MASTER

GEAP - 4474

EXPERIMENTAL AND ANALYTICAL PROGRAM RECOMMENDATIONS

Reactor Pipe Rupture Study

By
H. H. Klepfer

January 1965

Atomic Power Equipment Department
General Electric Company
San Jose, California

DISCLAIMER

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

DISCLAIMER

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

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

This report has been reproduced directly from the best available copy.

Printed in USA. Price \$3.00. Available from the Clearinghouse for Federal Scientific and Technical Information, National Bureau of Standards, U. S. Department of Commerce, Springfield, Va.

EXPERIMENTAL AND ANALYTICAL PROGRAM RECOMMENDATIONS
REACTOR PIPE RUPTURE STUDY

Compiled by
H. H. Klepfer

APPROVED: E R Kilsby Jr
E. R. Kilsby, Jr.
Project Engineer

APPROVED: D H Imhoff
D. H. Imhoff, Manager
Engineering Development

Prepared for the United States Atomic Energy Commission
Under Contract AT(04-3)-189
Project Agreement 37

January 1965

VALLECITOS ATOMIC LABORATORY
GENERAL ELECTRIC
ATOMIC POWER EQUIPMENT DEPARTMENT
SAN JOSE, CALIFORNIA

CONTRIBUTORS TO THE REPORT

E. R. Kilsby, Jr.	W. R. Smith, Sr.
S. W. Tagart	J. S. Armijo
M. B. Reynolds	W. L. Pearl
W. S. Gibbons	L. F. Coffin, Jr.*
J. L. Jaech	A. J. Brothers**
S. Yukawa**	

* General Electric Research Laboratory

** Large Steam Turbine-Generator Department,
Materials & Processes Laboratory

CONTENTS

	<u>Page</u>
SUMMARY	1
I. INTRODUCTION	2
II. PROBLEM AREAS	3
III. PROGRAM OBJECTIVES	5
IV. PROGRAM CONCEPT	6
V. RECOMMENDED RESEARCH AND DEVELOPMENT TASKS	17
1. Reliability Engineering	17
2. Stress Analysis	26
3. Fracture Mechanics	33
4. Fatigue	44
5. Localized Corrosion Cracking	61
6. Impact Erosion by Wet Steam	66
7. Quality Assurance Procedures	67
8. Operational Surveillance Development	70
9. Creep-Fatigue	72
10. Large-Scale Test Facility	72
REFERENCES	79

ILLUSTRATIONS

<u>No.</u>	<u>Title</u>	<u>Page</u>
1.	Time Sequence and Decision Points	15
2.	Probability Density as a Function of Strength Load Parameter	20
3.	Probability Density Distribution of the Differences Between Strength and Stress	22
4.	Probability of Failure Versus Standard Deviations of Margin	24
5.	Stress Field at a Crack Edge	35
6.	Simulated Pipe Joint Specimen for Fatigue Crack Growth Test	54
7.	Chloride Stress Corrosion-Time to Cracking for Stainless Steel	63
8.	Large-Scale Test Facility (Plans and Sections)	75
9.	Large-Scale Test Facility (P & ID).	76

EXPERIMENTAL AND ANALYTICAL PROGRAM RECOMMENDATIONS
REACTOR PIPE RUPTURE STUDY

SUMMARY

Investigations conducted under Phase I of the AEC Pipe Rupture Study, although generally confirming a high degree of piping reliability, have delineated areas of uncertainty in assessing the likelihood of pipe ruptures.

A three-year research and development program is recommended as Phase II of the Pipe Rupture Study:

1. To conduct analytical (30%) and experimental (70%) work to permit a more firmly supported assessment of piping reliability.
2. To combine the results of this program with available data in an attempt to evaluate the mathematical probability of occurrence of various size pipe ruptures.
3. To recommend, based on the results of these studies, any changes or additions to existing codes, standards, or procedures which will improve the reliability of nuclear plant piping.

Over twenty specific anticipated results necessary to achieve these over-all objectives have been identified, and the effort required to realize these specific results has been divided into ten tasks.

Program requirements, recommended programs, and the relevance of each of the Phase II objectives have been defined for the ten tasks: (1) Reliability Engineering, (2) Stress Analysis, (3) Fracture Mechanics, (4) Fatigue, (5) Localized Corrosion Cracking, (6) Impact Erosion by Wet Steam, (7) Quality Assurance Procedures, (8) Operational Surveillance Development, (9) Creep-Fatigue, and (10) Large-Scale Test Facility.

A time sequence, including task interrelations and definite technical decision points, has been established for the recommended program.

I. INTRODUCTION

This compilation of recommended experimental and analytical programs was prepared as one task under the AEC Reactor Primary Coolant Pipe Rupture Study. The Pipe Rupture Study is concerned with the reliability of water reactor piping.

In Phase I of the Pipe Rupture Study, the present state of knowledge regarding the likelihood, and possible magnitudes of, piping failures in nuclear plant primary system piping has been assessed. Investigations have been made to:

1. Determine the range of design, construction and operating parameters of interest and importance to the nuclear industry.¹
2. Collect and correlate industrial failure experience for piping systems with environmental conditions similar to those found in reactor plants.²
3. Examine, from a materials point of view, the various ways in which piping materials can fail, and determine the likelihood of failure by these modes for primary system piping.³
4. Evaluate the adequacy of current piping design criteria and analytical tools in preventing pipe rupture.⁴

As a result of the foregoing investigations, it has been possible to define the areas of uncertainty in present technology which prevent assurance that catastrophic failure of primary piping is not credible. In this report, recommended research and development programs are presented for the elimination or reduction of current uncertainties to allow improved design, construction, and operation procedures, to allow more precise safety evaluations, and to increase reactor piping reliability.

II. PROBLEM AREAS

The investigations conducted under Phase I of the Pipe Rupture Study, although generally confirming a high degree of piping reliability, revealed specific areas that require further work. These problem areas as described in the Phase I reports¹⁻⁴ are summarized in Table I.

It is evident (Table I) that there are four key areas of uncertainty for further study. In the Phase I reports¹⁻⁴ these four-key areas are defined further as:

1. Design tools, including analytical methods and the extension of fracture mechanics to the rapid low-energy, unstable, ductile, fracture case;
2. Fatigue with emphasis on low-cycle, plastic fatigue, including that induced by thermal effects and dissimilar metal expansion;
3. Localized corrosion with emphasis on the consequences of corrosion cracks;
4. Creep-stress rupture, with emphasis on combined creep-fatigue phenomena -- important for superheated steam piping systems.

TABLE I. Problem Areas Defined by Phase I Studies

Explicitly Stated Problem Area	SOURCE			
	Respondents to Task A Survey ⁽¹⁾	Industrial Piping Failure History-Task B ⁽²⁾	Fracture Modes Materials Study Task C ⁽³⁾	Review of Design Considerations Tasks D and E ⁽⁴⁾
<u>Design</u>				
Improved Tools	X		X	X
Stress Analysis			X	X
Criteria for Sensitive Areas	X			
Reliability Analysis				X
Improved Piping Flexibility Analysis	X			
Ductile Fracture Mechanics			X	X
Design Error		X		X
Pipe-to-Nozzle Design	X	X		
<u>Materials</u>				
Fatigue	X	X	X	X
Dissimilar Joints	X	X		X
Thermal	X	X	X	X
High-Cycle Elastic		X		X
Low-Cycle Plastic			X	X
Localized Corrosion	X	X	X	
Corrosion Fatigue				X
Erosion		X	X	
Unstable Ductile Fracture			X	
Creep-Stress Rupture	X	X		X
Creep-Fatigue				X
<u>Construction</u>				
Pipe Evaluation and Inspection		X		
Valves and Fittings Evaluation	X	X		
Weld Verification		X		
<u>Operation</u>				
In-Service Monitoring	X	X	X	

III. PROGRAM OBJECTIVES

The Phase II program should be focused on significant additions to the evidence in support of reactor piping reliability. The Phase I evaluations have delineated deficiencies in the present evidence which supports the incredibility of catastrophic pipe rupture. In Phase II, an attempt will be made to reduce or remove these deficiencies.

Specifically, the objectives of Phase II may be summarized as follows:

1. To conduct analytical and experimental work necessary to permit a firmly supported assessment of piping reliability;
2. To combine the results of this program with available data in an attempt to evaluate the mathematical probability of occurrence of various size pipe ruptures;
3. To recommend, based on the results of these studies, any changes or additions to existing codes, standards, and procedures which will improve the reliability of nuclear plant piping.

To achieve these three objectives and considering the problem areas outlined in the previous section of this report, it is required that research and development effort be applied to the following specific tasks:

1. Reliability Engineering
2. Stress Analysis
3. Fracture Mechanics
4. Fatigue
5. Localized Corrosion Cracking
6. Impact Erosion by Wet Steam
7. Quality Assurance Procedures
8. Operational Surveillance Development
9. Creep-Fatigue
10. Large-Scale Test Facility

IV. PROGRAM CONCEPT

Before presenting the details of each recommended task, the over-all program approach or program concept will be considered. In this consideration, the logic underlying the program, the relationship between tasks and program objectives, the relative level of effort recommended for specific tasks, and the time sequence of related tasks are included.

1. THE ROLE OF RELIABILITY ENGINEERING

Reactor piping reliability is now judged to be very high; catastrophic pipe ruptures are considered very unlikely. However, this judgment rests largely on qualitative logic. In designing the Phase II program at this time, only the qualitative logic is available. It would be very desirable to reduce this logic to quantitative mathematical statements. A major intent of the recommended program is to apply reliability engineering techniques in an effort to assign probability numbers in place of qualitative "likelihoods" to achieve a more quantitative approach to piping system safety analysis.

The qualitative judgment that reactor piping is highly reliable can be related first to a series of statements on reactor plant safety with respect to fission gas release; the following arguments could be made:

1. Small cracks can form in reactor piping, but neither large cracks nor subsequent ruptures can form in piping by any of the finite number of fracture modes. There is no significant credibility of these events if the proper specifications, inspections, and designs are applied.
2. Cracks, if formed, will not propagate rapidly and may be detected by operating surveillance.
3. Cracks, even if undetected, will result only in leaks which will be detected rapidly before they grow to a critical size which could precipitate a gross rupture.
4. Leaks, if they grow undetected to a critical size, will not lead to core uncovering, melting, and fission gas release because emergency cooling is supplied, even if gross rupture occurs.

5. Fission gas, even if released as a result of gross rupture, will not escape the plant.

It is clear since piping reliability is very high that the first three statements in this series are quite likely to be true. But it is equally clear that there is some small finite uncertainty in these statements. Absolute proof of the total validity of the three piping reliability statements is unlikely. The only accurate and realistic approach is to assign mathematical probabilities in place of these statements. The evidence in further support of any of these statements will accumulate from several sources: development programs, evolution in system design procedures, and reliable reactor operating experience. In the Phase II program of the Pipe Rupture Study, an attempt would be made to contribute to the development of the required evidence in support of the earlier statements in the series above, and to express these statements in terms of probabilities.

The first three statements in the series above can be broken down in much greater detail. These statements are necessary to arrive at the logical conclusion that piping is highly reliable. Most of, but not all, these statements can probably be shown to be almost, but not absolutely, valid. Again, a more realistic approach would be to replace these statements by probabilities. As examples of the detailed, qualitative, reliability statements, the following appear to be crucial items requiring substantiation on the basis of the results of the Phase I study:

1.1 Fatigue

- a. Even with typical reactor piping components loaded and cycled under the worst conceivable conditions, fatigue failures are first manifest as leaks -- not as catastrophic fractures. Further cycling cannot cause catastrophic propagation of the leaking crack if it should go undetected.

- b. Known cases of fatigue failure which might be considered catastrophic could not occur in reactor piping systems because the available

stress analysis tools and design criteria when properly applied, exclude the cycling parameters known to be required for even a noncatastrophic leak.

c. Fatigue crack propagation rates predicted by fracture mechanics theory are confirmed by experiment; these rates are slow under any conceivable reactor piping conditions, i.e., the propagation times are long compared to the times between inspection of even the most inaccessible pipes, and the propagation times approach the expected plant life.

1.2 Localized Corrosion

a. Extrapolation of time-to-failure data taken from short-term (2000-hour) tests of steels, stressed well above yield in simulated reactor waters containing chloride concentrations over the range from 100 ppm down to 1 ppm, indicates piping immunity to stress-corrosion cracking for times in excess of the plant design lifetimes at the chloride levels below 1 ppm common for reactor plants.

b. Even with stainless steel samples of the most crucial geometry - stressed below the nominal fracture stress by expected combinations of pressure, torsion, and bending - concentrated stress-corrosion media do not lead to catastrophic stress-corrosion failures, but only to leaks.

c. Any cracks and/or leaks which do form cannot be made to propagate catastrophically under subsequent cyclic loads typical of reactor systems.

1.3 Low-Energy Ductile Fracture

a. Inspection and qualification procedures, when properly applied, ensure against any possibility of brittle fracture in pipe materials under reactor operating conditions.

b. Long, shallow defects in starting materials which could propagate to give fast, low-energy, unstable ductile fractures are detected by existing inspection procedures.

c. In spite of every effort to produce long, shallow cracks, even under exaggerated service conditions, none could be produced by fatigue or stress corrosion.

d. Even when long shallow cracks do grow in piping, or are purposely and artificially produced in piping materials, neither fracture mechanics theory nor experimental evidence supports the contention that they can propagate by unstable ductile fracture in reactor piping materials under reactor piping conditions..

1.4 Detection

a. In-service inspection methods and procedures will detect any developing flaw before it develops into a leak.

b. The detection time constant for available leak detection systems is short compared to the long leak (crack) propagation times conceivable for reactor piping conditions.

(It can be seen that any lack of substantiation of these statements immediately delineates certain characteristics of the actual, most credible fracture case for reactor piping.)

An important aspect of the program recommendations is that the required reliability statements should be further extended toward a quantitative analysis by the application of reliability engineering. This probability approach may not lead directly to the assignment of precise pipe system reliability numbers. The assigned probabilities would, however, describe the present state of assurance; future experience and data could be used at any time to refine the assigned probabilities. Technical progress toward

lower and lower likelihood of piping failure would be reflected as an increase in precision in the mathematical reliability numbers. The mathematical analysis technique will, furthermore, delineate the most sensitive factors in the over-all reliability analysis and thus contribute to better perspective and objectivity in safety analysis.

The systematic approach of reliability engineering would also contribute immediately to the direction and coordination of the phase II program. The various sub-tasks recommended for Phase II and the experimental design of the work under each sub-task have been developed by considering the qualitative logic of piping reliability. As the program proceeds, each task would be further evaluated by the quantitative reliability engineering study.

2. PERTINENCE OF EACH TASK TO OVER-ALL OBJECTIVES

Ten tasks have been recommended. Each of these tasks contributes to one or more of the program objectives. In Table II, the relation of each task to the three primary objectives is summarized. For each general objective, specific anticipated results are listed. For each specific goal of the program, those tasks making a direct contribution are indicated.

3. RELATIVE LEVEL OF EMPHASIS

On a cost basis it is estimated that 30% of the over-all program would be analytical work with the remaining 70% experimental work. The recommended program would be anticipated to require the following division in the total professional man-year effort:

<u>Task</u>	<u>Percentage Total Professional Man-Years</u>
1. Reliability Engineering	11
2. Stress Analysis	16
3. Fracture Mechanics	9
4. Fatigue	22
5. Localized Corrosion Cracking	8
6. Impact Erosion by Wet Steam	2
7. Quality Assurance Procedures	4
8. Operational Surveillance Development	9
9. Creep-Fatigue	4
10. Large-Scale Test Facility	15
	100

TABLE II. Objectives, Specific Anticipated Results, and Contributing Tasks

<u>General Objective</u>	<u>Anticipated Specific Result Goal</u>	<u>Tasks Contributing Directly</u>
1. Conduct analytical and experimental work necessary to permit a firmly supported assessment of piping reliability.	1.1 Shell model computer code	1.1.1 Stress analysis
	1.2 Tabulate solutions to presently intractable stress analysis problems	1.2.1 Stress analysis
	1.3 Calculation method for fatigue crack growth rates	1.3.1 Stress analysis 1.3.2 Fracture mechanics
	1.4 Fatigue crack growth rate calculations for experimental tests	1.4.1 Fracture mechanics
	1.5 Calculation method for low-energy ductile fracture criteria	1.5.1 Stress analysis 1.5.2 Fracture mechanics
	1.6 Calculated predictions on low-energy ductile fracture for experimental tests	1.6.1 Fracture mechanics
	1.7 Stress concentration factors for asymmetric pipe components	1.7.1 Stress analysis 1.7.2 Fatigue
	1.8 Fracture toughness values for piping materials	1.8.1 Fracture mechanics
	1.9 Simple method for determining fracture toughness values	1.9.1 Fracture mechanics
	1.10 Fatigue crack growth rates and shapes for reactor piping materials	1.10.1 Fatigue 1.10.2 Large-scale testing 1.10.3 Fracture mechanics
	1.11 Nature of fatigue crack failures in pressurized pipes	1.11.1 Fatigue 1.11.2 Large-scale testing 1.11.3 Fracture mechanics

TABLE II. (Con't.)

<u>General Objective</u>	<u>Anticipated Specific Result Goal</u>	<u>Tasks Contributing Directly</u>
2. Combine the results of this program with presently available data in an attempt to evaluate the mathematical probability of occurrence of various size ruptures.	1.12 Combined creep fatigue data for piping materials	1.12.1 Creep-Fatigue 1.12.2 Large-scale testing
	1.13 Nature of localized corrosion failures in pressurized pipes	1.13.1 Localized corrosion 1.13.2 Large-scale testing
	2.1 Reliability equations form for reactor piping systems	2.1.1 Reliability engineering
	2.2 Identification of most sensitive factor in reliability equations for direction of all other tasks	2.2.1 Reliability engineering
	2.3 Assignment of probability numbers to the factors in the piping system reliability equation using stress-strength approach	2.3.1 Reliability engineering 2.3.2 Stress analysis 2.3.3 Fracture mechanics 2.3.4 Fatigue 2.3.5 Localized corrosion 2.3.6 Creep-fatigue 2.3.7 Quality assurance 2.3.8 Operational surveillance 2.3.9 Impact erosion 2.3.10 Full-scale testing
	2.4 Precise definition of "maximum credible" pipe rupture	2.4.1 Reliability engineering 2.4.2 Large-scale testing 2.4.3 Fatigue
	3.1 Determination of the essential parameters for operational surveillance tools	3.1.1 Operation surveillance 3.1.2 Reliability engineering 3.1.3 Fatigue
	3.2 Development and evaluation of one operational surveillance system	3.2.1 Operational surveillance 3.2.2 Large-scale testing
3. Recommend, based on the results of these studies, any changes or additions to existing codes, standards, and procedures which will improve the reliability of nuclear plant piping.		

TABLE II. (Con't.)

<u>General Objective</u>	<u>Anticipated Specific Result Goal</u>	<u>Tasks Contributing Directly</u>
	3.3 Determination of the essential recommendations for changes in codes, standards, and procedures to ensure most stringent quality assurance only where required by over-all system reliability	3.3.1 Quality assurance 3.3.2 Reliability engineering
	3.4 Improved design criteria for the creep range	3.4.1 Creep-fatigue 3.4.2 Stress analysis 3.4.3 Large-scale testing
	3.5 Design relationship to cover impact erosion	3.5.1 Impact erosion
	3.6 Improved design criteria for fatigue	3.6.1 Large-scale testing 3.6.2 Stress analysis 3.6.3 Fracture mechanics 3.6.4 Fatigue
	3.7 Other code, standard, and procedure recommendations	3.7.1 Quality assurance

Each task makes an essential contribution to the expected improvement in piping reliability, but without its interrelation to the other tasks, much less would be contributed. Reliability Engineering provides direction and coordination for all the other tasks. The Large-Scale Test Facility is necessary for the final confirmation of the results of Tasks 2, 3, 4, 8, and 9 and is in fact an integral part of these tasks; only the design, construction, and operation of the facility defines a separate task.

The major technical effort (about 60%) is on improving the understanding of the initiation of cracks by low cycle fatigue, the growth of flaws by fatigue, the conditions under which large cracks can become unstable and cause catastrophic failure by fast ductile fracture, and the application of this knowledge to large-scale piping components (Tasks 2, 3, 4, and 10). The approach recommended for this major effort is to separate effects and study them under controlled experimental conditions and then to apply the resultant relationships to cracking of successively more complex geometries with more complex loadings. Application of this approach requires improvements in stress analysis methods and in fracture mechanics analysis but will result in sound analytical relationships which have been modified and verified for actual large-scale piping components. Massive empirical testing of large scale components is not recommended as an initial approach because of the difficulty in deriving general analytical relationships from such testing. However, the possibility of extensive testing of small components to cover a range of pertinent conditions may be contemplated as a part of the program, particularly if analytical relations cannot be developed as the more desirable initial approach.

4. TIME SEQUENCE

The recommended time sequence and decision points for the tasks are presented in Figure 1. The time periods given in Figure 1 are nominally in years; these time periods could be expanded to 1-1/4 or 1-1/2 years but could probably not be shortened.

DECISION POINTS:

1. DECISION TO BUILD FULL SCALE FACILITY AND SPECIFICATION OF TEST RUNS #2 AND #3. (TEST RUN #1 HAS ALREADY BEEN SPECIFIED.) IF NEGATIVE, ALTERNATE METHOD MUST BE SPECIFIED FOR VERIFYING RESULTS, PARTICULARLY THOSE FROM STRESS ANALYSIS, FRACTURE MECHANICS, FATIGUE, OPERATIONAL SURVEILLANCE AND CREEP-STRESS RUPTURE TASKS.
2. DECISION TO PROCEED TO APPLY NEW CALCULATION METHOD TO SELECTED SPECIFIC PROBLEMS. IF NEGATIVE, A MAJOR INCREASE IN THE EXPERIMENTAL STRESS ANALYSIS EFFORT IS REQUIRED.
3. DECISION THAT CALCULATIONS CAN BE MADE NECESSARY FOR SUCCEEDING FRACTURE MECHANICS AND FATIGUE TASKS. IF NEGATIVE, FRACTURE MECHANICS WORK STOPS.

4. SPECIFY REMAINING PROTOTYPE FATIGUE TASKS.
5. DECISION ON KEY AREAS AND REQUIREMENTS FOR QUALITY ASSURANCE AND OPERATIONAL SURVEILLANCE TASKS.
6. PROGRAM RE-EVALUATION BASED ON FIRST RELIABILITY MODEL. DECISIONS TO CURTAIL OR EXPAND VARIOUS PROGRAM TASKS.
7. DECISION ON WHETHER TO BUILD BENCH SCALE LOCALIZED CORROSION LOOPS. IF NEGATIVE, LOCALIZED CORROSION WORK STOPS.

Figure 1. Time Sequence and Decision Points

The most important early decision points are:

1. The decision on the most sensitive areas affecting piping system reliability arising from the reliability engineering study. This decision determines the direction of the Quality Assurance and Operation Surveillance Tasks directly and will be the basis for a total re-evaluation of the relative emphasis devoted to each of the ten tasks.
2. The final decision on whether the large-scale test facility should be built.

Other decision points primarily affect individual task directions. These decision points are identified in Figure 1.

V. RECOMMENDED RESEARCH AND DEVELOPMENT TASKS

The details of the experimental and analytical tasks required to accomplish the program objectives are presented with a discussion of the technical approach in each task. For each task, the order of presentation of sub-tasks is: sub-tasks involving analytical work, sub-tasks involving bench-scale experimentation or engineering tests, sub-tasks involving full-scale pipe rupture tests. For each task, the need, program, and relevance to program objectives is presented.

1. RELIABILITY ENGINEERING

1.1 Program Requirements

Reliability engineering, as applied to reactor primary coolant pipe ruptures, is concerned with evaluating numerically the probability that a given piping system will operate, without developing a leak larger than any specified size, for a given length of time in a specified environment. Reliability engineering is an attempt to give quantitatively the chances that such an event will occur, as opposed to the present situation in which it can only be stated that such an event is "not likely to occur."

The primary benefit to be derived from such an approach is not so much related to the final answer as it is related to the systematic processes involved in reaching that answer. The reliability of the entire piping system can only be evaluated by evaluating the reliability of the component parts, in this case the term "component parts" refers also to the various ways in which a pipe could rupture. In performing this evaluation, the most sensitive areas will be uncovered, where an area may be sensitive either because of the difficulty in assigning reliability numbers because of the lack of knowledge, or simply because the assigned probabilities of rupture are large. In the first case, areas of experimentation required to reduce the uncertainty are pinpointed, while in the second case, design and/or procedural changes may be suggested which will reduce the probabilities to tolerable levels. The

determination of sensitive areas and the attempts to assign probabilities would then give direction and synthesis for the entire Phase II program.

1.2 Recommended Program

It is recognized that, in this particular application, historical pipe rupture data for reactor systems are virtually nonexistent which necessitates an approach that does not depend entirely on failure frequency data. Rather, it will be necessary to examine in detail the sequence of events that must occur to lead to a pipe rupture and to assign probabilities to each step in the sequence. The method of assigning probabilities depends on the step involved. For many steps, this will involve a study of the strength and load distributions over time (again possibly pointing out areas of insufficient existing information). For some steps, the assigned probabilities will reflect engineering judgment, with the uncertainty associated with the assigned probability reflecting the extent of disagreement among knowledgeable individuals.*

Since the strength-load probability approach (as opposed to the traditional Avionics or failure frequency approach) for assigning probabilities is a fairly recent concept, this approach will be discussed in detail. Reethoff, of the General Electric Jet Engine Department, has given an excellent discussion of the strength-load concept in a recent report.⁵ That discussion is repeated with his permission here as section 1.2.1.

1.2.1 The Probabilistic Strength-Load Relationship

"Failure will occur in a structural part, which is subjected to stress inducing loads, whenever the stress exceeds the strength.

* For many steps, such as crack growth in fatigue, instability toward rapid ductile fracture, localized corrosion cracking, precision in stress analysis, and crack detection, probabilities can be designed with fair accuracy as the result of Phase II experimental work. For some steps, such as fabrication errors, design errors, and misapplication of procedure, judgment based on industrial experience will be required. It is not clear at this time whether the "judgment" factor will predominate or not. However, the process of assigning numbers and determining predominance will of itself give important perspective on the problem and thus direction to the Phase II work.

This failure mechanism can be described by plotting the compatible load and strength probability density curves. A typical diagram might appear as in Figure 2. The strength probability density can be obtained from materials test data, process variability information, and nondestructive test information. As a rule the all important subnominal tail ends have to be extrapolated because of the limited data available. The stress probability density curve is structured from combinations of test data and estimates of potential extreme conditions. The calculations are demanding and require a significant amount of judgments. As in the other aspects of reliability design reviews, the disciplines required to establish the load probability density curve force a level of investigation considerably beyond the analysis requirements of the historical factor of safety approach. The benefit resulting from this discipline alone is not to be underrated. The failure mechanism typical for jet engine hot structural parts is the result of crack inception from low cycle fatigue (thermal cycling) followed by crack growth from high cycle fatigue to fracture. This mechanism is, of course, very difficult to model.

"Consider the general case of interfering distributions (see Figure 2). In the interval of stress parameter, ds , the probability that the load will exceed the strength and that failure will occur in the next time interval is

$$dP_F(s) = f_S(s)ds \int_s^{\infty} f_L(s)ds$$

since

$$f_F(s) = \frac{d P_F(s)}{ds}$$

and if

$$G_L(s) = \int_s^{\infty} f_L(s)ds$$

1744-2

Figure 2. Probability Density as a Function of Strength-Load Parameter

then the probability density of failure $f_F(s)$ is given by

$$f_F(s) = f_S(s)G_L(s)$$

and the probability of failure in the time interval is

$$P_F(s) = \int_{-\infty}^{+\infty} f_F(s) ds$$

$$P_F(s) = \int_{-\infty}^{+\infty} f_S(s)G_L(s) ds$$

where

$P_F(s)$ = Probability of failure in next time interval,

$f_S(s)$ = Probability density of part strength,

s = Strength-load parameter,

$f_L(s)$ = Probability density of highest load in time interval,

$G_L(s)$ = Probability that load is higher than s ,

$dP_F(s)$ = Probability of failure in interval ds , and

$f_F(s)$ = Probability density of failure.

"The interference model can be visualized in an alternate fashion by generating the probability density distribution of the differences between strength and stress (Figure 3). The mean difference D_M is given by the difference

$$D_M = S_M - L_M$$

between mean load and mean strength. The difference standard deviation, σ_D is the root sum of the squares of the standard deviations of load and strength

$$\sigma_D = \sqrt{\sigma_L^2 + \sigma_S^2}$$

1744-3

Figure 3. Probability Density Distribution of the Differences Between Strength and Stress

The probability of failure is, then again, given by the integral

$$P_F(D) = \int_{-\infty}^{+\infty} f_F(D) dD$$

where

$D = S - L = \text{Strength-load}$

"The values of probability of failure for the appropriate standard distributions can be found in statistical tables. For the case of the normal (Gaussian) distribution, Figure 4 gives the fascinating and somewhat frightening relationship between probability of failure and combined standard deviation separation. Thus, in the region of 7 sigmas separation (or 10^{-11} probability per unit of time) a reduction of one combined standard deviation (σD) results in a one thousandfold increase in probability of failure.

"In the region of 4.5 σD a unit reduction of σD results in a one hundredfold increase in probability of failure. Typically, one standard deviation of strength is equal to 8% of the strength. Thus, an 8% reduction in strength could result in a one hundredfold increase in failure rate. We have here a measure of the true impact of the reliability program.

"A complicating factor is the fact that the distributions tend to shift with time toward lower margins as a result of material strength degradation (and thus material strength degradation must be known and taken into account); on the other hand, skewing toward higher margins will result from the natural elimination of the weaker parts from the population.

"The interference model approach has been used with encouraging success on several cases, such as frames and buckets, for example, to estimate probability of failure."

1744-1

Figure 4. Probability of Failure vs Standard Deviations of Margin

1.2.2 Pipe System Reliability Prediction

The system reliability process consists of combining all conceivable individual failure probabilities to give reliability equations or tabulations for the system. Existing industrial pipe rupture experience data² are very useful in providing possible modes of rupture and sequences of events leading up to such ruptures. These data will be used for this purpose. Specifically, the results of the Phase I historical pipe rupture survey,² and the fracture modes report³ provide an initial list of potential kinds of ruptures. This list will be examined in detail by assigning probabilities of occurrences to each chain in the sequence leading to a rupture.

As a specific example experience has shown the possibility that, due to overload of a system, a fatigue crack might be initiated and grow circumferentially around the pipe. If the crack is not detected in time, a rupture would occur. The overload may be caused by a design error, in which, for example, the extent of thermal cycling to which the pipe is subjected may have been overlooked. Some probability can be assigned to this, depending on the amount of cross-checking of calculations that is made. The sequence of events also includes failing to detect the leakage in time. The probability of the failure to detect leakage depends on such things as the distribution of speed of crack propagation, integrity of the leak detection system, and number of flange leaks that may normally occur to obscure the presence of the leak in question. By appropriately combining the probabilities involved in the chain of events leading to the rupture, an over-all probability is found. While the over-all result depends on the uncertainty associated with each probability in the chain, some of which may be not much better than just a "guess," it is reasonable to expect that the resultant answer is more meaningful than a number assigned to the over-all rupture occurrence without the benefit of the synthesized approach.

1.3 Relevance to Program Objectives

The reliability engineering task is central to achieving the second objective of the program, that of making reliability estimates more quantitative. The

results of this task also will be used to focus effort of all other tasks on those areas revealed as most sensitive in determining over-all piping system reliability. In the performance of the task, the results of all the other tasks will be collected, summarized, and interrelated.

An essential feature of the total program recommended is the use of the systematic reliability engineering approach to focus the work of the various tasks on piping reliability. A program comprised of many diverse efforts, as is the program recommended here, requires continuing re-evaluation of relative emphasis and coordination of the various tasks. The results of work in one area must be related to the direction of work on the other tasks. Because the program objective is the improvement of piping reliability, the reliability approach is particularly appropriate as a mechanism of program coordination.

2. STRESS ANALYSIS

2.1 Program Requirements

The stress analysis methods which need improvement and should be included in the Phase II program lie in two generally separated areas. One area is that of increasing the capabilities of nuclear pipe designers to take full advantage of stress analysis techniques and tools which are known and used by some organizations today. The second area is that of elevating the stress analysis technology to cover the huge list of presently intractable but practically important problems. Solutions in both areas are possible⁴ and should be pursued.

In the first area, the use of the digital computer in the practical solution to piping flexibility problems and piping vibration problems (including earthquake and mechanical shock loading) must be recognized and standardized. Special-purpose digital computer programs, which vary in capabilities and accuracy, are used for analyzing almost all highly redundant, medium-sized piping systems. One important step in the direction of ensuring

minimum standards of design should be to devise critical qualification tests and ratings for these analysis tools. If a known and standard method of analysis has been properly applied, it will become possible to determine quantitatively the variability and magnitude of actual safety factors which exist in operating piping systems. This type of study, coupled with its experimental aspects, will result in positive recommendations to code bodies both to increase general pipe reliability knowledge and to indicate areas which may be now over-conservatively designed.

The second stress analysis area, which involves a general elevation of the stress analysis technology applied to piping, requires for the most part, an almost completely general elastic shell solution method. The need for this type tool has grown out of the recognition of fatigue as a predominant failure mechanism in piping systems.^{3,4} The rational analysis of fatigue and cyclic crack growth leading to fracture can be put on a more firm quantitative basis of understanding with the availability of this shell analysis tool. The requirements of this shell tool can be better understood by examining the stress analysis problems which need to be solved.

The Phase I program has clearly delineated a need to obtain solutions to the following specific stress analysis problems, if progress is to be made in improving the analytical methods of predicting both gross and local stresses at, or near, typical important piping geometric discontinuities.

1. Complete unreinforced and reinforced tee analysis for pressure, tangential and radial thermal gradients and pipe reaction forces with emphasis on diameter ratios between 0.5 and 1.0.
2. Complete unreinforced and reinforced lateral analysis for pressure, tangential and radial thermal gradients, and pipe reaction forces including intersection angles between 90° and 45° for straight and reducing outlets.
3. Complete unreinforced and reinforced wye analysis for pressure, tangential and radial thermal gradients, and pipe reaction forces including an interaction angle between 45° and 180° for straight and reducing outlets.
4. Complete concentric or straight reducer analysis for pressure and pipe reaction forces.

5. Complete flange nozzle or abrupt discontinuity analysis (e.g., stub ends or valve connections for pipe bending forces).
6. Analysis of the effects of integral and nonintegral pipe attachments, such as restraints, supports, anchors, stops, guides, hangers, dampers, clips, and gussets, for both the local thermal and reaction force loads.
7. Miscellaneous discontinuities, which if used must be considered from a fatigue viewpoint, such as crosses, special instrument connections, and weld fittings for loads caused by local thermal effects and any reaction forces or pressure if significant.

In addition, the Phase I program has indicated a need to solve the elastic stress analysis problem surrounding the growth direction or potential growth direction for both a through wall crack and a partial penetration crack. The purpose of this analysis is twofold: (1) a requirement for fracture mechanics analysis, and (2) a requirement for quantitative prediction of the leak area opened up by a through wall crack.

Most of the problems which need to be solved are in either fatigue analysis or fracture mechanics including crack propagation. The past design methods of fatigue analysis in piping systems, as included in ASA B31.1, have covered a far smaller scope of problems both in difficulty and in quantity than outlined in Items (1) through (7). The problems which have been solved relied almost wholly on a directly experimental fatigue program as performed by Markl and his associates.⁶ The only exception is the theoretical work of Bijlaard⁷ (and other similar projects as yet unreported). While the direct experimental fatigue approach has proved itself to be a reasonably sound and reliable method, there have been important recent developments in the understanding of low cyclic fatigue -- as evidenced by the work of Coffin-Manson and incorporated in the ASME Nuclear Pressure Vessel Code. This new work leads to an investigation of the possibility of using this more fundamental approach in solving the remaining fatigue problems in pipe design.

The essential ingredients of the more fundamental approach to fatigue are to replace the component fatigue test by three steps (1) elastic stress analysis

of the general stress distribution including gross discontinuity effects, (2) application of a local strain concentration to account for local discontinuities, e.g., fillets and notches,* and (3) comparison of peak strains with strain-controlled specimen fatigue test results. The technical soundness of this approach continues to improve as information accumulates on some of the problems, such as biaxial fatigue and fatigue notch sensitivity. At present, the major missing step in this fundamental approach as applied to piping design is Step (1) that of determining the elastic shell wall stresses including discontinuity effects of the typical nonsymmetrical components with nonsymmetrical loading, such as in tees, laterals, and wyes.

2.2 Recommended Program

2.2.1 Pipe Flexibility Analysis Tools

Piping flexibility analysis is generally made with digital computer tools, for example, at APED the FAST program is one such tool. The simplifying assumptions which are commonly used in piping flexibility analysis generally tend to produce higher forces in the pipes than actually exist in real piping systems, because most simplifying assumptions tend to make the pipe systems⁵ stiffer than they truly are. For example, neglecting shear distortion or neglecting anchor point flexibilities causes more restraint than real pipes have, and hence, raises the calculated forces above actual forces. The stress allowables were generally established with the more conservative assumptions, therefore, the more refined flexibility methods actually permit higher pipe forces with the older rules, and the need for a definite relation to exist between stress tables and stress analysis tools becomes apparent. It is recommended that several graded standards be established for the flexibility analysis tools and a correlation showing quantitative influence of the various assumptions be examined for several initial pipe flexibility models. One example of the possible form of this result is a list of assumptions

* As is done in pressure vessel design work, for example, by the use of Peterson's⁸ Tables.

associated with each class tool and an index of accuracy which this set of assumptions produces for several types of piping systems analyses. Another possible form of the result is a set of model tests which can be used to qualify any designer's flexibility analysis tool for its accuracy or degree of conservatism. This investigation will directly contribute to program objective 1 in providing the information on the accuracy and validity of flexibility analysis tools which is needed for the reliability model. This investigation with its experimental portions will allow a quantitative evaluation to be made of the accuracy with which the standardized tools will predict actual pipe forces and stresses. This is needed for program objective 2. Furthermore, this study may also aid program objective 3 by pointing out deficiencies which can then be corrected.

2.2.2 Analytical Shell Model

The elastic stress analysis solution, which must be found, must include the significant shell stresses at a general pipe intersection and a prediction of the gross* and the macroscopic** stress distribution around a slowly propagating through wall crack. This solution will be called the general shell solution.

The shell geometry of interest is the nonsymmetric middle plane location in 3-dimensional space with a variable thickness distribution. The general shell should include a middle plane with discontinuous slope, such as a 2-shell intersection, discontinuous thickness distribution (such as reinforced opening) and extremely versatile boundary conditions (which can handle any degree of constraint and such things as finite length cuts through the thickness of the shell). The major load mechanisms to be accounted for are pipe reactions, fluid pressure, thickness temperature gradients, membrane temperature gradients, and support restraint forces. The complexity of the geometry clearly indicates that a continuous shell-type analysis is completely intractable, and that any practical analytical solution will be in some form of a numerical procedure, use will be made of large digital computation facilities. Although a thick shell solution would be desirable, the

* Average force and moment type stress.

**Local stresses around the crack.

assumption of a thin shell approximation is necessary to reduce this very general geometric problem from a complete 3-dimensional elasticity problem to a tractable shell problem. The approximation resulting from the thin shell idealization can be corrected by use of localized stress or strain concentration factors. Such concentration factors would be required anyway to include peak stresses or strains around discontinuous middle plane slopes or discontinuous thickness distributions.

To be of maximum practical benefit for the pipe investigation, the following features of shell theory should be included in the model: bending and membrane effects, interaction effect of membrane on bending or beam-column effects. Stress distributions associated with the nonlinear portion of the thickness temperature gradients and partial thickness cracks are considered to be sufficiently calculable with present techniques.

The recommended approach is to develop a general solution which is adequate for the most difficult problems. After developing this general computer method, important specific problems should be selected for detailed solution. The accuracy of the method could be established for these selected examples; the general computer code could then accept any and all other specific cases that may arise in the future. Tabulation of results from the selected most important cases initially solved would, in itself, constitute a readily applicable engineering resource.

One shell solution method has been described and has been reported with simplified examples of its application to a piping elbow.⁴ The ability of the approach to handle both shell bending and membrane effects was demonstrated by the reported examples. It is recommended that this discrete multiended-member approach be refined and developed under the Phase II program.

2.2.3 Experimental Study of Local Stresses

Some experimental stress analysis work should parallel the theoretical analysis effort and could be increased in scope if difficulties are encountered in

developing the general shell analog. The recommended scope assumes that the general shell model will be developed on schedule. The following goals and programs are recommended:

1. An evaluation of the accuracy of the general shell model for both cracked and uncracked pipe discontinuities. At least three different 6-inch size actual pipe components will be experimentally tested with stress coat and strain gages to determine the accuracy of the developed tool. About 10 critical stress comparison points on each of the three experiments is expected to demonstrate the method's accuracy on actual problems of interest to the Phase II program. At least one of the 3 components will be a "wye" or "tee" cracked at the intersection. Attempts will be made to use previously published investigations or combine efforts on tests with other experimental phases of the program. However, it is recommended that provision be made for full-scale model testing of selected piping components.
2. An evaluation of the available flexibility analysis tools in predicting actual plant piping stress and deflection conditions. At least five different selected actual steam power piping systems will be instrumented with high-temperature-compensated strain gages and dial indicators to obtain about 20 critical stress and 10 critical deflection verifications. These test results will be compared with theoretical analyses of these same systems. Further efforts will be made to obtain an equal number of equivalent data points from previous investigations. If such data are not available or are not considered valid, more original experimental work will be required.
3. Specific experimental stress analysis of important design problems which cannot be handled by the general shell stress analysis or by available tools. This work will be fitted to maximize information evaluation from full-scale test results. The specific work will consist largely of instrumenting the full-scale test sections with strain gages.

The experimental strain studies will contribute primarily to program objectives 1 and 2 in obtaining the quantitative information for reliability modeling. In reliability modeling, it is necessary to determine the statistical accuracy of the theoretical stress analysis performed in comparison with actual stresses and strains in service piping. The emphasis in reliability studies is to evaluate possible inaccuracies of stress analysis.

2.3 Relevance to Program Objectives

The suggested work on flexibility models, the shell model, and experimental stress analysis relates to all three program objectives. Improvements in stress analysis directly contribute to the ability to assess piping reliability. A unique contribution will be the determination of the accuracy of stress analysis tools as input to the reliability engineering task of determining quantitative probabilities for possible failure events. It is quite possible that the results of this stress analysis task will allow improvements in design codes by allowing treatment of nonsymmetrical components.

3. FRACTURE MECHANICS

3.1 Program Requirements

The growth of a fracture of significant size can result from either overstressing metallurgically sound material or from the growth of a pre-existing defect to a critical size. The latter mechanism is the more common, since defects permit high local stress levels to be reached at rather nominal gross stress. Defects such as these may exist as fabrication flaws or may be conceivably produced by fatigue or localized corrosion. The behavior of metals under stress in the presence of stress raisers, such as defects or notches, has received considerable attention. Further extension of fracture mechanics to ductile fracture is possible and recommended. Two problems should receive major emphasis in the application of fracture mechanics to the ductile materials used for reactor piping: prediction of the conditions for the fast ductile propagation of relatively large crack-like flaws and prediction of the conditions for relatively slow propagation of small defects by fatigue. The two problems are related since fatigue is the most likely process of developing flaws large enough to initiate fast ductile fracture.

3.1.1 Fracture Mechanics Review

Fracture mechanics is defined as an attempt to describe accurately in mathematical terms the behavior of a fracture flaw in a solid, in terms of macro-

scopic materials properties and the gross stress system active upon it.³ This requires a mathematical description of the stress field about the fracture and a material fracture criterion in terms of strain, stress, or energy. Griffith⁹ defined the condition for growth of an existing fracture crack in a completely brittle material: If the surface energy required for creation of unit area of new crack is less than the reduction in elastic strain energy resulting from this growth, the crack can grow.

Sneddon¹⁰ developed equations for the stress components near the edge of a disk-shaped crack in a linearly elastic solid under a uniform tension σ . Assume such a crack to lie in the xz plane with the z axis tangent to its edge, as shown in Figure 5, and with the uniform gross tension in the y direction. The stress field in the xy plane near the crack edge then may be given in terms of the angle θ and the distance r from the crack edge:

$$\sigma_x = \frac{K \cos \frac{\theta}{2}}{\sqrt{2r}} \left(1 - \sin \frac{\theta}{2} \sin \frac{3\theta}{2} \right) \quad (1)$$

$$\sigma_y = \frac{K \cos \frac{\theta}{2}}{\sqrt{2r}} \left(1 + \sin \frac{\theta}{2} \sin \frac{3\theta}{2} \right) \quad (2)$$

$$\sigma_z = \nu(\sigma_x + \sigma_y) \quad (3)$$

The stress intensity factor, K , is defined in terms of the crack radius a and the gross tensile stress σ :

$$K = \frac{2\sigma}{\pi} \sqrt{a} \quad (4)$$

Irwin¹¹ gives similar expressions for the stress field about the boundaries of through cracks and edge cracks (notches) in plates under uniform tension. The constant K is common to all these expressions; it varies in form, but not dimensionally, with crack geometry. The magnitude of the stresses in the vicinity of the crack edge is determined by the value of K ; at some critical

Figure 5. Stress Field at a Crack Edge

value, K_c , instability sets in and the crack will propagate. This critical value, K_c , is ideally a material constant and defines the crack toughness of the material. The energy, G_c , required to generate unit area of crack* is related to K_c , the elastic modulus E , and the Poisson ratio ν by

$$G_c = \frac{K_c^2}{E} \quad (5)$$

for a condition of plane stress or

$$G_{IC} = \frac{K_{IC}^2}{E} (1 - \nu^2) \quad (6)$$

for the plane strain condition.

Relations (1), (2), and (3) were derived for a perfectly elastic, isotropic, brittle solid. Most metals, however, exhibit evidence of varying degrees of plastic deformation in the fracture process and, as indicated by Felbeck and Orowan,¹² the energy absorbed in the fracture process is orders of magnitude greater than would be predicted on a basis of crack surface energy alone. The Griffith-Irwin model does, however, describe reasonably well the behavior of high strength materials of limited ductility, and assumption of the existence of a plastic zone of limited radius ahead of the crack edge appears to remove the difficulty associated with the value $r=0$ without destroying the validity of the description of the stress field outside this zone.

The effective crack toughness (force per unit length) of a metal is dependent on the stress system as the distinction between the plane stress and plane strain conditions given in Equations (5) and (6) indicates. The radius of the plastic zone leading a crack edge depends upon constraint and is smaller under plane strain conditions than under conditions of plane stress. This is indicated by the fact that the plastic shear lips appear at the edge of a fracture surface where there is least constraint to restrict plastic flow.

* G_c is dimensionally equivalent to force per unit length of crack.

Irwin has defined a dimensionless plastic zone factor β which is a measure of the effect of plastic zone size (relative to specimen thickness) on the stress intensity factor

$$\beta = \frac{1}{B} \left(\frac{K}{\sigma_{ys}} \right)^2$$

in which B is the sheet thickness in units consistent with K , and σ_{ys} the yield strength of the material. It has been experimentally observed that a 50% fracture shear lip corresponds roughly to a β_c value of 2 to 3 or a β_{IC} value of unity.* The transition to 100% shear occurs at $\beta_c = 2\pi$. Measured crack toughness is dependent on specimen size, decreases with increasing specimen size, and approaches asymptotically a value characteristic of the material. Under conditions where crack toughness approaches a value characteristic of the material, one has conditions of plane strain because one has conditions approaching perfect constraint.

Measurement of the effective plane strain crack toughness of engineering alloys is rather more difficult than measurement of the more common mechanical properties. It would be desirable to be able to determine plane strain crack toughness from the more simple mechanical tests. Krafft and Sullivan¹³ have found that for mild steel the plane strain crack toughness determined with sharply notched round tensile specimens is simply related to the upper yield strength determined by dynamic compression tests on the same material. Bluhm¹⁴ has proposed a relatively simple model for the variation in G_c with specimen thickness which suggests that plane strain crack toughness can be determined from tests on a series of specimens of varying thickness. Winne and Wundt¹⁵ have compared the bursting behavior of notched rotating disks with results of notched-bend tests and described the determination of G_c from these latter tests. Results of work of these and other investigators are consistent enough to indicate that plane strain crack toughness is a material property even for reasonably ductile ferritic steels. There is still a dearth of information on

*The subscripts c and IC indicate the values of β corresponding to K_c and K_{IC} , respectively.

the behavior of face-centered cubic materials, such as the stainless steels and nickel alloys. However, since plastic zone size increases with ductility, it is likely that specimen size will need to be increased from standard Charpy size to perhaps ten times Charpy size in dealing with such alloys to obtain behavior comparable to that obtained in ferritic alloys.

3.1.2 Growth of Fatigue Cracks

Since modern inspection techniques are capable of detecting flaws well below the critical size for crack propagation under design stresses it may be assumed that cracks of significant size can only result from corrosion or from mechanical or thermal fatigue. In general, the fatigue problem in reactor piping systems will be limited to low cycle fatigue resulting from cyclic thermal stresses. While the exact relationship between cyclic strain range and fatigue life varies with conditions, cycles-to-failure generally vary inversely as the square of the strain range.¹⁶ According to Sessler and Weiss,¹⁷ during the early part of the fatigue life of a material, work hardening occurs followed by the development of small cracks beginning at approximately 15% of specimen life. These cracks continue to grow during the next approximately 60% of specimen life although the gross strength of the specimen decreases but slightly during this period. Finally, when 75 to 80% of the specimen life has been exhausted, rapid crack growth sets in with a sharp decrease in strength which continues until fracture is complete. Apparently, eventual fatigue failure occurs as a result of loss of ductility (and crack toughness) caused by strain hardening with concurrent growth and joining of microcracks to critical size for propagation. The life of any component subjected to cyclic strain fatigue is then determined chiefly by rate of crack growth during the relatively long period during which microcracks grow to critical size. Paris and Erdogan¹⁸ have reviewed the published literature on crack propagation. The rate of crack growth per cycle, $\frac{da}{dN}$, is dependent on the stress range, c , and the crack length although the exact dependence varies with different authors. Paris and Erdogan suggest that the relation

$$\frac{da}{dN} = \frac{c^n a^m}{c_0}$$

with $n=2m$ describes existing data reasonably well for stresses in the elastic range. The value of m appears to lie between 1 and 2. The stress range in a constant strain fatigue test (plastic range) is determined by the yield stress and strain-hardening coefficient of the material. Since crack growth rate depends upon stress range, it is determined by these two material properties which determine stress range. Crack toughness is also related to strain hardening characteristics, therefore, one may assume a relationship also exists between crack growth rates in plastic strain cycle tests and crack toughness. This relationship for the plastic case should be investigated, (see 3.2.3 and 4.2.2).

3.2 Recommended Program

Ideally, if the stress system of a piping system were accurately known, knowledge of the crack toughness of the pipe material and of the crack growth rate under cyclic stresses should permit the behavior of the system in service to be predicted with some confidence. In addition to the problem of determining the stress system, the following information is needed.

3.2.1 Data on Crack Toughness

Data on the crack toughness of materials commonly used in piping are needed, particularly for the more ductile austenitic metals, such as stainless steels and the nickel alloys. For through cracks in thin walls, plane stress conditions exist; for surface cracks in thick walls plane strain conditions exist. Service conditions may be expected to encompass this entire range of fracture toughness conditions. For materials undergoing little or no plastic deformation in the fracture process, the relation between plane strain and plane stress fracture toughness is simple and contains the elastic Poisson ratio. However, in the transition from elastic-to-plastic behavior, the Poisson ratio changes from a value of 0.3 or less to the value of 0.5 required by the plastic constant volume condition. Because of this and other uncertainties introduced by plastic behavior in the fracture process, mathematical treatment of the fracture of ductile metals is quite difficult under transition conditions and much of the

information needed will of necessity be obtained experimentally with notched specimens of various size and geometry. Every effort will be made to reduce the data to a mathematical model by using a material constant in a calculated stress field.

3.2.2 Crack Toughness Tests

Techniques for simpler determination of crack toughness parameters, G_c and K_{Ic} , or some other reasonable index of crack toughness need to be developed. These should be correlated with more sophisticated tests, such as the high-speed loading tests of Krafft and Sullivan.¹³ An effort should be made to utilize simple tests, such as the notched-bend test or the Charpy impact test to indicate both plane strain and plane stress notch toughness. How successful this effort would be remains to be seen since the specimen size required to obtain reproducible plane strain conditions increases linearly with elastic modulus and crack toughness and inversely as the square of yield strength.¹⁹ Energy absorption is related both to yield strength and extent of plastic deformation; plastic zone size may be expected to have the most effect on test conditions in those alloys of lowest yield strength. Feasibility of obtaining plane strain test conditions in reasonably sized samples of relevant ductile materials should be estimated on a basis of relations developed by Srawley and Brown,¹⁹ Irwin,¹¹ and others.^{14,15} Experimental tests should be made to verify these estimates of required sample size.

3.2.3 Effect of Cycling on Crack Toughness

The relation of crack toughness, G_c , to service behavior in the presence of flaws has been indicated. Any factor which can change the effective crack toughness of an engineering alloy in service can vitiate the calculations on which an engineering design is based. The factors which can change crack toughness include precipitation reactions and strain aging phenomena. The effect of strain cycling on the crack toughness of the engineering alloys of interest should be determined by a series of carefully chosen strain fatigue tests. These tests should include both torsional and bending stress tests to

simulate service conditions. The interrelation of low-cycle strain fatigue, crack growth rates, and crack toughness might be more clearly indicated by measuring crack toughness as a function of strain cycle exposure (we may define "exposure" as the product of a number of cycles and some positive power of the total strain range). This would be accomplished by performing crack toughness measurements on specimens of reference material (see 4.2.2) which had received various strain cycle exposures below the exposure necessary for fatigue failure. These experiments would determine the credibility of crack growth under monotonic stress as a result of fatigue-induced material property deteriorations. Any deterioration of toughness should be easily detected since measurement of materials of low toughness is easier than those of higher toughness. This fracture toughness experiment should be closely related to the low-cycle, strain-aging experiments described in Section 4.

3.2.4 Relationship Between Crack Toughness and Low Energy Ductile Fracture

Most treatments of fast fracture have dealt with ferritic alloys used below the brittle-ductile transition temperature. Under such conditions, the energy needed for crack growth is available from the stored elastic energy in the metal adjacent to the crack. One should not lose sight of the fact that the stability criterion for propagation of plastic deformation or ductile fracture is identical to that for brittle fractures. Stated simply, deformation or fracture will be arrested or will not begin if the energy required to produce a given increment of deformation is greater than the energy released from the driving system by this increment. If one chooses some arbitrary coordinate, λ , to represent the extent of deformation and represents the deformation driving force per unit deformation by F , the condition for stability becomes

$$F_2 < F_1 \text{ and } \frac{dF_2}{d\lambda} < \frac{dF_1}{d\lambda} \quad (8)$$

where the subscripts 1 and 2 refer to the force required for deformation and the driving force, respectively. On the basis of this criterion, it is apparent that unstable deformation can occur in pneumatically or spring-loaded systems in which reduction in effective load-bearing cross section by deformation is not compensated by work hardening. Irvine, Quirk, and Bevitt²⁰ in an

appraisal of theoretical and experimental work on fracture in pressure vessels indicate that this is indeed the case, and that fast fractures have been observed by Bevitt and Stott²¹ in pneumatically loaded pressure vessels under conditions such that, based on Charpy tests, the vessel material was ductile. The effects of stress-concentrating cracks on stability in brittle materials are derived from linear elastic theory in the Griffith-Irwin fracture mechanics of brittle materials. As was pointed out previously, these results are dimensionally correct even for ductile materials; i.e., the critical crack length for stability can be expressed in terms of the gross tensile stress on the material, its elastic modulus, and some quantity related to the energy absorbed in deformation. Irvine, et al., give this relation in the Griffith-Orowan form:

$$\sigma_g \ell = \frac{2EW}{\pi} \quad (9)$$

in which σ_g is the gross stress, ℓ the crack length, W the plastic work per unit area of fracture, and E the modulus. The failure criterion is also given empirically in terms of measurable properties of the material:

$$\sigma_g^{3.2} \ell^2 = \sigma_u^a \sigma_y^b (Q + R\emptyset) \quad (10)$$

in which σ_u and σ_y are the ultimate strength and yield strength of the material, respectively, $\emptyset$ is the Charpy V-notch fracture energy of the material, and a , b , Q , and R are constants. An equation of this type with proper constants was found experimentally to define the limit of stability for both shear- and cleavage-type failures for the particular material and geometrical conditions of Bevitt and Stott's experiments.

A series of experiments are needed to define stability conditions in ductile piping materials. While an equation of the type of (9) seems to be applicable to various failure modes, the constants vary with conditions. In piping systems, conditions can range from the plane strain case of a surface crack in a thick wall pipe to the plane stress case of a through crack in a thin wall pipe. It is desirable that the necessary constants for general triaxial stress systems be determined so that by using stress analysis techniques outlined

elsewhere in this report, stability conditions may be defined in terms of crack size in any of several common piping materials. Much of this information could be obtained by judicious tensile testing on notched and un-notched specimens in a testing machine of variable stiffness (i.e., variable $dF_2/d\lambda$). Since strain rate influences fracture behavior both because of its effect on notch toughness and inertia effects, this machine should have a wide range of head speeds. Finally, there should be a series of burst-test experiments on pneumatically loaded pipes containing flaws of various configurations to serve as crack starters or regions of plastic instability. Proper instrumentation (perhaps photographic) would permit measurement of both stresses and crack velocities. By use of a properly chosen ferritic alloy, crack toughness could be varied over a wide range by choice of test temperature. Actual behavior of these pipes could be compared with behavior predicted from mathematical analysis of the results of the tensile tests as a function of testing machine speed and stiffness. It is to be expected that strain hardening behavior would be the property with the most influence on the stability equations. Deformation characteristics have been calculated for cylinders by assuming rather simple stress-strain relationships.^{22,23} Future theoretical work should extend these calculational techniques to more complex, but metallurgically more realistic, stress-strain relationships, and include the effect of local yielding on deformation of structures, such as pipes or tees. These data should permit calculation of the constants in a generalized stability equation of the type of, or similar to, (10). This equation would then be used in design of full-scale verification tests.

3.2.5 Relationship Between Crack Toughness and Fatigue Crack Growth Rate

Just as knowledge of the effective crack toughness of a metal should permit calculation of the gross stress required for propagation of a crack of known size in an engineering structure, knowledge of the laws and constants governing growth of cracks should permit calculation of the life of a structure subjected to cyclic strain. Crack propagation laws relate growth rate per cycle to crack size and stress range, while most low-cycle fatigue data are in terms of strain range. The fatigue experiments carried out to investigate the effect of cyclic strain on metallurgical properties (Section 4) should be

planned to yield data on stress range and crack growth rates. Observed growth phenomena should be compared with predictions based on fracture mechanics analysis of crack behavior. Crack growth rates under cyclic strain should be predictable by the same laws which govern crack extension under monotonic stresses if the effect of cyclic strain on material properties is taken into consideration. Calculations based on this approach will be attempted for comparison with experimental fatigue data.

3.3 Relevance to Program Objectives

The program outline above should, if properly executed, provide the tools needed to predict the behavior of reactor piping systems with respect to either pre-existing or fatigue-caused defects. These tools would permit a more precise assessment of piping reliability. The following necessary information would be made available:

1. The material constants needed by the stress analyst to predict stresses at which flaws of known sizes would be unstable.
2. The stability of these material constants under service conditions.
3. Definition of the conditions for plastic instability and resultant fast ductile fracture in terms of material constants and system constants.
4. Definition of crack growth rates under cyclic strain in terms of material constants and strain range.

The uncertainties attached to this necessary information by comparison with experimental data will directly define the probability numbers for important factors in the reliability engineering equations for piping systems.

4. FATIGUE

4.1 Program Requirements

Fatigue failures are clearly the most credible of possible pipe ruptures.¹⁻⁴
The analytical improvements needed to prevent fatigue failures in piping include

improved stress analysis methods and an extension of fracture mechanics as already outlined. In addition, specific experimental programs are required: investigation of cyclic strain aging embrittlement, determination of crack growth rates, investigation of crack initiation in conditions of cyclic strain concentration, and testing of prototype components including production welds of actual piping material combinations.

Cyclic strain aging must be studied to determine if cyclic loading of the ferritic steels actually used for piping could result in a significant shift in the brittle-ductile transition temperature. Studies of fatigue-crack growth rates and fatigue-crack geometries are required to assess quantitatively the consequences of fatigue-cracking of reactor piping. Low cycle strain concentration tests are required to treat fatigue-crack initiation quantitatively at the most likely points of its occurrence. Prototype testing is required to assess the validity of the bench test results in piping samples where biaxiality, thermal stress, and geometric effects more closely simulate reactor piping. These experimental studies are required to compare the predictions of the bench tests and the analytical calculations made as part of the Stress Analysis and Fracture Mechanics Tasks. The purpose of comparing the predictions will be to determine the nature of any cumulative effects by noting the type and magnitude of any nonagreement with predictions. This process of investigation will then be extended to the case of pressurized, large-scale components under the Large-Scale Facility Task.

4.2 Recommended Program

4.2.1 Cyclic Strain Aging Embrittlement

In seeking to identify conceivable ways in which sudden rupture of nuclear piping systems might occur and cause the maximum credible accident, certain possible modes of fracture have been determined.³ One of these possibilities is the loss of ductility and the shift in transition temperature which can arise by the application of cyclic plastic strain to ferritic piping materials at elevated temperatures. Brittle fracture of reactor piping steels at the temperature at which they operate is not anticipated -- unless cyclic strain

aging causes a significant shift in transition temperature. If a significant shift is found, then considerably more detailed work on brittle fracture would become important in the total recommended Phase II program. Therefore, it is recommended that cyclic strain aging effects on actual piping materials be determined at the very outset of the program.

Although strain aging is known to be a cause for increasing the transition temperatures in ferritic steels, this effect has most commonly been identified and investigated by first introducing cold work, or plastic strain at room temperature, followed by aging at elevated temperatures, generally 200 to 250°C. It has also been shown that plastic strain applied at temperatures where aging reactions can occur considerably amplifies the effects of aging. Both monotonic (one direction only) and cyclic deformation at temperature have been shown to intensify the aging effects and reduce ductility. For example, comparative room temperature mechanical properties²⁴ measured after monotonic or cyclic straining at aging temperatures of a mild steel are shown in Table III. It is clear from these data that pronounced changes in properties occur to the detriment of ductility by cyclic strain at aging temperatures.

Coffin²⁴ has shown that the degree of strain aging can be strongly influenced by the particular heat treatment given to the material. For example, rapid cooling from below the eutectoid temperature (723°C) considerably increases the response to cyclic strain aging at 250°C for two steels. This is seen (Table IV) for two steels where the criterion for the ductility loss is the temperature at which the reduction of area in simple tension falls to 10%. Since the nil-ductility transition temperature is considerably higher than this tensile ductility transition temperature (by 100 to 200°C) it is apparent that possible metallurgical-mechanical treatments exist to embrittle the material at temperatures high enough to be of concern. Somewhat related experience on the effect of previous heat treatment on strain aging is being gathered at Brown University from plastic bending tests.

More recent data have shown that strain aging effects can occur in low alloy steels when they are subjected to cyclic straining temperatures in excess of 250°C. The exact temperature of maximum aging depends on the alloying

TABLE III. Room Temperature Mechanical Properties of Annealed 1111 Steel

Treatment	0.2% Offset Yield Stress, psi	True Stress At max Load, psi	Reduction in Area, %	Strain At max Load, %
Aged 1 hour at 200°C	41,000	80,000	66	29
Strained 7.5% at room temperature - aged 1 hour at 200°C	79,000	89,000	60	7.8
Strained 7.5% and aged 1 hour at 200°C	96,000	97,000	56	0.5
Cycled at 200°C - 4% strain range - 10 cycles	94,000	97,000	49	4.0

TABLE IV. Temperature at Which Reduction Area Falls below 10% (SAE 1010 and 1111 Steels)

Treatment	SAE 1010	SAE 1111
Annealed	-180°C	180°C
Ice brine quench from 675°C	-	-110°C
Ice brine quench from 675°C + 10 cycles, $\Delta\epsilon_d = 2\%$ At 250°C	- 75°C	- 40°C
2-1/2 cycles At 200°C $\Delta\epsilon_d = 0.02$	-	- 92°C

addition. Thus, the problem may be of importance in the superheat range as well as for boiling-water and pressurized-water conditions.

The cyclic strain aging effect may be the largest in the vicinity of welds. In and near welds, a broad spectrum of thermal treatment occurs, with respect to the maximum temperature reached during welding and the subsequent rate of cooling. Hence heat treatment becomes an additional variable in the problem.

Three ferritic steels, A-106B, A212B, and A302B should be investigated for their loss of ductility by cyclic strain aging.* Exploration of previous heat treatments should be undertaken to cover the situation at welds. Previous mechanical treatments should follow the techniques reported,²⁴ which involve the use of push-pull loading under controlled cyclic strain at various ranges for a specified number of cycles. Both the strain range and cycles of strain should be varied, and the cyclic strain aging effects observed at the temperature found to produce maximum strain aging (probably around 250°C).

To determine the transition temperature for a particular aging treatment, several specimens with identical treatment are required. Tensile specimens are most conveniently used for determining the effect, but some impact specimens should also be run to determine directly the relationship of these results to the nil-ductility transition temperature.

From these experiments it is believed that the likelihood of cyclic strain aging as a source for embrittlement can be better defined. If it is found that the phenomena is a cause for concern, larger scale experiments will be necessary.

*There is no brittle-ductile transition in austenitic alloys. A cyclic strain aging effect on the fracture toughness of stainless steels cannot be ruled out. This more subtle effect was pointed out in Section 3 and appropriate experiments were proposed.

4.2.2. Slow Growth and Geometries of Fatigue Cracks

Several concepts have been proposed for correlating the crack growth rates under cyclic loading. Of these concepts, that of using the stress intensity factor appears to have the greatest versatility. This approach is based on observations that the fatigue crack growth rate is related empirically to a single stress-field parameter (the stress intensity factor) which describes the elastic stress field near the tip of a crack-like defect. Since the stress intensity factor can be determined analytically for various geometries and crack sizes, this approach should provide a method of estimating the growth rate of fatigue cracks in reactor piping systems. However, the validity of this concept for fatigue crack geometries that might occur in piping systems has not been determined. The experimental program has been designed to determine the validity of the concept. In general, we would establish, with simple specimens of the pertinent materials, the empirical relationship between the stress intensity factor and crack growth rate, i.e., the Paris-Erdogan^{18,25} relationship

$$\frac{da}{dN} = f(k) = \frac{\sigma^n a^m}{C_0}$$

where

$\frac{da}{dN}$ = Crack growth rate, inches/cycle;

K = Stress intensity factor, ksi $\sqrt{\text{in.}}$;

σ = Applied stress, ksi;

a = Crack length, inches;

n, m, C_0 = Empirically determined constants.

Since this relationship is based on elastic stress analysis considerations, its use is restricted to maximum gross stresses of the order of the yield strength.

Having obtained the above basic relationship, an attempt would be made to compare actual and predicted crack growth rates with a more complex geometry

typical of service-related defects, e.g., short elliptical-shaped cracks and long shallow cracks. The details of these tests are described in the following paragraphs.

To obtain a similar correlation for those loading conditions in which the nominal alternating stresses exceed the yield stress and in which strain-cycling characteristics govern failure, a similar approach would be followed. However, here the crack growth rate will be determined as a function of the cyclic plastic strain range, i.e.,

$$\frac{da}{dN} = f(e^n)$$

where

$\frac{da}{dN}$ = Crack growth rate, inches/cycle;

e = Strain range, in./in.

Previous work by Quirk-Irvine²⁰ has determined that the above relationship for carbon steel pressure vessel material is:

$$a = a_0 \exp \left(\frac{e^{2.8} N^{1.4}}{2.5} \right)$$

where

a = Crack length, inches;

a_0 = Initial crack length;

e = Strain range, inches;

N = Number of cycles.

The validity of the above expression and its applicability to predicting crack growth rates in a more complex geometry will then be tested with the same general specimen type as that used for proving the stress intensity factor concept.

The basic fatigue crack growth rate data should be measured on plate-type specimens containing a central slot notch. Specimens about 1/4 inch thick

by 8 to 10 inches wide could be used with available machine loading capacity. The 1/4-inch thickness allows measurements to be made from both surfaces with reasonable assurance of a straight crack front across the specimen. Also, other studies indicate no effect of thickness on growth rate for thicknesses ranging between 1/8 to 1 inch in tests on mild steel.²⁶ The loading should be unidirectional tension cycling. It is expected that three specimens per material and test temperature condition would be sufficient to provide the information necessary to construct a plot of crack rate versus stress intensity factor over the necessary range of elastic strains. Sufficient specimens should also be tested under extension-controlled cycling rather than load-cycled to obtain data in the plastic strain range of nominal stress above the yield strength. The test materials should include three representative pipe materials: a carbon steel (A106B), a low-alloy steel (2-1/4Cr-1Mo) and an austenitic stainless steel (Type-304). Tests at room temperature and at 550°F are recommended to cover the temperature extremes of interest. The higher temperature would be of particular interest in carbon steel to determine the interaction between strain aging and fatigue crack growth rate.

These basic crack growth data can be used to predict the growth rate of a semi-elliptical-shaped fatigue crack growing into a relatively thick section. The predicted behavior should be experimentally checked by tests on plate-type specimens about 1 inch thick by 5 inches wide loaded in zero to tension cycling and in bend-cycling. These specimens should be provided with an initial fatigue pre-crack produced in the center of one of the wide faces by a bending fatigue pre-cracking technique. The pre-crack should be initiated from a small stress concentration and low cyclic stresses should be used to minimize plastic deformation effects in the pre-crack. The specimen dimensions selected will permit crack growth testing at cyclic stresses up to and above the yield strengths and to cyclic strains of the order of 1.0% for the materials of interest with the available testing capability. It is expected that three specimens of each material at room temperature and possibly two specimens at a higher temperature would provide sufficient information to determine the applicability of the Paris-Erdogan and Quirk-Irvin expressions to predict growth behavior of a relatively complex-shaped fatigue crack.

It is expected that the fatigue crack growing into these thicker specimens will have a semi-elliptical profile with a surface length-to-depth ratio somewhere between 3 and 4. If this is found to be so, it will provide further generality to the fact that this ratio is found for fatigue cracks formed in cyclically pressurized cylinders. At present, it is only known that this ratio is observed for the final crack profile; it is not known whether this ratio is generally maintained throughout the growth phase. It is recommended that a combination of dye staining and heat tinting to mark the fatigue crack at two or three stages during the growth phase be used to provide information on this point. Two cases of starting crack shapes should be investigated: elliptical and long shallow (produced by thermal stress)* or by machining to simulate a long, shallow fatigue crack.

A firm basis for predicting the shape (length-to-depth ratio) of fatigue cracks is very important in assessing the reliability of piping systems. It would provide a basis for fixing the maximum expected length when the crack may come through the wall and could be detectable as a leak. To provide additional information on this question, several other tests are recommended. Several of the thick plate specimens should be cycled in bending between zero and tension until failure. If this crack also has a length-to-depth ratio between 3 and 4, it would provide a strong indication that stress gradient has relatively little effect on crack shape.

Several other conditions may be expected to influence crack shape. One of these conditions is a cladding applied on a base metal; e.g., for a clad pipe. It is recommended that specimens of a representative cladding material be included in the thick specimen crack growth series. A suggested combination

* Thermal fatigue cracks tend to be long and shallow, and arise at the surface in a thermal gradient. A result of the thermal gradients is a stress gradient. Thus, growth of a thermal fatigue crack is decelerated as it grows into the thickness to lower stress regions. Through wall propagation would be expected by mechanical cycling. Thus, the shape of the crack in through growth may not differ from that in the purely mechanical case.

is austenitic stainless cladding on a low-alloy steel base metal with approximately 1/4-inch-thick cladding. The crack would be initiated in the cladding and its growth in the cladding and into the base metal determined. Special emphasis should be directed to cycling conditions where the stress is above the yield strength of the cladding material but below that of the base metal.

The shape of a fatigue crack can also be expected to be influenced by conditions introduced at geometric discontinuities, such as at a Tee joint in piping systems. All conceivable joints would be impossible to include in a test program but tests on a specimen of a general configuration (Figure 6) would be included in the prototype tests (Section 4.2.4). The specimen should simulate some of the conditions at a tee joint and the purpose of the test would be to determine whether the restraining effect of the welded-on pipe stub would tend to produce a long, shallow fatigue crack from the corner initiation site. It is expected that tests at room temperature would be sufficient to demonstrate the qualitative features of this effect.

The data and correlations developed from this program on fatigue crack growth should provide a more definite basis than those available for predicting the growth rate and final shape of a fatigue crack which may form under the normal and the worst conceivable service conditions in piping systems. These conclusions can then be compared with experiments in a few carefully selected tests in a full-scale pipe testing facility to determine the type and magnitude of any disagreement caused by superposition of effects.

4.2.3 Low-Cycle Fatigue Crack Initiation in Presence of Stress/Strain Concentrations

There has been an extensive amount of low-cycle fatigue tests on a variety of materials as indicated by recent reviews in this field.²⁷ However, most of the investigations have been directed toward obtaining the inherent low-cycle fatigue characteristics, and plain specimens have been used primarily in axial or bending loading. A major problem area exists in relating these inherent characteristics to the initiation of low-cycle fatigue cracks at

1744-7

Figure 6. Simulated Pipe Joint Specimen for Fatigue Crack Growth Test

geometrical discontinuities. Some experimental work now in progress at the General Electric Large Steam Turbine Department is directed toward determining the cyclic strains in the region of geometrical discontinuities, such as grooves in cylinders, and relating these strains to low-cycle fatigue crack initiation. The measurements have shown that the apparent cyclic strain concentration can be greater or less than predicted by elastic analysis. For example, tests on a Cr-Mo-V alloy steel have shown that the cyclic strain concentration may be as much as 30 to 50% greater than that predicted by elastic stress analysis. The magnitude of the departure from elastic prediction is a function of how far the material is stressed beyond the yield strength in the region of the discontinuity. This apparent discrepancy might involve inadequacy in the calculational methods²⁸ and/or differences between strain hardening (or strain softening) of the various materials. Furthermore, indications are that there may be drastic difference in the actual strain range between reversed loadings, zero-to-peak loading, and cycling about a large mean load.

An experimental program is recommended to extend these investigations to piping materials of specific interest to determine the strain concentrations for various cycling conditions. The test program would include three piping materials: a carbon steel (A106B), a low-alloy steel (2-1/4Cr-1Mo), and an austenitic stainless steel (Type-304). The metallurgical quality of the test materials would be of typical pipe products. As such, the materials can be expected to contain a fairly uniform distribution of small nonmetallic inclusions, such as sulfides and oxides. The influence of the nonmetallic inclusions on the reproducibility of cycles to initial cracking should be reasonably consistent. A gross flaw (e.g., inclusion lamination) in the critical test section would affect the results but its presence would be observed in a metallurgical examination after failure and accounted for in the analysis of the results.

The investigation would have two major parts or phases:

1. Comparison of the cyclic strain history or actual strain range in the discontinuities with values calculated from elastic analysis,

elastic stress concentration factors, and inelastic analysis. The comparisons will probably have to include modifications or improvements in the analytical methods for calculating cyclic strains from uniaxial behavior.

2. Based on the measured and calculated cyclic strains, determine if the cyclic life-to-crack development can be predicted for the specimen geometries and materials under consideration.

Comparatively simple specimen geometries, such as fillets, grooves, and notches in cylinders and bars loaded in direct tension and in bending, should be used. Discontinuities with elastic stress concentration factors around 3 or 4^{*} would be used to enable measurements of local strains by strain gages. Measurements at conditions approaching plane stress and plane strain should be included. It is intended that the tests would be at room temperature. Extending the tests to higher temperatures would be desirable but would require development of a suitable strain gaging technique.

The determination of the stabilized or "shakedown" strain cycle should be one feature of the investigation. The number of cycles to stabilization and the magnitude of stabilized strain cycle should be obtained for various load ranges. The information will demonstrate whether these materials will "shake-down" to some effective "hardness" (stress-strain behavior). This feature should be studied in specimens with and without discontinuities, and the relationship between the two established. Special attention should be directed to the validity and applicability of several methods which have been suggested to relate cyclic strains in stress concentrations to uniaxial behavior.^{28,29} One of these methods would be an extension of Stowell's procedure²⁸ originally developed to relate empirically the stresses and strains in a geometrical discontinuity with uniaxial stress-strain data through the use of the secant modulus. The other method²⁹ is a proposed procedure for calculating the stress and strain after any given number of cycles from a knowledge of stress-strain behavior on the initial cycle.

* With rare exception, elastic stress concentration factors of 1 to 4 cover the range of interest for local discontinuities in reactor piping.

The cycling tests on the various specimens should be carried through to the development of a fatigue crack to provide the experimental values of initiation time against which the predicted cyclic life can be checked. The results should provide a much firmer basis for analyzing the fatigue behavior at complicated geometrical discontinuities in piping systems. The conclusions derived would be highly pertinent in selecting the critical test parameters for the large-scale pipe tests.

The relationship of the three sub-tasks; Low-Cycle Fatigue Crack Initiation (Section 4.2.3), Slow growth of Fatigue Cracks (Section 4.2.2) and Low Energy Ductile Fracture (Section 3.2.4); is as follows. It would measurably improve piping reliability if one could predict the time dependence for the initiation, growth, and development of instability for a fatigue crack in piping. Knowledge of the relationships governing these events would be the basis for design precautions and for effective in-service surveillance procedures. Determination of the required relationships in controlled experimental conditions have been proposed in Sections 4.2.3, 4.2.2, and 3.2.4. The programs of prototype testing and large-scale testing to be described will involve the investigation of the applicability of the relationships for initiation, growth, and instability of cracks to piping conditions. This investigation will determine whether the relationships hold exactly in more complicated situations, and if not, what modifications of the relationships are required.

4.2.4 Fatigue Testing of Prototype Pipe Components

It is recommended that: fatigue testing of selected prototype piping components be performed to provide more complex situations for testing the results of the analytical and experimental work developed in several of the other problem areas. Specifically, these areas are: stress analysis, fracture mechanics, and the bench-scale fatigue testing. Prototype testing

of components would also serve as pilot testing for the large-scale test facility.* This work would directly support the first and second over-all program objectives.

As a workable compromise with respect to nondestructive testing inspection, testing equipment, test specimen preparation, and economy, it is recommended that test specimens be fabricated from 5- to 6-inch-diameter Schedule-80 pipe sections butt-welded together. Reference specimens, without detectable defects** should be initially tested. Subsequent specimens with weld defects, specifically, small root area cracks, protrusion, and with various profiles or surface finishes should be tested to assess the effect of flaws. These "defect" parameters were selected because a reasonable case can be made that they may escape detection during routine nondestructive testing inspection (small root cracks) and/or because their effect upon performance is relatively unknown. Significant piping base material defects should be excluded from consideration because the proper application of current nondestructive testing methods (for example, as specified in ASME Code, Section III) would reasonably ensure a maximum possible defect level of 5% of the wall thickness. Samples will be monitored by nondestructive testing and instrumented for temperature and strain measurement. When cracks develop, they will be real flaws; this approach circumvents the difficulties of producing meaningful artificial flaws. The time to initiate cracking will be compared with the predictions from the previous sub-task. Once cracking is detected, crack growth rates will be followed (as near to component failure as is practicable) by nondestructive testing and perhaps dye staining.

* At present, it is anticipated that prototype components will be tested without pressurization. However, feasibility studies will be made to determine if a relatively simple, low-cost, pressurization scheme could be developed for use in some of, or all, the fatigue tests on prototype components.

** Or, more precisely, with defects within code acceptability criteria as determined by nondestructive testing examination.

Recommended prototype specimen materials and materials combinations¹ are given (Table V) for the suggested configurations to be evaluated which include the tee, clad pipe,* attachment welds, and transitions (pipe to nozzle).

Initial test loading should be by thermal stress cycling and mechanical stress cycling (and possibly pressurization; see footnote on previous page). Water cooling coils and induction heating coils will be appropriately placed to achieve thermal stress. Mechanical loading will be done with jacks and fixtures to give both beam and diaphragm loading. The temperature range of immediate interest is 100 to 600°F, and in addition to the thermal strain associated with the ΔT , the strain ranges should include those associated with code allowable stress, yield point, and 1.5 times yield point. These latter two higher strain ranges are recommended to accelerate testing and to verify a worst case condition. Since low cycle fatigue is the mode of primary interest, initial testing should be performed in the highest plastic strain range - up to 1000 cycles.

Subsequently, the program may be extended to include temperatures to 1200°F, higher cycle maximums (2000), and superposition of high cycle fatigue upon low cycle fatigue. However, these areas are not recommended for initial investigation by prototype component testing.

Initial testing should be designed and instrumented to determine whether the analytical and bench-scale fatigue tests can predict location, growth rates, and cycles-to-failure. Then, "worst-case" components could be selected and tested with internal pressurization in the full-scale facility as indicated by the prototype tests.

Prototype component testing for this recommended program would require approximately 220 test specimens and considerable additional support work in metallurgy, instrumentation, and nondestructive testing. The prototype program provides the suitable necessary means of bridging the gap between bench and large-scale testing.

*For fabrication, clad pipe specimens will probably be greater than 6 inches in diameter.

TABLE V. Materials and Materials Combinations**

Pipe Base Materials to be Welded	A106B to A106B	A335 P22 to A335 P22	Type-304 Stain- less Steel to Type-304 Stain- less Steel	A106B to Type-304 Stainless Steel	A106B to Inconel- 600	A335 P22 to Type-304 Stainless Steel	A335 P22 to Inconel- 600	A234 GD 3 (304 to A212B)
Weld Filler Metal	TIG + E7018	TIG + E9018	TIG + ER308 and E308	E309, E308 TIG	Inconel 182, 82 TIG	E309, E308	Inconel 182, 82 TIG	

Configurations

a. Butt Welds

1. Without
Defects

X	X	X	X	X	X	X	X
---	---	---	---	---	---	---	---

2. With Defects

a. Root

Cracks	X	X	X	X	X		X
--------	---	---	---	---	---	--	---

b. Protrusion

X

c. Profile

X

b. Transition

Joints

X			X	X			
---	--	--	---	---	--	--	--

c. Attachment Welds

X

d. Clad Pipe

X

e. Tee

X

f. Pipe-to-Nozzle

Connections

X				X			
---	--	--	--	---	--	--	--

* Tungsten-inert-gas root welding probably with consumable insert rings.

** The order of testing will be from left to right in the table, the top row of tests will be completed first and then the second row, etc.

5. LOCALIZED CORROSION CRACKING

5.1 Program Requirements

One of the important areas of the recommended program is the study of localized corrosion in reactor piping, with special interest in the mode of failure and the effect of this mode of failure on fission gas release. Emphasis should be placed on determining the most severe form of localized corrosion attack (which is still credible) and the effect of this attack on the over-all failure of the pipe. Efforts should be directed toward determining whether severe localized corrosion attack will (a) produce through crack networks leading directly to sudden large-area ruptures, (b) result in long shallow cracks (which might lead to catastrophic failure of the pipe by mechanical means) or (c) result only in small area failures (which would result only in small leaks).

If it is found that localized corrosion might lead to large-area ruptures, either directly or by combined corrosion and mechanical propagation, it would be necessary to establish that the time-to-failure by stress corrosion is longer than the expected service life of the piping system. Aqueous stress corrosion time-to-failure depends on material composition, stress level in the material, and concentration of the offending ionic species in the water. For piping, the materials are fixed; local stresses must be assumed to be very high. Therefore, it is necessary to determine time-to-failure at high stress as a function of chloride contents in simulated reactor water (550°F) and to extrapolate to the known, low chloride contents in water reactor coolants (< 0.1 ppm). The experimental data available extend only down to 10 ppm Cl^- where time-to-failure is on the order of 2500 hours. An extrapolation of available data to less than 0.1 ppm Cl^- cannot be made with certainty, but reactor piping has now operated more than 50,000 hours without detected cracking.

The time-to-failure tests should include additional attention to the mode of failure, i.e., through crack networks and the possibility of long shallow

cracks. This additional aspect of the time-to-failure experiments would provide confirmation or rejection of the hypothesis implicit in the accelerated tests that the mode of failure is not dependent on chloride ion concentration.

5.2 Recommended Program

5.2.1 Concentrated Solution Fracture Tests

The primary objective in this sub-task is to explore reactor piping corrosion cracking in accelerated laboratory tests. For this purpose, small pipes should be used as laboratory specimens. Specimens would be made to duplicate reactor piping with respect to fabrication and heat treatment as closely as possible. The sealed tubular specimens would constitute their own pressurized corrosion chambers. Several combinations of geometry and loading - a straight section containing circumferential discontinuities, wyes, and tees, all loaded, e.g., by bending, torsion, or axial tension - should be employed. Accelerated tests would be performed to examine a broad spectrum of conditions in a relatively short time.

The materials of primary interest for reactor piping application are Types-304 and -316 austenitic stainless steels, 2-1/4Cr-1Mo and plain carbon steels. Of these, the austenitics are considered to be the most widely used and the most susceptible to localized corrosion cracking. Consequently, Type-304 stainless steel should be subjected to the largest number of test conditions, while the other alloys should be subjected only to tests under loading conditions which are found to be pertinent based on experiments with Type-304 stainless steel specimens.*

* Other chemical solutions would have to be used for ferritic alloys. It will be recalled, however, that the solutions known to produce cracking in ferritics are not at all similar to reactor waters.³ This is not the case for austenitics where dilute Cl^- solutions (at concentrations approaching those in reactor waters) are known to cause cracking.

Figure 7. Chloride Stress Corrosion-Time to Cracking for Stainless Steel

Of the many ions normally present in water reactor coolants, the most commonly recognized ion with potential for causing stress corrosion is the chloride ion. Most reactor water is usually controlled to chloride ion concentration below 0.1 ppm. Over long periods of time, concentration of chlorides as surface deposits could conceivably occur and result in stress corrosion cracking. Increasing chloride ion concentration will accelerate cracking. Therefore, initial tests should be run at least at 1000 ppm Cl^- .

Although reactor pipes are designed to operate at nominal stress levels below yield, local stresses above yield exist which could accelerate stress corrosion (Cl^-) cracking. Because of variations in power levels during operation, these stress levels could be cyclic and lead to a combination of low cycle fatigue and stress corrosion if the chemical environment is appropriate. Therefore, the fracture corrosion tests should be made at reactor water temperatures at, or above, the yield stress under static and cyclic loadings. Since the nature of the corrosion cracking failure may depend on stress field distribution, combinations of pressure loading and torsion or bending should be included. A few samples might be pre-cracked by thermal fatigue to simulate possibility of propagation of a fatigue crack by stress corrosion.

The ideal condition for stainless steel pipe with respect to resistance to localized corrosion cracking is the fully annealed (unsensitized) austenitic condition. However, welding operations during installation might cause sensitization of the pipe. It is generally recognized that sensitized alloys are more subject to localized corrosion than unsensitized alloys. Therefore, welded joints should be included among the accelerated test specimen.

Rideout³¹ has recently proposed that improper surface preparation of welded reactor nozzles resulted in their failure by chloride stress corrosion. The nozzles had been sensitized during welding, cleaned and pickled with HF-HNO_3 , and then exposed to a low-chloride (< 1 ppm), heavy-water environment. The failures could be duplicated in ex-reactor experiments only if a similar pickling operation was used to initiate cracking. Therefore, this "worst-case" surface treatment should be used.

Only if large ruptures are found with the initial "worst-case" accelerated tests need a systematic relaxation of each accelerating factor (chloride concentration, stress level, stress state) be undertaken. Any relaxation of the accelerating factors should be made to determine whether the catastrophic failures are observed under more nearly realistic reactor conditions.

5.2.2. Dilute Solution Tests

Although localized corrosion cracking of water reactor piping is very unlikely in times up to at least 6 years (50,000 hours), there are no data indicating 40-year immunity to cracking in dilute reactor coolant solutions.³ Very restricted long-term tests are recommended for Types-304 and -316 stainless steel in water precisely simulating boiling-water reactor and pressurized-water, reactor-coolant conditions - with the single variable of chloride ion concentration.

The objective of these experiments on small stainless steel tubing loops is to establish the relationship between chloride ion concentration and time-to-failure. Such data necessary for extrapolating to time-to-failure at operating-reactor chloride-ion concentrations are unavailable.

A secondary objective of the recommended tests would be confirmation of the results of the accelerated tests on the nature of the cracking failures. Therefore, it is recommended that provision be made for controlled external loading of sections of the pressurized bench loop and for the determination of corrosion crack growth rates.

Large-scale tests which might be required would be tests on pre-cracked pipe sections. Pre-cracking would be accomplished with concentrated solutions inside a capped pipe section.

5.3. Relevance to Program Objectives

The main task of determining the kind of fracture resulting from stress corrosion cracking of pressurized stainless steel pipes is necessary to support

firmly a precise assessment of piping reliability. The second task, if necessary, that of estimating time-to-failure, would directly refine the probability number for localized corrosion cracking as needed for the reliability engineering work.

6. IMPACT EROSION BY WET STEAM

6.1 Program Requirement

It has been found² that erosion is not an uncommon source of rather large leaks in industrial piping systems.

Previous experiments³² indicate for a wide range of materials that moisture particle erosion is dependent on velocity as shown below:

$$E = C(V - V_C)^2$$

where

C = Constant,

V_C = Critical velocity below which erosion is negligible,

V = Velocity in feet per second, and

E = Specific weight loss by erosion.

For a wide range of materials the critical velocity has been determined to be of the order of 420 ft/sec. If it could be determined that the critical velocity of the carbon steel, austenitic steels, and Inconel materials actually used for reactor piping is of this order and therefore less than the maximum anticipated reactor steam velocity (approximately 300 ft/sec), it would provide a convincing argument that wall thinning by erosion is of minor importance.

6.2 Recommended Program

Although information indicates that erosion is influenced by other factors, e.g., moisture, flow rate, and temperature, these factors appear to be of less

significance than moisture particle velocity. For this reason, the experimental procedures indicated below have restricted all variables but velocity.

The experimental program should be conducted with already available equipment designed for impact erosion tests. In general, wet-oxygenated plant steam at about 350 psia and 430°F could be temperature-controlled to maintain a moisture content of 9%.

Determination of the erosion rate of carbon steel and austenitic piping should be made at several velocities near the expected critical velocity to prove the general relationship as well as providing the value of V_C which is necessary for extrapolation. Since erosion rates at the anticipated critical velocity are low, a test duration of 1000 hours is anticipated.

6.3 Relevance to Program Objectives

The values of V_C determined for piping materials and the confirmation of the general relationship between coolant velocity and erosion weight loss would provide a specific design tool. The use of this tool might be recommended as a standard or code amendment for reactor piping and thus contribute to the third general program objective.

7. QUALITY ASSURANCE PROCEDURES

7.1 Program Requirements

The Phase I historical review indicated that when existing test and inspection criteria are properly specified, applied, and fulfilled, adequate system materials integrity resulted. That is, assuming no design error of misapplication or materials selection, there are no apparent consequential deficiencies in code allowable stresses or defect acceptability criteria. However, work is recommended to develop guidelines or procedures to ensure that the existing specifications and criteria are indeed applied when appropriate.

An example illustrating the type of problem to be resolved can be related as follows. The ASA Code for Pressure Piping B31.1-1955, Section 6, Par. 635 (b), states:

When required in the specification or contract, or by agreement between the purchaser and the manufacturer or contractor, the quality of butt welds shall be checked as follows:

1. When random radiographic examination, sectioning, or a combination of both, are specified
2. When full radiographic examination is specified*

Nowhere does this code require radiographic inspection of weldments - such inspection (and magnetic particle or liquid dye penetrant testing) will only be performed if required as stated above. This is proper treatment of this subject by the code since a large variety of piping applications fall within its scope. However, it is apparent that for a "critical" piping system, many designs and fabrications do not require radiographic inspection.¹ What should be delineated is: When are such inspections recommended, for which systems, and to what extent.

7.2 Recommended Program

Initially, nuclear power plant primary piping systems should be sub-divided into functional and material quality assurance categories or groups for convenience in handling for procedures, inspection, and testing.** Then, detailed recommended procedures (guidelines or check lists) would be generated for each quality assurance category or group. The specific subject areas

* Emphasis is the authors'.

** For example, the primary steam piping would be in the maximum quality assurance group whereas extraction steam piping would fall in a lesser inspection group.

include manufacturing and fabrication variables. Hence, for mill materials testing the following topics should be resolved:

1. Which, if any, supplementary tests are recommended.
2. Materials identification and marking to avoid inadvertent substitutions.
3. Which testing and/or processing steps should be witnessed and why.
4. What documentation should be collected.

Subsequently, the recommended procedures that should be developed for application during fabrication and erection include:

1. Welding qualifications - procedure and performance. What should be witnessed and why.
2. Welding specifications for such things as heat treatment, joint preparations, electrode storage, and handling.
3. In-process inspections of such things as fit-up, welding, and layout.
4. Nondestructive testing inspections - what should be applied, where, and why.
5. Pressure and leak testing.
6. Recommendations for those cases where inspection should be witnessed.
7. Documentation recommendations.

7.3 Anticipated Results

Procedures would be developed to reduce the opportunity for inadvertent errors during manufacturing, fabrication, and erection. This would provide additional assurance of piping reliability and constitute a specific contribution to the third general program objective.

8. OPERATIONAL SURVEILLANCE DEVELOPMENT

8.1 Program Requirements

It is believed that the probable piping fracture modes will be manifested as slowly growing cracks which will develop into leaks.^{2,3} Detection during the stage of crack growth or at the onset of leakage would prevent the occurrence of high-leak rate coolant loss and/or more severe rupture mode problems. An effective detection system must have a short detection time constant by comparison to the time for serious crack growth and/or leak growth. An effective operational surveillance system must be of sufficient scope to ensure that all potential problem areas are monitored. Current surveillance programs are not clearly delineated in scope, frequency, or content.^{1,2} These programs have not been specifically developed from a fracture prevention objective, rather they have in large part been derived and carried out on a convenience or plant-operation basis. The development of an effective, economic crack and/or leak surveillance system is recommended to ensure that piping system reliability has been maintained at the expected or design level.

8.2 Specific Program

To develop an objective, economic, monitoring system, an inter-disciplinary team ideally composed of a reactor plant systems piping designer, a materials engineer, a nondestructive testing specialist, a nuclear safety engineer, a plant safety engineer, and additional specialists or consultants, as appropriate, should conduct the initial investigations and data gathering. Under the direction of a team leader, the function of the team would be to identify and assess operating plant problems pertinent to the application of either a continuous or a periodic surveillance program. This would include detailed descriptions of the portions of the piping systems to be included, plant accessibility problems, and the detection objective.* The preliminary results

* Ideally cracks, but the onset of leakage may be a much more economical solution.

of the reliability engineering study on sensitive areas should be used to sharpen further the requirements for an effective system.

After establishing such guidelines, individual investigation could proceed on leak detection devices, inspection devices, inspection program and procedures, and plant design to facilitate monitoring surveillance. These factors should then be combined to develop an over-all optimum solution. The prototype surveillance system should be evaluated by use in the large-scale testing program.

The practicality of utilizing leak detection devices should be evaluated. Advantages and limitations of dew point, sonic, and ultrasonic devices should be tabulated and compared to monitoring service requirements. Modifications to improve the apparently limited usefulness of existing devices should be explored. Possible equipment combinations, for example, the use of leak detection devices in combination with a closed circuit television system, should be evaluated.

Nondestructive testing tools should be applied and modified for this specific application. In particular, it might be necessary to develop remote handling equipment.

Possible changes in plant design that would facilitate monitoring surveillance, such as removable insulation and more accessible piping chases and results, should be explored. Whether or not the monitoring system should be fully built-in, continuous, or intermittent should be resolved.

8.3 Relevance to Program Objectives

An economic monitoring surveillance program for nuclear power plant piping systems would be developed that would ensure continued system reliability by early detection of integrity changes. The results of this task would support and verify the improvements in designed reliability developed by the other tasks. The results of this program would greatly aid in assigning

several probability numbers in the reliability engineering task. Thus, contributions to all three general program objectives will result.

9. CREEP-FATIGUE

9.1 Program Requirements

Creep-stress rupture fracture of water reactor piping is considered highly unlikely.³ However, creep phenomena and particularly combined creep-fatigue failures deserve considerable attention for superheater applications. The deficiencies in basic data and design criteria for this high temperature application have been discussed in detail.⁴

9.2 Recommended Program

It is recommended that the Phase II program initially emphasize more immediate areas of concern, but later, work should be done on the creep-fatigue phenomena. Specifically, the major piping materials intended for superheat and supercritical designs should be examined experimentally at temperatures in the range 850 to 1250°F. Low-cycle, strain-fatigue tests should be run with between-cycle dwell times as one variable. Creep tests should be run with intermittent strain-cycle loading. The results of the material tests should be translated into design criteria. The design criteria should be confirmed on large-scale piping segments run at 850 to 1200°F.

9.3 Relevance to Program Objectives

Specific design criteria contributing to the first and third general program objectives would result from this program.

10. LARGE-SCALE TEST FACILITY

10.1 Program Requirements

Large-scale testing will be required to verify analytical results and to validate the extrapolation of small-scale laboratory tests. The work of the

previously described tasks is expected to supply missing information in specific areas of the pipe rupture problem. These data will be in the form of analytical and small-scale experimental results pertinent to singular effects. It is known, however, that some of the effects cannot be extrapolated linearly to large size piping. Similarly, the interaction of the basic rupture causing mechanisms must be quantitatively evaluated. Finally, it is evident, based on previous experience, that only large-scale tests of this type will convincingly demonstrate the validity of the test results to the majority of interested parties.

10.2 Recommended Program

It is recommended that a large-scale test loop be designed and constructed to permit a variety of investigations to be made. The number of test operations should be limited, and efforts made to combine several investigations in each test run. Final requirements for the large-scale test program cannot be specified until some of the initial Phase II work has been completed (Figure 1). It is evident, however, that the loop will be required to operate with pressurized water, saturated steam, and superheated steam. Preliminary specifications are:

1. Pressure - Design pressure shall be 3500 psig. Pressure control equipment shall be provided to maintain various pre-set pressure levels up to design level. Provision shall be made for cyclic pressure operation.*
2. Temperature - Design temperature shall be 1200°F. Temperature control equipment shall be provided to maintain temperatures in the system at any pre-set temperatures up to design level. Provision shall be made for cyclic temperature variation.**

* It would be possible, for example, to pressurize at say 1500 psi on a specimen with a defect calculated as just subcritical and then to increase pressure very quickly up to any pressure below the loop design pressure of 3500 psi.

** Severe local thermal stresses could be obtained, for example, by a cold water injection line on the test specimen.

3. Flow Rate - The system flow rate shall be sufficient to attain and maintain thermal equilibrium in the test section. For initial design purposes, 10 gpm is sufficient.
4. Water Chemistry - The test facility shall include demineralizer equipment capable of maintaining water purity equivalent to reactor water. Chemical injection equipment shall be provided for injection of various additives during operation.
5. Control and Instrumentation - Operation of the loop shall be automatically controlled with manual over-ride provisions. Pressures, temperatures, flow rates, and water conditions shall be monitored and recorded.
6. Test Sections - The facility shall be capable of accepting, without significant modification, test sections of varying size and geometry. Pipe sizes up to 18 inches in diameter will be tested.* Geometric arrangements will include bend sections, elbows, tees, wyes, and simulated pipe-to-vessel nozzle connections.
7. External Loadings - Provision shall be made for imposing external mechanical loadings on test sections. These loadings will include bending, torsion, and combinations thereof. Provision for cyclic loading operations shall be included. Sophisticated, mechanical loading devices capable of programmatic load variations are now commercially available.

A preliminary design for the large-scale test facility is shown in Figures 8 and 9. It is recommended that the test sections be located in a pit with a blast mat cover to minimize the possibilities of missile ejection from ruptured pipe sections.

It is considered that a minimum of five and a maximum of ten test sections will be required. The first test is planned to encompass the following.

A 12-inch-diameter test section will be fabricated and will consist of a carbon steel (A106B) tee to one leg of which a carbon steel welded pipe

*The facility could accept pipes of diameter below 18 inches and up to 36 inches. The 18-inch test size is recommended for economy and since at this size both extruded and welded piping is commercially available. Furthermore, the extrapolation factor from 18 inches to the largest reactor pipe sizes is less than 2, the commonly accepted upper limit for extrapolation.

Figure 8. Large Scale Test Facility (Plans and Sections)

SECTION A-A

SECTION B-B
TAKEN TWO PLACES

SECTION C-C

FIG.5: HIGH PRESSURE LOOP SCHEMATIC

1744-4

GEAR-4474

Figure 9. Large Scale Test Facility (P & ID)

section will be attached. A 2-1/4Cr-1Mo (A335-P22) section will be welded to the second leg of the tee and an austenitic stainless steel (A312 TP304) section will be welded to the third leg. No intentional defects will be incorporated in this section.

A major objective of this first test should be to shake down all instrumentation systems required for the subsequent tests. The test section will be instrumented with thermocouples, strain gages, and accelerometers in quantities and at locations indicated by the requirements of other task programs. Motion picture cameras, both ordinary and high-speed types, will be provided to record test section behavior. (Note that high-speed camera equipment will be used primarily to try to record crack propagation and one key to the successful use of this equipment will be the determination of a suitable camera triggering system. This camera control technique has not been determined as yet. The camera system would be used primarily for test sections containing pre-flaws, since it is necessary to know the failure location.)

The test section will be installed as part of a recirculating flow loop. For this test, the loop would be operated at a constant pressure of 1500 psig with water temperatures varied from 100 to 600°F. External loadings will be induced in bending, tension, and torsion. Electric heaters on pipe sections will be provided to induce both longitudinal and tangential thermal gradients. Additionally, any instrumentation developed in the operational surveillance task will be installed, tested, and evaluated.

The test section will be operated as a pressurized-water system under combined thermal and mechanical cycling conditions. The section will be tested to failure with crack propagation studies made until the leak rates exceed the make-up capability of the test loop. Initial failures would then be repaired and further testing of the specimen carried out.

10.3 Relevance to Program Objectives

This test will provide data in support of the following specific tasks:

1. Analytical accuracy of the shell model calculations for local stresses in the tee will be determined.
2. Experimental verification of strain concentration factors will be obtained.
3. Experimental small-scale fatigue studies, both under low cycle conditions, will be verified.
4. The behavior of joints (including dissimilar metal weld joints) under various loading conditions will be determined.
5. An operational check of promising surveillance equipment will be obtained.
6. The results of the tests will provide significant input to the reliability engineering effort in predicting failure probabilities.
7. Data will be made available for later comparison with the calculations coming out of development of the Fracture Mechanics studies.

From the above, it is apparent that the large-scale test program directly contributes to the three objectives of this study.

The comparison of full-scale experimental test results and the predictions of the task studies (Stress Analysis, Fracture Mechanics, and Fatigue) will determine both the nature and magnitude of any disagreement between experimental and analytical relationships. By "the nature of the disagreement" is meant whether the relationships between stress or strain, material parameters, and crack behavior differ in that the same form of the relation holds, with perhaps modified constants, or whether an entirely different situation applies. By "the magnitude of the disagreement" is meant whether the given analytical predictions are in error by 1, 10, or 100%, for example. Having performed controlled experiments on a smaller scale to determine the relationships of one variable at a time, it will be possible to determine how much of any disagreement between theory and practice is due to superposition effects.

REFERENCES

1. E. R. Kilsby, Jr., "A Survey of Water Reactor Primary System Conditions Pertinent to the Study of Pipe Rupture," GEAP-4445, January 1964.
2. W. S. Gibbons, "A Survey of Piping Failures," GEAP-4574, March 1964.
3. A. J. Brothers, L. F. Coffin, J. R. Low, H. H. Klepfer, and M. B. Reynolds, "A Review of Fracture Modes as Related to Reactor Primary Coolant Pipe Rupture," GEAP-4446, January 1964.
4. S. W. Tagart, "Mechanical Design Considerations in Primary Nuclear Piping," GEAP-4578, March 1964.
5. G. Reethoff, "Reliability Design Prediction Studies with Reference to Jet Propulsion," General Electric Report presented at 1964 SAE Automotive Engineering Congress and Exposition, October 22, 1963.
6. A. R. C. Markl, "Fatigue Tests of Piping Components," ASME Transactions (1952).
7. P. P. Bijlaard, "Stresses from Radial Loads and External Moments in Cylindrical Pressure Vessels," Welding Journal, Research Supplement (1955).
8. R. E. Peterson, "Stress Concentration Design Factors," Wiley, N.Y., (1962).
9. A. A. Griffith, Phil. Trans. Roy. Soc., A221, 163 (1920).
10. I. N. Sneddon, Proc. Phys. Soc. Lond., 187, 229 (1946).
11. G. R. Irwin, "Theoretical Aspects of Fracture Failure Analysis," Metals Engineering Quarterly, ASM, 3, No. 1, 25 (1963).
12. D. K. Felbeck and E. Orowan, "Experiments on Brittle Fracture of Steel Plates," Welding Journal Res. Supplement, November 1955, pp. 1-6.
13. J. M. Krafft and A. M. Sullivan, "Effect of Speed and Temperature on Crack Toughness and Yield Strength of Mild Steel," NRL Report 5776, U.S. Naval Research Laboratory, Washington 25, D.C.
14. J. I. Bluhm, "A Model for the Effect of Thickness on Fracture Toughness," Proc. ASTM, 61, 1324 (1961).
15. D. H. Winne and B. M. Wundt, "Application of the Griffith-Irwin Theory of Crack Propagation to the Bursting Behavior of Discs, Including Analytical and Experimental Studies," Trans. ASME, 80, 1643 (1958).
16. J. F. Tavernelli and L. F. Coffin, Jr., "A Compilation and Interpretation of Cyclic Strain Fatigue Tests on Metals," Trans. ASM, 51, 438 (1959).

17. J. G. Sessler and V. Weiss, "Low Cycle Fatigue Damage in Pressure-Vessel Materials," J. Basic Eng. ASME, 85D, 528 (1963).
18. P. Paris and F. Erdogan, "A Critical Analysis of Crack Propagation Laws," J. Basic Eng. ASME, 85D, 528 (1963).
19. J. E. Srawley and W. F. Brown, Jr., "Fracture Toughness Testing," NASA Technical Memorandum, NASA TMX-52030, National Aeronautics and Space Administration, Washington, D.C. (1964).
20. W. H. Irvine, A. Quirk, and E. Bevitt, "Fast Fracture of Pressure Vessels," J. Brit. Nuc. Energy Soc., 31 (January 1964).
21. E. Bevitt and A. L. Stott, "Fast Fracture in Pressure Vessels, UKAEA Report TRG-477C (1963).
22. M. A. Salmon, "Plastic Instability of Cylindrical Shells with Rigid End Closures," J. App. Mech. ASME 30E, 401 (1963).
23. P. Mann-Nachbar, O. Hoffman, W. E. Jahsman, "Plastic Instability of Cylindrical Pressure Vessels of Finite Length," AIAA Journal 1, 1607 (1963).
24. L. F. Coffin, Jr., "The Effect of Quench Aging and Cyclic-Strain Aging on Low Carbon Steel," Report 64-RL-3550M, January 1964.
25. P. C. Paris, "Crack Propagation Caused by Fluctuating Loads," Presented at ASME Meeting, Cleveland (1962).
26. N. E. Frost and K. Denton, "Effect of Sheet Thickness on the Rate of Growth of Fatigue Cracks in Mild Steel," J. Mech. Eng. Sci., 3, 4 (1961).
27. J. Yao and W. H. Munse, "Low Cycle Fatigue of Metals - Literature Review," Welding Journal, Vol. 41, (1962), p. 182s.
28. E. Z. Stowell, "Stress and Strain Concentration at a Circular Hole in an Infinite Plate," NACA TN 2073 (April 1950).
29. S. V. Sorensen and R. M. Schneiderovitch, "Elastoplastic Cyclic Deformation and Low-Cycle Fatigue," Proc. ASTM, Vol. 61, (1961), p. 789.
30. P. D. Neuman and J. C. Greiss, "Stress Corrosion Cracking of Type-347 Stainless Steel and Other Alloys in High Temperature Water," Corrosion, 19, 345t (1963).
31. S. P. Rideout, "Stress Corrosion Cracking of Type 304 Stainless Steel in High-Purity Heavy Water," DPSPV 63-40-26, Savannah River, (March 1963).
32. E. Honegger, "Tests on Erosion Caused by Jets," Brown Boveri Review, Vol. XIV, No. 4 (April 1927).

Pipe Rupture Study

6 - SURVEY PARTICIPANTS DISTRIBUTION(Total distribution
167)

1. Mr. Frank R. Ward
Coordinator, Government Markets
Application Development Dept.
The Babcock and Wilcox Company
P.O. Box 1260
Lynchburg, Va. ✓
2. Mr. W. H. Zinn, Vice President
Combustion Engineering Co.
Nuclear Division
Windsor, Conn. ✓
3. Mr. E. M. Powell
Combustion Engineering Co.
Nuclear Division
Windsor, Conn. ✓
4. Mr. M. F. Pravda, Manager
R Reactor Systems Section
The Martin Company
Nuclear Division
Baltimore 3, Maryland ✓
5. Mr. R. J. Wolf, Vice President
Kaiser Engineers Division
Henry J. Kaiser Company
300 Lakeside Drive
Oakland, California ✓
6. Mr. R. M. Campbell
Stone and Webster Engineering Corp.
49 Federal Street
Boston 7, Massachusetts ✓
7. Mr. Eugene C. Bailey
Administrative Engineer
Commonwealth Edison Company
72 W. Adams Street
Chicago 90, Ill. ✓
8. Mr. H. W. Dierman
Chief Mechanical Engineer
Consolidated Edison Company
4 Irving Place
New York 3, New York ✓
9. Mr. C. J. Maynard
Consumers Power Co
212 Michigan Avenue
Jackson, Michigan ✓

Gordon

9-1-65

10. Mr. Roger J. Coe ✓
Vice President
Yankee Atomic Electric Company
441 Stuart St
Boston, Mass
11. Mr. L. E. Link, Assoc. Director ✓
Reactor Engineering Division
Argonne National Laboratory
9700 S. Cass Avenue
Argonne, Ill.
12. Dr. Spencer H. Rush ✓
Hanford Laboratories
P.O. Box 550
Richland, Washington
13. Mr. J. B. Tinker, Manager ✓
Process Section
E. I. DuPont de Nemours and Co.
Savannah River Laboratory
Aiken, South Carolina
14. Mr. L. J. Weber, Assistant Manager Engineering ✓
Phillips Petroleum Company
Atomic Energy Division
P.O. Box 1259
Idaho Falls, Idaho
15. Mr. E. C. Miller ✓
Oak Ridge National Laboratory
P. O. Box X
Oak Ridge, Tenn.
16. Dr. James Wright ✓
Westinghouse Electric Corp.
Atomic Power Division
Box 355
Pittsburgh, 30, Pa.
16. Mr. E. E. Zwicky ✓
General Electric Co
Large Steam Turbine - Generator Dept.
1 River Road
Schenectady, N. Y.
17. The M. W. Kellogg Co. ✓
711 Third Avenue
New York 17, N. Y.
Attn: Mr. D. B. Rossheim
Mr. R. G. Bateman
Mr. J. J. Murphy

Gordon Th...
9-1-65

18. Mr. A. R. C. Markl ✓
Tube Turns Inc.
224 East Broadway
Louisville, Kentucky
19. Mr. F. S. G. Williams ✓
Taylor Forge and Pipe Works
4735 W. 14th St
Chicago 50, Illinois
20. Mr. Harvey Brush ✓
Bechtel Corp
220 Rush Street
San Francisco, Calif.
21. Mr. C. C. Welchel ✓
Pacific Gas & Electric Company
245 Market Street
San Francisco, Calif.
22. Prof. J. Marin ✓
Penn. State University
School of Engineering
State College, Pa.
23. Prof. T. J. Dolan ✓
University of Illinois
College of Engineering
Urbana, Illinois
24. Westinghouse Electric Corp. ✓
Research Laboratories
East Pittsburgh, Pa.
Attn: Mr. R. E. Peterson
Mr. J. D. O'toole
25. Mr. D. A. Monney ✓
Jackson & Moreland Inc.
600 Park Square Blvd.
Boston, Mass
26. Mr. A. B. Wilder ✓
U. S. Steel Corp
525 Wm Penn Place
Pittsburgh 30, Pa.
27. Prof. C. R. Soderberg ✓
Mass. Institute of Technology
Dept. of Applied Mechanics
Cambridge, Mass.

Gordon *Marin*
9-1-65

28. Mr. E. O. Bergman
Sr. Staff Engineer
National Engineering Service Company
785 Winthrop road
San Marino, California ✓
29. Arthur D. Little Inc.
20 Acorn Park
Cambridge 40, Mass
Attn: Mr. E. L. Field
Mr. B. C. Hanley
Mr. P. F. Strong ✓
30. Mr. E. Moncrief
Flour Corporation
2500 Atlantic Blvd
Los Angeles, Calif. ✓
31. Mr. D. Timo
General Electric Company
LST&G Dept.
1 River Road
Schenectady, New York ✓
32. Mr. F. R. Farmer
UKAEA
Safeguard Division
Authority Health & Safety Branch
Risley, Warrington, Lanc.
England. ✓

Gordon Mason

9-1-65

X - AEC CONTACTED

1. General Electric Co.
HAPO
P. O. Box 100
Richland, Washington
c/o Dr. S. H. Bush
Bldg. 328, Area 300

Gordon *Mason*
9-1-65

ASM CHAPTER CHAIRMEN - 1963-64

1. Mr. C. E. Kleis
Citizens Gas & Coke Utility ✓
2020 N. Meridian Street
Indianapolis 9, Indiana
2. Mr. John B. Campbell ✓
Managing Editor
Materials in Design Engineering
430 Park Avenue
New York, N.Y. 10022

Gordon Mason
9-1-65

I - UTILITIES

1. Mr. H. E. Kent
Director of Engineering
Edison Electric Institute
750 Third Avenue
New York, N.Y. 10017
2. Baltimore Gas & Electric Co.
Lexington Building
Baltimore 3, Maryland
c/o Mr. R. C. Fitzgerald
3. The Detroit Edison Co.
2000 Second Avenue
Detroit, Michigan 48226
c/o Mr. I. A. Rohrig
4. American Electric Power Service Corp.
2 Broadway
New York, N.Y. 10008
c/o Mr. G. E. Lien
Head-Piping Metal Section
5. Pacific Gas & Electric
245 Market Street
San Francisco 6, Calif.
c/o Mr. C. C. Welchel
Vice President-Engineering
6. Commonwealth Edison
72 West Adams Street
Chicago, Illinois 60690
c/o Mr. E. C. Bailey
7. Philadelphia Electric Co.
900 Samson Street
Philadelphia 5, Pa.
c/o Mr. G. H. Harlow, V.P.
Engineering & Research
8. Duquesne Light Co.
435 Sixth Avenue
Pittsburg, Pa. 15219
c/o Dr. S. F. Whirl
Supt. Chemical Serv.

9. Consolidated Edison Co. of N.Y., Inc.
4 Irving Place
New York, N.Y. 10003
c/o Mr. H. Knecht ✓
10. Michigan Consolidated Gas Co.
One Woodward Avenue
Detroit, Michigan 48226
c/o Mr. A. H. Cramer ✓
11. The Cincinnati Gas & Electric Co.
SWC Fourth and Main
P. O. Box 960
Cincinnati 1, Ohio
c/o Mr. E. C. Pandorf ✓
12. Tuscon Gas, Electric Light & Power Co.
35 West Pennington Street
P. O. Box 711
Tuscon, Arizona
c/o Mr. R. W. Swinehart
Supt. Power Production ✓
13. Arkansas-Missouri Power Co.
104 South Fifth Street
P. O. 641
Blythevill, Arkansas
c/o Mr. W. M. Jontz
Dir. Planning & Engrg. ✓
14. Arkansas Power & Light Co.
9th & Louisiana
Little Rock, Arkansas
c/o Mr. J. P. White
Gen. Supt. of Power Plants ✓
15. Burns & McDonnell Engineering Co.
4600 East 63rd Street-Trafficway
Kansas City, Missouri
c/o Mr. E. V. Doll ✓
16. California Electric Power Co.
2885 Foothill Boulevard
P. O. Box 1029
San Bernardino, Calif.
c/o Mr. A. A. Lingo
Supt. of Steam Generation ✓

Handwritten:
m
Gordon
9-1-65

17. San Diego Gas & Electric Co.
861 Sixth Avenue
Box 1831
San Diego 1, Calif. (92112)
c/o Mr. C. L. Hathaway
Supt. Electric Prod.
18. Southern California Edison Co.
601 West Fifth Street
P. O. Box 351
Los Angeles, Calif. 90053
c/o Mr. G. R. Woodman, Chief Engr. Designer
19. Burbank Public Service Dept.
164 West Magnolia Blvd.
Burbank, Calif.
c/o Mr. A. E. Capon
Asst. Gen. Mgr. & Ch. Eng.
20. Mr. H. E. Burke
Eng. - Steam Design
P. O. Box 3669 Terminal Annex
Los Angeles, Calif. 90054
21. City of Colorado Springs Dept. of Public Utilities
18 South Nevada Avenue
Colorado Springs, Colorado
c/o Mr. F. H. Wiley, Ch. Engr.
22. United Illuminating Co.
80 Temple Street
New Haven 6, Conn.
c/o Mr. E. H. Walton
Vice President-Eng.
23. Potomac Electric Power Co.
929 East Street, N.W.
Washington 4, D.C.
c/o Mr. R. R. Dunn, President
24. Florida Power & Light Co.
25 S.E. 2nd Avenue
P. O. Box 3100
Miami 1, Florida
c/o Mr. G. Kinsman
V.P.-Engineering
- Handwritten:* Gordon 9-1-65

25. Florida Power Corp.
101 Fifth Street South
P. O. Box 14042
St. Petersburg 1, Florida
c/o Mr. A. J. Ormston, Ch.Mech. Eng.
26. Gulf Power Co.
75 North Pace Blvd.
Pensacola, Florida
c/o Mr. R. L. Pulley
President & Gen. Manager
27. Central Illinois Light Co.
300 Liberty Street
Peoria, Illinois
c/o Mr. A. H. Davies
28. Illinois Power Co.
500 South 27th Street
Decatur, Illinois
c/o Mr. T. W. Schroeder
Mgr. of Power Supply
29. Winnetka Municipal Electric & Water Dept.
510 Greenbay Road
Winnetka, Illinois
c/o Mr. L. Ellis, Manager
30. Indianapolis Power & Light Co.
25 Monument Circle
P. O. Box 1595
Indianapolis 6, Indiana
c/o Mr. C. B. Vance
V.P. Power Prod.
31. Public Service Company of Indiana, Inc.
1000 East Main Street
Plainfield, Indiana
c/o Mr. Harold Goldberg
Ch. Eng. Design & Const.
32. Fort Wayne Municipal Light & Power
308 E. Berry Street
Fort Wayne, Indiana
c/o Mr. N. F. Cunningham
33. Kansas Gas & Electric Co.
201 North Market Street
Wichita 1, Kansas
c/o Mr. E. D. St. John, Sup. of Prod.

34. Kentucky Utilities Co.
120 South Limestone
Lexington, Kentucky
c/o Mr. Henry L. Johnson, Gen.Supt. of Prod.
35. Brockton Edison Co.
36 Main Street
Brockton, Massachusetts
c/o Mr. John Barry, Prod. Supt.
36. Western Massachusetts Electric Co.
174 Brush Hill Avenue (P.O. Box 10)
West Springfield, Mass.
c/o Mr. M. G. Moses, V.P.
Eng. & Elec. Opr.
37. Yankee Atomic Electric Co.
441 Stuart Street
Boston 16, Massachusetts
c/o Mr. J. F. Kaslow
38. Consumers Power Co.
1945 West Parnell Rd.
Jackson, Michigan
c/o Mr. Robert E. Kettner
Dir. of Nuclear Activities
39. Upper Peninsula Power Co.
616 Shelden Avenue
P. O. Box 246
Margnette, Michigan
c/o Mr. J. E. Zeigler, Supt. of Prod.
40. Detroit Public Lighting Commission
5425 West Jefferson
Detroit, Michigan 48219
c/o Mr. C. R. Kay
41. Montana-Dakota Utilities Co.
831 Second Avenue South
Minneapolis 2, Minn.
c/o Mr. David M. Heskett
Asst. to President
42. Hibbing Public Utilities Commission
19th Street & 6th Avenue E
Hibbing, Minn.
c/o Mr. W. T. Mattson
Results Eng. & Chemist

43. The Central Nebraska Public Power & Irrig. Dist.
Canaday Steam Plant
R.F.D. No. 2, Box 130
Lexington, Nebraska
c/o Mr. Wayne Hickok, Supt.
44. Jersey Central Power & Light Co.
Madison Ave. at Punch Bowl Road
Morristown, New Jersey
c/o Mr. J. E. Logan, V.P.
Engr., Oper. & Gen.
45. Public Service Co. of New Mexico
424 Central Ave., S.W.
P. O. Box 1360
Albuquerque, New Mexico 87107
c/o Mr. M. J. Niese, Sr. Mech. Eng.
46. Plains Electric Generation & Transmission Cooperative, Inc.
2401 Aztec Road N.E.
Albuquerque, New Mexico 87107
c/o Mr. R. T. Armstrong, Asst. Mgr.
47. Long Island Lighting Co.
175 Old Country Road
Hicksville, N.Y.
c/o Mr. W. J. Burns
48. New York State Electric & Gas Corp.
62 Henry Street
Binghamton, New York
c/o Mr. Walter Greacen
3rd Ch. Mech. Eng.
49. Niagara Mohawk Power Corp.
600 Electric Boulevard
Buffalo 3, New York
c/o Mr. J. N. Ewart
Ch. Sys. Proj. Engr.
50. Orange & Rockland Utilities, Inc.
10 North Broadway
Nyack, New York
c/o Mr. C. L. Hulswit, President
51. Duke Power Co.
422 South Church St.
P. O. Box 2178
Charlotte 1, N.C.
c/o Mr. A. C. Thies, Mgr. Steam Prod.
- Mason*
Gordon
9-1-65

52. Cleveland Electric Illuminating Co.
55 Public Square
P. O. Box 5000
Cleveland 1, Ohio
c/o Mr. R. L. Dombey
54. Dayton Power & Light Co.
25 North Main Street
Dayton 1, Ohio
c/o Mr. H. E. Deardorff
V.P., Ch. Eng.
55. Piqua Municipal Power Plant
919 South Main Street
Piqua, Ohio
c.o Mr. Dennis Ziemann
Reactor Supt.
56. Oklahoma Gas & Electric Co
321 North Harvey Avenue
P. O. Box 1498
Oklahoma City 1, Okla.
c/o Mr. R. E. Thornton, Supt., Eng.
57. Eugene Water & Electric Board
500 East 4th Avenue
P. O. Box 1112
Eugene, Oregon
c/o Mr. Byron K. Taylor
58. Saxton Nuclear Experimental Corp.
P. O. Box 99
Saxton, Pennsylvania
c/o Mr. W. H. Layman, Gen. Mgr.
59. Pennsylvania Power & Light Co.
901 Hamilton Street
Allentown, Pa.
c/o Mr. John F. West, Jr.
Atomic Power Eng.
60. Northwestern Public Service Co.
Northwestern National Bank Bldg.
Huron, South Dakota
c/o Mr. O. M. Sundberg
61. Tennessee Valley Authority
Chattanooga, Tennessee 37401
c/o Mr. E. F. Thomas

Moore

Hordon
9-1-68

62. Central Power & Light Co.
120 North Chaparral St. ✓
P. O. Box 2121
Corpus Christi, Texas
c/o Mr. M. H. Lovelady
V.P. & Ch. Eng.
63. Dallas Power & Light Co. ✓
1506 Commerce Street
Dallas, Texas
c/o Mr. L. J. Blaize, V.P.
Eng. & Sys. Operator
64. Southwestern Public Service Co.
3rd & Polk Street
Box 1261
Amarillo, Texas
c/o Mr. J. Alton Miller
Supt. of Prod. & Operation
65. Monongahela Power Co.
1310 Fairmont Avenue
Box 1392
Fairmont, West Va.
c/o Mr. R. H. Pell, Manager
66. Madison Gas & Electric Co.
100 North Fairchild St.
Madison 1, Wisconsin
c/o Mr. C. A. McElmurry
Supt. of Prod.- Electric
67. Wisconsin Electric Power Co.
231 West Michigan Street
Milwaukee 1, Wisconsin
c/o Mr. W. A. Pollock
Tech. Eng. of Power Plants
68. Wisconsin Power & Light Co.
122 West Washington Ave.
Madison 1, Wisconsin
c/o Mr. R. G. Johnson, Power Plant Eng.
69. Puerto Rico Water Resources Authority
P. O. Box 4267
San Juan, Puerto Rico
c/o Mr. A. J. Lizasoain
70. Edmonton Power Plant
104th Street & 95th Avenue
Edmonton, Alberta CANADA
c/o Mr. W. D. Kirkland, Supt.

Gordon Mason
9-1-68

71. The Manitoba Hydro-Electric Board
650 Harrow Street
P. O. Box 815
Winnipeg 1, Manitoba
c/o Mr. A. C. Blue
Mech. Eng. Eng. Division
72. New Brunswick Electric Power Commission
527 King Street
Fredericton, New Brunswick
c/o Mr. G. C. Kileel
Admin. Asst. to Ch. Eng.
73. Newfoundland Light & Power Co., Ltd.
489 Water Street
P. O. 1060
St. John's, Newfoundland
c/o Mr. D. S. Templeton, Op. Supt.
74. Nova Scotia Light & Power Col., Ltd.
357 Barrington Street (P.O. Box 848)
Halifax, Nova Scotia
c/o Mr. J. W. MacDonald
Chief Engineer
75. The Hydro-Electric Power Commission of Ontario
620 University Avenue
Toronto 2, Ontario
c/o Mr. J. L. Alexander
Mech. Maintenance Eng.
80. Southern Indiana Gas and Electric Co
P. O. Box 569
Evansville, Indiana 47703
Attn: A. M. Guy, Chief Mechanical Engineer

CANADA ✓

II - PETROLEUM

1. Phillips Petroleum Co.
Engineering Department
Adams Building
Bartlesville, Okla.
c/o Mr. C. E. Rawlins
2. American Oil Company
Manufacturing Department
2400 New York Avenue
Whiting, Indiana
c.o Mr. G. M. Keranen
Mgr. Gen. Engineering
3. ESSO Research & Engineering Co.
P. O. Box 209
Madison, N.Y. 77187
c/o Mr. James S. Clarke
4. Standard Oil Co. of California
225 Bush Street
San Francisco 4, Calif.
c/o Mr. D. R. Loper
5. Shell Oil Company
50 W. 50th Street
New York, N.Y. 10020
c/o Mr. S. J. Artese
6. Texaco, Incorporated
135 East 42nd Street
New York, N.Y. 10017
c/o Mr. R. E. Nage, Ch.Engr.
Engineering Department
7. Sinclair Refining Co.
410 E. Sibley Boulevard
Harvey, Illinois
c/o Mr. H. C. Kuhn
8. Panhandle Eastern Pipe Line Co.
P. O. Box 1348
Kansas City 41, Missouri
c/o Mr. L. E. Hanna, Ch. Eng.

9. Universal Oil Products Co.
30 Algonquin Road
Des Plaines, Illinois
c/o Mr. M. L. Potter, Met.
10. Standard Oil of Ohio
Midland Building
Cleveland 15, Ohio
c/o Mr. R. G. Gollen

Gordon
9-1-65

Mason

III - CHEMICAL

1. E. I. duPont deNemours & Co.
1007 Market Street
Wilmington 98, Delaware (19898)
c/o Mr. D. B. Wesstrom, Engineering Dept.

Gordon
2-1-65

IV - NAVAL & MARINE

1. Department of the Navy ✓
Bureau of Ships
Code 651F
Washington 25, D.C.
c/o Mr. K. R. Wichman
2. U. S. Coast Guard ✓
Commandant, U.S. Coast Guard Hdqtr.
Washington 25, D.C.
c/o Mr. G. C. Steinman
3. Puget Sound Naval Shipyard ✓
Bremerton, Washington
c/o Mr. James Wessel, Metlgt.
4. NAEL (SI) NAEC
Code SE531
Bldg. 75, Navy Yard ✓
Philadelphia, Pa. 19112
c/o Mr. Vincent P. Zimnoch
5. Admiralty
Ship Department (SEIV/130)
Bath, England
c/o Mr. F. Mathias
6. Mr. A. G. Hogaboom
26 Division Street
Braintree, Mass. 02185
7. Sun Shipbuilding Co.
Chester, Pennsylvania
c/o Mr. Charles L. Dooley
Welding Engineer
8. New York Shipbuilding Co.
P. O. Box 620
Camden 1, N.J.
c/o Mr. Ralph Bradway
Mgr.-Welding Engineering

Mass
London
9-1-68

V - ARCHITECTS-ENGINEERS

1. Ebasco Services, Inc. ✓
2 Rector Street
New York, N.Y. 10006
c/o Mr. J. A. Klapper
2. Bechtel Corporation ✓
101 California Street
San Francisco 4, Calif.
c/o Mr. G. B. Grable
3. Kaiser Engineers —
Nuclear Engineering Dev.
300 Lakeside Drive
Oakland 12, Calif.
c/o Mr. Patric J. Selak, Manager
4. Stearns-Roger Mfg. Co. ✓
Box 5888
Denver, Colorado
c/o Mr. J. Y. Parce, Ch.Eng.
Power Division

Gordon Mess
9-1-65

VI - PIPE FABRICATORS

1. Pittsburgh Pipe & Equip. Co. ✓
158 49th Street
Pittsburgh, Pa.
c/o Mr. Roy W. Emerson, V.P.
2. Grinnell Co., Inc. ✓
Providence 1, R.I.
c/o Mr. H. Thielsch, Mgr.
Industrial Piping Lab
3. Crane Midwest Piping Div. ✓
1450 South 2nd Street
P. O. Box 433
St. Louis 66, Missouri
c/o Mr. R. B. Gurnea
Metallurgist
4. The Babcock & Wilcox Co. ✓
20 van Buren Avenue
Barbeton, Ohio.
c/o Mr. T. F. Kooistra
Chairman PVRC

Mr. Paul Brister
Chg. of Design

Gordon
9-1-68
Mason

VII - PIPE, VALVE, ETC.; MANUFACTURERS

1. Taylor Forge & Pipe Works
4735 West 14th Street
Chicago 50, Illinois
c/o Mr. F. S. G. Williams. V.P.
2. Timken Roller Bearing
Steel & Tube Division
Canton 6, Ohio
c/o Mr. C. L. Clark
3. Tube Turns
Div. of Chemetron Corp.
224 East Broadway
Louisville 1, Kentucky
c/o Mr. M. Mattimore
4. U. S. Pipe & Foundry Co.
Steel & Tubes Division
Burlington, N.J.
c/o Mr. J. D. Lewis, Sales Manager
5. Atwood & Morrill Co.
285 Canal Street
Salem, Mass. 01970
c/o Mr. R. G. Newton
Project Engineer

Handwritten:
Gordon
9-1-65

VIII - INSURANCE

1. Hartford Steam Boiler Inspection & Insurance Co.
56 Prospect Street
Hartford 2, Conn.
c/o Mr. T. R. Hardin
Asst. Vice President

Mr. R. J. Brown

2. The Travelers Insurance Co.
Travelers Indemnity Co.
700 Main Street
Hartford 15, Conn.
c/o Mr. F. W. Catudal, Sup. Eng.
Eng. & Loss Control Division

3. Mutual Boiler & Machinery Insurance Co.
Engineering Department
225 Wyman Street
Waltham 54, Mass.
c/o Mr. C. L. Keene, V.P.

Cardon
9-1-65

IX - MISC., SOCIETIES, UNIVERSITIES, USERS, CONSULTANTS

1. X-Ray Engineering International
420 Market Street
San Francisco 11, Calif.
c/o Mr. W. W. Offner
2. Welding Research Council
347 East 47th Street
New York, N.Y.
c/o Mr. K. H. Koopman
3. I.I.T. Research Institute
10 West 35th Street
Chicago 16, Illinois
c/o Mr. W. N. McElroy
Mgr. Reactor Operations
4. Westinghouse Electric Corp.
Lester Branch Post Office
Philadelphia, Pa. 19113
c/o Mr. J. E. Donahue, Supv. Eng.
5. ~~Dep. Division of Res~~ Research Station
Abington Hall
Cambridge, England
c/o Mr. A. A. Wells
6. Combustion Engineering
1000 Prospect Hill Road
Windsor, Connecticut
c/o Mr. E. M. Powell, V.P. Eng.
7. Southwest Research Institute
8500 Culebra Road
San Antonio 6, Texas
c/o R. D. Wylie
8. Union Carbide Nuclear Co.
P. O. Box Y
Oak Ridge, Tennessee
c/o Mr. W. R. Gall, Chairman
ASA Nuclear Piping Committee

*British Welding Research Association
Deputy Director of Research*

*Gordon Mason
9-1-62*

9. Battelle Memorial Institute
505 King Avenue
Columbus, Ohio 43201
c/o Mr. D. C. Martin
Ch. Metals Joining Div.
10. International Nickel Co.
67 Wall Street
New York, N.Y. 10005
c/o Mr. Marcel A. Cordovi
11. U. K. Atomic Energy Authority
Authority Health & Safety Branch
Safeguards Division
Risley, Warrington
Lanes, UNITED KINGDOM
c/o Mr. Reginald Farmer
12. Huntington Alloy Products Division
International Nickel Co.
Huntington, West Virginia
c/o Mr. C. W. Case
13. General Electric Company
Small Steam Turbine Dept.
166 Broad Street
Fitchburg, Mass.
c/o Mr. H. J. Chase, Mgr-Engrg.
14. Charles T. Main, Inc.
80 Federal Street
Boston, Mass. 02110
c/o Mr. D. L. Glasscock
15. Stanley Engineering Co.
Stanley Building
Muscatine, Iowa
c/o Mr. F. M. Swengel, Head
Power & Industrial Design Group
16. Lloyds Register of Shipping
71, Fenchurch Street
London E.C.3
c/o Mr. B. Hildrew, Prin. Surveyor
for Engrg. Investigation
17. Associated Engineering Insurers
National Buildings
14, St. Mary's Parsonage
Manchester 4, GREAT BRITAIN
c/o Mr. W. D. Goldie, Chairman-
Inspecting Offices
18. J. G. Kerr, Chief Metallurgist
ARAMCO, Box 2588
Dhahran, Saudi Arabia

Gordon
Mason
9-1-68