMFBR plants. This plan will identify:

- 1) The design logic used in identifying PIPLAN program areas and needs.
- 2) The specific tasks required to achieve a high level of piping structural reliability.
- 3) Tasks required in support of a probabilistic assessment of piping integrity.
- 4) A schedule for completion and a definition of work under way for each task.

Another major task of this project is to assess and catalog relevant operating experience and failures in piping of SRE, HNPF, Fermi, EBR-II, SCTL, LCTL, other operating sodium systems and foreign reactors. These data will provide:

- 1) A basis for selecting one or more elevated temperature piping loops which were designed to a less stringent criteria than Code Case 1592, yet have been operating successfully without failures
- 2) Support for piping integrity assessments which have taken the position that low level leakage would precede any large rupture
- 3) Substantiation for judgemental assumptions, with regard to causes and modes of piping failures which must be made in a probabilistic reliability evaluation of piping.

Another major task of this project is to survey sodium piping construction records for defects detected at installation. These data will be assessed and catalogued in a manner which can assist the refinement of probabilistic characterizations of initial defects that may be present in LMFBR primary piping at reactor startup.

Another major task of this project is the Code Case 1592 evaluation of selected sodium piping systems which have been operating successfully, yet were designed to a less stringent criteria than contained in Code Case 1592. The results of both elastic and inelastic analyses will be used to demonstrate, based on actual operating experience, that the design rules contained in Code Case 1592 are conservative.

Another major task of this project is the evaluation of the impact on design margins of variations between actual and assumed material, geometry and loading characterizations. This will be achieved through data collection, testing and analysis activities. The results will provide:

- 1) An identification of those design parameters whose variations have the greatest impact on design margins
- 2) Guidance for preparing design specifications, selecting fabrication processes, defining critical tests and establishing dimensional tolerances

- 3) The groundwork for future reliability evaluations of the piping integrity obtainable using the current design codes.

Another major task of this project is the experimental evaluation of the creep-fatigue damage produced by high cycle, small amplitude oscillations in the presence of sustained stresses in the creep temperature range. These data will assist in resolving the current questions on the influence of mean stress on the high cycle fatigue life of Code materials and support extension of the Code Case 1592 fatigue curves beyond 10^6 cycles.

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

Another major detail of this project is the preparation of interpretive reports presenting a methodology for the design of elevated temperature sodium piping systems. These reports will present practical guidelines for the design and required analysis of LMFBR high temperature piping systems. Emphasis will be given to providing practical data in terms of analytical modeling methodologies and Code evaluation techniques.

The final major task of this project is the thermal transient and mechanical testing of piping elbows and bare pipe clamps. The elbow tests, as presently scoped, will:

- 1) Verify the current analytical assumption that radial thermal gradients do not influence the load-deflection characteristics of pipe elbows, nor the mechanical load carrying capacity.
- 2) Verify the current design methodology for elevated temperature piping by running combined thermal transient and cyclic load histories in an accelerated environment.

The bare pipe clamp tests are to provide a benchmark against which analytical modeling techniques can be developed for the clamp-pipe interaction.

II. MAJOR ACCOMPLISHMENTS DURING FISCAL YEAR 1976

A draft of the proposed Piping Integrity Plan (PIPLAN) was completed by the PIPLAN Working Group members and released to ERDA for review and comment. This plan establishes key tasks and schedules to assure piping integrity for current and future LMFBR plants.

A plan for piping failure data acquisition was released as AI Report, N146 TI350003. It sets up an extensive survey of US and overseas sodium piping facilities using verbal, written and in-person communications with identified cognizant personnel. An interim AI Report, N146 TI350004, on the results of the piping failure survey was released. It lists verified pipe leaks and their locations, a world-wide listing of sodium facilities, and a proposed questionnaire to be sent to the various facilities.

The selection of a long term high temperature piping line with a successful operating history was documented in AI Report, N146 TI1350001. The selected line was 2 in. (5 cm) dia, Type 316 stainless steel piping which operated over 10,000 h with a year of its life in-service above 1300° F (704° C). A plan for evaluating the piping line per Code Case 1592 was released as AI Report, N146 TI1250001. The intent is to establish the conservatism in the current Class 1 design rules using both elastic and inelastic analysis results. Stress Report, N146 SR250001, Change 1, presents the results of a Code Case 1592 elastic evaluation using the NB-3600 piping equations in a manner proposed by the ASME Working Group on High Temperature Piping. The results indicate the design could not have passed the Code Case 1592 criteria since damage fractions for some rules were as high as 7000.

The plan for performing a sensitivity study of elevated temperature design margins to variations in material, geometry, and loadings was completed and released as AI Document, N146 TI150-001. The efforts will be a combination of data collection, testing, and analysis.

An interim report, Battelle Memorial Institute (BMI), Order N615-0243P, on the high cycle fatigue behavior of metals at elevated temperature was completed. This report contains discussion of the technical approach, accomplishments during the reporting period, plans for future work and a tabulation of continuous fatigue data on 2-1/4 Cr - Mo.

A formal request for Approval-in-Principle (AIP) was completed and sent to LMEC for review and comment. The proposed testing was for thermal transient testing of piping elbows and clamps. Since then, meetings with LMEC and ERDA have identified revisions needed in the initial proposal.

III. PROGRESS DURING REPORT PERIOD

A. SUBTASK A - PIPLAN DEVELOPMENT

No activities in support of the Piping Integrity Plan were performed during the report period.

B. SUBTASK BI - COLLECTION OF PIPING FAILURE DATA

During the report period, additional information was obtained in the area of failure, facility, and cognizant personnel identification. A total of 29 piping failure incidences were identified as summarized in Table 1. These were obtained from those facilities listed in Table 2. Note that some of these facilities had not experienced any piping failures. Of the 29 reported failures, 9 of them can be positively attributable to environmental corrosion, 5 of them to heater malfunctions, 4 of them to human errors during service, and 4 of them to defective welds. Of the remaining 7 failures, 3 of them have unknown causes and the remaining four are as follows:

- 1) 1966 BR-5 facility failure in a drain pipe transition [1 in. (2.5 cm) to 2 in. (5 cm)] was caused by a restricted piping movement due to design errors.
- 2) 1973 CEL-1 facility failure in a 1/2 in. (13 mm) x 0.049 in. (1.2 mm) mixing tee due to thermal fatigue.
- 3) A failure in a GE pipe tee and in a MSAR pipe due to "cracks."

An interim report, N146TII350004, was released which presents the details of piping failure incidences identified to date. It also includes a sample of the questionnaire to be sent to sodium facilities in the US and abroad. The conclusions of the interim report are that only limited failure definitions can be obtained from the literature and a questionnaire/followup approach to data collection is required before sufficient detail for a comprehensive evaluation is obtained.

TABLE 1
SUMMARY OF SODIUM PIPING FAILURES

Item No.	Facility	Location	Cause
1	BR-5	Drain Pipe	Heater short circuit burn through
2	BR-5	Drain Pipe Transition	Restricted pipe movement - design
3	CEL-1	1/2 in. (13 mm) x 0.049 in. (1.2 mm)	Thermal fatigue
4	DFR	Main Pipe	Stress corrosion
5	DFR	Pipe Stub	Defective weld
6	DFR	Filling Line - 1 in. (2.5 cm)	External corrosion - environment
7	DFR	Dump Line - 2 in. (5 cm)	External corrosion - environment
8	DFR	Bypass Line - 3/4 in. (1.9 cm)	External corrosion - environment
9	DFR	Hx Feed Pipe	Defective weld
10	EBR-II	Hx System Pipe	Human error
11	GE	Pipe Tee	Cracks
12	GE	Piping	Not available
13	GPL-1	Fill Line - 1/2 in. (1.3 cm)	Thermal stress - human error
14	HNPF	Overflow Nozzle	Corrosion from products of primary leak in tank
15	KNK	Pipe - 1 in. (25 mm)	Not available
16	KNK	Pipe - 2 in. (50 mm)	Welding
17	KNK	Pipe - 1 in. (25 mm)	Not available
18	LCTL(LMEC)	Pump Discharge Line	Intergranular corrosion - environment
19	LCTL(LMEC)	Elbow - 1 in. (2.5 cm)	Intergranular corrosion - environment
20	MSAR	Piping	Heater arc burn through
21	MSAR	1/2 in. Pipe (1.3 cm)	Heater failure
22	MSAR	Pipe	Cracks
23	ORNL	Pipe	Corrosion
24	ORNL	Pipe	External corrosion
25	PFR	16 in. (40.6 cm) Pipe	Human error - touched by welder's torch
26	Rapsodie	Fill and Drain Pipe	Localized overheating burst innerwall of double-wall pipe
27	SCTI(LMEC)	10 in. Line (25 cm)	Human error - tack weld to line
28	SCTI(LMEC)	2 in. Line (5 cm)	Substandard weld
29	SRE	2 in. Line (5 cm)	Heater arc burn through

TABLE 2
FACILITIES WITH SOME DESIGN INFORMATION AVAILABLE

Argonne National Laboratories - Argonne, Illinois

*1. CCTL/FARET

Argonne National Laboratories - Idaho Falls, Idaho

2. EBR-II

Atomics International - Canoga Park, California

*3. HTSS

4. SRE

*5. STL

Fermi Atomic Power Plant - Newport, Michigan

*6. FERMI

Hallam Nuclear Power Facility - Hallam, Nebraska

7. HNF

Hanford Engineering Development Laboratory - Richland, Washington

*8. HTSF

*9. TTL

Liquid Metal Engineering Center - Canoga Park, California

*10. ITR

11. SCTI

*12. SCTL

*13. SPTF

Mine Safety Appliance Research - Evans City, Pennsylvania

*14. MSAR

Westinghouse Advanced Reactors Division - Waltz Mill, Pennsylvania

15. GPL-I

*16. GPL-II

*No sodium pipe leaks found reported from these facilities

C. SUBTASK BII - SURVEY OF CONSTRUCTION RECORDS

The subtask was initiated with interviews at Atomics International and LMEC to locate suitable construction records.

D. SUBTASK BIII - ANALYSIS OF SYSTEMS WITH PRIOR SUCCESSFUL OPERATING HISTORY

A structural evaluation of the SNAP 8-ER outlet piping was completed per the elastic criteria contained in Code Case 1592. The results are presented in stress report, N146SR250001, Change 1. It failed to pass the creep damage portion of the elastic creep-fatigue rules, even though only a portion of the service life was considered in the evaluation. A sketch of the Type 316 stainless steel, 2-in. (5 cm) diameter piping loop is presented in Figure 1. It was operated successfully for over 10,000 h with over a year of its life in service above 1300° F (704° C). A summary of the elastically computed maximum stress intensities are presented in Table 3, and a summary of the computed design margins are presented in Table 4. The magnitude of the negative design margins for creep damage indicates the current elastic based creep damage rules are excessively conservative for service lives similar to that of the SNAP 8-ER piping line (long term, high temperature sustained operation).

Next, a MARC inelastic analysis of the SNAP 8-ER was initiated. Due to the high cost of inelastic solutions and limited funding available, considerable effort was expended to develop the least expensive, yet sufficiently accurate, computer model. A reevaluation of the questionable weld integrity (see N146SR250001) at the top of the support cylinder was performed in order to avoid the need for two solutions based on differing boundary conditions. This resulted in a reasonable justification for assuming the weld unbroken at the end of service. Therefore, only the side of the piping loop above the weld, indicated in the elastic solution as the higher stressed portion, needed to be modeled. Additionally, several computer models of this section of the line were evaluated on an elastic basis in order to select the least expensive, yet convergent model.

Two models incorporated a series of straight pipe elements with two levels of refinement. The more refined model could predict internal moments adequately; however, predicted stresses were considerably in error. Therefore,

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Figure 1. S8ER Schedule 5 Reactor Outlet Line

TABLE 3
COMPUTED MAXIMUM STRESS INTENSITIES

Assumed* Support Conditions	Critical† Location NODE Number	P _m (psi)	P _l + P _b (psi)	(P _l + P _b + Q) Maximum (psi)
Type I: NODE 141 acts as a guide	80 (bend)	---	---	24,176
	240 (straight)	445	3,080	---
Type II: All motions restrained at NODE 141	45 (bend)	443	1,460	---
	190 (elbow)	---	---	90,248

*The integrity of the weld at NODE Location 141 is critical to the characterization of the piping line behavior. It could not be determined whether this weld failed or not during service and, therefore, two support conditions were assumed:

I: The weld had failed shortly after the beginning of service.

II: The weld had not failed during service.

†NODE numbers refer to Figure 1.

TABLE 4
COMPUTED DESIGN MARGINS*

Assumed Support Condition	Critical Location No.	Primary Stresses		Strain Limits		Creep-Fatigue	
		P _m	P _l + P _b	Test 2	Test 3	n/ND	t/TD
Type I: NODE 141 acts as a guide	80 (pipe bend)	0.908	0.789	-0.082	1.0	NC	-1280
Type II: All motions restrained at NODE 141	190 (elbow)	0.904	0.759	-2.98	1.0	NC	-7040

*Design margins were computed using: 1.0 - (value computer ÷ value allowed), i. e. , a negative value indicates inability to satisfy the applicable requirements.

NC= not computed.

the use of the MARC elbow element based on shell of revolution elements became necessary. Several models were evaluated and problems internal to the AI version of MARC were corrected before a satisfactory model was generated. The elbow models selected had 30° segments around the bend and 10 segments around the cross-section.

Inelastic runs were initiated and immediately problems were encountered when applying increment thermal loadings containing pressure loading. The problem was internal to the MARC program and could not be corrected. Therefore, pressure stresses, which are very low (<500 psi) were eliminated and, only dead weight and thermal loading considered. Completion of the inelastic runs is anticipated during the next reporting period.

E. SUBTASK C - EVALUATION OF SENSITIVITY OF PIPING DESIGN MARGINS TO VARIABILITY IN MATERIALS, LOADING, TEMPERATURE, AND GEOMETRY

Efforts on this subtask are approximately 1 month behind schedule as established in the sensitivity study plan (N146TI150-001). Over 80 documents have been obtained, and nearly one third of them have been reviewed to establish base cases (piping component - parameter variability to be studied and/or failure mode) for evaluation. This selection of base cases will establish the scope of the evaluation and must consider the availability of simplified structural models, the potential for parameter variability and the significance to CBR and PLBR of particular components and/or failure modes.

F. SUBTASK D - HIGH CYCLE FATIGUE BEHAVIOR AT ELEVATED TEMPERATURE (BMI)

The existing data for continuous cycling of 2-1/4 CR - 1 Mo steel at temperatures from 77 to 1100° F (25 to 593°C) were recorded on computer cards to facilitate analysis and comparison with data being developed.

Six fatigue tests were completed during the reporting period. These and the previous test are summarized in Table 5. Plots of the data obtained from the present study are presented along with other existing data in Figure 2 and 3. The difference between current data and previous data in Figure 2a is most likely a result of variation of material heat treatment; however, such variations are anticipated in actual practice and the data are considered to be representative of 2-1/4 Cr - 1 Mo steel.

TABLE 5
FATIGUE DATA ON ISOTHERMALLY ANNEALED 2-1/4 Cr - 1 Mo PLATE TESTED
UNDER FULLY REVERSED (NO MEAN STRESS) CYCLING IN AIR

Specimen	Control Mode	Total Axial Strain Range (%)	Inelastic Axial Strain Range (%)	Stable Stress Range, MN/m ² (ksi)	N _o	N _s	N _f	Time to Fracture (h)
At (600° F) 316° C								
FL-14	Strain at 0.004 sec ⁻¹ for entire test	0.40	0.09	606 (87.9)	23,000	26,200	28,400	15.8
FL-6	Strain at 0.004 sec ⁻¹ for entire test	0.31	0.02	549 (79.6)	224,700	-	236,800	105
FL-15	Strain at 0.006 sec ⁻¹ to cycle 73,900; load at 6 Hz thereafter	0.30	0.02	557 (80.7)	-	-	170,600	24.5
FL-18	Strain at 0.006 sec ⁻¹ to cycle 85,700, load at 1 Hz to cycle 1,267,600, load at 5.8 Hz, thereafter	0.29	0.00	553 (80.2)	-	-	1,441,600	50.2
FL-16	Strain at 0.005 sec ⁻¹ to cycle 32,200; load at 15 Hz thereafter	0.27	0.00	502 (72.8)	-	-	1,437,800	322
At (800° F) 427° C								
FL-19	Strain at 0.004 sec ⁻¹ to cycle 80; strain at 0.007 sec ⁻¹ thereafter	0.33	0.01	557 (80.8)	136,650	136,800	138,000	38.3
FL-7	Strain at 0.004 sec ⁻¹ to cycle 60,000; load at 1.2 Hz to cycle 1,742,300; load at 5 Hz thereafter	0.31	0.01	577 (83.7)	-	-	>2,242,600 [†]	>528 [†]

Load did not drop prior to failure

[†]Specimen damaged by equipment malfunction at 2,242,600 cycles

a. $\Delta\epsilon_t$ vs N_f at 600°F (316°C)

b. $\Delta\epsilon_t$ vs N_f at 800°F (427°C)

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Figure 2. Fatigue Life of 2-1/4 Cr - 1 Mo Steel as a Function of Total Strain Range
(From Battelle Memorial Institute, Columbus, Ohio)

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Figure 3. Fatigue Life of 2-1/4 Cr - 1 Mo Steel as a Function of Stable Stress Amplitude
(From Battelle Memorial Institute, Columbus, Ohio)

An interim report was issued (BMI Order N615-0243P) which covers the work done during the reporting period in more detail. In particular, the report contains:

- 1) An introduction section which discusses the need for generating the high cycle fatigue data and overall testing objective.
- 2) Discussions of the technical approach taken which includes:
 - a) background information on cyclic deformation history interpretation as applied to fatigue testing
 - b) selection of a cylindrical specimen geometry versus the more conventional hourglass shape
 - c) consideration of mean stress effects.
- 3) A listing of technical accomplishments during the reporting period which includes:
 - a) review of existing fatigue data
 - b) specimen fabrication
 - c) establishment of experimental procedure
 - d) data generation
 - e) correlation of data using a cyclic stress strain parameter
 - f) participation in ASME Code meetings.
- 4) A discussion of the plans for future work.

G. SUBTASK E - SIMPLIFIED HIGH TEMPERATURE PIPE ANALYSIS (BMI)

Three subtasks were identified for initiation during GFY 1977, and expanded definitions of these activities were solicited and obtained from Battelle. These are:

E.1 - Time-to-Failure Tests of Branch Connections

- 1) Compare life predictions using NB-3600 stress indices with the published Taylor and Sys data on elevated temperature testing of branch connections
- 2) Contact Taylor and Sys for test results they may have obtained since 1969.

E.2 - Comparison of ORNL Beam and Elbow Test Results with PIREX2 Calculated Results

- 1) Compare strain and deformation predictions using PIREX2 with the ORNL beam test results and with limit load tests on elbow test assemblies
- 2) Run a moderately complex pipe system elastic-plastic-relaxation analysis using PIREX2

E.3 - Development of Additional Stress Indices

- 1) Indices not presently included in NB-3600 will be developed to provide the capability of using the stress index approach for satisfaction of the (high temperature) 1592-7 elastic analysis based criteria.
- 2) A realistic example piping system will be evaluated to identify any problems which may exist in applying the newly developed stress indices and simplified analysis approach.

H. SUBTASK F - DESIGN METHODS AND CRITERIA FOR LMFBR PIPING

No activities in support of Subtask F were performed during the reporting period. This subtask is to be initiated in April 1977.

I. SUBTASK G - PIPE COMPONENT TESTING

A meeting was held between AI and LMEC personnel to reach agreement on particular details on the AIP for testing thermal transient and mechanical testing of piping elbows and clamps at the TTF. LMEC prepared a draft of a scoping cost estimate and facility schedule impact report for submittal to ERDA.

A meeting held among ERDA, ORNL, WARD, LMEC and AI personnel resulted in the concurrence that a redefinition of the prepared AIP for elbow and clamp tests is needed.

IV. IMPACT ON LMFBR PROGRAMS

This project specifically responds to currently identified tasks in the Piping Integrity Plan. It relates to substantiation and improvement of piping integrity for CRBR, PLBR and CRB programs.

V. NEXT REPORT PERIOD ACTIVITIES

The PIPLAN development task will be suspended to allow for ERDA review and comment. The collection of failure data and construction defects will continue with US and other sodium facilities. This work will be modified to include data for hangers and snubbers. Inelastic solutions of the pipe used for elastic solutions will be performed and evaluated. Continuation of the high cycle fatigue behavior studies will be performed by Battelle Memorial Institute Columbus, Ohio, in addition to the simplified high temperature pipe analysis which they will initiate. A revision of the Approval-in-Principle of elbow and clamp testing at LMEC will be issued.