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QUARTERLY TECHNICAL PROGRESS REPORT
HIGH-TEMPERATURE
PIPING DESIGN
TECHNOLOGY
OCTOBER – DECEMBER 1976

ERDA Research and Development Report

*Prepared for the United States
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Rockwell International

Atomics International Division
8900 DeSoto Avenue
Canoga Park, California 91304

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Program: High-Temperature Piping Design Technology

ERDA Task: 21 - High-Temperature Piping Design

Program Manager: R. W. Keaten

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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 cataloged 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, as presently scoped, is the thermal transient and mechanical testing of piping elbows and bare pipe clamps. The elbow tests are intended to clarify the effect of thermal shock damage on mechanical collapse strength and provide experimental verification of the use of piping stress indices for thin walled elbows typical of LMFBR piping. The bare pipe clamp tests are to provide a benchmark against which analytical techniques can be developed for the clamp-pipe interaction.

II. MAJOR ACCOMPLISHMENTS DURING REPORT PERIOD

A. SUBTASK A - PIPLAN DEVELOPMENT

At the end of the reporting period, communications were received from ERDA requesting comments on the PIPLAN draft. Key individuals within AI will be identified and funded to provide the requested comments. No work was performed on this subtask earlier in the reporting period since activities were halted until ERDA could review the draft and redirect efforts.

B. SUBTASK BI - COLLECTION OF PIPING FAILURE DATA

A revision (Change 1) to the interim report (N146TI350004) on sodium piping leaks was completed which deleted listings of verified nonsodium facilities from the original list and added additional information on other facilities.

Personal interviews with numerous cognizant engineers at LMEC were conducted. These interviews resulted in descriptions of facilities, approximate times in service, lengths and sizes of sodium piping, and definitions of all failures that could be recalled. Additionally, problems-failures associated with hanger and snubber assemblies on sodium piping lines were discussed. Data were collected on design (pipe size, length, etc.) and operating (time, temperatures, pressures) parameters for the EBR-II, Fermi, Hallam, SRE, LCTL, and SCTI facilities. In all cases, the data were considerably detailed and complete throughout the major operating life of the facility. No new piping failures beyond those listed in the interim report (N146SR250001) were noted.

Additional foreign translations of the survey questionnaire were prepared and copies were distributed to several identified foreign contacts. A request made by the CRBR project office for questions to be sent to the Japanese LMFBR organization as part of an exchange program was utilized to solicit failure data.

Additional information on the three piping failures at DFR (UK) was obtained through a personal interview with a visiting DFR plant operator. General data relating to PFR (UK) were also obtained during the interview. Personal interviews were also held with visiting personnel from France and Interatom which established sources within each organization for solicitation of piping failure data.

Partial response was received to the failure survey questionnaire sent to Electricite De France; however, the response document had not been completely translated during the reporting period. Reports were also received from the MONJU (Japanese) facility which contained failure related data that were reviewed and evaluated.

The record of discussion at the first meeting of the ERDA/PNC Working Group on Plant Experience (November 15-19, 1976) was received and reviewed.

Additional information, beyond that in the interim report, on two heater-related failures was requested by EPRI and the failure details were provided to the requester.

C. SUBTASK BII - SURVEY OF CONSTRUCTION DATA FOR DEFECT RECORDS

Activities on this subtask were initiated. Some difficulties were encountered in identifying data sources for experimental facilities where permanent records were either minimal or were destroyed after facility deactivation. Other facilities were solicited for information, and personal interviews were made with AI and LMEC facilities personnel, but, overall, only minimal data were received during the reporting period.

Included in these data are construction records for the SCTI and SPTF facilities. Evaluation of these data was initiated. Also, radiograph records for LMEC during GFY 1975 were obtained. Initial evaluation indicates that 2350 welds were radiographed with a 5% rejection rate.

A report from the JOYO (Japanese) facility on construction and preoperational test experiences was received and a review for construction defect data was initiated.

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

The initial MARC inelastic solution of the SNAP 8 ER outlet piping line was terminated before loading completion after high plastic strains occurred in a straight portion of the piping adjacent to an elbow. This predicted behavior resulted from too "soft" a choice of the 10th cycle bilinear stress-strain material characterization.

The selection of 10th cycle properties for the initial solution was based on elastic solutions in combination with Neuber's rule applied in a manner similar to the ASME Code Case 1592 elastic creep-fatigue criteria. The predictive method did not adequately account for the large amount of strain concentration-elastic followup in the schedule 5 straight piping adjacent to the schedule 40 elbows, and thus the high plastic strains. The ideal choice would be such that the resulting plastic strains justify the choice of properties, i. e., the bilinear representation depends on strain range which depends on the representation. A selection of strain range-10th cycle representation that is too low will result in unrealistically high inelastic strains resulting in failure to satisfy the fatigue portion of the 1592 creep-fatigue criteria. This was the case for the initial solution. A selection of too high a representation will lead to unrealistically high stresses and over-prediction of cyclically accumulated creep strains. These in turn may indicate failure to satisfy the creep portion of the 1592 creep-fatigue criteria or the strain limits.

A second inelastic solution was set up. This time the 10th cycle properties were based on the initial inelastic results. This solution was terminated after incremental loadings to 649°C (1200°F) were completed. At this point, the rate of plastic strain accumulation in a straight section adjacent to a heavier-walled elbow was beyond the program convergence limits. Additional load increments would need to be impractically small (<5° per increment) and evaluation of the previous inelastic solution indicated that unacceptably high strains (with respect to CC 1592 creep-fatigue criteria) would have occurred before the end-of-load ramp [704°C (1300°F)] was reached.

Activities were redirected to analytically maintain a 649°C (1200°F) hold period, the time span of which is identical to the last 704°C (1300°F) hold period experienced during service. The creep rupture damage during this long hold period (>7000 h) will be compared to the CC 1592 allowables. This approach will predict less damage than actually occurred during service and failure to satisfy the CC 1592 criteria will indicate conservatism in the design rules. Additionally, the thermal load will be reversed and accumulated tensile strains will be compared to the Code acceptable strain limits.

Initial analytical efforts to maintain the hold period and relax the stresses encountered convergence difficulties. The problem was traced to a percentage stress change convergence check which could not be satisfied with extremely small time steps (~ 1 sec) at low stress regions in the model. Later versions of MARC (e.g., the H version — our version is G) recognize this computational problem and provide user options to prevent what amounts to insignificant behavior controlling the solution. Unfortunately, the only approach available with the version in use is to loosen the stress change convergence check and monitor carefully the critical region behavior. This has delayed the hold period portion of the load cycle and final results are not expected earlier than mid-January.

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

All initially identified data sources for establishment of base case selection have been obtained and their review was completed. A preliminary selection of Phase I sensitivity base cases was completed and is summarized in Table 1. The selection is a matrix of 105 failure mode evaluations resulting from the variation of 18 geometry, material and loading parameters for 4 components under 4 loading situations. It is considered preliminary in that activities next quarter will include solicitation of evaluation recommendations from LMFBR design organizations. For example, sensitivity studies to support fabrication decisions such as welded pipe vs seamless pipe may be supportive to LMFBR design decisions, and could be worked into the sensitivity studies. If nothing else, such a solicitation of recommendations will help establish a priority for study of those variations now selected. It is considered Phase I, in that the sensitivity of design margins to assumptions on material behavior, continuum modeling and failure mechanisms implicit in the current design analysis-criteria methodologies are not included. For example, the effect of using bilinear material stress-strain representations (vs smooth) or loading sequence modeling are not included. It is believed that significant effects on design margins may exist from these assumptions and a recommendation for additional sensitivity studies in these areas will be submitted to ERDA in the near future.

TABLE 1
PRELIMINARY PHASE I SENSITIVITY BASE CASE SELECTIONS

Parameter Varied	Type Loading Imposed						
	Load Controlled End Moments	Cyclic Temperature Dependent Motion Controlled End Moments With Sustained Pressure	Cyclic Fluid Thermal Transient With Sustained Pressure	Cyclic Fluid Thermal Transient Plus Motion Controlled End Moments With Sustained Pressure	Failure Mode Evaluated		
Creep Collapse	Excessive Creep Strains	Creep- Fatigue Cracking	Excessive Creep Strains	Creep- Fatigue Cracking	Excessive Creep Strains	Creep- Fatigue Cracking	
Uniform Wall Thickness	S, E	S, E	S, E	S, E	S, E	S, E	S, E
Circumferential Variation Wall Thickness	S, E	S, E	S, E	S	S	S	S
Ovalization	S, E	S, E	S, E			S, E	S, E
Circumferential Variation Wall Thickness plus Ovalization	S, E	S, E	S, E'			S, E'	S, E
Wrinkling	E	E	E				
Diameter Mismatch Weld Shrinkage		W, E	W, E				
Thickness Mismatch-Weld Geometry		W	W	W	W		
Cone Angle		(R)	(R)				
Corner Radu		(R)	(R)				
Primary Creep Rate (material mismatch)			S, W		S, W		
Secondary Creep Rate (material mismatch)	S, W, E	S, W, E	S,W,E	S, W	S, W		
Intercept of Secondary Creep Curve with Strain Axis	S	S	S	S	S		
Sustained or Mean Tem- perature	S	S	S	S	S		
Bilinear Yield Point Value (material mismatch)		S,W,E	S,W,E	S, W	S, W		
Bilinear Inelastic Modulus Value		S, E	S, E	S	S		
Sustained Pressure	S	S	S	S	S		
Fluid Temperature Ramp Rate				S	S		
Fluid Temperature Ramp Total ΔT				S	S		

Letters in Table refer to components considered in sensitivity study

S - Straight pipe

W - Girth weld

E - Elbow

(R) - Reducer (tentative pending funding availability)

A primed letter refers to data to be obtained through the Westinghouse, ARD 189a CW138 activities

The four components to be evaluated are:

- 1) A straight pipe section
- 2) A straight pipe section containing a girth butt weld
- 3) A butt-welding elbow
- 4) A butt-welding concentric reducer

All components will be annealed 300 Series (Type TBD) stainless steel, nominally 32-inch diameter with 1/2-inch wall thickness in order to provide a consistent data base for evaluation. This geometry corresponds to the nominal elbow dimensions to be evaluated in a geometry sensitivity study by Westinghouse-ARD under 189a CW 138 funding.

The four loading situations to be evaluated were selected to address the significant loads typical of LMFBR primary hot leg system conditions. In particular (see Table 1):

- 1) The load controlled end movements are to model long term (time dependent) primary loading arising from dead and live weight loadings or component weight loadings due to thermal expansion of movable components.
- 2) The cyclic temperature dependent motion controlled end movements with sustained pressure are to model thermal expansion induced loadings resulting from normal startup - operation - load following service conditions.
- 3) The cyclic fluid thermal transient with sustained pressure are to model the thermal loading resulting from system transient events.
- 4) The cyclic fluid thermal transient plus motion controlled end moments with sustained pressure are to model the combined interaction of 2) and 3).

The magnitude of loading will be selected as discussed in the sensitivity plan and coordinated, where appropriate, with the ARD activities.

The selected failure mode - loading - component - parameter variation evaluation matrix was arrived at from the consideration of possible parameter variations in light of their potential for having significant failure mode effect under

particular loading situations and availability-cost of analytical models to quantify the effect. In several cases, consideration was limited to the simpler straight pipe model with the intent of implying the parameter variation effect to the more complicated geometries.

F. SUBTASK D — HIGH CYCLE FATIGUE BEHAVIOR AT ELEVATED TEMPERATURE

Some difficulties were encountered that resulted in test delays early in the reporting period. These were primarily in two separate areas: (1) instability of the electrohydraulic control system and (2) thermal gradients in specimens at 538°C (1000°F). The instability problems were caused by significant changes in specimen stiffness due to cyclic hardening during the initial portion of a test in strain control. A highly responsive system is desirable in order to cycle the specimens as rapidly as possible and shorten the total testing time once stable stress-strain response is achieved. However, the high test system response led to instabilities during initial strain-controlled cycling. Through adjustment and tuning of the system controls and servovalve, these problems were minimized and experiments at 427°C (800°F) were resumed. Experiments at 538°C (1000°F) were delayed briefly until the heating coil and grips could be properly modified to achieve uniform temperature in the gage section of the specimen.

During the reporting period, zero mean stress tests on Specimens FL-9, FL-10, FL-23 were completed. These are defined in Table 2 together with all other-zero-mean stress data to date. This completes the 2-1/4 Cr - 1 Mo baseline extension portion of the testing program.

An exploratory mean-stress experiment (Specimen FL-8 of 2-1/4 Cr - 1 Mo steel) was completed to evaluate the condition of a mean stress that does not cyclically relax. The results are summarized in Table 3. During the first 8000 cycles, the stress-strain response was recorded periodically using an X-Y plotter. There was no detectable relaxation of mean stress. A nominally elastic cyclic stress-strain response was noted after the first 606 cycles under strain control and the control mode was switched to load for experimental convenience. Further monitoring of stress-strain response showed no

TABLE 2
FATIGUE DATA ON ISOTHERMALLY-ANNEALED 2-1/4 Cr - 1 Mo STEEL 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 (hr)
	<u>At 316°C (600°F)</u>							
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)	--	--	17,437,800	322
	<u>At 427°C (800°F)</u>							
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†
FL-9	Strain at 0.004 sec ⁻¹ to cycle 63,603, load at 0.6 Hz to cycle 64,961, load at 1 Hz to cycle 334,500, load at 3 Hz to cycle 357,000, load at 10 Hz to failure	0.29	0.00	564 (81.7)	--	--	829,630	41.2
FL-23	Strain at 0.002 sec ⁻¹ to cycle 485, strain at 0.004 sec ⁻¹ to 168,599, load at 1 Hz to cycle 169,460, load at 5 Hz to cycle 175,705, load at 6.9 Hz thereafter	0.29	0.00	540 (78.3)	--	--	1,011,476	102
FL-10	Strain at 0.004 sec ⁻¹ to cycle 2,954, load at 10 Hz to cycle 666,900, load at 21 Hz to cycle 2,526,000, load at 35 Hz to failure	0.29	0.00	510 (74.0)	--	--	>1,919,421	277

*Load did not drop prior to failure.

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

TABLE 3

FATIGUE DATA ON ISOTHERMALLY ANNEALED 2-1/4 Cr - 1 Mo STEEL
UNDER STRAIN CYCLING WITH MEAN STRESS

Specimen	Control Mode	Strain (%)		Stable Inelastic Strain Range (%)
		Total Range	Maximum	
FL-8	Strain at 0.002 sec^{-1} to Cycle 606; load at 1 Hz to Cycle 8477; load at 35 Hz to 5,444,000; load at 32 Hz to failure	0.22	2.21	0.00
Specimen	Stable Stress, MPa (ksi)		Number of Cycles to Failure	Time to Failure (hr)
	Maximum	Range		
FL-8	367 (53.3)	367 (53.3)	60,541,000	527

cyclic creep (increase of maximum strain) and the response continued to be nominally elastic during cycles 607 to 8477. Therefore, the extensometer was removed and the cyclic frequency was increased to 35 Hz so that the experiment could be completed in a reasonable length of time. The specimen failed in 527 hours after 6.05×10^7 cycles.

Although this experiment lasted about six times longer than originally estimated, using the stress-strain parameter, it provides an extremely useful data point in the long-life region of primary interest. Thus, the long amount of time expended in completing the experiment was very well invested. The result is plotted in comparison with previous data for fully reversed conditions (zero mean stress or $R = -1$) in both Figures 1 and 2, as indicated by the half-filled diamond symbol. Note that use of only the stress amplitude (Figure 1) would indicate essentially infinite cyclic life, a nonconservative result from a design viewpoint. In contrast, inclusion of the effect of mean stress using the stress-strain parameter (Figure 2) gives a reasonably good and slightly conservative prediction of cyclic life. Thus, it is evident that mean stress can have a detrimental influence on cyclic life and cannot be ignored in long-life fatigue assessment.

Another mean stress experiment is being conducted at 427°C (800°F) using about the same maximum stress [365 MPa (53 ksi)] and a slightly larger total strain range (0.29%). This is expected to give a shorter life and an indication of how much cyclic relaxation of mean stress will occur when some inelastic deformation occurs early in the cyclic stress-strain history.

A 0.3 x 0.9 x 0.025 m (12 x 36 x 1 in.) plate of Type 316 stainless steel was received from ORNL. Dr. Brinkman has supplied this material at no cost to the present program.

G. SUBTASK E

Due to difficulties in getting this program started during the reporting period, no results are available.

H. SUBTASK G — PIPE COMPONENT TESTING

An AIP for pipe clamp testing was prepared and approved by ERDA. In summary, it requests approval for two phases of testing:

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)

Phase I — Small diameter clamp tests:

Mechanical and thermal transient tests utilizing numerous transducers to provide benchmark data for development of a suitable clamp analytic methodology and tests intended to clarify, on a failure mode basis, the interaction between clamps and piping.

Phase II — Large diameter clamp tests:

Mechanical and thermal transient tests to study additional problems associated with using support clamps on large diameter, thin-walled piping.

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. SUBTASK A

Individuals within the development and LMFBR project organization at AI will review PIPLAN, submit comments to ERDA, and respond to ERDA identified directives on PIPLAN development.

B. SUBTASK BI

Data collection and evaluation will continue with emphasis shifting towards foreign facilities.

C. SUBTASK BII

Identification of data sources and facility contacts will be continued and the appropriateness of developing a questionnaire in support of a mail survey will be investigated.

D. SUBTASK BIII

The inelastic solution of the SNAP 8-ER line will be completed and a stress report released. Additional lines for evaluation will be identified and recommendations for such evaluations will be made.

E. SUBTASK C

Model identification will be completed and simplified evaluations will be initiated. LMFBR design organizations will be contacted (through ERDA) for evaluation recommendations-priorities and a recommendation for extension of the sensitivity study will be prepared.

F. SUBTASK D

Mean stress high cycle fatigue testing of 2-1/4 Cr - 1 Mo will continue and zero-mean-stress high cycle fatigue testing of Type 316 stainless steel will be initiated.

G. SUBTASK E

Work will continue on development of additional stress indices for simplified analysis and, as they become available, results will be given to the ASME B&PV Code Section III TF on Class 1 High Temperature Piping Design.

H. SUBTASK F

There are no planned activities during this next reporting period.

I. SUBTASK G

Efforts will be initiated to provide a test plan for the piping clamp tests and a request for approval-in-principle of mechanical and thermal transient testing of elbows will be released.