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SUMMARY OF
RESEARCH AND DEVELOPMENT
RECOMMENDATIONS
FOR LMFBR PIPING
TECHNICAL REPORT 518

PREPARED FOR

U S ATOMIC ENERGY COMMISSION
CONTRACT NO AT(04-3)-781

BRAUN PROJECT 4122-W
UNITED NUCLEAR PROJECT 2351

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May 1, 1970

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BAL-120

Dear Mr Fry

R&D RECOMMENDATIONS
TASK REPORT 518
LMFBR PIPING DESIGN GUIDE
AEC SAN FRANCISCO
PROJECT 4122-W

Transmitted herewith are two copies of the final report containing our recommendations for R&D considered necessary in support of the development of the Piping Design Guide.

The eventual verification and adoption of the piping design guide will depend upon the successful completion of many of the R&D programs recommended. Priorities are indicated in the report where the need for verification of design rules and procedures were considered of paramount importance. Confidence in the guide can only be established when the procedures are verified by application to specific problems where corroborative data substantiate the theoretical analysis. Specific R&D programs are outlined as a first step in defining the problems requiring solution. Further detailed definition of these programs will be required by organizations qualified to undertake the R&D work.

Sincerely yours

Roger Detman
Project Manager

RFD IV

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FOR LMFBR PIPING

TECHNICAL REPORT 518

Prepared for US Atomic Energy Commission

Contract No AT (04-3) -781

Braun Project 4122-W

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C F BRAUN & CO

Alhambra California

May 1, 1970

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FOR LMFBR PIPING

TECHNICAL REPORT 518

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1 INTRODUCTION

The studies made preparatory to the development of the preliminary draft of the Design Guide for LMFBF Sodium Piping uncovered the need for much additional information and research in many areas of piping technology. Experimental data, and in some cases further analytical development, are considered essential in meeting the stringent requirements of LMFBF systems, by supporting and confirming the criteria of the LMFBF Piping Design Guide. Additionally, other programs are necessary in order to advance the state-of-the-art in high-temperature piping design, leading to enhanced criteria and design techniques.

In this report are summarized all those research and development programs which are considered prerequisite to the establishment of design procedures which provide adequate assurance of the safe design and operation of LMFBF piping. It has been recognized, however, that the proposed programs do not all deserve the same urgent priority, since conservative assumptions can in some cases be substituted for the needed information until the latter is available. Accordingly an attempt has been made herein to categorize the recommended R&D programs as to their relative priorities. These categories are as follows.

- 1 First Priority Short-Term Investigations
- 2 First Priority Long-Term Investigations
- 3 Second Priority Investigations
- 4 Investigations of Peripheral Interest

In the following four chapters, each program is described in its appropriate category, with a brief background discussion and a proposed course of action. Detailed work plans are being developed for each task, and these will be published separately as an Addendum to this Report. Task numbers in the Addendum will correspond to the paragraph numbers used herein, with a prefix of 6 - eg, the task described in paragraph 2.3 will be identified as Task 6.2.3.

This report was first issued in preliminary form on January 9, 1970. It has since been reviewed by interested agencies, and the review comments have been consolidated by Liquid Metal Engineering Center (LMEC). The report has been approved by USAEC for final issue.

1.1 GENERAL CONSIDERATIONS

A preliminary draft of the LMFBF Piping Design Guide was issued on August 22, 1969. Its contents reflect what is believed by its contributors to represent the best approach to liquid metal piping design consistent with proven technology and established data. In the course of its preparation, however, it became clear that the whole field of high-temperature design is undergoing a state of change, and that

1.1 GENERAL CONSIDERATIONS Continued

much work has yet to be done before an entirely satisfactory, unified basis for design can be established.

It was further recognized that the procedures and data yet to be developed for piping may be equally appropriate to the design of other parts of the LMFBR system such as vessels, pumps, and valves, although no deliberate attempt has been made to assess their applicability to the needs of others. This course has been dictated only by the immediate expediencies of the Piping Design Guide project, and should not be thought of as a display of indifference. Indeed, it is highly desirable that the products of the R&D programs recommended herein should ultimately furnish the basic information upon which a fully unified approach to system design can be founded. It is to be hoped that, by disseminating the resulting information as widely as possible, the programs described will be of timely interest and of immediate value to a very broad audience.

In a similar vein, it should be emphasized here that no attempt has been made to identify the programs recommended in this report with others at present being conducted in research laboratories and other institutions throughout the country. Again, the contributors recognize the desirability of correlating these activities in such a way as to benefit the greatest number. Accordingly, it has been left to those with the responsibility for coordinating LMFBR and other related programs to avoid unwarranted duplication of effort or, worse still, the pursuit of divergent courses of investigation.

The four categories of priority into which the recommended programs have been placed should be thought of as purely relative. It would be naive to anticipate their accomplishment in the sequence in which they are presented. Nevertheless it should be stressed that the successful attainment of the ultimate goals of the LMFBR Piping Design Guide project -- and, indeed, those of the LMFBR Program Plan as a whole -- is strongly dependent on the outcome of the R&D programs proposed in this report, and other closely related projects. If such an achievement is to be realized in a timely manner, the early initiation of at least the first-priority tasks is considered essential.

1.2 PROGRAM OBJECTIVES

The R&D programs outlined in this report fall into several general areas of investigation. These are, (1) materials properties; (2) materials behavior; (3) environmental effects; (4) component development; (5) analysis development; (6) fabrication and erection procedures; and, (7) quality assurance.

1.2 PROGRAM OBJECTIVES Continued

The need for more and better information in several of these areas has long been recognized; they already are the subject of intensive investigation in the United States and abroad. The very special nature of the LMFBR, with its unique environmental conditions and design conditions, however, has heightened that need and broadened its scope.

In particular, there is a very real need for a more satisfactory criteria for high-temperature design. This has become especially urgent for LMFBR system design by reason of the severe thermal transient problem that must be adequately accounted for. The development of such criteria, while theoretically capable of early attainment, has been frustrated by the very lack of reliable data to which this report addresses itself. The main thrust of the R&D programs outlined herein, therefore, is towards the goal of providing adequate data and the analytical tools to properly account for high-temperature phenomena.

2 FIRST PRIORITY SHORT-TERM INVESTIGATIONS

2.1 TIME DEPENDENT MATERIAL PROPERTIES

2.1.1 DURATION OF LOADING The present design "Codes" list one set of allowable stresses as a function of temperature. These allowable stresses are based on criteria related to certain mechanical properties, such as yield and ultimate strengths, obtained from standard tensile tests, and creep properties (i.e., creep rate and rupture strength). There is a need to develop allowable stress values which take the duration of the loading condition into account more explicitly.

The above testing will require short-term tests both at room temperature and elevated temperatures, and long-term tests at elevated temperatures where creep is a factor. It is recommended that the latter testing be done in an inert atmosphere to separate duration of loading from environmental effects.

It is well known that the yield strength, as defined by 0.2 percent permanent offset, is a function of the strain rate or alternatively the duration of loading. For very short duration loadings (high rates of deformation) the effective yield strength is enhanced, while for very slow strain rates it is diminished. It is recommended that time-dependent stress-strain data be developed in order that more rational design criteria can be developed to handle loading conditions which range from extremely short duration, such as those associated with sodium hammer or sodium-water reactions caused by steam generator tube leaks, to long duration operating loads where creep is a factor.

2.1.2 ISOCHRONOUS STRAIN CURVES For calculations such as instability, ratcheting, etc., there is a need for stress-strain properties of materials as a function of time. A literature survey should be conducted to obtain and summarize currently available data for LMFBR materials. These data then should be presented in a form suitable for use by the designer. One useful form is isochronous stress-strain curves, which may be generated from conventional short-time tensile tests and constant load creep tests. The data from these tests are utilized by plotting total strains at a given stress level as a function of time. This is repeated for each stress, giving a series of curves of strain vs time. The isochronous stress-strain curves then are drawn through the strains for the same time, thus the term "isochronous". The curve for zero time is the conventional stress-strain curve up to the maximum strain of interest, usually less than 10 percent. Each set of curves would represent a given temperature for a given material.

If sufficient data are not available, an experimental program is recommended for those areas and materials for which data are lacking.

2.1.3 THE ONSET OF TERTIARY CREEP AS A DESIGN STRESS CRITERION
Present code limits for design stresses in the creep range are based on the minimum of the following three criteria.

- 1) 100 percent of the stress to produce a creep rate of 0.01 percent in 1000 hours, based on average values
- 2) 67 percent of the stress to produce rupture in 100,000 hours, based on average values
- 3) 80 percent of the stress to produce rupture in 100,000 hours, based on minimum values

The Design Guide is based on similar criteria, but extended to 200,000 hours for the expected design life of LMFBR piping components.

Recently, other criteria have been proposed and are at present under investigation. Two of the most significant are a maximum strain limitation, such as 1 percent total strain in 100,000 hours, and the point of departure from secondary creep.

Various disadvantages have been pointed out in the total strain and strain rate criteria. Generally they are based on extrapolated data, which may introduce large errors, and in some cases may extend into the tertiary creep region. It has been pointed out that in some cases the stress to produce 1 percent strain may be greater than the stress to rupture. It has also been shown that the safety factor of the code values decreases at higher temperatures.

The strain for departure from secondary creep is always appreciably below the strain for rupture, and the ratio of time for departure from secondary creep to the time for rupture is a constant for a given temperature. These values can be obtained by much shorter tests without requiring extrapolation.

It is proposed that data for LMFBR materials be assembled, and a critical evaluation made of departure from secondary creep as a design criterion. To accomplish this, the following steps are recommended.

- 1) Conduct an intensive literature survey to assemble the current experimental data pertinent to the subject. This will also include contacting agencies conducting such work to assess the availability of recent experimental data not yet published.
- 2) If sufficient data are not available, outline an experimental program to obtain the required data. (This possibly could be combined with the long-term program covered by Paragraph 3.2).

2.1.3 THE ONSET OF TERTIARY CREEP AS A DESIGN STRESS CRITERION Continued

- 3) In the range of temperatures from 900 to 1200 F, establish design limits based on departure from secondary creep and compare them with present code bases described above, and with other proposed criteria.
- 4) Evaluate each method critically, considering such factors as consistent safety factor at all temperatures, accuracy of data, ease of obtaining data and establishing design values, etc. Recommend values to be incorporated in the Design Guide if changes are indicated.

2.2 ELEVATED TEMPERATURE FATIGUE DATA

In the LMFBR piping environment the severity of cyclic loading conditions and temperature transients require that particular attention be paid to strain concentration points and crack-like defects in evaluation of fatigue limits.

Other factors of importance to fatigue properties which should be considered are as follows. a) The effects of environment, since fatigue is a surface dependent phenomenon, b) strain produced by temperature cycling as compared with the same strain produced by applied load at constant temperature (i.e., the highest temperature in the temperature cycling test), c) material conditions (i.e., heat treated, annealed, cold-worked, etc).

There is now a fairly large body of data on fatigue at low temperatures (below the creep range) obtained from laboratory experiments under room-temperature conditions. (14, 15) The general procedure in such investigations is to control the strain between fixed limits, and if desired, to measure the stress, while cycling the specimen until failure is determined. Such tests may be under conditions of controlled diametral strain, longitudinal strain, bending strain, or torsional strain. The results can be represented in terms of total strain range versus cycles-to-failure, or if desired, of plastic strain versus cycles-to-failure. The former is most often used for direct design procedures such as in Section III of the ASME Code, (16) while the latter is applied when one is primarily interested in real material behavior. (17)

The high-temperature fatigue problem is in quite a different state. The material behavior becomes much more complicated at elevated temperatures because of the occurrence of creep and diffusion-controlled reactions.

2.2 ELEVATED TEMPERATURE FATIGUE DATA Continued

It has been shown that frequency has a strong effect on fatigue properties. This is the same thing as saying that the strain rate is important, and related to this, the hold-time in the cycle is important, with fatigue life decreasing as hold-time increases.

Plastic strain, and in this case cyclic plastic strain, can have an important bearing on the precipitation of intermetallic phases and the strengthening effects which take place in the metal structure. This strain age hardening, while developing additional strength, also causes a reduction of ductility in the material. Since ductility is of prime consideration for fatigue resistance, this hardening effect, while increasing creep strength, reduces fatigue capabilities.

Another problem, applicable over the whole temperature range, is cumulative fatigue damage, where cyclic strains of greatly different magnitudes are experienced, and in a varying and probably random order of application. The order of application, as well as the difference in magnitude, may have a significant effect on the overall fatigue life.

Much more experimental data are required to establish fatigue curves and verify the various theoretical relations which have been developed, particularly for elevated temperatures. It is especially important in the creep range to determine the effect of hold-time at a given stress level, and also the closely related effects of strain rate and frequency.

The development of high-temperature fatigue data is one of the most difficult problems still to be resolved because of the large number of operating parameters involved. The investigation should be undertaken with the initial objective of isolating the effects of individual parameters. Subsequent objectives should then consider various combinations of parameters with the objective of developing correlations which will simplify the analysis procedures. The parameters recommended for separate investigation are listed below.

- 1) Loading cycle frequency
- 2) Strain rate
- 3) Loading cycle hold-time
- 4) Test temperature
- 5) Test environment
- 6) Material condition
- 7) Order of load application
- 8) Cyclic strain hardening
- 9) Bauschinger effect

2.3 MATERIAL PROPERTIES OF WELDS

In reviewing the failures experienced in piping systems, (18) it was possible to predict the type of failure that potentially presents the greatest likelihood of occurrence in LMFBR 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.

Such a program might be set up in three parts.

2.3.1 MATERIAL PROPERTY INVESTIGATION Determination of material properties of the weld metal and adjacent material.

2.3.2 FATIGUE PROPERTY INVESTIGATION Fatigue testing of representative samples of weld and heat-affected zone.

2.3.3 ANALYSIS AND APPLICATION Determination of analytical techniques applicable to various transient and geometric conditions.

2.4 ENVIRONMENTAL EFFECTS ON WELDS

The assumption has been made in the LMFBR Piping Design Guide that weld metal mechanical properties will be similar to those of the base metal in similar metal joints, and to the inferior of the two base metals in a dissimilar metal joint. A further assumption has been made that the LMFBR environment will have no effect on the mechanical properties of weld joints different from or more severe than those which are expected for the base materials. The risks involved in these assumptions are such that some verification is required. Under Paragraph 2.3, Material Properties of Welds, the first assumption will be checked, while the present section covers the second.

2.4.1 EFFECTS OF SODIUM The recommended R&D effort will require testing of single metal and dissimilar metal welds, both after exposure to sodium and during sodium exposure. Of primary interest are the short-term tensile properties after long exposure and long-term creep and stress-to-rupture properties.

2.4.2 EFFECTS OF INSULATION Insulation materials for use with LMFBR piping systems will be selected to ensure their compatibility with the piping material and their resistance to reaction with sodium in the event of a leak. It is recommended, however, that an investigation be carried out to ensure the same compatibility between insulating materials and weld metal deposits as is enjoyed by the parent metal. This investigation should be extended to cover insulation cementing compounds if their use is contemplated.

2.4.3 OTHER EXTERNAL EFFECTS It is known that welding flux, if not properly removed upon completion of the welding operation, reacts chemically with austenitic stainless steels and may lead to stress-corrosion cracking. Cleaning materials and solvents may similarly have a harmful effect. Tests should be performed to determine whether these effects are further aggravated in the weld metal and immediately adjacent areas.

2.4.4 DATA ANALYSIS AND CORRELATION The results of the investigations described above may be expected to lead to additional specific requirements for welding procedures, and possibly to further restrictions on the use of certain insulation materials, cements, solvents and other externally-applied substances which have been shown to have harmful effects upon the integrity of welds and the heat-affected zone. Such requirements would be incorporated into appropriate sections of the LMFBR Piping Design Guide.

2.5 EFFECTS OF CARBON TRANSFER

Carbon losses from steels, Figures A-8 and A-9 in the LMFBR Piping Design Guide, have been estimated on the basis of extremely conservative assumptions which may lead to unacceptable economic penalties in pipe designs. Because the presence or absence of carbon exerts such a profound effect on the mechanical properties of the piping materials, it is important that the carbon transport behavior be known in order that carbon levels can be predicted over the lifetime of LMFBR systems. Both carburization and decarburization are of interest. Diffusion, solution, or precipitation mechanisms within the steels are important for estimating the carbon distribution, as well as mean carbon contents of the pipewall as functions of temperature, time, etc.

The recommended R&D effort is divided into two distinct phases - a data search and analysis phase, and a new measurements phase.

2.5.1 DATA SEARCH AND ANALYSIS In Phase I, an intensive literature search would be made to obtain all available information related to carbon transfer within candidate piping materials, and from the steels to sodium.

2.5.1 DATA SEARCH AND ANALYSIS Continued

Table A-19 in the LMFBR Piping Design Guide summarizes available information regarding the effects of changes in carbon level on the mechanical properties of LMFBR piping materials. The multiplying factors are based on widely scattered data and on the assumption that the mean carbon levels represent uniform carbon distribution throughout the piping material. Relatively little information is available regarding the mechanical properties, and none is available regarding the effect of the nonuniform carbon distribution which will result from prolonged exposure at LMFBR temperatures.

2.5.2 CORRELATION OF AVAILABLE DATA The survey would be supplemented by an analytic effort to correlate the data and to determine whether and where additional data are needed.

2.5.3 EXPERIMENTAL PROGRAM The findings of the Phase I effort will determine the extent of the Phase II effort. This would be an experimental program to generate the necessary data.

The recommended R&D effort will require mechanical testing of LMFBR piping materials with known carbon levels and known carbon distribution under conditions of interest to LMFBR designers. Those properties that are most affected by change in carbon level should be given most attention.

2.5.4 CORRELATION OF EXPERIMENTAL DATA The test program should be supplemented by an analytic effort to correlate the data and present them in a useful form.

2.6 EFFECTS OF NITROGEN TRANSFER

There is evidence that the nitrogen content of stainless steel piping materials has a strong influence on mechanical properties. A loss of nitrogen can seriously reduce their strength. Although there is evidence that stainless steels will be nearly completely denitrided in a few thousand hours, when submerged in liquid metal at 1600 F, it is not known how LMFBR conditions will affect nitrogen transfer between steels and sodium. If nitrogen mobility parallels that of carbon under LMFBR conditions it will be necessary to be aware of it and to predict its consequences.

2.6.1 DATA SEARCH AND ANALYSIS The recommended R&D effort encompasses first a thorough review of the literature and of experience with nitrogen transfer in sodium systems. This may include nitrogen analysis of steel test pieces which are or could be made available from selected long-term sodium exposure sites. The data accumulated will be subjected to critical analysis to determine whether there is, in fact, a problem of nitrogen depletion in LMFBR piping materials, particularly submerged piping in a pool-type system.

2.6.1 DATA SEARCH AND ANALYSIS Continued

The results of the analysis will determine whether the program to determine the conditions which cause nitrogen transfer and the effect of those conditions on transfer rates will be performed. The results will likewise determine whether the following program to determine the effect of nitrogen of mechanical properties should be performed.

There are two situations, either of which will necessitate the inclusion of both programs in the R&D work. (1) The literature review indicates that insufficient information is available upon which to make a judgment of whether a problem exists, and (2) the data are sufficient and indicate that there is a problem. If, as presently expected, nitrogen depletion is found to be only of concern in piping which is completely submerged in sodium or surrounded by nitrogen-free gas, e.g., argon/helium cover gas, the R&D efforts will be limited to the austenitic stainless steels, since 2 1/4 Cr-1 Mo is not expected to be used under such conditions.

2.6.2 EXPERIMENTAL PROGRAM The recommended R&D effort will require an experimental program to measure nitrogen transport properties in the LMFBR piping materials at temperatures of interest. Conditions conducive to nitrogen transfer to and from piping materials and sodium will be determined. An analytical effort will supplement the test program to correlate the data generated and to present the results in usable form.

2.6.3 TESTING, ANALYSIS, AND CORRELATION Nitrogen has a pronounced effect on the mechanical properties of LMFBR piping materials. Recognition of the superior elevated temperature strength and stress-rupture behavior of nitrogen bearing austenitic stainless steels has led to the approval for the use of higher stress limits for such steels by ASTM and ASME committees (Code Case 1423-1). There is no information regarding the effect of nitrogen distribution on these properties.

The recommended R&D effort will require mechanical testing of LMFBR piping material with known nitrogen levels and known nitrogen distribution under LMFBR conditions. All mechanical properties must be investigated because there are now very scant data available. The test program should be supplemented by an analytic effort to correlate the data and to present them in a useful form.

2.7 EVALUATION OF LINEAR DAMAGE RULE

A number of methods have been proposed for evaluating the effects of cyclic loads on the fatigue life of steels. The most commonly used of these relations is the linear damage rule and it is incorporated in the Design Guide. It has been adapted for use in the creep range by combining it with the life-fraction concept based on stress-rupture. This assumes that the "damage" or percentage of useful life consumed by a given cyclic stress is directly additive to that used by a different level of cyclic stress. In addition, the assumption is made that this fraction of life used can be added directly to the fraction of life consumed by a constant stress, based on the time to rupture.

The above method provides a procedure to account for the hold-time at a given stress, but there is considerable question as to its accuracy. In addition to the above factors, it is known that frequency has a strong effect on fatigue properties. This is the same thing as saying that the strain rate is important. Similarly, the order of application of loads, as well as the difference in magnitude, may have a significant effect on the overall fatigue life.

It is recommended that a literature survey be made to obtain the available data on high-temperature fatigue with varied loading conditions, and to identify the available theoretical relations for predicting cumulative damage. Information should also be sought on environmental influences on test results.

If sufficient data are available, a critical evaluation should be made of the linear damage rule and all other methods of accounting for hold-time and other effects on fatigue life. If better methods are available, revisions should be made to the Design Guide.

If additional experimental data are needed to evaluate any of the above effects, the necessary experimental programs should be outlined.

2.8 HIGH-TEMPERATURE DESIGN CRITERIA

The present status of design criteria for high-temperature piping is exemplified by the Nuclear Power Piping Code, B31.7 (12), supplemented by Code Case 1331 of the ASME Boiler and Pressure Vessel Code. A review of these codes (28) has shown that their criteria and methods are satisfactory for the types of plants to which they are applicable. In assessing their applicability to LMFBR piping systems, however, it was recognized that some difficulty would be encountered in meeting all of their requirements. In particular, the limits set by B31.7 on primary-plus-secondary stresses would present a major problem in LMFBR sodium piping by reason of the unusually severe thermal transient stresses induced by the rapid excursions in sodium temperature that have been conjectured for these systems.

As an interim measure, a distinction has been made in the LMFBR Piping Design Guide between loading conditions that are sustained and those that are purely transient. This was done in order to divorce the transient stresses from consideration of creep effects, and thereby permit the setting of limits on such stresses based on short-term tensile or ultimate strength properties, rather than on the lower creep rupture values which would otherwise have been limiting at LMFBR temperatures.

While this procedure is defensible, and appears to have met general acceptance, it was nevertheless an expediency taken primarily for the purpose of sidestepping those rules of the existing nuclear codes which were proving too restrictive. As the result of further reflection on the significance of the thermal transient phenomena, and in the light of the results of an elastic-plastic transient strain analysis (29) recently developed for the LMFBR Piping Design Guide, it has become increasingly evident that this interim procedure does not, in itself, furnish all that is needed to meet these conditions. It is now clear that a whole new approach to high-temperature design is urgently needed, if only to meet the very special problems of LMFBR sodium piping. If such a new approach should also provide a more satisfactory basis for high-temperature design in general, then so much the better.

The deficiencies in existing criteria for coping with LMFBR sodium piping design conditions lie in their inability to account properly for the interdependence of transient and creep effects upon each other. The state of stress and strain due to these effects is strongly dependent upon the prior loading history at the point of interest. Predictions of plastic or creep strain accumulations are governed by considerations of strain hardening, hold-time, previous deformation, residual stress patterns and their subsequent relaxation, as well as by the stress-vs-strain and creep strain characteristics of the material at temperature. All of these factors must play a part in the formulation of appropriate criteria and analysis procedures.

2.8 HIGH-TEMPERATURE DESIGN CRITERIA Continued

The proposed R&D task to develop a satisfactory high-temperature design criteria for LMFBR piping comprises the following steps.

- 1) Make a critical evaluation of existing code philosophy with regard to the definition of secondary stresses, with special attention to its applicability to the thermal transient stresses in LMFBR systems.
- 2) Conduct an intensive literature survey in an attempt to establish a relationship between residual stresses and creep strain rates in a multi-axial reference frame. This subtask will also entail personal contact with organizations and individuals now working in related areas, since it is probable that recent work may be as yet unpublished.
- 3) In consultation with others having an expertise in the general field of high temperature phenomena, formulate a unified design basis which takes proper account of all the identified contributing factors.
- 4) In areas where substantive data or qualitative information is lacking, draw up a test program for obtaining it.
- 5) Publish the findings of the subtasks enumerated above, and circulate for review. Consolidate review comments, resolve differences, and incorporate in Design Guide.

2.9 PRESSURE ANALYSIS OF PIPING COMPONENTS

The failure of pipe and piping components from excessive general and local primary membrane stresses is prevented by the provision of an adequate pipe wall thickness, utilizing appropriate stress indices to account for structural discontinuities. In conventional nuclear systems these methods have proven satisfactory, and any overconservatism has been of no great concern. In LMFBR piping systems, the provision of excess wall thickness is an embarrassment because it will result in higher thermal stresses, and hence increase the danger of failure from low-cycle fatigue. On the other hand it remains of paramount importance that full protection against primary failure be maintained. As a result, an optimum pressure analysis procedure must be developed for all LMFBR piping components. This task may be approached in the following manner.

2.9.1 EVALUATION OF EXISTING PROCEDURES Stress indices are now being developed for some piping components under a continuing program sponsored jointly by AEC and PVRC at ORNL and elsewhere. This work is in support of the present nuclear vessel and piping codes, and the constraint on overconservatism has not been a matter of concern. The procedures so far developed under this program must first be evaluated to assess their applicability to LMFBR piping. Means must then be sought to modify them if they are found to lead to excessive pipe wall thicknesses.

2.9.2 DEVELOPMENT OF NEW PROCEDURES Since the stress index program referred to in 2.9.1 has not yet been completed, the work remaining to be done could perhaps be modified or extended to consider the special needs of LMFBR piping components. Alternatively, a separate program could be initiated specifically for LMFBR piping components. In either case, the program would involve the experimental testing of prototypical components under LMFBR loading conditions, directed towards the establishment of empirical, and at the same time optimum, design formulas.

2.9.3 FINITE ELEMENT METHODS As a subtask under this R&D program element, it is recommended that a survey be made of recent developments in finite element analysis methods, to ascertain their suitability as a design tool for LMFBR piping components. Since these methods take discontinuity stresses directly into account, the development of stress indices becomes unnecessary, thereby removing a potential source of overconservatism.

2.9.4 DEVELOPMENT OF UNIFORM PROCEDURES The results of the three subtasks described above should be further studied and correlated, with the object of attempting to define uniform pressure analysis procedures for all pressure-containing piping components. If this ideal objective is unattainable then, alternatively, uniform procedures should be sought for as many different components as may prove amenable to such treatment.

2.10 DESIGN OF PIPING COMPONENTS

In Paragraph 2.9 a task was outlined for developing pressure analysis procedures for LMFBR pipe and piping components, with the object of affording adequate protection against primary failure. It was pointed out, however, that excessive wall thicknesses can be detrimental because they lead to higher thermal stresses. For some components the optimization of pressure analysis methods will still leave unresolved the problem of designing them to meet the severe secondary and peak stress conditions to be encountered in LMFBR systems. The problem is particularly acute in components having complex asymmetric geometries, or profiles where local thickening of the wall cannot be avoided. The task to be described in this section is aimed at the further development of such components, to establish design procedures for meeting secondary and peak stress limitations in an optimum manner, without sacrificing their adequacy for primary loadings.

2.10.1 PIPE INTERSECTIONS The methods traditionally employed for compensating for the material removed from the main run of a pipeline at a branch connection, have involved reinforcement of the opening by concentrating additional material in the vicinity of the crotch. These methods frequently introduce sharp discontinuities, and are the site of high stress concentrations. In LMFBF piping, thermal transient conditions further aggravate the problem. While the requirement for reinforcement at pipe intersections cannot be avoided, the careful contouring of the reinforcement material, whereby sharp discontinuities are eliminated and the additional material is distributed over as wide an effective area as possible, will do much to lessen the stress concentration.

Another solution to the problem appears to lie in the provision of thermal shielding in the vicinity of the branch connection, so designed as to arrest the thermal transient effect. Economic considerations make this solution undesirable, but there may be no alternative in large size, heavy wall pipe intersections.

This task would comprise a detailed study of branch connection profiles, to establish optimum design procedures for the range of pipe sizes and wall thicknesses for which reinforcement methods can be utilized without resorting to thermal shielding. The study would involve the use of finite element analysis methods to establish suitable geometries, combined with a testing program to verify the adequacy of the design procedures. For the latter purpose the use of a sodium test loop is recommended, although photoelastic or other suitable model test methods could also be employed.

2.10.2 INSTRUMENT CONNECTIONS The provision of small connections on the pipewall for the attachment of various instrumentation devices presents problems similar to those discussed in 2.10.1 above except that the effects are more localized. Again, the problem is primarily one of establishing optimum profiles for the connection, to avoid sharp discontinuities.

As a minimum effort, it is recommended that an analytical study of existing instrument connection design practices, including the use of proprietary fittings, be carried out to determine their suitability under LMFBF transient conditions. If such a study should show them to be inadequate, then a development program should be instituted to seek alternative methods of attachment, and recommend appropriate design procedures.

2.10.3 SUPPORT ATTACHMENTS The attachment of structural elements to the outside surface of the pressure-containing wall of LMFBR piping, for the purpose of connecting pipe supports, sway braces, vibration dampeners, and the like, is another potential source of severe stress concentration aggravated by thermal transient conditions.

A sample design problem of this type is being developed for inclusion in Volume II, Chapter 3 of the LMFBR Piping Design Guide. Upon its completion it may be expected to point the way towards a more general design procedure. It is recommended that this work be expanded to embrace the development of design procedures for a variety of suitable structural attachments capable of carrying a range of loads sufficient to meet most LMFBR piping requirements. These procedures would then be used to establish a range of standard attachments, as described in Paragraph 4.5.

2.10.4 THERMAL SHIELDING As was mentioned in Paragraph 2.10.1, one proposed solution to the problem of protecting the pressure-containing wall of LMFBR sodium piping systems from the effects of severe thermal transients is the provision of an internal shield or baffle, so designed as to arrest the progress of the thermal shock radially through the wall. Such a shield might take the form of a series of thin concentric cylindrical sleeves of stainless steel, separated from each other by spacers, with stagnant sodium filling the annular spaces between them. The baffles would be accommodated within a swaged out portion of the pipe local to the region where protection is required.

From the very limited data accumulated so far, it appears initially that the concept has promise. There are, however, some unresolved questions concerning the performance and structural integrity of the baffles under operating conditions. Answers to these questions are urgently needed.

It is proposed that a high-priority R&D program be initiated to further explore the feasibility of thermal shielding and to obtain much-needed design data. The program should be addressed to the following.

- 1) Structural integrity - analysis to demonstrate that shielding can sustain the imposed cyclic transient loads.
- 2) Minimum dimensional data - thickness of baffles, annular spacing, and number required. Length-to-diameter ratios should also be developed.
- 3) Performance characteristics - effective conductivity of selected configurations under typical LMFBR transient conditions.

2.10.4 THERMAL SHIELDING Continued

- 4) Performance verification - test program to evaluate performance, locate structural weaknesses, and verify analytical predictions.

2.10.5 MIXING TEES When two streams of liquid sodium at markedly different temperatures are joined in a piping system - e.g., at the point of reentry of a bypass line around a heat exchanger (IHX, or steam generator) - provision must be made for the extremely severe thermal transient conditions experienced in the immediate vicinity. High fluid velocities and accompanying turbulent flow patterns lead to rapid, random fluid temperature perturbations at the inside surface of the pipe wall, resulting in high-frequency cyclic thermal stresses. Since these conditions take place in the locality of a branch connection, which is inherently more susceptible to such conditions than any other structural component in the piping system, special attention must be paid to its design.

The present status of the formulation of suitable design procedures for mixing tees is essentially the same as that for thermal shielding. Since the mixing tee will require thermal shielding, the further development of mixing tee design is closely dependent upon the development of the latter. It is recommended that an R&D task be initiated in parallel with that for thermal shielding, or as an extension to it. In addition to establishing the performance characteristics of the thermal shielding, the task would be directed towards setting both the upper and the lower limits upon their applicability - i.e., the maximum as well as the minimum temperature differences between two converging sodium streams for which mixing tees must be designed.

2.11 ELASTIC-PLASTIC TRANSIENT AND CREEP ANALYSIS

2.11.1 ELASTIC-PLASTIC ANALYSIS OF ELBOWS In Task 610, a computer program (HANSEL) was prepared for performing an elastic-plastic analysis of a straight section of pipe for the effects of thermal transient loadings combined with other primary and secondary loads. The program computes the true stresses, accumulated plastic strains, and equivalent elastic stresses, for a selected number of points through the pipewall. An analysis is now required to obtain similar information about the behavior of elbows under transient conditions. This is regarded as an essential second step towards the ultimate goal of developing an elastic-plastic flexibility analysis of a piping system comprising an assembly of straight pipe and elbows.

2.11.1 ELASTIC-PLASTIC ANALYSIS OF ELBOWS Continued

The elastic-plastic analysis of an elbow presents a problem an order of magnitude more difficult to formulate than was the case for the straight section of pipe. In the latter a one-dimensional plane-strain solution was achieved, but for the elbow a three-dimensional solution appears desirable.

There are several ways in which this problem might be initially approached, each having advantages and disadvantages of its own. In making a selection, a trade-off has to be made between them in which the relative costs of formulation, programming, debugging, verification, and computer running-time must be factored.

The following candidate methods should be considered.

- 1) Finite element method
- 2) Equivalent force method
- 3) Directed unified vector method
- 4) Stiffness method

Before a final choice can be made, the governing equations of the candidate methods must first be examined, to determine whether closed form or numerical solutions to them are feasible and practicable, and whether they are inherently capable of yielding solutions compatible with the desired results.

The selected analysis must conform to the following analysis specification.

- 1) INPUT Input to the analysis shall consist of the state of plastic strain and residual stress resulting from previous loading cycles, at selected stations in the elbow - initially these would be zero, but may be nonzero after a succession of transient and steady-state operating conditions have been experienced. The analysis shall account for radial thermal gradients and external loads due to pressure, deadload, and thermal expansion. Pressure, deadload, and expansion loadings may be assumed to be constant for the duration of the transient. Additionally, the temperature distribution at each station, as a function of time and computed by other means, must be introduced.

2.11.1 ELASTIC-PLASTIC ANALYSIS OF ELBOWS Continued

- 2) ANALYSIS Starting with a predetermined set of initial conditions, the analysis shall follow the transient cycle, taking into account the strain-hardening properties of the material. The analysis shall account for all temperature-dependent variables. These are stress-vs-strain, elastic modulus, Poisson's ratio, and expansion coefficient. The analysis may assume that the wall thickness around the elbow is uniform.
- 3) OUTPUT The plastic deformations, residual stresses, and equivalent elastic stresses, must be reported at each station.

It should be anticipated that the elastic-plastic elbow analysis, and that for the straight sections of pipe, will play a vital role in the formulation of appropriate high-temperature design criteria. Close liaison between the organizations and individuals working in these areas is essential.

2.11.2 ELASTIC-PLASTIC FLEXIBILITY ANALYSIS The methods at present used to compute the input stresses - flexibility analyses, and thermal stress analyses - are based on the assumption of purely elastic behavior. However, the procedures now developed for the elastic-plastic transient and creep strain analysis are amenable to further extension, making elastic-plastic flexibility and thermal stress analyses achievable objectives. As a third step in the development program, a solution should be sought to the more general problem of the elastic-plastic flexibility analysis, by treating the piping system as an assembly, or network, of straight and curved members having stiffness characteristics determined from the analysis of each individual component as outlined above.

It is strongly recommended that these objectives be urgently pursued.

2.12 DEVELOPMENT OF INSTABILITY ANALYSIS PROCEDURES

Based on studies previously carried out under this contract (13), a limited R&D program is recommended to establish whether the failure of LMFBR piping - particularly at elbows - from buckling due to instability under multiaxial loading is a possible eventuality. If such an investigation yields positive results, then a more detailed program should be undertaken to determine appropriate design limits, together with analytical methods to ensure they have been maintained.

2.12 DEVELOPMENT OF INSTABILITY ANALYSIS PROCEDURES Continued

Since no failures of large piping components from instability appear to have been recorded, and in view of the relatively compact nature of LMFBR piping configurations, such an eventuality seems unlikely. Nevertheless, an investigation should be made to establish with certainty whether this is the case, by more clearly defining the conditions giving rise to instability failure.

2.13 MODEL TEST METHODS

2.13.1 PHOTOELASTICITY Photoelastic methods for determining three-dimensional, time-dependent stress distributions resulting from creep in piping components are not well developed. An R&D program is required to extend existing methods into this domain and to establish their accuracy. The following research and development should lead to viable test methods for model testing of piping components under creep conditions.

- 1) A survey of available plastic materials should be made to identify the materials having creep properties similar to those of the candidate piping materials.
- 2) Tests, such as uniaxial tensile, should be performed to characterize completely the time-dependent optical and mechanical creep properties of the identified plastics for both transmitted and scattered light.
- 3) Studies should be conducted to establish techniques for fabrication of piping geometries and to establish proper adhesives for bonding parts or imbedding polariscopes.

2.13.2 RESISTANCE STRAIN GAGES The use of resistance-type strain gages to monitor the structural behavior of complex structural configuration under "in situ" loading and thermal conditions promises to be an extremely valuable tool. At this point in time, resistance-type strain gages cannot be used at LMFBR temperatures for any significant period of time. In order to overcome this shortcoming, additional work is necessary to develop a strain gage which will be stable in this environment. It requires the development of the gage itself, quantitative determination of gage behavior so that known and understood thermal corrections can be applied, and the development of application techniques.

It should be noted that, despite the limitations mentioned above, a significant amount of the experimental stress analysis of components that has been recommended elsewhere in this report can meanwhile be carried out, at temperatures below 900 F, using commercially available gages.

2.13.3 HOLOGRAPHIC INTERFEROMETRY Recent developments in the application of holographic interferometry, such as the use of pulsed lasers operating in the nanosecond regime, appear to make this method of more immediate interest to the LMFBR program. It is recommended that a limited study task be initiated to determine whether the technique is capable of accurately predicting simple uniaxial stresses in pipe sections. Verification can be obtained directly by other proven methods of strain measurement. If affirmative results are obtained, then additional studies would be recommended to establish the capabilities of holography in more complex strain fields.

2.14 NEUTRON RADIOGRAPHY In Technical Report 243, on LMFBR In-Service Surveillance Methods (29), reference was briefly made to the potential use of nuclear methods for displacement measurements and crack detection. At the time that study was made there was insufficient evidence to support any positive recommendations for further work. Since then, neutron radiography has been demonstrated to be a highly effective nondestructive testing technique (30 - 33). Accordingly, it is now recommended that this subject be investigated more thoroughly.

It is proposed that a comprehensive literature survey be made to ascertain any limitations or restrictions to the use of neutron radiography in the LMFBR environment, in the light of operating experience with this technique to date. If further experimental verification of the method subsequently appears desirable, an appropriate testing program will then be formulated.

3 FIRST PRIORITY LONG-TERM INVESTIGATIONS

3.1 CREEP BEHAVIOR OF PIPING COMPONENTS

The most pressing requirement is to perform evaluations of experimental data to establish the validity of presently available analytical methods which include the effects of creep, plastic cycling, and ratcheting. Experimental data to perform such evaluations are meager. The Pressure Vessel Research Committee (19) had four cylindrical vessels with spherical heads tested in creep, but to date there has been no attempt to calculate the stresses and deformations either analytically by hand or with the digital computer. Membrane shells of constant stress ratio were tested by Gemma, Rowe, and Spahl (20). They also gave some analytical results which, unfortunately, did not agree very well with their experimental data.

A method was developed by Corum (21,22) for putting the instantaneous and creep buckling characteristics of initially out-of-round tubes subjected to lateral external pressure. Both the critical pressure causing collapse and the deformation of a tube at the instant of impending collapse may be determined by the method. The method was used to predict the instantaneous and creep buckling characteristics of a series of 8.0-inch OD, Type 304 stainless steel tubes that were collapsed at a temperature of 1200F. Although the experimental tests did not represent an adequate sample, the instantaneous collapse pressure agreed closely with the predicted values, and the time-dependent collapse test results substantiated the observation that the theoretical creep-collapse predictions become increasingly conservative with time. Based on the work of Hoff et al (23) and Ellington (24) on the creep buckling of tubes under external pressure, Glukler, Passig, and Huchel (25) derived equations to predict the increase in ovality of fuel element cladding under external pressure. The authors indicate that the results of autoclave tests at 1250F and 2700 psi on seamless Inconel tubes were in satisfactory agreement with theory.

3.1.1 EVALUATION OF ANALYTICAL AND EXPERIMENTAL METHODS

It is recommended that a critical comparison between predictions of various analytical methods and available experimental methods be made. The results of the study should include recommendations for obtaining additional data to substantiate prediction methods.

3.1.2 EXPERIMENTAL PROGRAM

The analytical study should be followed by an experimental study in which representative geometries and loadings are tested in the creep range, and under conditions of plastic cycling. The computed and measured results then can be compared in order to resolve questions of the validity of analytical methods.

3.3 CREEP AND STRESS-RUPTURE IN A MULTIAXIAL STRESS FIELD

Continued

A comprehensive study of creep damage would need to consider creep under simultaneous changes of load and temperature, including random reversals of stresses in each of the three principal stress directions. Other pertinent factors would include the type and extent and type of defects, residual stresses, initial surface conditions, and progressive surface attack and alloy depletion during exposure to creep. However, to achieve a program of manageable scope, some of the variables must be substantially eliminated or considered over a narrow range. It is proposed that the tests be conducted at one temperature, which would represent many operations where the temperature is not changed deliberately, and remains within reasonably narrow limits for extended time periods. Standard pipe sections will be used, which will provide surface conditions typical of those to be expected in service. Variations in surface finish and wall thickness may require some duplication of tests to minimize effects of scatter from these sources. Test specimens will be of sufficient size and tested at a moderate enough temperature to minimize influence from oxidation of the exposed surface.

3.4 THERMAL CONDUCTIVITY OF 2 1/4 CR-1 MO

Values given in Table A-7, Volume II of the Design Guide for the Thermal Conductivity of 2 1/4 Cr-1 Mo are different from those shown in current codes by a factor of 2. In view of this discrepancy, it is recommended that sufficient investigation be made to verify the new values and that the results be reported to interested Code Committees.

4 SECOND PRIORITY INVESTIGATIONS

4.1 LOW TEMPERATURE IMPACT BEHAVIOR

There are limited data available concerning the effect on impact behavior of long-time exposure of piping material at LMFBR temperatures. The existing data indicate a severe reduction in the room temperature toughness of 316 SS after exposures up to 60,000 hours at temperatures to 1500 F. These data should be supplemented to determine impact behavior after exposures up to 100,000 hours at temperatures between 900 F and 1200 F. Of particular interest is the impact behavior at shutdown temperatures between 300 F and 400 F of base materials and welds, since it is in this temperature range and above that shock loading can have serious consequences.

The recommended R&D effort will provide for exposure of base materials, similar metal welds and dissimilar metal welds at temperatures and times compatible with LMFBR requirements. The test program will be designed to verify existing data and to extend these data for the samples tested to temperatures of primary interest in LMFBR design.

The test program will be supplemented by an analytic effort to correlate the data and to provide information in a form of maximum usefulness to designers.

4.2 INTERGRANULAR ATTACK

The expression for corrosion allowance given in the LMFBR Piping Design Guide includes a constant term to account for intergranular attack. This term was included because GE loop tests had shown such attack to occur in the cross-over piping between heater leg and cooler leg in both monometallic and bimetallic systems. Because the location in which it was found corresponds to hot leg piping in LMFBR systems, it is important that an effort be made to determine whether LMFBR conditions are conducive to such attack.

The recommended R&D effort requires corrosion testing in a facility which simulates LMFBR conditions. The test program should be designed to permit the determination of the factors that lead to intergranular attack and the measures required to limit or prevent it. It should be noted that insulation materials also contribute toward intergranular attack on pipe surfaces, and there is a need for testing of insulation in service.

4.3 DEVELOPMENT OF IMPROVED MATERIALS

4.3.1 EVALUATION OF STABILIZED AUSTENITIC STAINLESS STEELS

Exposure of Type 304H and 316H stainless steel to sodium at LMFBR temperatures in monometallic nonisothermal systems leads to decarburization of hot leg piping. This may result in degradation of mechanical properties if the carbon level is reduced to L-grade levels. The addition of elements which form highly stable carbides prevents re-resolution of the carbides in the steel, which in effect reduces the carbon activity in the steel. A reduction of carbon activity may prevent or reduce the decarburization. For example, Types 347 and 321 stainless steel contain columbium and titanium, respectively, as additives. Since they form highly stable carbides, these steels may be more resistant to decarburization than the 304 SS and 316 SS steels.

The recommended R&D effort would require the exposure of stabilized stainless steels to sodium under LMFBR conditions to determine whether they are more resistant to decarburization. The test program would be supplemented by appropriate chemical and interpretive analytical efforts to establish and correlate the data and to determine their significance. If the results show promise for one or more of these materials, and R&D program must be undertaken to confirm their suitability on the basis of other considerations, for example weld characteristics, and to establish design criteria.

4.3.2 EVALUATION OF STABILIZED 2 1/4 CR-1 MO STEELS

Exposure of ferritic alloys to sodium at LMFBR temperatures in bimetallic systems leads to the decarburization of those alloys and carburization of the stainless steels. The loss of carbon can result in severe degradation of mechanical properties. Stabilized low-chromium ferritic alloys, which are in commercial use in other countries, may provide the required resistance to decarburization.

The recommended R&D effort will require the testing of stabilized ferritic steels in bimetallic systems under LMFBR conditions and comparison of the behavior with normal 2 1/4 Cr-1 Mo steels. The test program will be supplemented by appropriate chemical and interpretive analytical efforts to establish and correlate the data and to determine their significance.

A long-term approach is needed to assure that the desired material will become commercially available and receive code acceptance, as long as steam generator designs with ferritic steels are being considered. If the plans for using such steels in steam generators are changed, the major incentive for the use of ferritic steels in sodium piping would be eliminated.

4.4 DYNAMIC ANALYSIS PROCEDURES

Technical Report 237, A Study of Dynamic Analysis Methods as Related to LMFBR Piping Systems, describes several types of transient loading conditions that may be imposed. General solutions are indicated along with the mathematical analysis usually applied to the solution of such problems. Further development is needed of specific solutions to these loading conditions to assure adequate design.

4.4.1 HYDRAULIC PRESSURE SURGES Very high pressures of short duration may be generated by sudden changes of sodium velocity due to a valve closing, a sodium-water reaction in the steam generator, or other such normal or abnormal operating conditions. A theoretical method of analyzing these conditions has been outlined in Technical Report 237, A Study of Dynamic Analysis Methods, (9) but further analytical and experimental development is required to establish actual boundary conditions for the various geometries and materials involved.

This topic should probably be divided into two phases.

- 1) An analytical, or study phase, including a review of pertinent literature, in which necessary experimental work would be outlined.
- 2) Experimental testing, which might be to determine necessary physical constants, or to verify the results of theoretical evaluations.

4.4.2 EXTENSION OF DYNAMIC ANALYSIS METHODS The present recommended dynamic analysis procedures in the Design Guide are based on analysis of a lumped parameter system. Preparation of a finite element beam model program, or utilizing a currently available program, embodying the consistent mass matrix and consistent forcing vector, is identified as a development requirement. It is recommended that trial runs be made using the SAMIS program, some of which might be accomplished during the test of the Design Guide.

4.5 DEVELOPMENT OF STANDARD COMPONENTS

The complexity of the analytical methods which must be used to establish the compatibility of piping component designs with the various design criteria of the LMFBR Piping Design Guide requires much costly and time-consuming effort on the part of the designer. While it is clearly undesirable to limit the designer in his choice of permissible components, and thereby restrain him from seeking novel and more satisfactory solutions to special problems as they arise, it is considered essential that standard geometries be established for those components which he will frequently need to use.

4.5 DEVELOPMENT OF STANDARD COMPONENTS Continued

Many such components - e.g. elbows, tees, wyes and laterals, instrument connections, and certain special design features such as thermal shielding, pipe support attachments, and mixing tees - are either not available in the full range of sizes likely to be needed for LMFBR piping systems, or do not possess the most desirable profiles for meeting the design conditions, particularly thermal transient stresses.

The objective of this program, which is a logical extension to the first priority short-term task described in Paragraph 2.10, would be to establish optimum standard geometric properties, fabrication specifications, and other desirable design parameters, for a full range of such components. These would then be verified by a testing program wherein representative samples of each would be fabricated to the applicable dimensional tolerances, and then subjected to a comprehensive series of tests under LMFBR service conditions in an appropriate sodium test facility.

4.6 DEVELOPMENT OF LEAK DETECTION DEVICES

Published literature on detectors and the methods of detecting leaks is presently limited, as revealed during the study of in-service surveillance methods (10). If new, better performing devices are developed, some emphasis should be given to publishing this information in sufficient detail. More performance and design information is desirable on present-day detectors.

The complex devices have possibilities of improvement and reduction of manufacturing costs. Simple devices, like single or double wire resistance detectors and level detectors cannot be reduced in cost very much, but optimum design specification and standards of construction would be valuable. These simple detectors should be optimized with regard to sensitivity, response time, and reliability. Correlation with more data is required before this can be accomplished.

Based on this survey, efforts toward the following are considered useful for the advancement of sodium leak detection.

- 1) Development of simple, inexpensive detectors which would be more effective on vertical piping
- 2) Improve the response time and reliability of present detectors
- 3) Define and publish design standards after various designs are optimized

4.7 DEVELOPMENT OF PREHEATING METHODS

Studies of preheating methods conducted during the preparation of the LMFBR Piping Design Guide have been published in a Technical Report (27). The study revealed certain deficiencies in the preheating methods developed to date, and pointed up the need for further investigation. This task is therefore concerned with seeking means for improving the reliability of existing preheating methods, establishing design practices and minimum operational standards, and recommending areas where additional development might be warranted.

4.7.1 DETERMINE OPERATING CHARACTERISTICS Representative samples of proprietary and custom-made preheat systems of several types would be installed in a suitable test facility in which liquid metal service conditions may be effectively simulated. The types of preheat system recommended for investigation are as follows.

- 1) Electrical resistance
- 2) Fluid tracing
- 3) Radiant heating
- 4) Electric blanket
- 5) Annular fluid heating

The test program to which the selected systems would be subjected would determine their operating characteristics. In particular, a critical evaluation would be made of the following.

- 1) Conformance to specification
- 2) Performance
- 3) Behavior under adverse environmental conditions
- 4) Service life
- 5) Service limits
- 6) Accessibility
- 7) Maintainability
- 8) Controllability

4.7.2 EVALUATE RELIABILITY The results of the test program outlined above would then be evaluated to establish the relative reliability of each system, and to determine whether their performance accords with the stringent requirements of LMFBR systems. Where improvements appear to be needed, specific recommendations would be made.

4.7.3 DEVELOP DESIGN PRACTICES AND MINIMUM STANDARDS Based on the critical evaluation of the test program results, a definition of the minimum design standards and performance requirements would be made.

4.8 FABRICATION AND INSTALLATION STANDARDS

The following problems have been identified (11) as requiring further study before incorporation in the Design Guide as acceptable for LMFBR systems. There are solutions to the problems, and a limited amount of experience in these areas, and it is anticipated that the principal effort will be to select limits and procedures which are satisfactory after evaluation of available data.

4.8.1 HELIUM MASS SPECTROMETER LEAK TEST STANDARDS Tentative limits have been set for the sensitivity of the helium mass spectrometer at 5×10^{-9} cc/sec, and for permissible helium leaks at 1×10^{-7} atm cc/sec for a sodium system. Study of experience in this field might serve to verify this limit as a realistic value or to modify it as necessary.

4.8.2 PRESSURE TEST METHODS Pneumatic and hydrostatic testing are discussed in the above reference report, and also various fluids for hydrostatic testing. In the preliminary Design Guide Draft pneumatic testing is specified. A study might indicate acceptable alternatives which might be more applicable to some systems.

4.8.3 SURFACE AND INTERNAL DEFECTS Tentative specification has been made of inspection methods and acceptance standards in accordance with B31.7. (12) Studies should be made to determine and evaluate the effect of such defects on the fatigue life of LMFBR components, and also any effect on other modes of failure. Some of these evaluations might be made in conjunction with testing the Design Guide on a typical piping configuration.

4.9 CLEANING METHODS

The most practical method for cleaning the installed system was found to be by circulating sodium through the system and using its deoxidizing properties as a final cleaner. If extreme care is taken in cleaning and installing the spools, this should prevent an unacceptable impurity load for the sodium purifying system.

Development and testing might determine a more effective method.

5 INVESTIGATIONS OF PERIPHERAL INTEREST

5.1 SODIUM CORROSION ALLOWANCE AND DEPOSITS

5.1.1 SURFACE REMOVAL RATES The metal loss rates in Figure A-10 of the Piping Design Guide are related only to oxygen level and sodium temperature. There is conflicting evidence of additional effects such as velocity, system temperature differences, position downstream, and their interactions. In addition, there may be a size effect related to hydraulic diameter (Reynold's number).

The recommended R&D effort would require corrosion testing in a facility which simulated LMFBR conditions. The test program should be set up to permit the measurement of metal loss rates as a function of the secondary variables enumerated above, singly, in combination with each other, and in combination with the primary variables, oxygen level, and temperature. The test program should be supported by an analytic effort to correlate the data.

Priority development of this data is not considered essential because it is anticipated that the effects of the secondary variables, which themselves are relatively small for sodium piping will not significantly affect verification of the Design Guide.

5.1.2 SURFACE DEPOSITS In nonisothermal sodium systems mass transfer deposits will build up in cold leg locations. How these deposits will affect the pressure losses in large diameter pipe is not known, but this information would be important if high sodium velocities in the cold leg are utilized to reduce piping costs. In the recommended R&D effort the distribution of deposits and their effects on surface roughening would be investigated. Consideration would also be given to the effect of deposits on heat transfer coefficients.

This effort is not considered essential because it is judged to be of minor importance for most LMFBR systems.

5.2 DUCTILE RUPTURE

As described in Technical Report 210 (Reference 1) experimental research is being done at Battelle Memorial Institute (2, 3, 4, 5, 6) to determine what size defects in typical reactor piping are required to produce unstable fracture propagation in ductile materials. These tests are being conducted on A106-B carbon steel and Type 316 stainless steel and are to be extended to Type 304 stainless. It would be useful to extend this investigation to other materials, particularly 2 1/4 CR-1 MO, for the LMFBR systems. It seems reasonable that a literature survey might add additional data to the failure stress for unflawed vessels, as well as the additional testing proposed.

5.2 DUCTILE RUPTURE Continued

The development of the data mentioned is not considered to be essential, since, in general, failure by ductile rupture is not expected to be a controlling factor in LMFBR piping. However, in the event of specific conditions of design, fabrication, or material properties, methods are available for predicting the failure stress.

5.3 BRITTLE FRACTURE

Considering brittle fracture, a need exists for applied research in the fracture mechanics area. For engineering purposes the principal research is to delineate clearly the type of engineering situations to which fracture mechanics now can be applied, and to demonstrate its applicability, within stated limitations, to a wide variety of materials and geometries.

Before fracture mechanics can be applied with confidence to the design of engineering structures, model tests should be run on simple structures such as box beams or pressure vessels, with suitable cracks of various sizes introduced, to verify the results of fracture mechanics analysis utilizing fracture roughness determinations by "standard" laboratory methods. There is a need to correlate the various methods by which fracture toughness is measured and to recommend a standard test procedure for future data.

Important parallel problems are slow crack growth preceding the onset of fast fracture under varying load conditions, particularly at high stress levels, greater thicknesses, and higher temperatures. More data should be obtained and summarized for low-alloy steels, particularly 2 1/4 CR-1 MO. This should represent normal conditions and also the effect of environment, irradiation, etc.

Research in this area is not considered essential since the conditions are limited under which brittle fracture would be a consideration in LMFBR systems.

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