R.E. STANBRIDGE

MASTER

JAN-781-214

A REVIEW OF
PIPING FAILURE
EXPERIENCE

TECHNICAL REPORT 214

PREPARED FOR

U S ATOMIC ENERGY COMMISSION

CONTRACT NO AT(04-3)-781

BRAUN PROJECT 4122-W

UNITED NUCLEAR PROJECT 2351

RECEIVED

APR 1 1969

LMIC

C F BRAUN & CO

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

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.

C F B R A U N & C O
Engineers

ALHAMBRA CALIFORNIA

March 31, 1969

Mr H B Fry
Contracting Officer, Contract AT(04-3)-781
AEC San Francisco
2111 Bancroft Way
Berkeley, California 95704

BAL-42

Dear Mr Fry

PIPING FAILURE STUDIES
TECHNICAL REPORT 214
LMFBR PIPING DESIGN GUIDE
AEC SAN FRANCISCO
PROJECT 4122-W

Transmitted herewith are two copies of the final report covering studies of piping failures experienced by sodium piping systems and other systems of related characteristics.

The purpose of the study was to tabulate and categorize failure incidents as background experience information to be used in later development of rules and procedures for preventing similar failures.

Comments on the report from reviewers will be welcome, but further revision is not contemplated. The results of the study will be utilized in the preparation of the piping design guide.

Yours very truly

Roger Detman
Project Manager

RFD IV

Project 4122-W
AEC Contract AT(04-3)-781
March 31, 1969

Mr H B Fry

Page 2

CC Director, RDT, HQ
Asst. Director, Project Management, RDT, HQ
Asst. Director, Plant Engineering, RDT, HQ
Asst. Director, Engineering Standards, RDT, HQ
Asst. Director, Reactor Engineering, RDT, HQ
Asst. Director, Reactor Technology, RDT, HQ
Chief, Liquid Metal Projects Br., RDT, HQ
Project Manager, LMEC, RDT, HQ -2
Program Manager, LMFBR, RDT, HQ
Chief, Facilities Br., RDT, HQ
Chief, Components Br., RDT, HQ
Chief, Instrumentation and Control Br., RDT, HQ
Chief, L.M. Systems Br., RDT, HQ
Manager, SAN
Director, LMFBR Program Office (ANL)
RDT Senior Site Representative (AI) -2
Director, LMEC -3
Contract Representative, CP-AEC

United Nuclear Corporation
Dr R J Slember, Project Manager -10

A REVIEW OF
PIPING FAILURE EXPERIENCE

TECHNICAL REPORT 214

—LEGAL NOTICE—

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or 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.

Prepared for US Atomic Energy Commission

Contract No AT (04-3) -781

Braun Project 4122-W

United Nuclear Project 2351

C F BRAUN & CO

Alhambra California

March 28, 1969

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

PREFACE

This Technical Report presents a survey of piping failures reported in the literature, a discussion of the causes identified, and a review of the measures that must be undertaken to prevent their occurrence in LMFBR piping systems.

Although every effort has been made to produce a definitive document, it is recognized that developments under this and other Task Areas of the LMFBR Program Plan may tend to modify its contents from time to time. New experiences with liquid metal systems may reveal potential failure modes and causes not herein identified. This Technical Report is therefore subject to periodic review and revision.

This report is one of a series designed to present the findings of studies made by the authors in the development and verification of a Piping Design Guide for LMFBR sodium piping systems for the US Atomic Energy Commission. The following studies have so far been identified under this task.

TECHNICAL REPORT NO	TITLE	ISSUE DATE
100	The Development and Verification of a Design Guide for LMFBR Sodium Piping	1-24-69
110*	LMFBR System Requirements	10-25-68
210	A Study of Failure Theories as Related to LMFBR Piping Systems	1-31-69
211	Selection of Interim Design Basis for LMFBR Piping Systems	(Aug 1969)
214*	A Review of Piping Failure Experience	3-28-69(F)**
217	A Review of Piping and Pressure Vessel Code Design Criteria	4-4-69 (F)**
220	A Review of Fabrication and Installation Requirements for LMFBR Piping	2-28-69
223	A Study of Heating and Insulation Methods for LMFBR Sodium Piping	2-28-69
228	A Review of LMFBR Piping Materials	(Feb 1969)
231	A Study of LMFBR System Interfaces	3-28-69
234	A Study of Scale Model Testing Methods Applicable to LMFBR Piping Design	(March 1969)
237	A Study of Dynamic Analysis Methods as Related to LMFBR Piping Systems	12-20-68
240	A Study of Instability Analysis Methods as Related to LMFBR Piping Systems	2-13-69
243	A Review of In-service Surveillance Methods Applicable to Liquid Sodium Piping	(April 1969)

* Subject to periodic review and revision

** (F) Date of final issue, all others are for preliminary issue

1

A REVIEW OF
PIPING FAILURE EXPERIENCE

TECHNICAL REPORT 214

CONTENTS

	<u>PAGE</u>
1 INTRODUCTION	1-1
2 GENERAL DISCUSSION	2-1
2.1 APPROACH	2-1
2.2 LITERATURE REVIEW	2-2
2.3 SUPPLEMENTAL SEARCH	2-2
2.4 FAILURE STUDY	2-3
2.5 CONCLUSIONS	2-3
2.6 GENERAL ELECTRIC STUDY	2-3
3 CLASSIFICATION OF FAILURE MECHANISMS	3-1
3.1 LOW-TEMPERATURE BRITTLE CLEAVAGE	3-1
3.2 DUCTILE RUPTURE	3-2
3.3 FATIGUE (MECHANICAL AND/OR THERMAL)	3-2
3.4 EMBRITTLEMENT	3-3
3.5 CREEP STRESS-RUPTURE	3-3
3.6 STRESS-CORROSION CRACKING	3-4
4 CAUSES OF FAILURE	4-1
4.1 MATERIAL SELECTION	4-1
4.1.1 IMPROPER SELECTION	4-1
4.1.2 DESIGN CHANGES	4-1
4.1.3 IMPROPER IDENTIFICATION	4-1
4.2 MANUFACTURING DEFECTS	4-2
4.2.1 BASE MATERIAL DEFECTS	4-2
4.2.2 MATERIAL NOT TO SPECIFICATION	4-2
4.2.3 WELDING	4-2
4.2.4 ASSOCIATED WITH WELDING	4-3
4.2.5 HEAT TREATMENT DEFECTS	4-3
4.2.6 DIMENSIONAL AND GEOMETRICAL DEFECTS	4-4

CONTENTS

	<u>PAGE</u>
4 CAUSES OF FAILURE Continued	
4.3 FABRICATION AND ERECTION	4-4
4.3.1 WELD DEFECTS	4-4
4.3.2 ASSOCIATED WITH WELDING	4-4
4.3.3 DIMENSIONAL & GEOMETRICAL DEFECTS	4-5
4.3.4 ENVIRONMENTAL EFFECTS	4-5
4.4 OPERATIONAL AND SERVICE PROBLEMS	4-5
4.4.1 OVERPRESSURE	4-5
4.4.2 THERMAL STRAIN CYCLING	4-6
4.4.3 MECHANICAL STRAIN CYCLING	4-6
4.4.4 EXCESSIVE LOADING	4-7
4.4.5 OVERHEATING	4-7
4.4.6 CORROSION AND/OR EROSION	4-8
4.4.7 EMBRITTLEMENT	4-9
4.4.8 RADIOACTIVITY	4-9
4.4.9 SYSTEM DISCONTINUITY	4-9
4.5 SPECIAL CONTRIBUTING FACTOR IN SODIUM SYSTEMS	4-10
4.5.1 CORROSION	4-10
4.5.2 THERMAL STRAIN CYCLING	4-11
4.5.3 OVERPRESSURE	4-11
4.5.4 DEFECTS IN BASE MATERIAL AND/OR WELDS	4-11
4.5.5 SHORT CIRCUITING OF ELECTRIC RESISTANCE HEATERS	4-12
4.6 FAILURES DUE TO HUMAN ERROR	4-12
5 APPLICATIONS TO DESIGN GUIDE	5-1
5.1 DESIGN GUIDE OBJECTIVES	5-1
5.2 DESIGN CONSIDERATIONS	5-2
5.2.1 LOW-CYCLE FATIGUE	5-2
5.2.2 HIGH-CYCLE FATIGUE	5-2
5.2.3 INSTRUMENT CONNECTIONS	5-2
5.2.4 PREHEAT SYSTEM	5-2
5.3 MATERIALS	5-3
5.3.1 MATERIAL SELECTION	5-3
5.3.2 MATERIAL IDENTIFICATION	5-3
5.3.3 MATERIAL INSPECTION	5-3
5.4 FABRICATION AND ERECTION	5-3
5.5 IN-SERVICE SURVEILLANCE	5-3
6 CONCLUSIONS AND RECOMMENDATIONS	6-1
7 BIBLIOGRAPHY	7-1
APPENDIX A GE STUDY STATUS REPORT	A-1

1 INTRODUCTION

C F Braun & Co has been awarded a contract⁽¹⁾ by the US Atomic Energy Commission for the development and verification of a Piping Design Guide for sodium-cooled fast breeder reactor power plants (LMFBR). The work is a Priority 1 Task under the LMFBR Program Plan⁽²⁾ prepared for the USAEC Division of Reactor Development and Technology (RDT) by the LMFBR Program Office, Argonne National Laboratory. It is identified in the Program Plan as Task 3-8.2, Development of Design Technology for Piping.

This Technical Report summarizes the findings and conclusions of a study of piping failures. The purpose of the study is to identify the failure mechanisms and potential causes of failure in LMFBR sodium piping systems, as well as the means for preventing them. The information developed will be factored into appropriate chapters of the Piping Design Guide.

It is anticipated that the criteria developed in this Technical Report will be subject to revision and/or expansion as the work progresses. A review procedure has been established to ensure consistency between interdependent studies currently being performed under this and other task areas of the LMFBR Program Plan.

Under the review procedure, the Liquid Metal Engineering Center, (LMEC), is the coordinating agency. Technical Reports prepared by Braun under this contract have been distributed by LMEC to appropriate Review Agencies designated by USAEC. Braun has evaluated the comments from these Agencies and valid ones have been incorporated into this final issue of the reports.

Figure 214-1 shows the interrelationship of tasks under Task Area 3-8, Coolant Transport and Storage Systems.

(1) AT(04-3)-781, AEC San Francisco Operation Office (SAN)

(2) Liquid Metal Fast Breeder Reactor Program Plan, LMFBR Program Office, Argonne National Laboratory - AEC R&D Report, Reactor Technology, WASH-1101, August 1968

FIGURE 214-1 INTERRELATIONSHIP DIAGRAM-TASK AREA 3-8
COOLANT TRANSPORT AND STORAGE SYSTEMS

2 GENERAL DISCUSSION

2.1 APPROACH

The consequences of a catastrophic in-service failure of the primary or secondary coolant loop piping in the LMFBR are such that they cannot be permitted to occur from predictable causes. Even small leaks, of the kind that are merely a nuisance in more conventional plants, can be extremely hazardous in the LMFBR, calling for emergency remedial action.

The study reported in this document has been addressed to the identification of all predictable causes of failure and the means of preventing their occurrence by sound and reasonable engineering procedures. The one exception is expansion bellows. Their failures were not studied as their use will not be permitted in LMFBR piping. This is considered to be an essential step in the development and verification of the LMFBR Piping Design Guide, wherein the appropriate preventive procedures will be prescribed.

The study of piping failures presented in this Technical Report has been accomplished in three stages.

- 1) A review of references *(1) and (2), representing a thorough treatment of piping failures experienced through 1964.
- 2) A search for supplemental information on failures and failure studies conducted from 1964 to the present, particularly those related to liquid metal experience.
- 3) A careful study of all the identified causes of failure, to determine both the likelihood of their occurrence and the feasibility of their prevention in the LMFBR environment.

No attempt has been made to analyze the failure reports statistically. Unless the statistics cover every known failure, and unless the cause of every failure has been established beyond doubt, such statistics can be both inconclusive and misleading. Furthermore, failure patterns tend to change with time, no doubt because increasingly more competent design methods rule out many of the types of failures previously experienced. In recent years, low- and high-cycle fatigue have come in for closer scrutiny, because this type of failure has become more prevalent. This does not mean that fatigue failure is but a recent phenomenon; rather, it suggests only that other, more elementary modes of failure are being dealt with more effectively.

*References are listed numerically in Section 7, Bibliography

2.2 LITERATURE REVIEW

A very considerable effort has been expended in recent years in the analysis of piping failures, and no attempt was made during the present study to duplicate the work already done. The significant contributions of references (1) and (2) have formed the basis of this study, and appropriate acknowledgement must be made here to Helmut Thielsch for his pioneer efforts in this field.

It was the first concern of the present investigators to establish whether other contemporary literature in any way modified the conclusions of Thielsch and his associates in the GE study (2). References (3) through (8) and (21) through (30) were reviewed in this context, but very little was found to shed new light on failure mechanisms.

2.3 SUPPLEMENTAL SEARCH

Several sources have been referenced for supplementary information, particularly that relating to nuclear power plant and liquid metal experience. Here the review has proven more rewarding.

Two prime sources of supplemental information were used - the Liquid Metals Information Center (LMIC), Canoga Park, California; and the Nuclear Safety Information Center (NSIC), Oak Ridge, Tennessee. Both centers responded with abstracts retrieved from their computerized data banks; LMIC came up with 77 references on failures of piping, fittings, and equipment, while the search at NSIC yielded 154 abstracts under the key words, "failure, pipe." Naturally many references were duplicated, and some proved to be of no direct interest to the present study. Those of significant interest are included in the Bibliography.

In addition to the sources revealed by the LMIC and NSIC computers, other references have also been consulted to bring the search for supplemental literature right up to date. These are listed as references (10), (17), (20), (21), (23), (24), (26), (37), (64), (68), (70), and (73).

Requests for published and unpublished information were also sent to operators of sodium systems. The information received has been reviewed and unfortunately found to be of small value due to the laboratory scale dimensions of most systems. However, the valuable information has been taken into account and more replies are expected after this reports issue date. In any event, all present and subsequent conclusions will be again surveyed before the LMFBR Piping Design Guide is prepared in draft form. A further opportunity for review will be afforded when comments on the Design Guide draft are evaluated.

2.4 FAILURE STUDY

The results of the study are summarized in the following three sections of this report. Failure mechanisms identified are given in Section 3; Section 4 lists causes of failure and discusses the likelihood of their occurrence in the LMFBR; and Section 5 describes the actions considered necessary to prevent failures or to minimize their effects.

Although very few failures have been reported for piping in liquid metal service, those that have occurred have proven to be of particular interest. The Dounreay failure (20) dramatically illustrates the acute difficulties associated with even a minor leak, and underscores the necessity for the most rigorous quality assurance procedures at every stage of development of the LMFBR.

2.5 CONCLUSIONS

Conclusions reached from the study are given in Section 6. In summary it may be stated here that most of the identified causes of failure appear capable of prevention in the LMFBR during the design stages. Of the areas that the designer can exercise control over, in only three are real difficulties anticipated - the control of high-cycle fatigue in mixing tees; the development of adequate procedures for predicting low-cycle fatigue life and accumulated strains and ratcheting in components operating in the creep range; and the proper design of attachments (instrument bosses, brackets, etc) to avoid or minimize local effects. Recommendations for pursuing these problems are made in Section 6.

2.6 GENERAL ELECTRIC STUDY

The piping rupture study being conducted by GE for the US Atomic Energy Commission under Contract AT(04-3)-189 is a continuing effort. The current status of the study is summarized in a private communication from Mr L C Hsu, Design Analysis Unit, General Electric Company, San Jose, California to members of the Mechanical Design Committee (MDC) of USAS B31, dated November 11, 1968. The summary is reproduced in Appendix A with permission.

3 CLASSIFICATION OF FAILURE MECHANISMS

Although the cause of many past failures in industrial and power piping systems have defied positive recognition, the mechanisms of failure in most cases have been determined with some degree of certainty. A review reveals that failures are associated with one - and sometimes more than one - of the following mechanisms.

- 1) Low-temperature brittle cleavage
- 2) Ductile fracture
- 3) Fatigue (mechanical and/or thermal)
- 4) Embrittlement
- 5) Creep stress-rupture
- 6) Stress-corrosion cracking

Each of these will be described and discussed in this Section.

3.1 LOW-TEMPERATURE BRITTLE CLEAVAGE

The brittle cleavage phenomenon is in general associated with materials having body-centered cubic and close-packed hexagonal crystal structures, and low temperature environments. Face-centered cubic crystal structures are not subject to this failure mechanism. Austenitic stainless steels have this structure and one of them (Type 304 or 316) may be used for the entire LMFBR sodium piping system. However, 2 1/4 chrome - 1 moly alloy steel is under consideration for some areas. Although this alloy steel is subject to low-temperature brittle cleavage, the design guide will contain provisions to ensure this material is never subjected to an environment that could result in this type of failure. For this reason this failure mode will not be experienced in the LMFBR. The mechanism will be described briefly here so that it may be more readily distinguished from other modes of failure.

In BCC and CPHex materials at low temperatures, brittle cleavage failure will occur at the critical stress. The failure will be abrupt, taking the form of a simultaneous tensile separation between the faces of adjoining planes in the structure, and indicating a complete lack of cohesion or homogeneity. The failure is trans-crystalline.

Low-temperature brittle cleavage failures are often catastrophic in nature. A classic example occurred during World War II with the failure of over 1,000 welded Liberty merchant ships, many of which broke completely in two, some even before they had been put in service (21, 23). Failure usually initiates in a notch defect or sharp stress concentration - in the Liberty ship failures, many were reported to have initiated at the sharp corners of a deck hatch opening.

3.2 DUCTILE RUPTURE

While generally less spectacular than brittle cleavage failures, ductile rupture failures are numerically far more common. The mechanism differs from brittle behavior only in the manner in which "tearing" action (plastic slippage) takes place, the ensuing crack propagating linearly at a relatively slow pace. In piping such a crack will often first be evidenced by a minor leak of the contents, making it possible to repair the break before complete failure ensues.

Abrupt collapses due to ductile rupture have been reported, some of which have had catastrophic consequences (1). In the majority of such cases the failure has been caused by extreme conditions for which the system was never designed. Examples of this are the abrupt bursting of pipes due to upset pressure conditions or by the expansion forces induced by the freezing of an unprotected waterline, or the melting of a center section of a plugged sodium line as discussed in Paragraph 4.5.3.

Since ductile rupture is virtually independent of temperature, its prediction is very difficult. With the implementation of suitable surveillance procedures, detection will be possible in all but the most unusual cases, and a high measure of prevention may be achieved if system operating procedures are faithfully followed.

3.3 FATIGUE (MECHANICAL AND/OR THERMAL)

Material fatigue may emanate from a variety of causes. Although generally resulting from cyclic conditions, it may also follow from sustained primary loads not necessarily of a cyclic nature.

Fatigue failures generally display the characteristic of ductile rupture. The factor which distinguishes a fatigue failure from the mechanisms previously described is that of time. It is convenient to categorize fatigue according to the relative frequency of the applied loading which gives rise to it; low-cycle fatigue, in which the frequency may be as low as unity; and high-cycle fatigue resulting from very high frequencies.

In the low-cycle category are failures resulting from the relatively low frequency of operating cycles from one shutdown to another. Fatigue due to cycling thermal expansion and contraction is typical.

In the high-cycle category are failures associated with severe mechanical vibration, and to extremely rapid fluctuations in fluid temperatures at points local to mixing tees due to turbulent flow conditions. The latter case is aggravated when the merging fluid streams possess high thermal conductivity, as with liquid sodium.

3.3 FATIGUE (MECHANICAL AND/OR THERMAL) Continued

While early warning of low-cycle fatigue can generally be achieved by proper surveillance measures, high-cycle fatigue often eludes detection, and thus presents a difficult engineering problem.

Many of the piping failures reported for liquid sodium service have been attributed to fatigue (see Section 4), and it must therefore be recognized as an area of special concern in the LMFBF.

3.4 EMBRITTLEMENT

Embrittlement can result from many causes ranging from phase changes within the alloy to interaction between the alloy and its environment. Sigma phase formation in stainless steels at elevated temperatures is one example of embrittlement. The effect of absorbed hydrogen on high strength steel is an example of environmental interaction. The only way to avoid embrittlement is to select alloys that are stable under the operating conditions and are not adversely affected by the environment.

3.5 CREEP STRESS-RUPTURE

Under high stress at normal temperatures, most materials exhibit hardening and strengthening as a result of elastic-plastic deformation. As the stress is increased, plastic flow will increase until instability occurs resulting in failure. The stress-strain curve for the material furnishes the data necessary to determine the stress limit for stable control of deformation.

At higher temperatures the shape of the stress-strain curve changes; the elastic range decreases and the slope of the plastic zone flattens. Instability therefore occurs at appreciably lower levels of stress. Above a certain critical temperature no strain hardening is experienced, and the material will deform more-or-less continually under a constant stress. This is the characteristic of creep.

The essential parameters of the creep-resistant properties of steels are stress, temperature, and time. Creep-rupture or stress-rupture tests on specimens at different temperatures will yield families of curves showing the stress-to-rupture times with temperature.

3.5 CREEP STRESS-RUPTURE Continued

Plastic strains in materials operating under cyclic stress conditions at creep range temperatures are not self-reversing, and will consequently accumulate until failure occurs. Where structures are being designed to operate under stress at creep-range temperatures, it is necessary to predict the nonreversing strains and determine the cycle-life history. Analytical procedures to deal with this problem are under development. Since the LMFBR coolant loop piping will be operating at creep temperatures, these procedures will have to be implemented in the LMFBR Piping Design Guide.

3.6 STRESS-CORROSION CRACKING

The mechanism of stress-corrosion failure is a complex one in which mechanical and chemical actions combine to produce effects more severe than either one alone. Small cracks on the surface of the material, produced by cold-working or by residual welding stresses, will tend to propagate rapidly when subjected to prolonged static stresses in the presence of a corrosive medium. Under cyclic loading conditions, stress-corrosion fatigue is possible.

Detection is often difficult until propagation is well advanced, and a great many failures have been reported due to this phenomenon (1, 9, 10, 21). In liquid sodium systems, however, experience has been good with Type 304 stainless, and generally proper material selection is the first line of defense.

4 CAUSES OF FAILURE

It will be the purpose of this Section to identify all the predictable causes of failure in piping systems, whether they have been contributory to past failure experience or not. Adequate corrective measures will also be summarized. It should be pointed out that in some instances the contributory conditions will not exist in the LMFBF environment, or their likelihood is extremely remote.

4.1 MATERIAL SELECTION

Failures in this general category have in the past been associated with (a) improper initial selection, (b) failure to be cognizant of changes in environmental conditions subsequent to initial selection, (c) improper material identification, and (d) carelessness on the part of the fabricator. All of these imply errors in human judgment and can be avoided entirely with the implementation of thorough procedures in communication and inspection.

4.1.1 IMPROPER SELECTION If the wrong material is initially selected and goes unchallenged, no subsequent inspections will correct the error - indeed, they will only serve to perpetuate it. Rigid procedures are therefore necessary to ensure that the initial selection is correct. In large industrial complexes where many different materials are being used, errors of this type are perhaps understandable, although still unexcusable. For the LMFBF sodium piping, final selection will be narrowed down to a very small and exclusive group of candidate materials, making errors unlikely. Nevertheless, emphasis must be placed in the LMFBF Piping Design Guide on ensuring proper initial material selection for all piping components.

4.1.2 DESIGN CHANGES It sometimes happens that, due to a breakdown in internal communications, changes made in design criteria subsequent to initial material selection are not passed on to the individuals responsible for material specifications. Here again, adequate procedures can prevent this occurrence.

4.1.3 IMPROPER IDENTIFICATION Reference (54) cites a case where improper material identification was the primary cause of failure in a superheater piping fitting. In this instance the mill product bore an incorrect material identification stamp. Thielsch (1) refers to several other similar cases. Such errors are intolerable in the LMFBF, making positive material identification mandatory for every individual run of pipe, and every fitting. The use of spectrography (2) is recommended to each major step in manufacture, fabrication, and erection.

4.2 MANUFACTURING DEFECTS

4.2.1 BASE MATERIAL DEFECTS The base metal is subject to a wide range of manufacturing defects. Forged or wrought items can have slag or impurity inclusions on their surface or internally, resulting in slivers, scabs, laminations, or seams. The forming operations can leave cracks, gouges, tool marks, and surface laps.

Cast items can also suffer from slag or sand inclusions and are more susceptible than wrought materials to internal voids due to gas pockets. In addition castings are subject to shrinkage voids, segregation, cracking, and occasionally a chaplet or core support will not fuse into the casting (1). Due to their many inherent weaknesses, castings may not be used in the LMFBR sodium piping systems.

Failures from base metal defects such as the cracked tubes mentioned in Reference (40) will have to be eliminated by a rigorous inspection and testing program for all LMFBR materials at every stage from manufacture to final acceptance.

4.2.2 MATERIAL NOT TO SPECIFICATION Material not furnished to specification can create failures in many ways, whether the material is the wrong specification, or fails to meet one of the many chemical, physical, or geometrical requirements of the specification.

Failures can cover the full range of metallurgical problems from those related to material misapplication to heat treatment and corrosion related types (31, 55).

Thorough inspection of the material on receipt from the mill, including the employment of spectrography, will do much to eliminate these problems, as discussed in 4.1.3.

4.2.3 WELDING There is extensive literature on weld defects and failures, covering both historical and theoretical considerations. There are so many types that it is beyond the scope of this report to cover them all and their usual causes. Thielsch (1) identifies many of them, including arc strikes, burn through, centerline crevices, cracks of many types, crater pits, mismatch, incomplete fusion, lack of penetration, overlap, oxidation, porosity, sink or concavity, slag inclusions, slugging, undercut, weld reinforcement, and others. Reference (39) discusses some incomplete fusion failures and (57) describes a line failure partially due to an arc strike.

4.2.3 WELDING Continued

It is sufficient to say that the use of the best qualified welders, welding equipment, weld procedures, and an extremely thorough testing and inspection procedure will be necessary to keep these problems to a minimum. And for the LMFBR system the establishment of what will be the minimum defects allowed will be an important area for development.

4.2.4 ASSOCIATED WITH WELDING Defects associated with welding, but not due to the weld itself, have two main causes. These are poor fit-up and poor end preparation.

Poor fit-up can occur with or without backing rings and often takes the forms of wall mismatch, improper or uneven root gap or misalignment. These often result in notch type stress risers and cracks or poor penetration into the pipe or backing ring. So many of these defects are associated with backing rings that their use should not be permitted in the LMFBR.

The angle and shape of the bevels on butt weld ends is also quite important and if improperly done can result in poor penetration, burn through, or other fusion zone defects.

The establishment of suitable weld profile geometries, together with rigorous inspection and checking, will be the main prevention of this type of defect and must be given careful attention in the development of the LMFBR Piping Design Guide.

4.2.5 HEAT TREATMENT DEFECTS Heat treatment can cause problems if not done correctly, if it is not proper for the material or application, or if it is simply not done. It is summed up very well in Reference (1).

"Among the failures ascribed to improper heat treatment are:

- 1) excessive hardness differences
- 2) variations in metallurgical structures
- 3) localized stresses
- 4) surface defects
- 5) high transition temperature
- 6) reduced creep strength

Consideration of the proper heat treatment, and the consequences of failures when heat treatments have not been properly done, or have been eliminated, covers the whole thermal history of a pressure vessel or piping component. It includes preheat as well as postheat treatments."

4.2.5 HEAT TREATMENT DEFECTS Continued

Time versus temperature curves must be obtained and checked for all heat treatments, and the heating method verified for its appropriateness to avoid these failures.

4.2.6 DIMENSIONAL AND GEOMETRICAL DEFECTS Defects such as lack of straightness, out-of-roundness or ovality, corrugations, and wall thinning can result from manufacturing processes. As they are relatively easily identified, it is unusual for them to be the source of failures. However, these defects may assume much greater significance in LMFBR piping, much of which may be expected to have larger D/t ratios than in present nuclear systems. A task in the development of the LMFBR Piping Design Guide will be the establishment of appropriate dimensional and geometrical tolerances which may well prove more demanding than those in general acceptance at present.

4.3 FABRICATION AND ERECTION

4.3.1 WELD DEFECTS All the weld defects that can occur in the manufacture of piping materials (4.2.3) can also occur during the fabrication and erection of piping systems. However, good erection welding can be much more difficult to accomplish due to field conditions and to the fact that welds are being made on large, continuous systems. Difficulties are inherent in the immobility of the large sections to be joined, coupled with the necessity for maintaining close dimensional tolerances. Space and other limitations may make it impossible to rotate the work during welding, causing the welder often to work in awkward and cramped positions.

Inert gas welding is considered mandatory for LMFBR piping, and purge gas control may prove to be a problem due to environmental factors. In large pipe sizes it may be undesirable or impractical to purge the entire system internally, and recourse must then be made to dams or plugs, which may in turn give rise to purge gas contamination.

Not only will defective welding be more likely to occur in the field, but they may be harder to detect due to limited or difficult access to the welds when using portable inspection equipment.

All of the foregoing considerations point up the necessity for formulating stringent welding procedures and quality control methods, enforceable with equal assurance both in the fabrication shop and in the field.

4.3.2 ASSOCIATED WITH WELDING The defects discussed in 4.2.4 will also occur in association with fabrication and erection welds, and, as was pointed out for welding defects in 4.3.1, they may be expected to be more prevalent under field conditions, and will be harder to detect. Fit-up, too, will be more difficult to achieve.

4.3.3 DIMENSIONAL AND GEOMETRICAL DEFECTS Even if the defects noted in 4.2.6 are all satisfactorily avoided in the piping during manufacture, it must still be shipped, stored and handled with great care to avoid creating new flat spots, ovality, bending, and other damage.

Fabrication and erection can then create the additional problems of overlooked cold springing, excessive loading by misplaced or ineffective supports, and excessive stresses due to incorrect, ineffective, or nonexistent thermal expansion anchors, guides, and other engineered restraints.

In only one of the reported failures in sodium systems was the primary cause blamed on faulty fabrication and erection procedures. This failure occurred in one of the primary coolant loops of the Dounreay Fast Reactor (DFR), at the joint between a NaK outlet line and the lip of a thermocouple block (20). The factors contributing to the failure were misalignment, a poor quality weld (4.3.1) and a high thermal stress due to a rather sharp temperature gradient.

It was conjectured that if any one of these factors had been absent, the failure would not have occurred. (In Reference (20) it was mentioned that the failure was detected at the junction of a thin walled pipe and a substantially heavier thermocouple block. Although not mentioned in the literature, discontinuity stresses would result at the crack location because of the restraining effect of the block upon the pipe).

4.3.4 ENVIRONMENTAL EFFECTS During storage and often after installation, steps must be taken to protect piping from hostile environments. This will be a problem for any LMFBR which is located near an ocean, as many will be for a source of cooling water or a heat sink. The large amounts of stainless steel used at such locations must be carefully protected against chloride corrosion from the marine atmosphere. A recent report (76) tells of leaks in fill and dump lines at Dounreay due to external pitting of unprotected austenitic material which was often wetted by moisture-laden air from the sea.

4.4 OPERATIONAL AND SERVICE PROBLEMS

4.4.1 OVERPRESSURE A common source of overpressure failure is the blocking in of an unrelieved liquid-filled line when the fluid is subject to expansion. This is especially true of sodium systems because of the high coefficient of expansion of sodium and its high melting point. Care must be exercised in preheat operations to ensure that the melting of resident frozen sodium is carried out sequentially from a free surface to avoid the problem discussed in Paragraph 4.5.3.

4.4.1 OVERPRESSURE Continued

Valve misoperation and faulty equipment operation are other sources of overpressure. Water hammer and sodium hammer can result from the too-rapid opening or closing of block valves in the system.

4.4.2 THERMAL STRAIN CYCLING Thermal fatigue has long been recognized as a problem in piping systems (22), and has been associated with a wide variety of contributing conditions. Low-cycle fatigue failures are usually caused by severe cyclic operational conditions (67), while high-cycle fatigue is more likely to be attributed to rapid fluctuations in fluid temperatures at points in the vicinity of the confluence of two streams having sharply different temperatures. Mixing tees in sodium systems must be considered highly susceptible to the latter mechanism.

Incipient failures were reported in two mixing tees in the 2000 Kw sodium test facility at Los Alamos Scientific Laboratory (8). Mixing of sodium streams at different temperatures had occurred continuously during operation of this loop. High frequency flow oscillations during the mixing of the hot and cold streams led to rapid temperature fluctuations at the downstream surfaces. This resulted in high-cycle strain which was the probable cause of the many surface cracks. The major crack in one of these tees had propagated through 75 percent of the wall thickness after 9,500 hours of operation. Continued operation undoubtedly would have produced rupture. On the other tee the major crack had propagated only through 12 percent of the wall thickness in the same time period.

Another incipient failure was found in a mixing tee on a Forced Convection loop operated by United Nuclear Corporation. Two cracks had penetrated about 12 percent of the wall thickness after 2,000 hours of operation.

In all three of these mixing tee cases, significant cracks were found in the outlet of the tee where the majority of mixing occurred.

A complete fracture was experienced in the loop operated by United Nuclear Corporation in a tee which connects the 800 F surge tank to the 1600 F main circuit. Here again it was established that fluctuating temperature conditions existed and were the primary cause of failure. Other contributing factors were thermal strains and mechanical loads. Machine grooves introduced during fabrication were a source of stress concentration which no doubt accelerated the propagation of the crack.

4.4.3 MECHANICAL STRAIN CYCLING Fatigue failures similar to those from thermal strain cycling have occurred in systems subject to repeated mechanical loads such as vibration. References (38), (65), and (66) discuss some typical vibration failures.

4.4.3 MECHANICAL STRAIN CYCLING Continued

Sources of mechanical strain cycling are given by Thielsch (1) as,

- 1) Pressure cycling
- 2) Variations in flow
- 3) System changes
- 4) External factors

By "system changes", Thielsch is referring to fluctuating thermal expansion forces acting, for example, on a vessel nozzle or on a piping branch connection or tee. External factors include vibrations induced by reciprocating machinery and other similar excitations.

Mechanical fatigue is basically a system design problem and has to be minimized by the isolation or reduction of equipment vibrations, careful pressure reduction valve design, designing the piping layout for optimum flow conditions, and in designing for the expected thermal expansions.

4.4.4 EXCESSIVE LOADING Failures due to excessive primary or secondary loads - ie, in excess of those for which the system was initially designed - are relatively rare, and are caused by oversight in plant layout and piping design, or by system misoperation or malfunction. Inadequate pipe support design will result in high primary stresses; and the omission of measures to take care of thermal expansion will cause excessive secondary stresses. A sodium heater tube failure has been reported (15) that was attributed to improperly applied insulation which in turn fouled an obstruction and restricted free thermal expansion growth.

A failure occurred in a sodium system connecting pipe near a point where a drainage pipe was welded to an expansion piece of the main piping (19). Detailed inspection showed a through crack had developed and extended half way around the pipe. The cause of failure was attributed to inadequate freedom of movement of the drainage piping.

This failure indicated the importance of a careful and thoughtful stress analysis program combined with a detailed consideration of how all thermal expansion will be accounted for. Specific rules for countering these problems must be spelled out in the Piping Design Guide.

4.4.5 OVERHEATING Although many failures have arisen from internal overheating, most have been due to external heating in boilers, heaters, and heat exchanger tubes. Failures due to overheating in external piping are rare and are usually due to equipment failure or a higher process temperature than was originally specified, resulting in a material breakdown.

4.4.5 OVERHEATING Continued

The provisions for preheating the LMFBR sodium piping must be designed to minimize or eliminate the possibility of overheating the piping material or creating harmful temperature gradients by nonuniform heating. Proper material selection, and careful operation, will do much to avoid failures.

4.4.6 CORROSION AND/OR EROSION Corrosion and/or erosion was the most frequent cause of failure found in the GE survey (2), arising from a great variety of causes.

The more common types of corrosion failures associated primarily with service conditions are given by Thielsch (1) as,

- 1) general corrosion
- 2) galvanic corrosion
- 3) corrosion pitting
- 4) intergranular corrosion
- 5) knife-line corrosion
- 6) crevice corrosion
- 7) stress-corrosion cracking and corrosion fatigue
- 8) stress-enhanced corrosion
- 9) erosion
- 10) exfoliation
- 11) corrosion by soil or insulation
- 12) scaling and oxidation

There have been many sodium system failures due to corrosion and this will be another major area of concern to the Design Guide.

A failure was reported in a thermocouple well on the 2000 Kw sodium test facility at Los Alamos Scientific Laboratory (8). The well was severely cracked on the inner and outer surfaces besides containing a complete rupture at one location. The primary cause of failure was attributed to the intercrystalline corrosion due to carbide precipitation at the grain boundaries. It was concluded that high residual stresses accelerated the propagation of cracks and the rupture occurred at the location of an undetected flaw.

A second failure attributed primarily to corrosion was experienced in the dump line of the Dounreay Fast Reactor system (18). The corrosion mechanism was envisioned as proceeding along grain boundaries as precipitates formed and ultimately penetrating the pipewall intergranularly. It was surmized that grain boundary precipitation was caused by operating the tube at temperatures in excess of 650 C for long periods of time.

4.4.6 CORROSION AND/OR EROSION Continued

It was established that sodium oxide was an important constituent in the corrosive mechanism. It was postulated that the presence of the liquid metal in the line was due to incomplete drainage. The sodium in the residue of NaK reacted with the oxygen in the air that had also leaked into the pipe. (Although not mentioned in Reference 18, moisture in the air could have reacted with the sodium to form hydroxides which could have then contributed to the corrosion). The stress-corrosion cracking of a sodium expansion tank at Hallam is discussed in (9) and (11).

Nonsodium nuclear piping system failures due to stress-corrosion cracking are discussed in (25), (59), and (71).

4.4.7 EMBRITTLEMENT Embrittlement from service conditions has resulted in many severe failures. It can arise from many sources, the most common being the graphitization of steel from excessively high temperature operation, (1)(2), the use of material below its transition temperature, and the use of materials in an atmosphere which results in hydrogen embrittlement. Other sources are the high temperature formation of sigma phase in some stainless steels and the effects of neutron irradiation (1).

4.4.8 RADIOACTIVITY No failures have so far been identified as having been associated with radioactivity. Gamma heating is recognized as a possible cause of trouble, but there is insufficient information on this subject at present to discuss it as a potential cause of failure. The primary system sodium piping is not expected to be subjected to a fast neutron flux for a long enough time to cause embrittlement from this source.

4.4.9 SYSTEM DISCONTINUITIES Many of the failures reported for liquid sodium systems have occurred in the vicinity of gross geometric discontinuities (8, 18, 19, 20). Abrupt changes in pipewall profile, such as are encountered in branch connections, instrument connections, and external attachments for pipesupports, anchors and guides, give rise to sharp local stress intensification. The condition is aggravated by the presence of defects in welds or those caused by cutting and machining operations. Careful design of the component is necessary to reduce the effects of stress raisers, by ensuring a smooth profile transition.

Standard component geometries, in which these factors have been minimized, will be developed for the LMFBR Piping Design Guide in a separate task under this contract.

4.5 SPECIAL CONTRIBUTING FACTORS IN SODIUM SYSTEMS

In describing the failures associated with sodium systems in Items 4.1 through 4.4, it is apparent that there are factors contributing to these failures which are special to or greatly aggravated in sodium systems. In addition, there are factors which have not yet induced a failure but which must be considered as a possible cause of failure.

4.5.1 CORROSION Basic mechanisms in corrosion of solids in liquid metals are solution attack and impurity reactions. These, together with temperature and material differences cause mass transfer in sodium systems. These mechanisms can cause deleterious effects by surface removal, surface deposits and changes in composition of the base material, as depicted in the following diagram (10).

Surface removal causes thinning of structural members with a resultant loss in load carrying capability. In the design of piping systems, this is conventionally covered by a "corrosion allowance."

Mass transferred surface deposits can affect pressure drops in small diameter lines. In a primary system, they can greatly increase radiation levels around the pipe.

Changes in material composition such as decarburization of ferritic steels reduce the strength of the base material. Carburization of austenitic material produces a hard surface with less ductility than the base material making it more susceptible to cyclic fatigue failure.

4.5.1 CORROSION Continued

Surfaces of stainless steels can be depleted of nickel, chromium and manganese. This affects the strength properties of the surface material, making a pipe more susceptible to failure.

Impurities in the sodium, especially interstitial oxygen, carbon, hydrogen, and nitrogen, play an important role in sodium corrosion processes. Maximum impurity levels must be specified and maintained to prevent excessive corrosion (4, 10).

4.5.2 THERMAL STRAIN CYCLING Temperature cycling and/or fluctuations are more severe in sodium systems than in water or steam systems because of the excellent heat conduction between the sodium and pipe and the generally applicable larger temperature differences between hot and cold legs. With sodium, there are no thermal boundary layers which insulate the pipe from rapidly changing temperature in the bulk stream. Thermal shock is also more severe because the rate of change of sodium temperature is more rapid than the rate of change of steam and water temperatures.

As discussed under Item 4.4.2 thermal strain cycling has been a contributing factor in many of the reported failures in sodium piping systems.

4.5.3 OVERPRESSURE Upon melting of solidified sodium in a system, there is always the danger of melting some sodium between solid plugs of sodium. Because of volumetric expansion of the sodium during melting, this can result in overpressure and possibly rupture the pipe. Such a failure has been experienced in the secondary system of Rapsodie (12) and with a small laboratory rig at the University of Michigan (17).

4.5.4 DEFECTS IN BASE MATERIAL AND/OR WELDS Much of the early failure experience with sodium systems has not been documented in the open literature. However, it is well known that material and/or weld defects such as voids, pinholes and inclusions were the cause of many failures.

Defects are undesirable in any piping system, but are of particular concern to LMFBR coolant systems. The piping must give the maximum reliability since it will be at high levels of stress and temperature while carrying highly reactive sodium. Sodium will react with inclusions, substances found in voids and air in pinholes, to form corrosive compounds. These will enlarge the original defect, and combined with stress concentrations at the defect, will lead to failures.

4.5.4 DEFECTS IN BASE MATERIAL AND/OR WELDS Continued

For these reasons it has become accepted practice to:

- 1) Radiograph all welds and reject those which show excessive voids or inclusions.
- 2) Perform helium mass spectrometer leak tests and eliminate any indications of a leak.
- 3) Perform ultrasonic and eddy current inspections for critical applications.

For these same reasons, castings and mechanical pipe joints are to be avoided.

A combination of weld defects, poor weld design, and large thermal stresses is the probable cause for failures which have occurred with instrument connections, such as thimbles for level gages (19) and thermocouple wells (8, 20).

4.5.5 SHORT CIRCUITING OF ELECTRIC RESISTANCE HEATERS

Many unreported failures were caused by a short circuiting arc between an electric resistance heater and a pipe. A typical example is given in Reference (19). These failures generally occurred in systems in which the heater wire is spaced from the pipe by electric insulators. They can be avoided by the use of grounded sheathed heaters or by a device which locates and disconnects the damaged portion of the heating circuit before it causes pipe burnout (19).

4.6 FAILURES DUE TO HUMAN ERROR

Most of the causes of failure discussed in the foregoing sections can be eliminated or minimized by taking appropriate preventive measures. These measures include proper design analysis, adequate material specifications and fabrication and erection procedures, thorough inspection and testing requirements, and other quality assurance and surveillance measures, all of which must be fully spelled out in the Piping Design Guide. The intent of these measures, however, can be frustrated if they are not conscientiously followed.

The Piping Design Guide must ensure the faithful implementation of its provisions, by requiring the independent review of all design analysis stress reports, procedures and specification documents.

Although the Piping Design Guide will not discuss the prevention of errors in plant operation, it must anticipate the consequences of plant misoperation and provide such safeguards as are practicable in initial plant design.

5 APPLICATION TO DESIGN GUIDE

5.1 DESIGN GUIDE OBJECTIVES

Existing Power Piping Codes have proven themselves to be entirely adequate for assuring the safe design of piping for the types of installation for which they were written. Responding to the GE failure study questionnaire in 1964, an insurance company spokesman has stated (Page 3-8 of Reference 2),

"We would say, based on our experience, piping systems built to the requirements of Section I of the ASME Code and the ASA Piping Code* have a high degree of reliability. We have had no serious or catastrophic pipe failures."

Although written specifically for fossil-fuel power plants, most of the existing water-cooled thermal reactor plants in the US were built to USAS B31.1, their designers being obliged to augment these rules to meet the more exacting demands of a nuclear plant, and the need has been recognized for a more stringent set of rules for nuclear power piping. A draft of the new USASI Code for Nuclear Power Piping, USAS B31.7, has now been released for trial use and comment. No experience has yet been reported: indeed, it will be several years before its reliability can be established with certainty. Representing a significant advance in technological procedures, it appears reasonable to conclude that the new Code will offer assurance of greater reliability over its Section I predecessors.

With the advent of the LMFBR Program, the following question now poses itself: Do the terms of USAS B31.7 meet in any respect the special needs of the LMFBR environment? The study summarized in this Technical Report, and the finding of other studies currently being made under this and other Task Areas of the LMFBR Program Plan will, no doubt, supply at least part of the answer; some indications are beginning to emerge, however, that suggests the answer will be that in some respects USAS B31.7 does meet the needs of the LMFBR environment.

The failures experienced to date in liquid sodium piping systems, and reported herein, have often been associated with low-cycle and high-cycle fatigue, due at least in part to the unusually severe thermal transients to which these systems are subjected. The high thermal conductivity of liquid sodium greatly aggravates this problem. Furthermore, LMFBR sodium systems will operate at creep-range temperatures with the attendant problems of creep strain cycling and the ratchetting phenomenon. In this area at least, the present investigators do not feel the rules of USAS B31.7 are entirely adequate, based upon admittedly meager experience.

*Now USASI Code for Power Piping, USAS B31.1

5.1 DESIGN GUIDE OBJECTIVES Continued

Much further study will be needed before this tentative conclusion can be substantiated, or proved wrong.

Meanwhile, liquid metal piping systems for the LMFBR must be designed with absolute integrity, and this effort must go ahead immediately if the goals of the LMFBR Program Plan are to be met on schedule. The LMFBR Piping Design Guide might well parallel the rules of the USASI Nuclear Power Piping Code in many areas; but development of the Guide must be predicated first and foremost upon the special needs of the LMFBR. The study reported here has brought some of these special needs to light.

5.2 DESIGN CONSIDERATIONS

5.2.1 LOW-CYCLE FATIGUE The procedures outlined in USAS B31.7 for determining the cycle life of piping systems are not considered adequate for LMFBR sodium piping systems. Based on the assumption only of elastic or elastic-plastic behavior, they do not properly account for creep or cumulative plastic strain ratchetting. Work on this problem is currently being conducted in a separate study under this contract, and will be the subject of a Technical Report to be issued later.

5.2.2 HIGH-CYCLE FATIGUE Failures in liquid sodium mixing tees are attributed primarily to high-cycle fatigue. Special consideration must be given to the design of mixing tees, and a solution found that minimizes the effects of temperature fluctuations downstream of the mixing zone. The use of thermal barriers must be explored further, and alternative designs evaluated.

5.2.3 INSTRUMENT CONNECTIONS Small yet relatively heavy-walled connections for instrumentation impose a severe local restraint on piping, and have been the seat of failures in sodium systems (20) (see also 4.3.3). Consideration of this problem must be given in the development of the Piping Design Guide. Standard geometries must be designed to minimize discontinuity stress concentrations.

5.2.4 PREHEAT SYSTEM Misoperation of preheat systems is identified as a cause of overpressure (4.4.1). Segmentation of the preheat system must be specified, to permit sequential heating of frozen sodium from the free surface.

5.3 MATERIALS

5.3.1 MATERIAL SELECTION Emphasis cannot be too strongly placed upon the necessity for maintaining surveillance over material properties at every significant stage from the mill to final plant acceptance. Chemical and physical properties must be established, followed by procedures to ensure their integrity. Material properties are the subject of a separate study of this contract, and the findings will be published as a Technical Report, to be issued later.

Careful attention must also be given to the selection of materials, such as cleaning and pressure testing fluids, which will come into contact with the piping materials. Fluids whose residue could be harmful to the piping or could react with or contaminate sodium must be completely removed after their use.

5.3.2 MATERIAL IDENTIFICATION Design Guide procedures must be developed to ensure proper and permanent identification of materials. The use of spectrography is considered mandatory, and suitable provision for it should be included in the Design Guide.

5.3.3 MATERIAL INSPECTION Besides the surveillance of material properties mentioned above, inspection procedures that ensure maintainance of geometric tolerances must be developed, together with the establishment of what tolerances shall be considered satisfactory. It is recognized that present procedures may prove inadequate for the large sizes of pipe (up to 48-inch) envisioned for the LMFBR. For high D/t ratios, determination of circularity is difficult to achieve due to a tendency for the pipe to ovalize from its own weight.

5.4 FABRICATION AND ERECTION

The wealth of information on weld failures, together with the problems identified in 4.2.3, 4.2.4, 4.3.1, and 4.3.2, point up the necessity for making this an area of special concern in the LMFBR Piping Design Guide. Further study of every aspect of welding and weld quality control will be undertaken under this contract before any attempt is made to formulate appropriate rules.

5.5 IN-SERVICE SURVEILLANCE

Many of the failures reported in the literature studied might have been avoided - or at least detected before failure ensued - if adequate in-service surveillance methods had been in operation. The consequences of failure in the LMFBR are such that in-service surveillance becomes mandatory. Here again, further study will be required before reliable methods can be identified and factored into the Piping Design Guide. This study of in-service surveillance will result in the publication of a separate technical report under this contract.

6 CONCLUSIONS AND RECOMMENDATIONS

For the reasons given in Section 2, no attempt has been made to analyze the failures reviewed in this report on a statistical basis. It has been our purpose here to identify all the causes of failure in pipe and pipe fittings that potentially could be experienced in an LMFBF piping system, and more importantly, to discuss the means of preventing them. Since the emphasis is upon prevention, it has been considered relatively of little importance to this study whether a particular type of failure has been experienced frequently or only seldom.

Some caution is therefore necessary in drawing conclusions from this report. There has been very little experience of failures in nuclear plants, and even less in liquid metal systems. The great majority of piping failures in such systems have been related to components with which the LMFBF Piping Design Guide will not be directly concerned, and for this reason have not been given the same close scrutiny as has been directed towards failure in pipe fittings and welds. The reader should not infer from this that those failures that have been reported in nuclear and liquid metal service are considered to be insignificant; on the contrary, their importance cannot be overemphasized.

There are indications which appear to justify some cautious optimism with regard to the elimination of potential failures in LMFBF sodium piping systems, although some reservations must be expressed. While the technology exists to ensure adequate initial design, and enough is known about fabrication and erection procedures and welding techniques to ensure a safe and reliable piping structure, reliance has to be placed very heavily upon the integrity with which these activities are carried out. It is here that the LMFBF Piping Design Guide must play a vital role. Not only must it specify design, fabrication, installation and testing procedures reflecting the very best proven technology in all of these fields, but it must also spell out, in unequivocal language, what measures must be undertaken to guarantee their faithful implementation.

In reviewing the types of failure discussed in this report in the light of the characteristics of the LMFBF, it is possible to conjecture upon the type of failure that potentially presents the greatest likelihood of occurrence in LMFBF piping systems. Such a failure would probably be located in the primary or secondary loop at a weld, or in the heat-affected zone adjacent to a weld, in the presence of a notch defect or gross geometric discontinuity. The primary cause of failure would probably be low-cycle thermal fatigue or creep strain ratcheting, with high-cycle thermal fatigue a possible factor. It is therefore recommended that the effect of these mechanisms upon the life of weld joints be the subject of a thorough research and testing program.

6 CONCLUSIONS AND RECOMMENDATIONS Continued

It is further recommended that additional study and development be carried out in the following areas.

- 1) Develop procedures for predicting cumulative creep strains and ratcheting in pipe and fittings.
- 2) Develop mixing tee geometries to minimize the effects of high-cycle thermal action on the pressure-containing pipewall.
- 3) Develop piping component geometries and establish maximum geometric tolerances for manufacture, fabrication and erection.
- 4) Study, develop and select in-service surveillance methods, including leak detection methods and strain-measuring.
- 5) Determine the candidate materials minimum allowable physical and chemical properties.
- 6) Study the effects of low and high cycle thermal fatigue and creep strain ratcheting upon weld joint life.

All of these tasks except the last are currently planned as part of the development and verification of the LMFBR Piping Design Guide. In addition, much reliance must be placed upon the results of other studies presently under way, or planned, under the LMFBR Program Plan. A free interchange of knowledge and experience between all the participants is essential to the progress and the achievement of the goals of the program.

7 BIBLIOGRAPHY

- 1 Thielsch, H Defects and Failures in Pressure Vessels and Piping, Reinhold Publishing Corp, New York, 1965
- 2 Gibbons W S, and Hackney B D Survey of Piping Failures for the Reactor Primary Coolant Pipe Rupture Study, General Electric Co, San Jose, GEAP-4574, May 1964
- 3 Baldwin, E E Investigation of Alplaus Atmospheric Pressure Sodium Still, Knolls Atomic Power Lab, General Electric Co, KAPL-337, July 1950
- 4 Ward, A G, Taylor, J W Metallurgical Investigations of Sodium Heat Transfer Rig, Atomic Energy Research Establishment, AERE R and R 2190, Page 15, August 1957
- 5 Cottrell, W B Aircraft Nuclear Propulsion Project Quarterly Progress Report for Period Ending December 10, 1952, Oak Ridge National Lab, ORNL-1439, January 15, 1959
- 6 Sutherland, C Tests of AN-Type Tube Couplings, Atomics International Division of NAA, NAA-SR-MEMO-4772, December 18, 1959
- 7 Atsumo, H Corrosion in Stainless Steel Pipes due to Sodium System Liquid Metals, Hitachi Manufacturing, NP-TR-1228, 1962
- 8 Bowers, H I, Ferguson, W E Structural Materials in LASL Liquid Sodium Systems, California University, Los Alamos Scientific Lab, LADC-5783, 1963
- 9 Wagner, R K, Stearns, J D Evaluation of Non-Fuel Material Behavior in HNPR, Proceedings of Sodium Components Development Program Information Meetings, Chicago, June 1965, Atomic Energy Commission, CONF-650620, Page 47, 1965
- 10 Goldman, K and Meniskin, B Sodium Technology, Reactor Technology Selected Review 1965
- 11 Landler, G HNPF-Stress Corrosion Study, Atomics International Division of NAA, NAA-SR-MEMO-11607, August 30, 1965
- 12 Bussy P, Denielou G, Gajac G, Guillet H, Labat P, Pontier R, Rozenholc M, Vautrey L, and Zaleski P Rapsodie Development Program from Design to Operation, Commissariat A L'Energie Atomique, France and Groupement Atomique Alsacienne Atlantique April 1966, Paper Presented at the National Topical Meeting of The American Nuclear Society, April 10-12, 1967

- 13 Leppard, J A Review of SCTI Bellows Failures, Atomics International Division of NAA, NAA-SR-MEMO-11970, May 26, 1966
- 14 Peters N T, and Amorosi A Features of Second Generation Sodium-Cooled Fast Reactors, Atomic Power Development Associates, Inc, 1966 Annual Meeting American Nuclear Society, Denver, Colorado June 20-23, 1966, Ans Trans 9 (1), Page 215
- 15 Anderson, W F et al SCTI Sodium Heater Failure, Atomics International Division of NAA, NAA-SR-MEMO-12090, August 1, 1966
- 16 Robertson, W M Propagation of a Crack Filled with Liquid Metal, Science Center, North American Aviation, Inc, TMSA-236-1478 and 1482-66, 1966
- 17 Balzhiser, R, to Goldman K, Personal Communication, February 1, 1967
- 18 TRG Memorandum 4126, September 1967
- 19 Orlov, VV, Pinkhasik, M S, and Aristarkhov, N N Some Problems of Safe Operations of the BR-5 Plant, Proceedings of the International Conference on the Safety of Fast Reactors AIX-EN-PROVENCE September 19-22, 1967, CONF-670416, Edited by Denielon, G
- 20 Matthews, R R, and Henry, K J The Location and Repair of the DFR Leak, Nuclear Engineering, 13:149 Page 840-845, October 1968
- 21 Murray, W M (Editor) Fatigue and Fracture of Metals, Wiley, New York, 1952
- 22 Kennedy, G E, and King, E C Thermal Shock Preliminary Report Number 12, Sir Mark A, 8-inch Valve Body-Seat Ring Mock-up Number 3, Mine Safety Appliances Co, MSA MEMO Report 86, July 29, 1955
- 23 Parker, E R Brittle Behavior of Engineering Structures, Wiley, New York, 1957
- 24 Shanley, F R Strength of Materials, McGraw-Hill, New York 1957
- 25 Gall, W R Heavy Water Leaks at Savannah River, Nuclear Safety 3 (1), Pages 87-90, September 1961
- 26 Stanyukovich, A V, and Levin, E E Causes of Failure of Steam Superheater Pipes Made from 18CR/12NI/ITI Steel, Translated by Z Januszewski from Energomashinostroenie, Number 10, 27-30, 1961

- 27 Tabor, W H, and Costner, R A Problems Encountered During Four Years of Orr Operation, Oak Ridge National Laboratory, Oak Ridge ORNL-TM-275, August 23, 1962
- 28 Kilsby, E R A Survey of Water Reactor Primary System Conditions Pertinent to the Study of Pipe Rupture, General Electric, San Jose GEAP-4445, January 1964
- 29 Tagart, S W Mechanical Design Considerations in Primary Nuclear Piping, General Electric Company, San Jose, GEAP-4578, March 1964
- 30 Brothers A J, Coffin, L F, Klepfer H H, Low J R, and Reynolds, M B A Review of Fracture Modes as Related to Primary Coolant System Rupture Study, General Electric Company, San Jose, GEAP-4446, May 1964
- 31 Gerken W W, West J M, Jameson A S, and Withers W T Bonus Reactor-Operating Performance, Combustion Engineering, and Puerto Rico Water Resources Authority, Ans Transactions 8 (2) Pages 604-605, 1965 Winter Meeting
- 32 Klepfer, H H Experimental and Analytical Program Recommendations Reactor Pipe Rupture Study, General Electric Company, San Jose, GEAP-4474, January 1965
- 33 *Docket Number 50-62, January 10, 1965
- 34 Quarterly Operating Report (Of Shippingport Atomic Power Station) Second Quarter 1965, Duquesne Light Co, Shippingport Pa, DLCE-5000265, June 1965
- 35 Love, W J The Influence of Small Weld Cracks on the Fatigue Life of Steel Pipe for Nuclear Service, General Electric Company, Schenectady, New York, Nuclear Structural Engineering 2 (2) - 181-202, August 1965
- 36 Reynolds, M B Fracture Mechanics and the Stability of Engineering Structures, General Electric, Atomic Power Equipment Department, San Jose, California, GEAP-4678, September 1965
- 37 Walpman, L A, and Doumas, M Fatigue and Burst Tests on Irradiated In-Pile Stainless Steel Pressure Tubes, Nuclear Applications, 1:5 Page 439-445, October 1965
- 38 McCool, W J Leak in 36-Inch Outlet Header at the Engineering Test Reactor (ETR), Division of Operational Safety, U S Atomic Energy Commission, Reactor Operating Experience 65-17-AEC-DOS, October 13, 1965

- 39 Long, E L Examination of Bonus Preheater-Dryer Piping, Oak Ridge National Laboratory, ORNL-TM-1282, October 1965
- 40 Winborne, R A Brittle Failures of Carbon Steel Tubes, Atomics International Division of NAA, NAA-SR-MEMO-11707, November 15, 1965
- 41 Garigliano Nuclear Power Plant Operation Report for the 4th Quarter of 1965, Ente Nazionale Per L'Energia Elettrica, Rome, TID-23320, December 31, 1965
- 42 Reactor Primary Coolant System Rupture Study, Quarterly Progress Report Number 1, April-June 1965, General Electric Company, Atomic Power Department, San Jose, California, GEAP-4911, July 1965
- 43 Reactor Primary Coolant System Rupture Study, Quarterly Progress Report Number 2, General Electric Company, Atomic Power Equipment Department, San Jose, California, GEAP-4964, October 1965
- 44 Reactor Primary Coolant System Rupture Study, Quarterly Progress Report Number 3, October-December 1965, General Electric Company, Atomic Power Equipment Department, San Jose, California, GEAP-5082, December 1965
- 45 Reactor Primary Coolant System Rupture Study, Quarterly Progress Report Number 4, January-March 1966, General Electric Company, Atomic Power Equipment Department, San Jose, California, GEAP-5147, March 1966
- 46 Reactor Primary Coolant System Rupture Study, Quarterly Progress Report Number 5, April-June 1966, General Electric Company, Atomic Power Department, San Jose, California, GEAP-5192, August 1966
- 47 Reactor Primary Coolant System Rupture Study, Quarterly Progress Report Number 6, July-September 1966, General Electric Company, Atomic Power Equipment Department, San Jose, California, GEAP-5279, November 1966
- 48 Reactor Primary Coolant System Rupture Study, Quarterly Progress Report Number 7, October-December 1966, General Electric Company, Atomic Power Department, San Jose, California, GEAP-5427, December 1966
- 49 Reactor Primary Coolant System Rupture Study, Quarterly Progress Report Number 8, January-March 1967, General Electric Company, Atomic Power Department, San Jose, California, GEAP-5474, May 1967
- 50 Reactor Primary Coolant System Rupture Study, Quarterly Progress Report Number 9, April-June 1967, General Electric Company, Atomic Power Department, San Jose, California, GEAP-5512, August 1967

- 51 Reactor Primary Coolant System Rupture Study, Quarterly Progress Report Number 10, July-September 1967, General Electric Company, Atomic Power Department, San Jose, California, GEAP-5554, August 1967
- 52 Reactor Primary Coolant System Rupture Study, Quarterly Progress Report Number 11, October-December 1967, General Electric Company, Atomic Power Department, San Jose, California, GEAP-5587, March 1968
- 53 Reactor Primary Coolant System Rupture Study, Quarterly Progress Report Number 12, January-March 1968, General Electric Company, Atomic Power Department, San Jose, California, GEAP-5637, June 1968
- 54 Boiling Nuclear Superheater (Bonus) Power Station, Startup Summary Report, February 1966, Combustion Engineering, Inc, Connecticut and Puerto Rico Water Resources Authority, San Juan, Puerto Rico, CEND/PRWRA-257, February 1966
- 55 Appendix B, Steam Dryer Preheater Piping Investigations Combustion Engineering, Inc, Connecticut and Puerto Rico Water Resources Authority, San Juan, Puerto Rico, Appendix B of Boiling Nuclear Superheater (Bonus) Power Station, Startup Summary Report, CEND/PRWRA-257, February 1966
- 56 Smith E H, Liebenthal, J L, Killian, H D, Hoppingarner, K R, and Moen R A Crack in the Engineering Test Reactor Primary Cooling System, Phillips Petroleum Company, Idaho, IDC-17158, March 1966
- 57 Purcell, R H Failure of Primary Pump Seal Injection Line, Battelle-Northwest, Pacific Northwest Lab, Richland, Washington, BNWL-SA-557 and OONF-660516-1, Page 36 and 37 of Plutonium Recycle Test Reactor Experience, 1962-1966, April 15, 1966, Presented at Annual Conference on Organic and Heavy Water Reactors, Winnipeg, Canada
- 58 Rouston, B F Loss of Coolant at Manhattan College Reactor, May 19, 1966, Manhattan College, Bronx, New York, May 31, 1966 Docket 50-199, Atomic Energy Clearing House, 12(26), Page 39, June 27, 1966
- 59 Gronwall B, Ljungberg, L, Hubner, W, and Stuart, W Intercrystalline Stress Corrosion Cracking of Inconel 600 Inspection Tubes in the Agesta Reactor, Aktiebouaget Atomenergi, Stockholm, Sweden, AE-245, August 1966
- 60 Eiber, R J et al Investigation of the initiation and extent of Ductile Pipe Rupture, Progress Report, May-December 1966, Battelle Memorial Institute, Columbus, Ohio, BMI-1793, January 1, 1967

- 61 Eiber, R J et al Investigation of the Initiation and Extent of Ductile Pipe Rupture, Quarterly Progress Report, January-June 1967, Battelle Memorial Institute, Columbus, Ohio, BMI-1813, September 1, 1967
- 62 Eiber, R J et al Investigation of the Initiation and Extent of Ductile Pipe Rupture, Quarterly Progress Report, July-September 1967, Battelle Memorial Institute, Columbus, Ohio, BMI-1817, October 1, 1967
- 63 Eiber, R J et al Investigation of the Initiation and Extent of Ductile Pipe Rupture, Quarterly Progress Report, April-June 1968, Battelle Memorial Institute, Columbus, Ohio, BMI-1849, July 1, 1968
- 64 Le Levier, M and Bonnin, P Ruptures of Nuclear Reactor Pipes and Vessels, (A Bibliography), Commissariat a L'Energie Atomique, Paris, CEA-BIB-79, 1967
- 65 Vulcain Project, Status Report, Nuclear Engineering 12(128) Pages 34-36, October 18, 1967
- 66 *Docket Number 50-238, November 27, 1967
- 67 Savage, H C, Compere, E L, Baker, J M, and Bohlmann, E G Operation of Molten-Salt Convection Loops in the Orr, Oak Ridge National Laboratory, ORNL-TM-1960, December 1967
- 68 Tetelman, A S, and McEvily, A J Jr Fracture of Structural Materials, John Wiley and Sons, Inc, New York, 1967
- 69 IRL Reports Corrosive Failure of Primary Piping, Industrial Reactor Laboratories, Inc, Docket 50-17, January 11, 1968
- 70 Nuclear Power Piping, (USAS B31.7), American Society of Mechanical Engineers, New York, February 1968
- 71 Small Diameter Primary Piping Weld Heat Affected Zone Cracks Found in a BWR Plant, USAEC, Division of Operational Safety, AEC Bulletin, Operating Experiences, Reactor Safety, ROE-68-3, May 20, 1968
- 72 *Docket Number 50-16, June 4, 1968
- 73 Holyoak, R H, Forrer, G R, and Higgins, J P In-Service Inspection of Dresden-1, Nuclear News, 11:11 PP32-43, November 1968

*Availability - USAEC Public Document Room, Washington, D C

- 74 Jens, Wayne H General Manager Atomic Power Development Associates, Inc., letter to Donald J Nolan, United Nuclear Corporation, March 5, 1969
- 75 Wykoff, W R Associate K Division Leader, Los Alamos Scientific Laboratory, letter to Donald J Nolan, United Nuclear Corporation, December 23, 1968
- 76 Fraser, A S and Porter, J D Metallurgical Examination of Failures on Dounreay Fast Reactor Thermal Siphon, TRG Memorandum 4213 (D), November, 1968

APPENDIX A

GENERAL ELECTRIC PIPE RUPTURE PROGRAM
(USAEC CONTRACT AT(04-3)-189)

STATUS SUMMARY - NOVEMBER 1968

Appendix A reproduces a private communication from Mr L G Hsu, Design Analysis Unit, General Electric Company, San Jose, California to members of the Mechanical Design Committee of USAS B31, dated November 11, 1968.

GENERAL ELECTRIC
COMPANY

NUCLEAR ENERGY
DIVISION

A-2

175 CURTNER AVE., SAN JOSE, CALIF. 95125 . . . AREA CODE 408, TEL. 297-3000
TWX NO. 910-338-0116

ATOMIC POWER EQUIPMENT DEPARTMENT

November 11, 1968

GE-AEC PIPE RUPTURE PROGRAM INFORMATION

To: MDC MEMBERS

In response to the MDC's request on the subject matter we have made a survey of the reports written for the Pipe Rupture Program. This program consists of Phase I and Phase II. The Phase I was aimed at establishing the range of parameters which should be considered in studying reliability of nuclear piping. The Phase II of the program is mainly to carry out the analytical and experimental work outlined in the Phase I.

The Phase I was completed in 1964, while the Phase II of the program is still being undertaken at the General Electric Company for the U. S. Atomic Energy Commission.

Attached, please find a copy of the summaries of the Pipe Rupture reports. These reports may be obtained from:

The Clearing House for Federal, Scientific and Technical
Information
Department of Commerce
Springfield, Virginia

We entrust that this information will be of some value to you.

Sincerely yours,

L. C. Hsu
Design Analysis Unit
General Electric Company

LCH/jm
attachment

A. Phase I

Phase I of the program was initiated in 1963 and completed in 1964. The following five reports have been issued:

1. GEAP - 4445

A Survey of Water Reactor Primary System Conditions Pertinent to the Study of Pipe Rupture - E. R. Kilsby, Jr., January, 1964

Summary

A range of parameters, conditions and criteria to be identified for consideration in the pipe rupture study are summarized below:

1. Materials

1.1 Primary piping materials of interest for present applications are:

Austenitic Stainless Steels - Type 304 and 316

Low Alloy Steels - 2 1/4 Cr - 1 Mo and 1 1/4 Cr - 1/2 Mo
Carbon Steels

1.2 For future applications, Inconel-600 piping, and carbon steel piping clad with austenitic stainless steel or Inconel should also be considered.

1.3 Dissimilar metal joints such as reactor vessel nozzle joints, pipe flange joints, etc., should receive close attention in the study of pipe rupture.

1.4 Materials properties of particular interest are those associated with fatigue, corrosion, creep and stress rupture

1.5 Pipe sizes of interest range from 1/2 - inch diameter to 30 - inch diameter. Wall thickness associated with each of the diameters should be those calculated by appropriate design code formulas.

2. Loadings

2.1 For immediate applicability to present water cooled reactor plants, the pipe rupture study should concentrate on the pressure range from 1000 to 2500 psig with associated temperatures ranging from 550F to 650F.

3. GEAP - 4466

"A Review of Fracture Modes as Related to Reactor Primary Coolant Pipe Rupture", by A. J. Brothers, L. F. Coffin, Jr., H. H. Klepfer, J. R. Low, Jr., M. B. Reynolds, May, 1964

Summary

Following a definition of the finite number of known fracture modes and a delineation of the specific materials, components and operating conditions of interest, the state of present knowledge of each fracture mode was related to the reactor piping case; the application of fracture mechanics to the pipe rupture question was also studied. The findings of these reviews were illustrated by application to specific components of typical examples of water-cooled reactor piping systems.

The review leads to the following conclusions:

- a. With the proper application of present knowledge, fracture by fibrous ductile fracture due to gross over-stress or by brittle cleavage can be virtually ruled out as credible events. (Unless cyclic strain aging is found to raise the brittle--ductile transition temperature above the service temperature for carbon steels).
- b. With the proper application of present knowledge, fracture by creep-rupture at 500-650°F can be virtually ruled out, although combined creep-fatigue should be further studied with respect to superheat plant piping.
- c. Relationships exist which could be used to eliminate any possibility of impact erosion failures if the critical velocity parameters were determined for the specific piping steels.
- d. The remaining possible fracture modes: fatigue, low-energy ductile fracture, and localized corrosion cracking, are not well enough understood to be able to predict complete immunity from their occurrence.

Important questions which cannot be answered on the basis of present knowledge are:

- a. Whether long, shallow, crack-like defects can develop undetected due to fatigue or localized corrosion, and whether such defects, if developed, could propagate to large-areas fractures by unstable ductile rupture.
- b. Whether the time for serious fatigue or corrosion crack (or leak) propagation, in the specific materials of interest, is fast or slow compared to the inherent response time for flaw and leak detection procedures.

- c. Whether service experience thus far, and short-term experimental results showing freedom from localized corrosion fracture, can be taken to imply complete immunity from attack over a 10 to 40-year service exposure.

The implications of this review of fracture modes were supported by the results of other tasks of the Pipe Rupture Study. The combined results were taken as the basis for recommending areas of needed development work.

4. GEAP - 4578

"Mechanical Design Considerations in Primary Nuclear Piping", by S. W. Tagart, March, 1964.

The critical examination of piping design methods has indicated the following conclusions:

- a. The current 1955 ASA B31.1 Power Piping Code is frequently misused as a complete design guide for which it is quite incomplete.
- b. In the fatigue design of many common components such as tees, wyes, and laterals, adequate analysis methods are not available to the designer for the purpose of local stress and strain computation. Gross and macroscopic local stress analysis provides the correlation parameters (stresses or strains) necessary for the quantitative evaluation fatigue crack initiation and growth. The fatigue behavior of metals used in nuclear piping can be adequately predicted if accurate local stress analysis either experimental or analytical is available.
- c. The loading mechanism associated with local cyclic thermal stresses has frequently been overlooked in pipe design.
- d. The rational design concepts employed in the current A.S.M.E. Section III Code for Nuclear Pressure Vessels should be extended and used where possible for a more complete coverage of piping fatigue problems.
- e. A general elastic shell analysis tool designed to handle many unsolved problems of local stress analysis for piping has been examined and appears to be feasible by the use of matrix structural analysis on a large digital computer. This tool, if developed, should remove the present major uncertainties in the rational design of unsymmetrical type pipe components such as tees, wyes and laterals for all significant types of pipe loading which are pertinent to water reactor piping.
- f. Many theoretical uncertainties exist in the basic understanding

of pipe material behavior in the creep temperature range.

- g. An infrequent but potentially dangerous mode of piping failure is associated with the impact forces of a high velocity water slug. This potential problem has been frequently unrecognized.
- h. Reliability modeling must attempt to assess the statistical overlap of all potential loading mechanisms with critical failure parameters for specific sets of design conditions. This new and powerful analytical tool has the potential to extend the concept of safety in the structural design of reactor piping to a rational quantitative basis.

5. GEAP - 4474

"Experimental and Analytical Program Recommendations - Reactor Pipe Rupture Study", by H. H. Klepfer, January, 1965.

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 rupture.

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 overall objectives have been identified, and the effort required to realize these specific results have 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.

B. Phase II

Phase II of the program was initiated in April, 1965. To date, 12 Quarterly Progress Reports have been issued:

1. GEAP - 4911 (July, 1965)
2. GEAP - 4964 (October, 1965)
3. GEAP - 5082 (January, 1966)
4. GEAP - 5147 (April, 1966)
5. GEAP - 5192 (August, 1966)
6. GEAP - 5279 (November, 1966)
7. GEAP - 5427 (February, 1967)
8. GEAP - 5474 (May, 1967)
9. GEAP - 5512 (August, 1967)
10. GEAP - 5554 (December, 1967)
11. GEAP - 5587 (March, 1968)
12. GEAP - 5637 (June, 1968)

A status report of the above documents may be found from the following report:

GEAP - 5653 - "Status of Pipe-Rupture Study at General Electric - II" by S. R. Venderberg, July, 1968.

Abstract

The pipe-rupture study is concerned with extending current understanding of failure-causing mechanisms and providing improved capability for evaluating reactor piping systems to minimize the probability of failures. Following a detailed review to determine the work most needed to improve nuclear system piping (Phase I), analytical and experimental efforts (Phase II) were started in April, 1965. This status report summarized the accomplishments during the initial 3 years of a broad program in (a) reliability engineering of actual reactor piping systems, (b) solution of heretofore intractable problems in stress analysis, (c) fracture mechanics, (d) fatigue studies through bench-scale and large-component tests, and (e) at-reactor tests of the effect of primary coolant environment on the fatigue life of primary piping steels.

- C. The following type reports are related to the Pipe-Rupture Program done at the General Electric Company for the U. S. Atomic Energy Commission
-

1. GEAP - 4678

"Fracture Mechanics and the Stability of Engineering Structures", by M. B. Reynolds, September, 1965.

Summary

The literature relating to the stability of engineering structures has been reviewed. Catastrophic failures in structures are of two types: (1) those resulting from the very rapid propagation of a brittle crack, and (2) those of the ductile tearing type. The conditions for unstable deformation are developed by examining the deformation behavior of a solid cylinder under uniaxial tension. The effect of both the stress-strain characteristics of the material and the stiffness of the applied load are considered. It is shown that for stability the condition

$$\frac{dP}{d\lambda} \geq -k$$

must be satisfied, where k is the stiffness of the applied load and $dP/d\lambda$ is the slope of the load-deformation curve for the structure.

The Tresca and von Mises criteria for plastic yielding under multiaxial stresses are given, followed by a review of several papers on the homogeneous plastic deformation of hollow spheres and cylinders under internal pressure. The Griffith and Irwin criteria for stability of a brittle crack are described, followed by development of the fracture toughness

concept and discussion of the corrections necessary to apply the Griffith-Irvin fracture mechanics to relatively ductile materials. The brittle-ductile fracture transition is described in terms of the effect of temperature on the yield and fracture stresses of the material.

Finally, the commonly used criteria for fracture-safe design in ferritic alloys are discussed, including the work of Pellini, Brothers, Irvine, and others.

Two appendices are devoted to techniques for fracture toughness testing and to a brief summary of fatigue crack growth laws.

2. GEAP - 5014

"Fracture Toughness of Some Engineering Alloys", by M. B. Reynolds, March, 1966.

Summary

This report included a review of the fracture mechanics technique for determining the stability limit in a structure containing a crack and pointed out the limitations of fracture mechanics with respect to ductile materials, such as the low carbon steels. Under certain service conditions these steels, however, are amenable to the fracture mechanics technique. This report is a summary of published fracture mechanics data for a number of commonly used alloys.

3. GEAP - 5410

"Low-Cycle Fatigue Strength Reduction in Notched Flat Plates", by E. Krempl, January, 1967.

Summary

Very little data are available on the influence of stress raisers on low-cycle fatigue life. Low-cycle fatigue differs from high-cycle fatigue insofar as it involves cyclic elasto-plastic deformation on a macroscopic scale.

After a brief review of the design procedure in high-cycle fatigue an approach is outlined for the low-cycle fatigue region. A differentiation between a stress and a strain approach seems to be mandatory in evaluating the influence of stress raisers on low-cycle fatigue life.

Good correlation is found when analytical elasto-plastic strain values are compared with strain gage measurements in the root of the notch of flat-plate specimens under monotonic loading.

Low-cycle fatigue tests on edge-notched flat-plate specimens, of three standard piping materials, at room temperature, under pulsating tension

loading, are analyzed under special consideration of crack initiation and crack propagation. Fatigue-strength-reduction factors are derived and compared with the proposed approach.

4. GEAP - 5471

"PAPA - Structural Analysis of Plates and Shells using Trapezoidal and Triangular Plate Elements", by E. L. North, March, 1967.

Summary

An original approach to the plate-panel element was undertaken by L. Beitch^{8,9} at GE/FPD Evendale and is based upon the concept of two intersecting beams connected at their center point. Poisson's ratio, not normally considered in beam analyses, is incorporated into the panel elements by equating strains in one direction to Poisson deflections normal to the strains. Work carried out on rectangular plate elements showed that the philosophy of this method overcomes many of the limitations inherent in most plate element approaches.

A section of this report shows the correlation between the plate element approach and classical theory. Also, as a means of further checking our work, cases analyzed using a shell-of-revolution solution for cones and the plate-panel element are included.

5. GEAP - 5620

"Failure Behavior in ASTM A106B Pipes Containing Axial Through-Wall Flaws," by M. B. Reynolds, April, 1968.

Summary

The pressure load limit for a cylindrical shell containing a flaw is a function of cylinder radius and wall thickness, flaw dimensions, and the properties of the material. The strength of large diameter thin-wall cylinders of brittle material containing axial through-wall flaws can be predicted by linear elastic fracture mechanics, by applying suitable corrections for the effects of curvature. For cylinders of more ductile material, it is necessary also to take into account the effect of plastic yielding at the tip of the advancing flaw, and workers in the United States and the United Kingdom have developed relations between burst pressure, flaw size, and material properties which predict the behavior of axially flawed cylinders for which the product of radius and wall thickness is 20. in² or greater.

Results of hydrostatic tests at 60°F on flawed ASTM A106B pipes in the diameter range of 4 to 12 inches are presented. Variation of limit pressure with flaw length and pipe dimensions is described for pipes having radius-wall thickness products as low as 0.5 in². Development of an empirical equation to predict behavior of small diameter, ductile pipes having axial through-wall flaws is discussed.

6. GEAP - 5622

"A Failure Diagram for Axially Flawed Pipes", by M. B. Reynolds, April, 1968.

Summary

The relationship between flaw configuration and the maximum pressure load which can be sustained by axially flawed pipes is discussed. Both axial through-wall flaws and part-through flaws are considered. A method of plotting burst strength versus flaw length data to produce a useful "failure diagram" is presented.

7. GEAP - 5553

"PAPA - The Digital Computer Program for the Static Analysis of Structures Made up of Plate and Panel Elements", by L. Beitch and N. L. North, October, 1967.

Summary

PAPA is a general digital computer program for the static analysis of complex three-dimensional plate-and shell-like structures. The physical structure is represented mathematically by plate-panel elements. Currently, the plate-panel elements consists of a rectangle, trapezoid, and triangle. The three panels are finite elements which consider curvature in two directions. Poisson's ratio is considered without restriction to numerical value. In-plane and out-of-plane effects are completely coupled. This analytical approach is restricted to thin elastic shells. Mechanical (point or distributed loads) and/or thermal loads are handled readily by the program. Any linear combination of boundaries on the structure is acceptable. Resulting deflections, forces, moments, and stresses are automatically calculated and displayed for every plate-panel element. Currently, the program has a maximum capacity of 2,000 joints. By dividing the mathematical structure into substructures, solutions are obtained accurately and economically. A detailed explanation of how to use the computer program, a program description as defined for the GE-635 digital computer, and correlations with known solutions are presented. This report was prepared under the Atomic

Energy Commission's Pipe Rupture Study Program, Contract AT (04-3)-189, Project Agreement 37.

8. GEAP - 5557

"Stress Intensity Factor for a Circumferential Through-Wall Crack in a Straight Pipe", by J. D. Gilman, January, 1968.

Summary

The stress intensity factor for a circumferential crack in a cylindrical shell subjected to internal pressure and symmetric bending is calculated using energy methods. Application of the results to the failure analysis of piping in a nuclear power plant is discussed.

Results are based on the calculation of strain energy as a function of crack length. The shell displacements are expressed in terms of Fourier series, and the strain energy due to shell bending and extension is represented as a function of the Fourier coefficients. The theorem of minimum potential energy is applied to obtain a set of linear equations, which are programmed for digital computer solution. The accuracy of the numerical results is discussed.

9. GEAP - 5607

"Fatigue Crack Growth in Nuclear Reactor Piping Steels", by A. J. Brothers, March, 1968.

Summary

The general objective of this part of the Pipe Rupture Study is to determine the feasibility of rationally designing against fatigue crack growth in piping systems, and materials. The approach is based on correlating measured crack size with an analytically-derived stress field parameter, K , the stress intensity factor, introduced by Irvin⁽¹⁾ and as proposed by Paris, et al⁽²⁾. Fatigue crack growth rates are being measured for three steels, plain carbon, 2 1/4 Cr-Mo, and Type-304 stainless steel, which are used for nuclear piping.

This report contains a discussion on the fracture mechanics approach and a description of the progress made to date of tests of plate specimens to determine the effect of test temperature, cyclic frequency, and superposed

mean stress. Also, the applicability of the fracture mechanics approach to predict the rate of growth and geometry of part-through, semi-elliptical surface defects is reported.