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QUARTERLY TECHNICAL PROGRESS REPORT
HIGH-TEMPERATURE
PIPING DESIGN
TECHNOLOGY
JANUARY – MARCH 1977

ERDA Research and Development Report

*Prepared for the United States
Energy Research and Development Administration,
Division of Reactor Research and Development,
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Rockwell International

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The preceding Progress Report was AI-ERDA-13191

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Program: High-Temperature Piping Design Technology		
ERDA Task: 21 -- High-Temperature Piping Design		
Program Manager: R. W. Keaten	Project Manager: L. Baurmash	
Reporting Period: January-March 1977	Category: KG-10-04-02.2	
General Order: 09146	Subaccount: 13000	189a Number: SA020

Principal Investigators: R.I. Jetter, F.V. Naugle

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 REPORT PERIOD

A. SUBTASK A – PIPLAN DEVELOPMENT

Key individuals within AI were given a copy of the latest PIPLAN draft and requested to review it and prepare written comments. These in-house comments were collected and sent, along with all received out-of-house comments to D. S. Griffin (WARD) and J. J. Morabito (ERDA-RDD).

B. SUBTASKS BI and BII – COLLECTION OF PIPING FAILURE AND CONSTRUCTION DEFECT DATA

1. Subtask BI– Collection of Piping Failure Data

- 1) The piping report data, conforming to the requirements of the new format, have been completed with the exception of proofing and incident detail description on SRE, SRE-PEP, SCTI (old configuration), SCTL, LCTL, LLTR, Building 016 Loops, Building 032 Loops, and Hallam. Data on SPTF, FERMI, and EBR II has been reformatted but is not complete.
- 2) The piping report data questionnaire has been completed and will be mailed to U. S. facilities along with a sample of the format.
- 3) A review of background documentation to establish a more precise expectation of the various types of failures has been undertaken.
- 4) Data on the lengths and number of welds are being collected. The weld data on SCTL, the main cooler systems for SPTF, and EBR II secondary systems have been completed. Additional drawings for all other systems will be obtained.
- 5) In most cases, the same drawings that identify welds in the piping systems also note the location and types of snubbers/supports used in piping systems. At this point, the data collected are sparse but

most AI-LMEC facility piping isometric drawings have been identified and ordered. The data reporting format will note the number and type of supports, spacing, and type of piping run (i. e., horizontal, vertical) as well as problems experienced.

2. Subtask BII – Survey of Construction Data for Defect Records

- 1) Much scattered data on construction defects at AI and LMEC facilities have been gathered but require considerable analysis and collation to incorporate them into a meaningful format. So far, the only defects noted have occurred in welds which failed to pass quality assurance provisions.
- 2) The study will attempt to correlate any subsequent operational piping failures with initial defects noted and repaired during construction.

C. SUBTASK BIII – ANALYSIS OF SYSTEMS WITH PRIOR SUCCESSFUL OPERATING HISTORY

Progress on the inelastic evaluation of the SNAP 8-ER outlet piping has been minimal due to MARC-G4 program problems. Specifically, the version currently on file at AI does not correctly handle incremental-cyclic thermal loadings which are essential for the evaluation. Additionally, computed stress values at specific locations in the elbow elements have become suspect following recent reports by HEDL that problems have occurred in this area. Analytical work during the reporting period has been addressed toward evaluating, by means of comparative test case runs, the possibility of an elbow stress prediction problem in the AI version of MARC program. The problem was traced to out-of-core solution routines and since our solutions are in-core type, no problems for our runs are anticipated. Additionally, arrangements have been established with MARC Corporation to install a debugged version of their program which should eliminate the incremental-cyclic thermal loading problem.

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

Based upon review of the literature, a tentative approach has been selected for evaluating the effect of ovality on straight pipe subjected to bending moments.

E. SUBTASK D – HIGH CYCLE FATIGUE BEHAVIOR AT ELEVATED TEMPERATURE (BCL)

This section describes work completed on the subtask during the report period. Specific items covered include:

- 1) Continuation of exploratory mean stress tests on 2-1/4 Cr - 1 Mo steel
- 2) Continuation of tests of 2-1/4 Cr - 1 Mo steel under fully reversed strain cycling conditions at 538°C (1000°F)
- 3) Completion of fabrication of Type 316 stainless steel specimens
- 4) Participation in special meeting of the ASME Subgroup on Fatigue Strength
- 5) Brief analysis of published mean stress data on Inconel Alloy 718.

1. Mean Stress Effects on 2-1/4 Cr - 1 Mo Steel

Results of mean stress fatigue experiments completed this reporting period are summarized in Table 1. Mean stress was induced under strain-controlled conditions by initial loading to a large maximum strain, with subsequent strain cycling between this level and a level below it by the amount of the strain range. Due to cyclic relaxation of mean stress, the initial maximum stress associated with this maximum strain decreased from 367 MPa (53.2 ksi) and 364 MPa (52.8 ksi) to the stable values of 332 MPa (48.1 ksi) and 330 MPa (47.9 ksi) for Specimens FL13 and FL21, respectively, during the initial 10 to 20 cycles of straining. Once it was assured that the stress-strain response was completely stable from cycle to cycle, the control mode was changed and the cyclic frequency was increased so that the experiments could be completed within a reasonable period of time.

In contrast to the earlier mean stress test of Specimen FL8 (see October-December 1976, Quarterly Report) where the minimum stress was zero (i. e., all stressing was tensile), the minimum stress was compressive for both of these experiments. Also, no relaxation of mean stress was noted for Specimen FL8. The data points for these two experiments have been added to both Figures 1 and 2 (half-filled diamond symbols). On the basis of stress amplitude (Figure 1), the data fell close to those for zero mean stress, indicating no significant effect of mean stress on fatigue life. As would be expected, both data points fell (conservatively) above the trend of zero mean stress data based on the stress-strain damage parameter (Figure 2).

It appears that significant mean stress effects will occur only when the minimum stress is near or above zero. For this case, the stress-strain parameter accounts for the effect reasonably well. Thus, it can be used to estimate the worst-case effects of mean stress and provide important guidance in design calculations. For example, if 414 MPa (60 ksi) is assumed to be a reasonable upper bound to the maximum stress, $\sigma_{\max}$, that may be induced in actual service, then the corresponding total strain range, $\Delta\epsilon_t$, at 10^8 cycles would be computed from the relation,

$$\sqrt{\Delta\epsilon_t \sigma_{\max}} E/2 = 248 \text{ MPa (36 ksi) [from Figure 2].}$$

Hence, at 427° C (800° F),

$$\Delta\epsilon_t = \frac{2 \cdot (248)^2}{414 \cdot 177,200} = 0.00168 \text{ .}$$

Applying the ASME Code factor of 2 gives a design strain range of 0.00084 for 10^8 cycles at 427° C (800° F).

On Specimen FL-1, mean stress was induced under strain control conditions by initial loading to a large maximum strain followed by strain cycling between this and a lower strain level. Due to cyclic relaxation of mean stress, the maximum stress associated with the maximum strain decreased slightly from 385 MPa (55.9 ksi) to a stable value of 375 MPa (54.4 ksi). After the

Figure 1. Fatigue Life of 2-1/4 Cr - 1 Mo Steel as a Function of Stable Stress Amplitude
(Furnished by Battelle Memorial Institute)

Figure 2. Fatigue Life of 2-1/4 Cr - 1 Mo Steel as a Function of Stress-Strain Parameter (Furnished by Battelle Memorial Institute)

stable stress response was achieved, load control was used so that the cycle frequency could be increased to reduce the time of the test. The data point for Specimen FL-1 has been added to both Figures 1 and 2 (solid circle symbol).

As summarized in Table 1, another mean stress experiment on 2-1/4 Cr - 1 Mo steel is in progress at 316°C (600°F). This specimen (FL-3) was strained to a large tensile value of 4.10% with a corresponding high maximum stress level of 452 MPa (65.5 ksi) and then cycled between zero stress and this maximum level. Based on a computed stress-strain parameter ($\sqrt{\Delta\epsilon_t \sigma_{\max} E/2}$) value of 327 MPa (47.4 ksi), it was expected that this experiment would last only about 60,000 cycles. However, it has lasted 100 times as long and still has not failed! This confirms the trend of the other mean stress experiment (Specimen FL-1 reported last month) at 316°C (600°F), which had a stress-strain parameter value of 287 MPa (41.6 ksi) and was expected to fail in about 300,000 cycles but lasted 100 times as long without failure. Thus, the parameter gives an extremely conservative prediction of the effect of mean stress on fatigue life at this temperature. In fact, it appears that these two data points correlate with the fully-reversed cycling data on the basis of stress amplitude alone. In other words, there seems to be little effect of mean stress on cyclic life at this temperature. It must be kept in mind, though, that this trend is based upon the results of only two tests at 316°C (600°F).

2. Fully-Reversed Cycling of 2-1/4 Cr - 1 Mo Steel

Five tests were conducted under fully-reversed strain cycling conditions, and a sixth one has been started. These were all on specimens of 2-1/4 Cr - 1 Mo steel at 538°C (1000°F), as summarized in Table 2. Results of the five completed tests are plotted in terms of two different variables versus number of cycles to failure:

- Stress amplitude in Figure 3
- Stress-strain parameter in Figure 4.

The two data points near 10^5 cycles to failure (Specimens FL-20 and FT-1) fell below the trend of all of the other past data in both figures. However, the three points at longer lives agreed well with the trend of the other data in both figures. The best consolidation of the data was achieved when they were plotted

TABLE 1
FATIGUE DATA ON ISOTHERMALLY ANNEALED 2-1/4 Cr - 1 Mo STEEL CONDUCTED
UNDER STRAIN CYCLING WITH MEAN STRESS DURING THIS REPORT PERIOD

Specimen	Temperature C (F)	Control Mode	Strain (%)		Stable Inelastic Strain Range (%)	Stable Stress MPa (ksi)		Number of Cycles to Failure	Time to Failure (h)
			Total Range	Maximum		Maximum	Range		
FL-13	427 (800)	Strain at 1.6×10^{-3} sec ⁻¹ to cycle 895; strain at 2.6×10^{-3} sec ⁻¹ to cycle 6615; load at 11 Hz to cycle 3,536,820; load at 22 Hz until failure	0.275	2.31	--	332 (48.1)	484 (70.2)	24,132,463	358.2
FL-21	427 (800)	Strain at 2×10^{-3} sec ⁻¹ to cycle 1820; load at 0.3 Hz to cycle 2035; load at 15 Hz to failure	0.320	2.15	--	330 (47.9)	571 (82.8)	848,085	17.6
FL-1	316 (600)	Strain at 2.0×10^{-3} sec ⁻¹ to cycle 345; load at 0.2 Hz to cycle 442, load at 21.6 Hz until completion of test	0.23	2.16	--	375 (54.4)	438 (63.6)	>33,910,007	>437
FL-3*	316 (600)	Strain at 0.002 sec ⁻¹ to cycle 213; strain at 0.004 sec ⁻¹ to cycle 189,206; load at 1 Hz to cycle 320,000; load at 5.1 Hz to present	0.25	4.10	--	452 (65.5)	452 (65.5)	>5,691,600	>395

* Test in progress.

TABLE 2
FATIGUE DATA ON ISOTHERMALLY ANNEALED 2-1/4 Cr - 1 Mo STEEL
CONDUCTED THIS MONTH UNDER FULLY REVERSED CYCLING

Specimen Number	Temperature C°(F)	Control Mode	Stable Axial Strain Range (%)			Stable Stress Range MN/m ² (ksi)	Fatigue Life (cycles)			Time to Failure (h)
			Total	Inelastic	Elastic		N _o	N _s	N _f	
FL-20	538 (1000)	Strain at 0.004 sec ⁻¹ to failure	0.29	0.08	0.21	394 (57.1)	75,580	75,840	76,490	30.8
FT-1	538 (1000)	Strain at 0.004 sec ⁻¹ to failure	0.30	0.08	0.22	385 (55.8)	105,800	107,250	108,472	45.2
FT-3	538 (1000)	Strain at 0.004 sec ⁻¹ to cycle 47,524; load at 0.74 Hz to cycle 54,568; load at 15.5 Hz to failure	0.26	0.03	0.23	376 (54.6)	-	-	1,279,722	41.8
FT-4	538 (1000)	Strain at 0.004 sec ⁻¹ to cycle 4,000; load at 19 Hz to failure	0.24	0.02	0.22	367 (53.3)	-	-	2,225,212	33.8
FT-5	538 (1000)	Strain at 0.004 sec ⁻¹ to cycle 1,000; load at 24.6 Hz to failure	0.21	0.00	0.21	351 (50.9)	-	-	5,993,426	68.0
FT-6*	538 (1000)	Strain at 0.004 sec ⁻¹ to cycle 1,631; load at 27 Hz to present	0.19	0.00	0.19	297 (43.1)	-	-		

* Test in progress.

Figure 3. Fatigue Life of 2-1/4 Cr - 1 Mo Steel as a Function of Stable Stress Amplitude at 538°C (1000°F) (Furnished by Battelle Memorial Institute)

Figure 4. Fatigue Life of 2-1/4 Cr - 1 Mo Steel as a Function of Stress-Strain Parameter at 538°C (1000°F) (Furnished by Battelle Memorial Institute)

in terms of the stress-strain parameter (Figure 4). Since all but one (Specimen FL-20) of these specimens was taken transverse to the rolling direction of the plate, it is apparent that the specimen orientation had little effect on the fatigue resistance at this temperature. It is expected that Specimen FT-6 will fail after about 5×10^7 cycles to failure. If so, this will complete the planned experiments on 2-1/4 Cr - 1 Mo under fully-reversed conditions.

3. Work on Type 316 Stainless Steel

Thirty Type 316 stainless steel specimen blanks have been cut from plate 13C of the reference heat 8092297 (see ORNL/TM-5196, January 1976) and have had the following heat treatment:

Anneal in argon for 1/2 hour at 1066° C (1950° F)

Rapid air cool at a rate of at least 82° C (180° F)/minute.

Fabrication of the Type 316 stainless steel specimens has been completed. Experimental work on this alloy will begin next month. Tests will be at four different temperatures 21, 427, 538, and 650° C (70, 800, 1000, and 1200° F), with work progressing in order of increasing temperature, as listed. The planned experimental matrix at each temperature will be as follows:

Total Strain* Range, $\Delta\epsilon_t$ (%)	Mean Stress Condition	Estimated Number of Cycles to Failure
1	None	3×10^4
2		10^5
3		3×10^5
4		10^6
5		3×10^6
6		10^7
7		3×10^7
~ 3	Tensile	3×10^5
~ 5		3×10^6
~ 7		3×10^7

* Exact values of $\Delta\epsilon_t$ will be selected to give approximately the desired cyclic life based upon estimates from past data and from data as developed in this study.

As data are generated, it may be necessary to alter these plans to some extent in order to ensure efficient and economical definition of material behavior trends within the time and funds available.

4. Participation in Meeting of the ASME Subgroup on Fatigue Strength

On March 16, 1977, Mr. Carl Jaske of Battelle-Columbus attended the meeting of the above Subgroup in Pittsburgh, Pennsylvania. Development of fatigue design curves for austenitic steels (such as Type 316 stainless steel) were discussed, with emphasis on the long-life regime. Items of relevance to the present program were effects of mean stress and experimental methods for development of long-life data.

5. Effect of Mean Stress on Inconel Alloy 718

Although Inconel Alloy 718 is outside of the scope of this program, it is instructive to examine some data recently developed at EG&G Idaho, Inc. (see ORNL-5200 and ORNL-5237). These data were analyzed using the same stress-strain parameter being used for 2-1/4 Cr - 1 Mo steel in this program, and the results are plotted in Figure 5. The detrimental influence of mean stress was extremely well accounted for by this parameter (compare solid symbols with open ones in Figure 5). If plotted on the basis of stress amplitude alone, the solid symbols would have fallen about 20 to 30 ksi (138 to 207 MPa) below the corresponding open ones. These results give added confidence in the use of this parameter to account for mean stress effects.

The parameter, P , can be used to estimate worst-case mean stress effects. For example, at 10^7 cycles to failure, the parameter's value is about 80 ksi (552 MPa). For this value, the stress amplitude, $\Delta\sigma/2$, will be nominally elastic for this alloy because 80 ksi is below the proportional limit of its cyclic stress-strain curve. In the worst-case, the maximum stress, $\sigma_{\max}$, will certainly exceed the yield stress and it could approach the ultimate strength of 200 ksi (1380 MPa). In such a case,

$$\Delta\sigma/2_{(10^7)} = P^2/\sigma_{\max} = 80^2/200 = 32 \text{ ksi (224 MPa)}.$$

Figure 5. Fatigue of Inconel Alloy 718
(Furnished by Battelle Memorial Institute)

In a less severe case, $\sigma_{\max}$ may be near the cyclic yield strength [about 150 ksi (1030 MPa)] and

$$\frac{\Delta\sigma/2}{(10^7)} = P^2/\sigma_{\max} = 80^2/150 = 42.7 \text{ ksi (294 MPa)}.$$

F. SUBTASK E – SIMPLIFIED HIGH TEMPERATURE PIPE ANALYSIS (BCL)

A recommendation on primary stress indices was presented to the ASME Working Group on Piping. A summary report on Phase I work entitled "Appropriate B Indices for Evaluating Load Controlled Stresses in Piping Products at Elevated Temperature" was issued during the report period.

G. 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.

H. SUBTASK G – PIPE COMPONENT TESTING

A detailed test procedure was prepared as a basis for evaluation of test specimen, fixture, and instrumentation requirements to determine costs and schedule for testing of small diameter (6 in.) pipe clamps. The purpose of the test is to investigate the interaction of clamp preload, support load, and transient temperature cycles with respect to the limiting failure mode and to evaluate temperature limitations on the use of a bare pipe clamp.

III. 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. Subtasks B1 and B2 are in response to CRBR DRS 02.22, Rev. 1.

IV. NEXT REPORT PERIOD ACTIVITIES

A general revision of PIPLAN will be submitted. The collection of failure data and construction data will continue. Following MARC program revisions, the inelastic analysis of the SNAP 8-ER piping will be completed. An interim report on simplified sensitivity evaluations will be prepared. High cycle fatigue testing of 2-1/4 Cr - 1 Mo at elevated temperature will continue. Fatigue testing of Type 316 stainless steel specimens will be started. A test request for transient testing of a bare pipe clamp will be submitted.