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**REACTOR PRIMARY COOLANT SYSTEM
RUPTURE STUDY
QUARTERLY PROGRESS REPORT NO. 18
JULY - SEPTEMBER 1969**

U.S. ATOMIC ENERGY COMMISSION
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ATOMIC POWER EQUIPMENT DEPARTMENT
GENERAL ELECTRIC
SAN JOSE, CALIFORNIA

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AEC Research and
Development Report
October 1969

REACTOR PRIMARY COOLANT SYSTEM RUPTURE STUDY
QUARTERLY PROGRESS REPORT NO. 18

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SAN JOSE, CALIFORNIA

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SECTION I

INTRODUCTION

The Reactor Primary Coolant System Rupture Study is being conducted for the Safety Branch, Division of Reactor Development and Technology, USAEC. This eighteenth quarterly report documents progress for the period of July 1 to September 30, 1969. The overall objective of the program is to improve the reliability of reactor system piping by increasing current knowledge of failure-causing mechanisms and by enhancing capability for design evaluation and analysis.

Toward the attainment of this objective, work is proceeding on the following tasks:

- Task A—Probability Study,
- Task B—Stress Analyses,
- Task C—Fracture Mechanics,
- Task D—Fatigue, and
- Task K—Effect of BWR Environment.

The specific objectives of the tasks and technical progress are covered in the following sections. Previous reports issued as a part of this program are listed as follows.

Quarterly Reports

GEAP-4911—Reactor Primary Coolant System Rupture Study Quarterly Progress
Report No. 1, April-June 1965.

GEAP-4964—No. 2, July-August 1965.

GEAP-5082—No. 3, October-December 1965.

GEAP-5147—No. 4, January-March 1966.

GEAP-5192—No. 5, April-June 1966.

GEAP-5279--No. 6, July-September 1966.

GEAP-5427--No. 7, October-December 1966.

GEAP-5474--No. 8, January-March 1967.

GEAP-5512--No. 9, April-June 1967.

GEAP-5554--No. 10, July-September 1967.

GEAP-5587--No. 11, October-December 1967.

GEAP-5637--No. 12, January-March 1968.

GEAP-5680--No. 13, April-June 1968.

GEAP-5716--No. 14, July-September 1968.

GEAP-5770--No. 15, October-December 1968.

GEAP-10024--No. 16, January-March 1969.

GEAP-10072--No. 17, April-June 1969.

Topical Reports

GEAP-4445--A Survey of Water Reactor Primary System Conditions Pertinent to the Study of Pipe Rupture, January 1964.

GEAP-4446--A Review of Fracture Modes as Related to Reactor Primary Coolant Pipe Rupture, May 1964.

GEAP-4474--Experimental and Analytical Program Recommendations-Reactor Pipe Rupture Study, January 1965.

GEAP-4574--Survey of Piping Failures for the Reactor Primary Coolant Pipe Rupture Study, May 1964

GEAP-4578-- Mechanical Design Considerations in Primary Nuclear Piping, March 1964.

GEAP-4678-- Fracture Mechanics and the Stability of Engineering Structures,
September 1965.

GEAP-5014-- Fracture Toughness of Some Engineering Alloys, March 1966.

GEAP-5410-- Low-Cycle Fatigue Strength Reduction in Notched Flat Plates, January 1967.

GEAP-5471-- PAPA-Structural Analysis of Plates and Shells Using Trapezoidal and
Triangular Plate Elements, March 1967.

GEAP-5553-- PAPA-The Digital Computer Program for the Static Analysis of Structures Made Up of Plate and Panel Elements, October 1967.

GEAP-5557-- Stress Intensity Factor for a Circumferential Through-Wall Crack in a
Straight Pipe, January 1968.

GEAP-5607-- Fatigue Crack Growth in Nuclear Reactor Piping Steels, March 1968.

T&AM-677-- A Three-Dimensional Photoelastic Study of Stress Near Cracks in Shell
Structures, University of Illinois, March 1968.

GEAP-5622-- A Failure Diagram for Axially Flawed Pipes, April 1968.

GEAP-5653-- Status of Pipe Rupture Study at General Electric-II, July 1968.

GEAP-5714-- Notched High-Strain Fatigue Behavior of Three Low-Strength Structural
Steels, September 1968.

GEAP-5724-- BWR Primary Piping Stresses for System Reliability Analysis,
September 1968.

GEAP-5726-- Influence of Stress/Strain Concentration and Mean Stress on the Low-
Cycle Fatigue Behavior of Three Structural Steels at Room Temperature,
September 1968.

GEAP-10007—Restart for the PAPA Program, March 1969.

GEAP-10090—The 550°F Notched High-Strain Fatigue Behavior of Three Low-Strength Structural Steels, August 1969.

SECTION II

SUMMARY

2.1 TASK A-PROBABILITY STUDY

Task K fatigue specimens have been tested in air to determine the variability of cyclic life. This was found to be 1-1/2 times that assumed before testing ($1\sigma = 0.21$ log-cycles in place of $1\sigma = 0.14$ log-cycles). Now the smallest effect of environment which can be considered significant will be a factor of between 1.5 and 2 on cycles, compared with factors between 1.1 and 1.5 previously determined.

2.2 TASK B-STRESS ANALYSIS

As part of the PAPA development effort, a review and evaluation of related computer codes and of the PAPA code are in progress. An assessment report is in preparation to summarize the findings and state recommendations regarding future work. The NASA general computer code, NASTRAN, and Air Force program, FORMAT, are discussed.

2.3 TASK C-FRACTURE MECHANICS

Machining of flaws in a series of ell pipe specimens has been completed. An unflawed tee specimen was hydraulically burst, fracturing at 8880 psi.

2.4 TASK D-LOW-CYCLE FATIGUE

In subtasks D-1 and D-2, covering laboratory crack initiation and growth studies, effort centered on preparation of final topical reports. In prototype pipe fatigue, one stainless tee and two carbon steel elbows were tested. A topical report is in draft form for the prototype pipe work. In cyclic strain aging, the results of Charpy impact tests of A-212B plate following monotonic tensile deformation at 350°F indicate an appreciably lower shift in the 50% FATT for a given total strain than similar specimens cyclically strain aged at 350°F. Also, comparison of the notch strength of a virgin notched bend bar indicates notch strength properties similar to a specimen cyclically strain aged to induce a brittle region near the notch.

2.5 TASK K- EFFECT OF BWR ENVIRONMENT

The Dresden-I test loop piping installation was completed. Failure of the stem tip in one of the loop motor-operated root valves prevented operating the loop prior to the September Dresden-I outage. Preparations were made for shakedown testing at San Jose of the fatigue test machine containing dynamic test specimens of the final design. Operation will be at design conditions of temperature, pressure, and mechanical loading. The dynamic and static test specimen plan was reviewed and minor revisions were made. Manufacture of the final complement of dynamic and static test specimens progressed to the stages of final drilling and machining, respectively.

SECTION III

TASK A—PROBABILITY STUDY

(S. A. Wilson)

3.1 OBJECTIVE

The objective of the probability study task is to develop methods for:

- a. Estimation of the reliability of a reactor primary piping system in terms of leak rate and time of reactor service.
- b. Identification of the principal sources of real variability or uncertainty in service life.

3.2 SUMMARY

Task K fatigue specimens have been tested in air to determine the deflection-strain hysteresis loop and the variability of cycle life for this specimen. Analysis of the deflection-strain hysteresis loop revealed that a setup error of 0.004 inch on the tip deflection range could lead to spurious indication of significant effect of environment on cyclic life due to the corresponding change in strain range. This high sensitivity led to specimen redesign to increase flexibility by reducing body thickness from 0.126 to 0.120 in.

Variability of cyclic life in air was found to be 1-1/2 times that assumed before testing ($1\sigma = 0.21$ log-cycles in place of $1\sigma = 0.14$ log-cycles). Now the smallest effect of environment which can be considered significant will be a factor of between 1.5 and 2 on cycles, compared with factors between 1.1 and 1.5 as previously determined.

3.3 FACTOR DESCRIPTIONS

Listed in the following paragraphs are those factors whose effect on cycles to failure will be estimated by the fatigue experimental work under Task K—Effect of BWR Environment. Also included are the actual piping conditions intended to be simulated by each factor, and some of the control and inspection practices essential to ensuring that the intended levels of the factors are actually achieved in each specimen.

"Effects" will be estimated as the difference between responses at high and low levels for each factor. Each high-level response is the mean of results (cycles to failure) of the specimens at the stated test condition in BWR water, or is the value predicted by a regression line or surface at the stated conditions. Thus, only the high-level description is given with each factor; "in BWR water environment" is understood to be included in each high-level description. Each low-level response is the value at the same strain range on a regression line fitted to failure data for this specimen in air. Each low-level is "as machined, at room temperature in air." Air data are also planned at 500°F to match BWR water temperature at the test station.

Factor 1: Initial surface strain range, in compression-tension loading

Levels: 0.5%, 0.75% and 1.0%

Using the equation fitted to air test data appearing in Figure 7-2 of the Seventeenth Quarterly Report: $\log_{10} N = 6.07 - 215.\epsilon_t$, where ϵ_t is the strain range in in./in., mean failure cycles in air for the above levels will be:

<u>Strain Range</u>	<u>Predicted Cycles to Failure in Air</u>
0.5%	96,600
0.75%	28,700
1.0%	8,300

At a cycling rate of four per hour, 87,600 cycles will be attained in 2-1/2 years. Thus, mean failure time for the 0.5% strain range can be less than 2-1/2 years only if there is an environmental effect; mean cycles to failure for the two higher strain ranges will occur within 2-1/2 years, ensuring that failure for most of these specimens will be obtained. If the environmental effect is small, it can be revealed only if the cycling rate is low, such as four per hour, thereby ensuring long exposure times. Thus, choice of cycling rate represents a balance between allowing a maximum time for any environmental effect to operate and the necessity for definite test data within the 2-1/2-year period.

Initial surface strain ranges will be achieved by deflecting the specimens through a range determined by the gap between fixed stops at the specimen tip and the ram stroke, and the relationship between strain and deflection has been established. Nevertheless, individual test specimens can be subject to strains considerably different from the intended levels

unless great care is used during machining and assembly. Preliminary information on deflection versus surface strain reveals the sensitivities shown in Table 3-1. Such sensitivities indicate the importance of toolmakers' tolerances on setup of the fatigue machine, and sufficient testing to indicate that the planned deflections are actually achieved under load.

TABLE 3-1
SENSITIVITY TABLE

At nominal strain range of:	total deflection error to cause 5% error in strain range for 0.126-in. - thick specimen* is:	and total deflection error to cause significant environment effect to be falsely indicated, for 90% nonsignificance limit shown, is:
0.5%	0.0029 in.	0.0121 in. for ± 0.227 log-cycles
0.75%	0.0022 in.	0.0041 in. for ± 0.151 log-cycles
1.0%	0.0020 in.	0.0044 in. for ± 0.236 log-cycles

*0.120-inch-thick specimen adapted. Replacement data to follow.

Factor 2: Initial surface strain range, in zero-to-tension loading

Levels: 0.5% and 0.75%

This factor was introduced to estimate an effect due to loading in only the opening mode, which is possibly different from the effect due to loading in balanced compression-tension mode. It does not appear feasible to run a test with load applied to bend the specimen in only one direction in such a way that the specimen will not be subject to permanent deformation at the surface after each cycle. Such a surface strain for Type-304 stainless steel probably does not exceed 0.1%, which is well below the endurance limit. Thus, failure would never be expected in air; and failure would occur in reactor water only if there were an unexpectedly large environment effect. The two strain ranges chosen are the lowest two to be run in compression-tension.

Factor 3: Material

Levels: Type-304 stainless steel, Type-304L stainless steel, Inconel-600, carbon steel

These levels were chosen to represent present and candidate piping materials of greatest interest. One-inch plate will be used for all base metal fatigue specimens, and all WOL's; 3/8-inch plate will be used for the welded fatigue specimens and all stress bends. The materials are ordered in 3/8-inch plate to the following specifications:

Type-304 stainless steel	ASTM A-240, Type-304
Type-304L	ASTM A-240, Type-304L
Inconel-600	ASTM B-168
Carbon steel, 0.3%	ASTM A-516, KC-70

Test conditions 6 and 7 in Table 7-1 (in Section 7) use materials on hand from the Dresden-1 plant; see Factor 5.

Factor 4: Material Condition (codes are also shown in Table 7-1)

Levels: For Type-304 stainless steel, 304L stainless steel, and Inconel-600

- Code 1. Intended to simulate as-received piping.
Machine, solution anneal (surface only), and pickle.
- Code 3. Intended to simulated welding which subjects the material to excessively high temperatures: "block" welding of circumferential seams, thermocouple, and other instrumentation welds, repair welds, etc.

Weld by a high heat input process, inspect metallographically for zone maximum sensitization in heat affected zone (HAZ), and machine specimen so this zone is in reduced section (do not anneal or pickle). If no sensitization can be seen, machine to place reduced section 1/8 inch from weld.
- Code 4. Intended to simulate normal heat input, multipass welding.
Weld by low heat input process, inspect metallographically for zone of maximum sensitization in HAZ, and machine specimen so this zone is in reduced section (do not anneal or pickle). If no sensitization can be seen, place reduced section 1/8 inch from weld metal.
- Code 5. Intended to simulate furnace-sensitized material.
Machine, solution-anneal, pickle, and furnace sensitize.
- Code 8. Intended to simulate inside surface cold work in piping due to hand grinding.
Machine, and surface grind (do not anneal or pickle).

For carbon steel:

Code 2. Intended to simulate as-machined condition.
Machine to size (no heat treatment).

Code 4. Same as for Type-304, above.

Code 6. Intended to simulate carbon steel which has been stress-relieved.
Machine, and stress-relieve.

Code 7. Intended to simulate welds which have been stress-relieved.
Weld with low heat input, locate zone of maximum sensitization in HAZ metallographically, machine to place this zone in thin section, and stress-relieve. If no sensitization can be seen, place reduced section 1/8 inch from weld metal.

Code 7A. (For WOL's only) Same as Code 7, except place crack path in weld metal

Factor 5: Irradiation, as from Piping with 8 Years of Reactor Recirculation Line Service Levels: Base material and sensitized zone near weld

Use Dresden-I equalizer line pipe specimens of base material and weld material. Examine weld material metallographically to place sensitized zone in reduced section of test specimen. Use Material Condition Code 2.

Factor 6: Presence of Initial Crack

Levels: Initial crack produced mechanically by spark discharge machining
Initial crack produced chemically

This factor is introduced to estimate the effect of having a previously initiated site. This effect (difference between cycles to failure for normal specimen and these specimens) represents cycles to initiation only, compared with cycles for both initiation and growth through to leakage. The two crack preparation methods are used to estimate a possible different effect due to either sharpness of crack tip or having chemical residue in the crack tip which may grow immediately by the same chemical process which manifests itself as stress corrosion, not requiring any initiation time.

The mechanically initiated cracks are to be machined in Type-304 stainless steel, Type-304L stainless steel, and Inconel-600 specimens in both as-received (Code 1) and sensitized (Code 5) material conditions; and for the Type-304 stainless steel only, in both C-T and O-T loadings. The mechanically initiated cracks are to be machined in carbon steel specimens in the base metal, stress-relieved condition (Code 6). The chemically initiated cracks are to be placed in Type-304 (only) specimens that are machined, solution-annealed, and pickled (Code 1).

For both methods, procedures should be chosen that result in cracks of nearly the same depth—in the vicinity of 0.010 inch.

3.4 POWER OF TESTS

The power of the fatigue portion of Task K has been reappraised in terms of how different from the cycles to failure predicted in air the results in environment must be for the "effect" of environment to be declared significant. In general, given the characteristic variability of results, we wish to run sufficient specimens at each test condition that some satisfactorily small effect is significant (i.e., is genuine; has only a low probability of having occurred by chance alone). In the Twelfth Quarterly, GEAP-5637, Table 7-3 and Figures 7-9 and 7-10 display information on this question using two repeatability values taken from the literature. But repeatability data have now been taken in air on the chosen specimen shape, as shown in Figure 7-2 of the Seventeenth Quarterly, GEAP-10072. Based on the new data, and assuming the same variability of points in environment, the power of the tests is revised as shown in Table 3-2 and Figure 3-1.

Comparison of the power information in the Twelfth Quarterly with the information in this report reveals that repeatability for the Task K fatigue specimen will apparently be 1-1/2 times that for the less favorable case in the Twelfth Quarterly, which was for the variability of points about the line given in the ASME Section III Criteria section. The number now adopted, from experiment, is $1\sigma = 0.21$ log-cycles; previously assumed was $1\sigma = 0.14$ log-cycles. The 0.21 is based on 11 points in Figure 7-2 of the Seventeenth Quarterly.

Figure 3-1 and Table 3-2 show that the factor on cycles by which the predicted value in environment must differ from the cycles to failure predicted by the air line, to be considered significant at the 10% level, varies from 1.42 to 2.10, depending on how the predicted value in environment is found, and also on the strain range. The most favorable

TABLE 3-2

NINETY PERCENT NONSIGNIFICANCE INTERVALS

Effect of environment, estimated by the method shown, must exceed interval value shown in log-cycles for the difference to be considered significant at the 10% level. Equivalent factor on cycles is shown for easy comparison.

Variability of Points		At Strain Range, $100\epsilon_t$ (%)	"Effect of environment estimated as difference between cycles to failure on air line, and cycles to failure in environment found as"							
Found, about air line	Assumed, in environment, about repeated points (1) (2); about line (3) (4)		(1)	(2)		(3)		(4)		
			Mean of 2 points at the strain range	Mean of 4 points at the strain range		Predicted value on regression line through n points, n/3 at each strain range				
			Log Cycles	Factor on Cycles		n = 6		n = 12		
				Log Cycles	Factor on Cycles	Log Cycles	Factor on Cycles	Log Cycles	Factor on Cycles	Factor on Cycles
0.21	0.21	0.5	0.314	2.06	0.246	1.76	0.287	1.94	0.227	1.68
0.21	0.21	0.75	0.292	1.96	0.218	1.65	0.189	1.54	0.151	1.42
0.21	0.21	1.0	0.322	2.10	0.256	1.80	0.295	1.97	0.236	1.72
0	0.14	All	0.163	1.46	(from Table 7-3, Twelfth Quarterly, for comparison)

FIGURE 3-1. NINETY PERCENT NONSIGNIFICANCE INTERVALS ABOUT AIR LINE

case illustrated in when twelve data points (two for each of two test conditions not displaying a significant difference between their regression lines at each of three strain ranges) are fitted by a line; the values predicted by that line must differ from values predicted by the air line by more than factors of 1.42 to 1.72 to indicate a significant environmental effect. The least favorable case illustrated is for an effect estimated by the difference between the air line predicted value and the mean of two tests in environment at the same strain range; here differences must exceed factors of 1.96 to 2.10 to be considered significant—obviously a less powerful test. The line-fitting approach will be used for all test conditions feasible. The nonsignificance interval is shown as flared around the air line, due to the greater uncertainty characteristic of points near the ends of regression lines compared with those near the middle.

From a practical viewpoint, greater testing power can be gained by pooling results of more test conditions in environment, and by running more points on the air line.

SECTION IV

TASK B-- STRESS ANALYSIS

(E. North)

4.1 OBJECTIVE

The purpose of the stress analysis task is to develop a method for the stress and strain analyses of those piping components which have been intractable problems. The designer must be able to determine the detailed stress and strain distributions in complex piping geometry under complex loadings for avoidance of leaks and severance in piping, and to take into account low-cycle fatigue, corrosion, and critically sized flaws.

4.2 TASK B-1-- COMPUTER PROGRAM DEVELOPMENT

The objective of the computer code development is to develop the analytical tools required to define the state of stress and strain in complex piping in service.

4.2.1 Summary

As part of the PAPA development work, an evaluation of related computer codes and a review of the PAPA code are in progress. An assessment report will be prepared, stating recommendations for future effort. The discussion following is an evaluation of the NASA general computer code, NASTRAN, and the Air Force computer program, FORMAT. These codes, developed over the last 3 to 4 years, have many similarities (see subsection 4.5--Bibliography).

4.3 FORMAT COMPUTER CODE

FORMAT (FORmat MAtrix ABstruction TEchnique) is the United States Air Force general-purpose structural analysis program. This computer program was developed by the McDonnell/Douglas Aircraft Company under a USAF contract from Wright-Patterson Air Force Base. Documentation of the program is extensive and complete. Review of items 1, 2, 3, and 4 in Subsection 4.5 was the primary source of this evaluation.

As presently conceived, the computer program FORMAT is divided into three independent computer programs, referred to as Phases I, II, and III. To arrive at a solution to a problem and have output from the computer, all three phases must be instituted. Two modes of operation are available: (1) all three phases can be coupled to run from beginning (input data) to final solution (deflections and stress); or (2) as recommended in the manuals, the user initiates and executes Phase I, inspects all matrices developed for completeness, equilibrium, etc., and then initiates Phase II, to arrive at the problem solution. After checking this output, the user specifies what quantities are to be calculated (forces, stresses, etc.) and what output format (graphics, report form, etc.) is to be displayed. Then Phase III is initiated to complete the analysis.

4.3.1 Phase I Computer Program

The Phase I computer program processes all program input data and develops the necessary matrices required for Phase II. As already noted, this program can stand alone and be run independently of any other phase of the FORMAT program. The user writes all necessary control statements for this program, such as naming of tapes, editing to be performed, and structural generation to be performed.

Operation of Phase I and all other portions of this program are user controlled. This can be of great value in operations concerning input editing, merging, and generation.

When a user has filled out his input forms to specify structural joints, geometry, type of analysis, vector data, and element data, this information is stored on tape. The user can then use the edit capability of Phase I to couple this new data with previously submitted data (stored on a different tape) to build a larger structural analysis.

The edit capability can also be used to do geometry generations. A mirror image of the inputted structure can be generated. This permits the user to input only one-half of a large structure and ask the program to generate the data for the other half.

Coordinates for evenly spaced points on straight lines (beam or bar analysis) can be generated. Simple surfaces can be automatically divided into finite element representation. Available surfaces are a triangle, a warped quadrilateral, a segment of a cone, and a curved quadrilateral.

A varying pressure load can be developed as a series of evenly spaced, discrete load vectors. The user specifies the coefficients for a third-degree polynomial in two variables. A preprocessor will automatically generate the concentrated, statically equivalent loads at the plate nodes.

After all coordinate input generations and load generation, the user specifies what structural matrices are to be developed. Two methods of analysis are available: the force method, and the displacement method; the analysis comprises the following points:

- If the user or computer code develops a stiffness matrix and defines the boundary conditions of the problem, the unknowns are the deflections of the joint nodes. This is the displacement method of analysis. In the case where a flexibility matrix is developed, the unknowns are forces at the nodes.
- The primary advantage of the flexibility approach is in handling very stiff members. The flexibility can be set equal to zero. However, for complicated structures, development of the total flexibility matrix based on compatibility of a node is prohibitive. Stiffness matrices for structures are based on the equilibrium of the node in question and are simple to formulate for complex structures.

The advantage of having both methods of analysis available is a desirable feature of a computer program, even with much loss of generality in using the force method.

Phase I limits the use of structural elements for the force and displacement methods of analysis.

a. Force Method

1. Bar elements that can take axial force, torque, and bending in two perpendicular planes
2. Shear panels
3. Triangular and parallelogram membrane elements

b. Displacement Method

1. General bar elements
2. Shear panels
3. Triangular and rectangular membrane elements
4. Triangular and quadrilateral bending and membrane elements

Using all the foregoing items, the necessary matrices are developed to perform mechanical, mechanical/thermal, stability, and vibration analyses.

At the user's option, advantage may be taken of symmetry and antisymmetric structural restraints by disconnecting reactions to benefit from the smaller analysis.

In Phase I, all matrices necessary to perform substructure analysis are developed. Each individual substructure stiffness or flexibility matrix, joints (external joint) matrices for each substructure, and the total external joint matrix are built. The user then saves this information out on tape and/or specifies in what format this information is to be printed out for checking.

Last, Phase I can pass control to Phase III to plot out the idealized structure to show the user what his mathematical model encompasses. This is helpful in debugging errors in structural geometry.

4.3.2 Phase II Computer Program

Phase II is the matrix abstraction capability that provides standard matrix manipulation capability to the user (matrix add, subtract, transpose, transpose multiply, etc.). This permits the user to control the actual formulation of his problem.

Solution of static matrix equations is by standard elimination or iterative techniques. For vibration problems, an eigenvalue/eigenvector (Given's method) is provided. Maximum size of the characteristic matrix is 160 x 160 for 32K available computer core storage. Buckling analysis extracts only the first few eigenvalues. A nonsymmetric matrix of

2000 x 2000 can be handled in this routine. Caution on using this portion of the program is stated in item 4 (subsection 4.5), page 272: "Results are questionable and expensive to obtain."

If the user does not use Phase I to develop flexibility or stiffness matrices, options are provided to input matrices of up to 2000 x 2000 in size. The only restriction on a card inputted matrix is that only 4500 randomly ordered, single, precision numbers can be in the matrix. This restriction does not apply to matrices developed using matrix operations or pseudo-matrix operations.

4.3.3 Phase III Computer Program

Phase III is the output medium of the computer program. To initiate this phase, correct matrices must be saved on tapes from Phases I and II. The user specifies the format to be used and what quantities are to be output. If the user is going to use the joint deflections for a report, the computer output is ordered to print correct heading, page numbers, labels, etc., for immediate inclusion in reports. Any calculated matrices from Phase I and II can be outputted in proper formats for checking and report writing.

For user information, the graphical display from this program is impressive. Any structure can be displayed showing member types, reactive forces and moments, deflected shapes, etc. In addition, the user can specify multiple views of the structure rotated in three-dimensional space. For presentations and quick summaries of outputted data, graphics seems to be a large and useful contribution of this program.

4.3.4 Conclusions

As FORMAT has not been used as a part of Task B studies, conclusions are necessarily limited to the information in items 1., 2., 3., and 4. of subsection 4.5—Bibliography. However, a presentation on FORMAT at Wright-Patterson Air Force Base was attended by the writer in the summer of 1968, followed by a discussion of applications of FORMAT with some users.

The editing and merging control of Phase I permits wide latitudes in making small changes in structural geometry and rerunning of a problem. Also, much of the matrix development of other nonchanged substructural data does not have to be re-inputted or modified. This feature is desirable on any large structural analysis program.

As no, or very little, work has gone into updating the solution portions of the program, Phase II, these routines are probably not as efficient as they could be.

After reviewing the finite elements used in FORMAT, it is found that the elements are linear displacement elements or constant stress elements. All illustrative examples are in terms of displacements or frequencies. For the example of a pressurized flat plate, the authors say that problems developed in using triangular elements. "Results were poor, apparently due to inconsistent xy coupling in the fundamental deformation function for the element," quoted from page 577 of item 4 (subsection 4.5).

It should be noted that for finite elements developed using displacement functions, this restriction will always be present.

Because stresses are not discussed in any example, no conclusions are made regarding the adequacy of the analysis for stress.

The basic formulation of the program user manuals, flow charts, error messages for the program, and overall organization of this data into report form, has been a formidable task.

4.4 NASTRAN COMPUTER CODE

The following evaluation and description are based on a presentation at a recent SESA symposium.*

NASTRAN is derived from NASA STRuctural ANalysis program. This is conceived to be both a finite element program, and a general-purpose structural analysis program. Static and dynamic analysis can be handled by the program, and it is adaptable to most large computers:

IBM	360
Univac	1108
CDC	6600
IBM	7094 Coupled

*NASTRAN Computer Program, T. Butler, Society for Experimental Stress Analysis meeting, October 15, 1969, Goddard Space Flight Center, Greenbelt, Maryland.

This program has taken over 3 years to develop and will be ready for release next summer.

The computer program is adaptable to different computers and plotters because of its modular organization. All machine-dependent portions of the program are in one package. The rest of the program is machine independent. Plotters can be table type, microfilm, and incremental.

Formulation and development can be broken down into three categories:

- Applied Mechanics
- Numerical Analysis
- Advanced Computers

With this breakdown, the program is predicted by its developers to have a useful life span of ten years. After that, new computers will have the capability to do design optimization.

NASTRAN can be used to analyze all types of structures:

- Bridges
- Airplanes
- Spacecraft

The content and capabilities of the program have been described as including:

Rigid Format is a PAPA-type input where geometries and boundaries are inputted and the program runs to a final solution.

Matrix Abstraction permits the user to specify his matrix equations and control every step in the solution of the problem. This is similar to the MIT program STRESS, and the Air Force program FORMAT. A special language named DMAP has been developed for this portion of the program.

Input Preprocessor has been developed for some basic structures, flat plates, and cylinders.

A problem can be so constrained that it will have one degree of freedom per joint/node.

The plot package can be so controlled that each substructure is plotted separately or as a whole. Characters can be specified for plotting of curves of output.

The internals of the program, such as types of structural elements available, and types of analysis permitted, are as follows:

Displacement Method

At present, the displacement method is the only one working. The force method is being checked out.

Structural Segment

Control Systems

Two types of problems can be analyzed: structural and control systems. This discussion centers on the structural aspects of NASTRAN.

Having 21 elastic constants implies an anisotropic material.

4.4.1 Elastic Elements

- a. Scalar elements are mass-spring-dashpot systems that reflect nonlinearities. These are used in control systems or for analyzing one-dimensional problems. The one-dimensional dampers are the only portion of the programs where nonlinear behavior is permitted.
- b. Line elements are straight beams permitting 6 static degrees of freedom at each end of the beam.
- c. Offsets in connections are accounted for by rigid connectors.
- d. Rods and tube members are permitted. Only axial motion and torsional motion are permitted in these two members.
- e. Two-dimensional elements are the plate and shell finite elements. Panels used for shear, membrane, twist, and bending reflect only this single behavior per element. The bending and membrane elements are uncoupled. Sandwich elements reflect membrane and bending of the faces of the honeycomb. The finite elements are triangular and quadrilateral displacement elements.

- f. Two-dimensional axisymmetric elements consist of conical shells and toroidal shells. The conical shell can be degenerated to a cylinder and disc. Non-axisymmetric loads are permitted on this element only. A toroidal shell does not degenerate to a cone or cylinder and can be used only for axisymmetric loading.
- g. Three-dimensional axisymmetric elements are either triangles or quadrilateral. The quadrilateral element comprises four triangles.

Stiffness Matrix

- Automatic generation in the program
- Manual input of spring constants

Mechanical/Thermal Loads

- Surface
 - Point
 - Distributed
- Body Forces
 - Centrifical
 - Inertia
 - Gravity

Form Equations of
Equilibrium and Compatibility

Static

- Deflection at the nodes
- Forces, stress, and strains are calculated at the center of each element.

Piecewise linear-elastic-linear plastic analyses are provided but not completed (a costly analysis).

Segment Joining

- Some
- All

This is the substructure option of the program.

Dynamic Degrees of Freedom

Each joint/node can have from 1 to 6 dynamic degrees of freedom.

This is basic forced response or shock analysis problem.

4.4.2 Random Field Vibration

- Frequency response using transfer functions
- Green's functions
- Random forcing spectrum
- Response auto-spectrum
- Fourier transform to auto-correlation

4.4.3 Control System Dynamics

Transient Response. This is the scalar portion of the program—utility in feedback control and in flying a mission from launch to orbit.

4.4.4 Application to Structures

Utilization of NASTRAN helps in defining

- Pre-design parameters
- Design iterations to verify a final design
- Behavior properties
- Mission performance
- Test basis and instrumentation

The following examples are of machine-plotted geometry in the original and deformed state.

- a. OAQ Structure. This is an octagonal structure consisting of plate elements. Two thousand static degrees of freedom (≈ 300 joints) and 650 dynamic degrees were used in the analysis (a very complex structure, without reported results).
- b. Cylindrical Shell with a Spider Stiffener at One End. This is a thermal analysis where two metals (titanium and aluminum) were combined. The deflected structure shows the center bulging outward.
- c. Part of Astronomy Satellite Plus Equipment Bay. This is a frequency analysis with poor experimental-analytical correlation. Insufficient boundary restraint plus poor modeling where structural parts join led to discrepancies.
- d. Sounding Rocket Internals. This is a top and bottom disc, with dividers connecting the two ends. No results were reported.

After 3 years work, NASTRAN is well along in its checkout. Release is set for next summer to non-NASA installations.

4.4.5 NASTRAN Features

- NASTRAN has a large portion of its work in plotting graphical displays—very good plot package for input/output displays.
- NASTRAN has eigenvalue routines that can yield all frequencies of a structure.
- NASTRAN will do control analysis leading to transient response, random excitation, and feedback control.

- NASTRAN has a matrix abstraction (DMAP language) associated with it.
- NASTRAN has a poor element representation constituting a basic weakness, and no curvature can be accounted for in any element.

4.4.6 Conclusions

Given that stresses were not reported for any of the examples studied, any final conclusion regarding the potential applicability NASTRAN for pipe problems must await such demonstration and correlation with experiments.

4.5 BIBLIOGRAPHY FOR SECTION IV.

1. Cogan, J. P.; Morris, Serpanos, and Wells, "FORMAT- Fortran Matrix Abstraction Technique, Volume VI. Description of Digital Computer Program - Phase I" AFFDL-TR-66-207, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, December 1968, 735 pages.
2. Lackey, W. J. and Wild, R. E., "FORMAT II-Second Version of Fortran Matrix Abstraction Technique, Volume II, Supplement I. Description of Digital Computer Program," AFFDL-TR-66-207, Supplement I, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, December 1968, 82 pages.
3. Morris, R.C.; Wells and Yoon, "FORMAT- Fortran Matrix Abstraction Technique; Volume VII. Description of Digital Computer Program - Phase III," AFFDL-TR-66-207, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, December 1968, 169 pages.
4. Pickard, J., "FORMAT- Fortran Matrix Abstraction Technique, Volume V. Engineering User and Technical Report," AFFDL-TR-66-207, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, December 1968, 688 pages.

SECTION VI

TASK D--LOW-CYCLE FATIGUE

6.1 OBJECTIVE

The objectives of the Fatigue Task are: (a) to extend the understanding of low-cycle fatigue cracking in high-pressure piping components which have mechanical or defect flaws, and (b) to apply this knowledge in developing rational design bases for prevention or control of fatigue crack initiation and growth in reactor piping systems.

6.2 TASK D-1--FATIGUE CRACK GROWTH STUDIES (A. J. Brothers)

6.2.1 Summary

Practically all tests have been completed; final prototype material tests, two each, of carbon steel and Type-304 stainless steel await completion. A topical report on plastic strain crack growth is in preparation.

6.3 TASK D-2--CRACK INITIATION (E. Krempl)

6.3.1 Summary

A final report is in preparation that will include: (1) a summary of all important tests performed, (2) an analysis of bend tests, and (3) the experimentally determined fatigue strength reduction factors which are compared with the theoretical solution derived from the Stowell Method.

6.4 TASK D-3--PROTOTYPE PIPE FATIGUE (J. D. Heald)

6.4.1 Summary

Testing was completed on the following samples during the report period:

- a. CSTS-2--Cold stainless steel tee, in-plane loaded through the run;

- b. CCLS-2—Cold carbon steel elbow, loaded out-of-plane; and
- c. HCLS-2—Hot carbon steel elbow, loaded out-of-plane.

Initial setup was begun on a hot, stainless steel, out-of-plane elbow sample, HCLS-2. Pertinent test data are summarized in Table 6-1. A topical report summarizing the work through June 1969 was prepared in draft form.

6.4.2 Data Obtained

6.4.2.1 Crack Initiation

Ultrasonic inspection test methods have been used to determine cycles to crack initiation for the specimens tested. In the case of sample CCLS-2, the internal crack was detected when it was approximately equal to 5% of the wall thickness, while in the case of sample HCLS-2 the crack was approximately 10% of the wall thickness.

Cycles to crack initiation (NI) reported in Table 6-1 are either the ultrasonically indicated values or values designated as less than the measured cycles to fully penetrate the wall. These data have been added to the previously published data for crack initiation versus nominal stress range, and are shown in Figures 6-1, 6-2, and 6-3.

6.4.2.2 Through-Wall Growth

Quantitative data for through-wall crack growth has not been obtained from post-mortem metallographic examination due to the extremely rough fracture surface that results from fatigue testing in the elbow and tee samples; however, ultrasonic inspection is continued after crack initiation and prior to through-wall penetration. For example, the ultrasonic through-wall crack growth indications for sample CCLS-2 are shown schematically in Figure 6-4.

6.4.2.3 "Circumferential" Crack Growth

After through-wall penetration (i. e., leakage) occurs, fatigue testing is continued to obtain the following information:

TABLE 6-1
DATA SUMMARY

Sample Description	Test Temperature (°F)	Internal Pressure (psi)	Stress Range (psi)	Cantilever Cycles to Cycles to			Test Terminated (NO)
				End Deflection (in)	Crack Initiation (NI)	Fully Penetrate (NW) Wall	
CSTS-2, ASTM A-182 F Type-304 SS Schedule-40, Tee Loaded Through Run	68 84	1000	67,800	±8.31	<3,310 ^(b)	3,310	8,000 (4,690)
CCLS-2, ASTM A-234 WPB Carbon, Schedule-40, Elbow Out-of-Plane	64 87	1000	42,600	±5.62	≤3,249 ^(a)	7,899 (4,650)	13,599 (5,700)
HCLS-2 ASTM A-234 WPB Carbon, Schedule-40, Elbow Out-of-Plane	550	None	43,100	±7.19	≤3,299 ^(a)	26,100 (22,801)	31,100 (5,000)

(a) Determined by ultrasonics

(b) Values taken at less than the number of cycles to fully penetrate the wall.

FIGURE 6-1. TYPE-304 STAINLESS STEEL, ROOM TEMPERATURE, STRESS RANGE VERSUS INITIATION CYCLES

FIGURE 6-2. CARBON STEEL, ROOM TEMPERATURE, STRESS RANGE VERSUS INITIATION CYCLES

TOP FRONT VIEW
CYCLE 3249

TOP FRONT VIEW
CYCLE 4999

BOTTOM FRONT VIEW
CYCLE 5099

TOP FRONT VIEW
CYCLE 7899

FIGURE 6-4. ULTRASONIC THROUGH-WALL CRACK GROWTH HISTORY,
SAMPLE CCLS-2

- a. Crack growth data,
- b. Establish whether or not a critical crack size (instability) is obtained under low-cycle fatigue loading conditions, and
- c. Provide knowledge of the final fracture characterization for the ell or tee components; i. e., the location, size, shape and extent of the fracture surface.

Post-through-wall crack growth for ells and tees in general is quite complicated—the cracks do not grow in any one general direction, such as circumferentially or longitudinally. For example, post-through-wall crack growth history for sample CCLS-2 is shown schematically in Figure 6-5. The final crack geometry is shown in Figures 6-6 through 6-9. Crack growth in the stainless tee CSTS-2 and carbon steel ell HCLS-2 are shown in Figures 6-10 through 6-15.

6.4.2.4 Stress Indices

Stress indices, as defined in Quarterly No. 16, GEAP-10024, for an elbow loaded in out-of-plane bending are shown plotted with previous data in Figure 6-16. Data for the in-plane tee sample loaded through the run are shown in Figure 6-17.

EXTERNAL CRACK GROWTH DIRECTION
INITIATION CYCLE 3249
THROUGH-WALL CYCLE 7899

EXTERNAL CRACK GROWTH DIRECTION
THROUGH-WALL CYCLE 7925

EXTERNAL CRACK GROWTH DIRECTION
THROUGH-WALL CYCLE 9200

EXTERNAL CRACK GROWTH DIRECTION
THROUGH-WALL CYCLE 10025

FIGURE 6-5. POST-THROUGH-WALL CRACK GROWTH HISTORY, SAMPLE CCLS-2, FOR FOUR SEPARATE CRACKS NOTED AS NOS. 1, 2, 3, AND 4. ARROWS SHOW DIRECTION OF FATIGUE CRACK GROWTH

FIGURE 6-6. FINAL FRACTURE GEOMETRY IN ELBOW SAMPLE CCLS-2, LOADED BY OUT-OF-PLANE BENDING, TOP OF CROTCH SIDE SHOWN

FIGURE 6-7. FINAL FRACTURE GEOMETRY IN ELBOW SAMPLE CCLS-2, LOADED BY OUT-OF-PLANE BENDING, BOTTOM OF CROTCH SIDE SHOWN

FIGURE 6-8. FINAL FRACTURE GEOMETRY IN ELBOW SAMPLE CCLS-2. LOADED BY OUT-OF-PLANE BENDING, BOTTOM OF BACK SIDE SHOWN

FIGURE 6-9. FINAL FRACTURE GEOMETRY IN ELBOW SAMPLE CCLS-2, LOADED BY OUT-OF-PLANE BENDING, TOP BACK SIDE OF LEVER ARM SHOWN

FIGURE 6-10. THROUGH-WALL PENETRATION SAMPLE CSTS-2

FIGURE 6-11. THROUGH-WALL PENETRATION CLOSEUP SAMPLE CSTS-2

FIGURE 6-12. FINAL FRACTURE GEOMETRY IN TEE SAMPLE CSTS-2,
LOADED IN-PLANE THROUGH THE RUN, RIGHT SIDE SHOWN

FIGURE 6-13. FINAL FRACTURE GEOMETRY IN TEE SAMPLE CSTS-2,
LOADED IN-PLANE THROUGH THE RUN, LEFT SIDE SHOWN

FIGURE 6-14. FINAL FRACTURE GEOMETRY IN ELBOW SAMPLE HCLS-2, LOADED BY OUT-OF-PLANE BENDING, CROTCH SIDE SHOWN

FIGURE 6-15. FINAL FRACTURE GEOMETRY IN ELBOW SAMPLE HCLS-2, LOADED BY OUT-OF-PLANE BENDING, BACK SIDE SHOWN

FIGURE 6-16. STRESS INDICES FOR OUT-OF-PLANE BENDING OF A 6-INCH, SCHEDULE-40 STAINLESS STEEL ELBOW PIPE RUPTURE STUDY, TASK D-3.

FIGURE 6-17. STRESS INDICES FOR IN-PLANE BENDING, LOADED THROUGH THE RUN, AND PRESSURE FOR A 6-INCH, SCHEDULE-40 STAINLESS STEEL TEE, TASK D-3.

6.5 TASK D-4-CYCLIC STRAIN AGING (A. J. Brothers)

6.5.1 Summary

Results of Charpy impact tests of A-212B plate following monotonic tensile deformation at 350°F indicate an appreciably lower shift in the 50% FATT for a given total strain than similar specimens cyclically strain-aged at 350°F. Also, comparison of the notch strength of a virgin notched bend bar indicates notch strength properties similar to specimens cyclically strain-aged to induce a brittle region near the notch. A test of the effect of a low total strain range (i.e., 0.5% for a low number of cycles, 75) indicates that strain range rather than number of cycles is the primary variable influencing embrittlement due to cyclic strain aging.

6.5.2 Effect of Monotonic Strain Aging on Charpy Impact Properties

Previous studies, covered in Quarterly Reports 12 through 15, have determined the influence of temperature, cyclic strain range, and number of cycles on the increase in Charpy impact transition temperature. To determine whether strain-aging effects result predominantly from cyclic rather than monotonic deformation, 2 x 1 inch thick plates of A-212B were strained monotonically to 0.5, 1.75, and 3% at 350°F. Heating was performed using resistance-heated tapes wound about the specimen.

The Charpy impact properties of these specimens machined with orientations identical to those tested previously after cyclic strain-aging are listed in Table 6-2 and shown in Figure 6-18. These results, with the qualifications noted later, suggest that monotonic deformation of a given range has an appreciably lower effect than cyclic deformation of the same range. The monotonically deformed specimens were machined from a different plate of A-212B that used for the cyclic straining. Also, they were tested in the as-received condition without stress relief or a pre-test age. Because of these differences, there was a question regarding the comparison of the two sets of results, and therefore tests were performed to evaluate the influence of stress relief at 1050°F-1-1/2 hours, or a pre-test age of 350°F-24 hours. The results indicate that these variables could increase the 50% FATT by perhaps 10°F, which is within the scatter of the Charpy impact test and presumably has little influence. The possibility that this plate represents a second plate of unknown virgin properties is relevant, and this possibility is strengthened by the rather high but not unusual maximum energy values for these tests.

6.5.3 Effect of Local Cyclic Strain-Aging on Notch Bend Strength

Previous tests, described in Quarterly Report No. 16, suggested that prior cyclic strain aging of a 2-inch-deep by 1-inch-thick notch bend bar (containing a 0.4-inch-deep notch with a 0.050-inch radius) had no significant influence on notch bend strength, and that there was no evidence of incipient pop-in type fracture at nominally low bend strength. To provide a more direct comparison with the non-cyclically strain-aged condition, a test of a virgin bar of identical geometry was tested at -105°F , using procedures similar to those described previously. This test resulted in a bend strength at maximum load equal to 131,000 psi; previous notch bend strengths were 132,500 and 138,000 psi. This recent result indicates conclusively the absence of significant cyclic strain-aging effects on notch bend strength for the range of conditions tested.

TABLE 6-2
CHARPY IMPACT PROPERTIES OF A-212B PLATE
FOLLOWING MONOTONIC DEFORMATION AT 350°F

Condition	Charpy 50% FATT ($^{\circ}\text{F}$)	Maximum Energy (ft-lb)
As-received plate	-12	27.0
	-10	24.5
	0	24.0
As-received plus	-5	24.5
stress-relieved $1050^{\circ}\text{F}-1-1/2$ h	0	25.5
plus $300^{\circ}\text{F}-24$ h		
Monotonically deformed		
0.5% at 350°F	15	38.0
1.75 at 350°F	20	41.0
3.00 at 350°F	35	39.5

6.5.4 Effect of Number of Cycles on Cyclic Strain Aging Embrittlement

To supplement earlier work describing the effect of number of cycles on 50% FATT following cyclic strain at 350°F , an additional test has been performed at $\pm 0.5\%$ total strain for 75 cycles. The shift in transition temperature resulting from this test is plotted in Figures 6-18 and 6-19, and suggests within scatter similar trends to those observed previously.

FIGURE 6-18. EFFECT OF CYCLIC STRAIN ON SHIFT IN CHARPY 50% FATT

FIGURE 6-19. EFFECT OF NUMBER OF CYCLES AT A GIVEN STRAIN RANGE ON SHIFT IN CHARPY TRANSITION TEMPERATURE

SECTION VII

TASK K—EFFECT OF BWR ENVIRONMENT

(D. A. Hale)

7.1 OBJECTIVE

The objective of Task K is to determine quantitatively the effect of BWR primary coolant on the low-cycle fatigue life of piping steels. Measurements of cycles-to-failure will be obtained employing a specially-designed fatigue testing unit in an experimental piping loop at a boiling water reactor. The planned test duration is 2-1/2 years, allowing time for corrosion, if any, to affect crack initiation and growth.

7.2 SUMMARY

The Dresden-I test loop piping installation was completed. Failure of the stem tip in one of the loop motor-operated root valves prevented operating the loop prior to the September Dresden-I outage. Preparations were made for shakedown testing at San Jose of the fatigue test machine containing dynamic test specimens of the final design. Operation will be at design conditions of temperature, pressure, and mechanical loading. The dynamic and static test specimen plan was reviewed and minor revisions were made. Manufacture of the final complement of dynamic and static test specimens progressed to the stages of final drilling and machining.

7.3 DRESDEN-I TEST LOOP

Installation of the loop cubicle piping was completed. The loop piping was successfully hydrotested, and pre-startup checkout procedures were begun. The motor-operated isolation valve on the loop return piping (MOV-2) did not operate correctly during this preliminary checkout period. The cause of the malfunction was traced to a fractured stem tip; a replacement stem could not be located in time to operate the test loop at full reactor pressure and temperature conditions prior to the scheduled September 7 plant shutdown. The replacement stem is scheduled for delivery early in the next quarter. As soon as it is received, it will be installed and checkout will be performed on both motor-operated valves.

The support frames for the lead shielding that will be provided around the dynamic and static test vessels are on order. They are scheduled for installation in late November.

7.4 HOT SHAKEDOWN TESTS

The fatigue test machine was reassembled with six dynamic fatigue test specimens and 144 dummy spacers as stand-ins for actual specimens. The gap clearances on the dummy spacers have been adjusted to provide loading for the drive system which simulates the service loads expected from the final complement of 150 test specimens. The cantilever spacers and specimens are gripped at the central drive shaft and are deflected variable amounts, depending on the setting of the gap clearances. These gaps on the fatigue specimens were adjusted to impose strain ranges high enough ($\approx 0.9\%$ and 0.7%) for failures to occur. This will enable checkout of the individual specimen failure detection circuits as a part of shakedown testing at 530°F , 1000 psig.

7.5 TEST SPECIMENS

7.5.1 Fatigue Specimen Plan

To ensure that a reasonable number of specimens fail in the absence of an environmental effect (80,000 loading cycles in 2-1/2 years), the following strains are planned: 1.0%, 0.75%, and 0.5% (fully reversed). On this basis, one can predict failure at 8,300, 28,700, and 96,600 cycles, respectively, if there were no significant environmental effect. The prediction is made using the ASME "best fit" curve for the fatigue of stainless steel, presented in Section III, Criteria. This loading schedule is summarized in Table 7-1. Note that the welded specimens have been selected to emphasize "normal" weldments (i.e., 27 of the 33 weld specimens); only the Type-304 stainless steel will be studied in an abnormal (high heat input) condition simulating welds made using techniques believed to introduce undesirable amounts of sensitization.

7.5.2 Static Specimen

The static specimen plans have been slightly adjusted:

- a. The stress bend program has been increased from 26 to 30 specimens to include Inconel-600 in the as-machined or reference condition, and carbon steel in the normal welded condition (see Table 7-2).

TABLE 7-1

Test Condition No.

Material

Type-304 Stainless Steel
Type-304L Stainless Steel
Inconel-600
Carbon Steel

Material Condition

Material Condition Code
Welded—Low Heat (Normal)
Welded—High Heat (Block)
Machined
Surface Cold Work
Solution Annealed
Pickled
Sensitized^(c)
Stress-Relieved

Simulated Crack Preparation

**Mechanical
Chemical**

No. of Specimens Loading

$$\sigma_T^{(d)} \text{ (Initial Surface Strain Range)}$$

0.5%

0.75%

CT^(d) (Initial Surface Strain Range)

0.5%

0.75%

1.0%

10

Subtotal

Total

Type-304 Stainless Steel 72

Type-304L 28
Stainless Steel

Inconel-600 · 23

Carbon Steel	27
	<u>150</u>

- (a) Equalizer line base material—8-year service pipe.
- (b) Equalizer line weld material—8-year service weld.
- (c) Equivalent to furnace sensitization.
- (d) OT = Zero to tension loading.
CT = Compression to tension loading.

TABLE 7-2
TASK K STRESS- BEND SPECIMENS

Material				Material Condition								Load Level		
304 Stainless Steel	304L Stainless Steel	Inconel- 600	Carbon Steel	Material ^(a) Condition Code	Welded, Low Heat (Normal)	Welded, High Heat (Block)	Machined (Ground)	Solution Annealed	Pickled	Sensitized	Stress Relieved	<u>Initial Surface Strain</u>		No. of Specimens
												0.25%	0.5%	
x				1			x	x	x			1	1	2
x				2			x					1	1	2
x				3		x	x							2
x				4	x		x					1	1	2
x				5			x	x	x	x		1	1	2
	x			1			x	x	x			1	1	2
	x			2			x					1	1	2
	x			4	x		x					1	1	2
	x			5			x	x	x	x		1	1	2
		x		1			x	x	x			1	1	2
		x		2			x					1	1	2
		x		4	x		x	x	x	x		1	1	2
		x		5			x					1	1	2
			x	2			x					1	1	2
			x	4	x		x				x	1	1	2

(a) See subsection 3.3 of this report.

- b. The WOL program (see Table 7-3) was reduced from 28 to 26 specimens by removing two carbon steel specimens.

7.5.3 Dynamic Test Specimen, Compliance Calibration

The load-deflection-strain characteristics of the final dynamic test specimen (Figure 7-3, GEAP-10072) were measured using the specimen stress fixture (Figure 7-10, GEAP-5770). These results were used to generate values for the service loads which will be required of the fatigue test loading system by the final complement of 150 dynamic test specimens.

7.5.4 Specimen Material Properties

Test coupons from all the plates used in the manufacture of the static and dynamic test specimens have been analyzed to determine chemical compositions. The results are listed with the vendor analyses in Table 7-4.

7.5.5 Specimen Manufacturing Program

7.5.5.1 Dynamic Specimens

The first stage in the manufacture of the wrought specimens has been completed. The specimens, completely machined except for the axial hole, are undergoing final quality control checks.

Four of these specimens (one from each material group) have been forwarded to the vendor selected to EDM* the axial holes. The vendor will machine one 3-stage axial hole in each of these four specimens, using the same production parameters (electrolyte, amperage, feed rates, and electrode material) intended for use on the final production run.

The four specimens will then be metallographically examined to characterize the microstructure of the specimen material immediately adjacent to the axial hole. If the results for these four "process qualification" specimens prove positive (i.e., no micro-cracking introduced by the EDM process), the final production order will be placed.

*Electro Discharge Machining.

TABLE 7-3
TASK K MODIFIED WOL SPECIMENS

Material				Material Condition							Load Level			
Type-304 Stainless Steel	Type-304L Stainless Steel	Inconel-600	Carbon Steel	Material ^(a) Condition Code	Welded, Low Heat (Normal)	Welded, High Heat (Block)	Machined Ground	Solution Annealed	Pickled	Sensitized ^(d)	Stress Relieved	Initial Applied Load		No. of Specimens
x				2			x					1	1	2
x				3		x ^(b)	x					1	1	2
x				4	x ^(b)		x					1	1	2
x				5			x	x		x		1	1	2
	x			2			x					1	1	2
	x			4	x ^(b)		x					1	1	2
	x			5			x	x		x		1	1	2
		x		1			x					1	1	2
		x		4	x ^(b)		x					1	1	2
		x		5			x	x		x		1	1	2
			x	2			x					1	1	2
			x	7A	x ^(b)		x				x	1	1	2
			x	7	x ^(c)		x				x	1	1	2

(a) See subsection 3.3 of this report.

(b) Test Section in HA7.

(c) Test section in filler metal.

(d) Equivalent to furnace sensitization.

TABLE 7-4
SPECIMEN PLATE MATERIAL, CHEMICAL ANALYSES

Material Specification	Vendor Heat Number	ASTM Chemical Requirements ^(a) (%)	3/8-in. Plate		1-in. Plate	
			Vendor Certified Analysis (%)	Check Analysis (%)	Vendor Certified Analysis (%)	Check Analysis (%)
ASTM A-240 Type 304	1 in. - 24236 ^(b)	C - 0.08 Max Si - 1.00 Max P - 0.045 Max Cr - 18.00-20.00 N - 8.00-12.00 S - 0.030 Max Mn - 2.00 Max	WILL USE 1-INCH PLATE		0.06 ^(b) 0.56 0.025 18.56 9.40 0.016 1.77	0.07 0.54 0.016 18.57 9.5 0.013 1.63
ASTM A-240 Type 304L	3/8 in. - 2P1864 1 in. - 341913	C - 0.03 Max Si - 1.00 Max P - 0.045 Max Cr - 18.00-20.00 N - 8.00-12.00 S - 0.030 Max Mn - 2.00 Max	0.016 0.62 0.013 18.60 10.45 0.014 1.48	0.006 0.65 0.017 19.52 10.93 0.012 0.45	0.022 0.49 0.021 18.23 10.30 0.016 1.48	0.017 0.51 0.018 19.09 10.16 0.013 2.25
ASTM B-168	3/8 in. - NX6962 1 in. - NX-6159	C - 0.15 Max Si - 0.5 Max Fe - 6.00-10.00 Cr - 14.00-17.00 N - 72.00 Min S - 0.015 Max Mn - 1.0 Max Cu - 0.5 Max	0.07 0.21 7.45 14.92 77.09 0.007 0.16	0.062 2.09 7.26 15.02 71.4 0.013 1.98	0.09 0.32 7.86 16.44 74.75 0.007 0.28	0.079 1.69 7.82 16.30 71.6 0.014 2.96
ASTM A-516 KC-70	3/8 in. - 3D-202 1 in. - 66C586	C - 0.28 Max Si - 0.13-0.33 P - 0.035 Max Cr - ---- N - ---- S - 0.04 Max Mn - 0.8-1.25	0.23 0.20 0.011 ---- ---- 0.026 1.08	0.23 0.24 0.013 ---- ---- 0.024 2.85	0.26 0.23 0.012 ---- ---- 0.022 1.06	0.24 0.28 0.017 ---- ---- 0.033 2.85
(a) Material Code			(b) Material from M & P Lab in Schenectady (reference GEAP-4911, Page 6-13).			
C = Carbon Si = Silicon P = Phosphorus Cr = Chromium			N = Nickel S = Sulfur Mn = Manganese Fe = Iron			

Metallographic examinations have been performed on seven axial hole specimens which had been tested as part of the fatigue specimen evaluation program. These specimens were all Type-304 stainless steel and were all EDM'ed, using a high-purity oil electrolyte. The results (Figure 7-1) indicate that for this combination of specimen material and electrolyte, the metallurgical effects of the EDM axial hole drilling operation are confined to a region less than 1 mil in depth.

7.5.5.2 Static Specimens

The WOL specimens made from wrought material are being machined and will be transferred to the M&P Lab in Schenectady for fatigue pre-cracking. The weld bars from which the WOL weld specimens will be machined have been completed. These specimens will also be fatigue pre-cracked.

7.5.5.3 Evaluation of Ultrasonic Measurement Capabilities

Axial hole eccentricity measurements were made on three Type-304 stainless steel fatigue specimens, using ultrasonic techniques. These values were compared with actual eccentricity measurements made after the specimens were sectioned. The results (Table 7-5) were very good, indicating that this nondestructive tool may be quite adequate to ensure that the holes in the finished specimens are correctly drilled.

TABLE 7-5
AXIAL HOLE ECCENTRICITY MEASUREMENTS

Specimen Number	Axial Hole Diameter (in.)	Ligament Thicknesses (in.)			
		Top		Bottom	
		Ultrasonics	Actual	Ultrasonics	Actual
1	0.025-0.026	0.034	0.034	0.027	0.024
2	0.024-0.025	0.034	0.031	0.026	0.026
3	0.022-0.023	0.027	0.030	0.032	0.031

7-9/7-10

SPECIMEN MT-D-27

500X

500X

SPECIMEN CDS-1

500X

500X

FIGURE 7-1. RESULTS, LIGHT METALLOGRAPHY STUDIES OF EDM AXIAL HOLE SPECIMENS
(Reduced to 90 % for reproduction purposes)

GEAP-10120

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