2AN-781-500

PHILOSOPHY AND CRITERIA
OF THE DESIGN GUIDE FOR
LMFBR SODIUM PIPING

TECHNICAL REPORT 500

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

October 2, 1970

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.

PRELIMINARY
FOR REVIEW ONLY

1

PHILOSOPHY AND CRITERIA
OF THE DESIGN GUIDE FOR
LMFBR SODIUM PIPING

TECHNICAL REPORT 500

CONTENTS

	<u>PAGE</u>
1 INTRODUCTION	1-1
2 LMFBR PIPING DESIGN	2-1
2.1 LMFBR SYSTEM REQUIREMENTS	2-1
2.2 LMFBR MATERIALS	2-1
2.3 DESIGN CONSIDERATIONS	2-2
2.4 DESIGN REQUIREMENTS	2-3
2.5 LMFBR DESIGN CONDITIONS	2-3
3 STRESS CATEGORIES	3-1
4 PRIMARY STRESSES	4-1
4.1 BASIC STRESS INTENSITY LIMIT	4-1
4.2 ENVIRONMENTAL EFFECTS	4-3
4.3 PRIMARY STRESS CALCULATIONS	4-3
4.4 ALLOWABLE PRIMARY STRESSES	4-3
4.5 DISCUSSION	4-7
5 SECONDARY STRESSES	5-1
5.1 SECONDARY STRESS CALCULATIONS	5-2
5.2 ALLOWABLE SECONDARY STRESS INTENSITY RANGE	5-2
5.3 DISCUSSION	5-2
6 THERMAL STRESS RATCHET	6-1
6.1 SPECIAL PROVISION AGAINST RATCHETING	6-1
6.2 DISCUSSION	6-2
7 PEAK STRESSES AND FATIGUE	7-1
7.1 PEAK STRESSES	7-1
7.2 CREEP-FATIGUE INTERACTION	7-1

CONTENTS Continued

	<u>PAGE</u>
8 INELASTIC ANALYSIS	8-1
8.1 LIMIT ON TOTAL EQUIVALENT STRAIN	8-2
9 CONCLUDING REMARKS	9-1
10 BIBLIOGRAPHY	10-1

PHILOSOPHY AND CRITERIA
OF THE DESIGN GUIDE FOR
LMFBR SODIUM PIPING

1 INTRODUCTION

In October 1968, C F Braun & Co was awarded a contract by the US Atomic Energy Commission for the development and verification of a Design Guide for LMFBR Sodium Piping, with United Nuclear Corporation as a principal subcontractor. The objectives and work plan for this project are described in detail in Technical Report 100 (1).

A preliminary draft of the Design Guide was published in August 1969. Copies were distributed by Liquid Metal Engineering Center (LMEC) to a selected group of organizations and individuals for review. Their comments have been consolidated by LMEC, and the resolution of differing opinions has been achieved by further discussions with the people concerned. In the light of comments received, and with due consideration of other developments which have taken place in the intervening period, a first issue of the Design Guide is now in preparation incorporating such changes as can appropriately be made at this time. The first issue is scheduled for publication at the end of December, 1970.

This present Technical Report summarizes the philosophy and criteria adopted for the first issue of the Design Guide.

* * *

A design guide is ordinarily thought of as a manual or handbook to which the designer may refer for help in solving day-to-day problems. However, such a guide must relate to some established discipline or technology, clearly defined in existing source references, through which the guide then steers a course. In the case of the LMFBR Piping Design Guide the existing source references -- the nuclear vessel and piping codes* -- had proven on review to be inadequate. It was clear, therefore, that an appropriate source reference had first to be prepared, and Volume I of the Design Guide was written accordingly.

* The nuclear codes referred to herein are ASME Boiler and Pressure Vessel Code, Section III, Nuclear Vessels (2), and ANSI Code for Nuclear Power Piping, B31.7 (3), including all applicable addenda and Code Case Interpretations through Summer, 1970.

It has all along been clearly recognized that Volume I of the Design Guide can carry no authority within the jurisdictional framework of the ASME and ANSI nuclear codes, nor is it intended that it should. Rather, it furnishes rules supplementary to the nuclear codes, for the specific purpose of meeting the unique design and safety requirements of LMFBR sodium piping, in those areas where the nuclear codes are inapplicable or inappropriate. Utilization of the Design Guide in the design of LMFBR sodium piping that is to be code stamped in conformance with contractual or other legal requirements may not be construed as meeting the requirements of applicable ASME or ANSI Code rules. In such cases the stress report shall show that the rules of the applicable ASME or ANSI Codes have been met, and that in addition the special requirements of Volume I of the LMFBR Piping Design Guide have also been complied with.

* * *

An important clause in the contract between USAEC and C F Braun & Co required that the LMFBR Piping Design Guide was to be " ... based on the best proven technology, extrapolating as necessary and considering all other developments". It was therefore recognized from the outset of the project that the first objective was to ascertain what constituted the "best proven technology", and to determine its adequacy for designing critical LMFBR piping with the requisite degree of safety and reliability. With this purpose, studies were undertaken into all significant facets of piping engineering technology, the results of which were published in a series of Technical Reports (4-15). These reports furnished the basis upon which the preliminary draft of the LMFBR Piping Design Guide was prepared.

It is characteristic of modern technology that it is in a constant state of change. In establishing what constitutes the present state-of-the-art it is therefore necessary to be somewhat arbitrary in deciding at what point in time to cut off considerations of new developments. Faced with the contractual obligation to prepare the first draft of the Design Guide in the early Fall of 1969, the decision was taken to formulate the requirements and procedures of the preliminary draft of the Design Guide upon the methods and data -- the "proven technology" -- as they stood in mid-1969. This decision was not taken easily, for the collaborators in the project were well aware of developments in the field of high-temperature design which, though as yet lacking clear definition, will surely have a profound effect upon the contents of subsequent editions of the Design Guide, as well as upon future revisions of the ASME and ANSI nuclear codes. Furthermore, it had become clear in the course of the preliminary studies that there were some serious deficiencies in the technology, as related to the special nature of LMFBR system requirements, which could not be made good until much additional research and development has been accomplished.

A summary of the research and development needed to remedy the technological deficiencies of present high-temperature design practices has been published in Technical Report 518 (16). It covers three broad fields of interest: the establishment of new criteria; the development of appropriate inelastic analysis techniques; and the acquisition of needed data. Collectively they point to the fact that at the present time neither the technology nor the data exists to fully account for the phenomena experienced under the complex loadings conditions and creep-range temperatures which are anticipated for LMFBR primary and secondary coolant transport systems. In consequence the methods employed at present are of necessity conservative, and at the same time relatively simple. Elastic analyses are still being used almost exclusively, although inelastic behavior is a fact of life in LMFBR piping. No recognition is given to the time-dependent characteristics of elevated temperature phenomena, although it is recognized that they are significant. And long-term, high-temperature material properties data are sorely lacking.

The question now arises whether enough progress has been made since mid-1969 to justify a publication of the Guide at this time. The urgent needs of ongoing projects which utilize liquid metal piping -- in particular, FFTF and SPTF -- demand that advantage be taken of any advances that have recently been accomplished, and this in itself is sufficient incentive. While the progress that has been made is admittedly meager, and is certainly insufficient to answer all the shortcomings mentioned above, it has been significant enough to warrant its immediate implementation.

* * *

The formulation of enhanced design criteria and procedures has come in for considerable attention in recent months. Among those engaged in this activity have been the ASME Code Committees, the national laboratories, and the contractors involved in a number of LMFBR-related projects. The review of the preliminary draft of the LMFBR Piping Design Guide was carried out by people representing all these groups, and their comments rather naturally point up their own experiences and problems with existing practices. It is also rather natural that the opinions of so broad a representation, ranging from the pragmatist to the theoretician, should not always be in full agreement. Expediency has dictated that, in resolving their comments, consideration be given primarily to those recommendations which are most immediately capable of implementation. Those proposals which have not been acted upon at this time have not been ignored, nor have they been discounted.

The activities of the various groups referred to above have resulted in some important contributions to the technology, to which due consideration has been paid. Particular note has been taken of the

supplementary structural design criteria for FFTF applications, as contained in Westinghouse document FRA-152 (17), and the various interim drafts of Code Case 1331-5 prepared by ASME Subgroup on Elevated Temperature and circulated for review. Attendance at two meetings called by RDT to discuss FFTF design criteria -- at Bethesda on May 6-7, 1970, and at Germantown on July 22-23, 1970 -- provided a further opportunity to ascertain the current views of the people most intimately concerned with elevated temperature technology.

While the material presented in this Technical Report primarily reflects the views of the Braun, United Nuclear, and LMEC personnel responsible for the LMFBR Piping Design Guide, they are very ready to acknowledge their indebtedness to their friends and colleagues around the country, collectively representing all of the activities mentioned above, whose opinions and contributions have obviously helped to shape it.

2 LMFBR PIPING DESIGN

2.1 LMFBR SYSTEM REQUIREMENTS

Although operating conditions within various LMFBR systems will naturally differ quite widely, the LMFBR Piping Design Guide has to cater to the most severe conditions that can reasonably be expected to occur. In order to circumscribe the scope of the Design Guide, the New York Operations Office, USAEC, in its RFP dated May 7, 1968, enumerated certain general LMFBR system requirements, as follows.

- 1 Piping sizes up to 48-inch nominal diameter
- 2 Internal pressures from 10 psia to 225 psig
- 3 Liquid sodium temperatures up to 1200F
- 4 Single and multiple configurations of pipe and fittings
- 5 Radiation to 10^8 r/hr gamma field
- 6 Plant design life about 30 years (200,000 hours)
- 7 Operating cycles 1,000 to 10,000 startup and shutdown
- 8 Temperature transients
 - 1200F operating - 300 cycles at -20F/sec for 15 secs
25 cycles at -30F/sec for 10 secs
 - 800F operating - 300 cycles at -10F/sec for 30 secs
25 cycles at +25F/sec for 10 secs

Tables 3-1-I and 3-1-II, Volume 3, Components, of the LMFBR Program Plan (18) identify a much broader set of design requirements for LMFBR system components, but these all appear to fall within the bounds of the conditions listed above. This also is true of the conditions for the Fast Flux Test Facility (FFTF), except that the number of transient events is somewhat greater (19).

2.2 LMFBR MATERIALS

Following an intensive investigation (10) into the suitability of a number of potential candidate materials of construction for LMFBR piping, the materials selected for consideration in the Design Guide were limited to austenitic stainless steels, Types 304 and 316, and $2\frac{1}{4}$ Cr-1Mo alloy steel. The temperature limits on these materials are 1200F for the stainless steels, and 1100F for the ferritic alloy.

2.3 DESIGN CONSIDERATIONS

It has been stated previously that the provisions of the existing nuclear codes (2,3) are in many important respects inadequate for the design of LMFBR piping systems, and this calls for further discussion.

One significant limitation of the nuclear codes has been that of temperature. Both Section III and B31.7 have been restricted to 700F for ferritic materials and 800F for stainless steels. Code Case 1331 (20) has attempted to raise these limits for Section III to 1100F and 1200F respectively, but despite the fact that several revisions of this Code Case have been approved by ASME Council -- the current revision, 1331-4, was approved in June 1967 -- the ASME Subgroup on Elevated Temperature has continued to give the whole question of high-temperature design more searching consideration. A further revision is now being formulated which may be expected to differ markedly from the provisions of 1331-4.

A second factor, and one which tends to distinguish LMFBR piping from what may be classified as conventional nuclear power piping, is the unusually severe conditions which accompany the rapid temperature excursions which may occur in the LMFBR. These transients may attain rates of 20 to 30 degrees per second, and frequently induce stresses in the inner and outer fibers of the pipe wall well in excess of the yield strength of the material at temperature. Local plastic straining takes place, resulting in residual stress patterns quite different in nature from those caused by membrane-type yielding. High local cyclic plastic straining, in the presence of only moderate sustained membrane stresses, contributes to cyclic fatigue and to the ratchet mechanism, both of which must be considered prime failure modes in LMFBR piping, particularly at creep-range temperatures.

While adequate provision must, of course, be made for primary membrane and bending loads in LMFBR piping, it is the provision of protection against excessive secondary and peak stress effects that has called for the greatest emphasis in the formulation of Design Guide rules.

The nuclear codes have naturally addressed themselves to the problems associated with secondary and peak stresses, and Code Case 1331 has extended the code rules to creep range temperatures. In the types of plants for which the nuclear codes are intended to apply, however, severe thermal transients are not the dominant problem. It is in this respect, therefore, that LMFBR piping design procedures must depart from present practice.

2.4 DESIGN REQUIREMENTS

Within the scope of the LMFBR system requirements listed in Paragraph 2.1, and in the light of the special requirements discussed in Paragraph 2.3, it is possible to define the objectives to be met by the design rules prescribed in the LMFBR Piping Design Guide. These rules must be phrased to satisfy certain appropriate criteria, which in turn must be framed to satisfy an acceptable design philosophy.

The overriding objective, of course, is to assure the structural integrity of the piping system under all predictable conditions, to the highest degree of reliability attainable within the available technology. To this end it is deemed essential that rigorous detailed design analyses be performed on each piping system which adequately demonstrate that this objective has been met. Such analyses must satisfactorily account for all the phenomena associated with the conditions to be experienced by the piping system. While the rules of ASME Section III and ANSI B31.7 are consistent with this objective, their criteria and procedures are not, for the reason that these nuclear codes do not properly account for the unique conditions in LMFBR piping.

2.5 LMFBR DESIGN CONDITIONS

It is possible to identify several operating regimes in the LMFBR wherein different design requirements exist. These comprise various combinations of the following.

- 1 Steady-state operation at sub-creep temperatures
- 2 Steady-state operation in the creep range
- 3 Relatively slow transitions from (1) to (2), or the reverse
- 4 Rapid thermal transients at sub-creep temperatures
- 5 Rapid thermal transients in the creep range
- 6 Rapid thermal transients from a sub-creep temperature to a creep range temperature, or the reverse
- 7 Any one of the above, accompanied by a pressure transient

A histogram of the conditions hypothesized for a typical LMFBR piping system covering, say, a five-year period, might at one time or another show that all of these operating regimes might occur in virtually any sequence. Furthermore there may be numerous repetitions of any or all of them.

It will be apparent that in only the first of the regimes listed above will there be any likelihood of purely elastic behavior taking place. At creep range temperatures creep strain accumulation is unavoidable, while under rapid thermal transient conditions plastic action is inevitable -- except perhaps in small, thin-walled piping.

2.5 LMFBR DESIGN CONDITIONS Continued

The criteria inherent in present nuclear code practices are based, either explicitly or implicitly, upon strain-invariant elastic considerations. The criteria for LMFBR piping design must ultimately account for inelastic behavior and for strain accumulations, both of which infer some degree of time dependency. While the latter criteria are as yet unattainable in their entirety, progress has been made in this direction. The design philosophy and criteria presented and discussed in the following chapters reflect this progress and represent the best compromise attainable at the present time. Not until all the developmental tasks described in Technical Report 518 have been accomplished will the technological gap be finally bridged.

3 STRESS CATEGORIES

The criteria of Section III of the ASME Boiler and Pressure Vessel Code for Nuclear Vessels (21) are based upon the recognition of three distinct categories of stresses. These are,

- A Primary Stress
 - (1) General primary membrane stress
 - (2) Local primary membrane stress
 - (3) Primary membrane plus bending stress
- B Secondary Stress
- C Peak Stress

The characteristics of these stress categories are defined in Reference 21, and the rationale whereby the designer is able to determine to which category the stress induced by any given loading condition belongs is explained. ANSI B31.7 is based on the same concepts. We will now consider whether the conditions prevailing in LMFBR piping can properly be said to conform within the framework of the nuclear code rationale.

Stress categorization provides a convenient means for ensuring that adequate consideration has been given to the deleterious effects which can accompany all foreseen conditions of loading, in a simple and logical sequence. The primary and peak stress categories furnish protection against specific modes of failure, by setting appropriate limits on stress intensity or frequency of loading. The secondary stress category is intended to establish whether the structure will "shake down" to elastic action under conditions of cyclic loading, and hence validate the calculation of the ranges of stresses due to cyclic loading on an elastic basis.

To establish whether these categories are appropriate to the design of LMFBR piping, it is necessary to ascertain whether there can exist in LMFBR piping any condition of loading which might be sufficiently different, either in effect or degree, from those already covered by the nuclear codes to justify their reconsideration.

If there is such a condition of loading, it has to be the severe thermal transients, for all the other conditions -- pressure, dead and live load, thermal expansion, seismic -- are no different from those already accounted for, and are not likely to be any more severe in LMFBR piping than they are in conventional nuclear power piping.

Thermal stresses are classified by the nuclear codes as belonging to both the secondary and peak categories. Those which can produce distortion of the structure are placed in the secondary category,

3 STRESS CATEGORIES Continued

while those which result from virtually complete suppression of the differential expansion, and consequently cause no significant distortion, are classified as peak stresses.

Studies recently conducted by Braun (22) have led to the conclusion that at the severe transient rates anticipated for LMFBR sodium piping, thermal transient effects are significant only at the inner and outer pipe surfaces, and that gross distortion of the structure is prevented by the constraint of the inner fibers of the pipe wall. The failure mode primarily associated with these effects is crack initiation due to fatigue, and they thus appear properly to belong to the peak stress category. The linear thermal expansion stresses accompanying these temperature excursions clearly belong in the secondary category. And it is also necessary to take thermal transient stresses into account in considering possible ratcheting effects. Because of the severity of thermal transients in LMFBR piping, it is inevitable that the designer will have more difficulty in meeting the criteria associated with these categories than in the past, but this can be no reason for changing a well-established procedure.

In general, then, there appears no justification for modifying the basic structure of stress categorization established by the nuclear codes. If any relief can be found from any inherent over-conservatism in present practices, however, it will be to the designer's advantage, and it is in this light that the selection of appropriate criteria for each stress category has been carefully re-evaluated.

4 PRIMARY STRESSES

Reference 21 defines primary stress as "... a stress developed by the imposed loading which is necessary to satisfy the laws of equilibrium between external and internal forces and moments. The basic characteristic of a primary stress is that it is not self-limiting. If a primary stress exceeds the yield strength of the material through the entire thickness, the prevention of failure is entirely dependent upon the strain hardening properties of the material".

Stress rupture and, at elevated temperatures, creep rupture are the failure mechanisms against which appropriate provision must be made. This is accomplished by setting limits on primary stresses in terms of the yield strength or rupture strength of the material. Additionally, gross distortion short of rupture is prevented by limiting primary stresses to values such that the creep strain shall not exceed some acceptable limit over the lifetime of the system.

4.1 BASIC STRESS INTENSITY LIMIT

In the LMFBR Piping Design Guide, the basic stress intensity limit, S_m , is defined as the lowest of the following.

- (a) One third of the minimum specified tensile (ultimate) strength at room temperature. This value is derived from tensile tests of uniaxial specimens at conventional deflection rates in which the ultimate load per unit of original cross sectional area is reported.
- (b) One third of the tensile strength at metal temperature multiplied by 1.10. The elevated tensile strength is the product of the average ultimate strength at temperature multiplied by the minimum specified ultimate strength at room temperature and divided by the average ultimate strength at room temperature.
- (c) Two thirds of the minimum specified yield strength at room temperature. This value is derived from tensile tests of uniaxial specimens tested at conventional deflection rates in which the reported stress values are the ratio of the applied tensile load divided by the original cross sectional area. The definition of yield may be either (i) that stress at which the conventional (engineering) strain first exceeds the extrapolated linear strain by 0.2%; or (ii) that stress at which the conventional extrapolated strain equals 0.27% under load.

4.1 BASIC STRESS INTENSITY LIMIT Continued

- (d) Ninety percent of the yield strength at metal temperature. The metal temperature yield strength is the product of the average yield strength at temperature multiplied by the minimum specified yield strength at room temperature divided by the average yield strength at room temperature.
- (e) Two thirds of the minimum stress to cause rupture in $\bar{t}$ hours. The term "minimum" refers to the stress level which will be below 95% of the experimental data 95% of the time. The stress to cause rupture is that initial stress in a conventional constant load uniaxial tensile stress-to-rupture test which is associated with rupture of the specimen at $\bar{t}$ hours.
- (f) Eighty percent of the minimum stress to cause initiation of tertiary creep at the end of $\bar{t}$ hours. The initiation of tertiary creep is defined as that point in a conventional constant load uniaxial tensile creep test where the observed strain departs from the linear secondary creep stage by 0.20% strain. The term "minimum" refers to the stress level which will be below 95% of the experimental data 95% of the time.
- (g) The minimum stress to produce 1.0% total effective equivalent strain at the end of $\bar{t}$ hours for a constant stress type of loading. This value corresponds to the stress at 1.0% strain from an isochronous stress-strain curve. The elastic, plastic, primary creep, secondary creep, and tertiary creep strains are accounted for in the isochronous formulation. The term "minimum" refers to the stress level which will be below 95% of the experimental data 95% of the time. (The data necessary to establish this value may not be available. This factor may be ignored if the Owner agrees that the data are not currently available).

In (e), (f) and (g) above, the term $\bar{t}$ is defined as follows.

- (i) For piping that is to be code stamped, $\bar{t} = 100,000$ hours
- (ii) For piping that is not to be code stamped, $\bar{t}$ shall be the design lifetime of the component.

4.2 ENVIRONMENTAL EFFECTS

The material properties (tensile strength, yield strength, stress-to-rupture, creep rate, etc) used in the basic stress intensity limits of Paragraph 4.1 are those for normal unirradiated material. When radiation or other environmental effects may modify material properties, the basic stress intensity limits shall be downgraded to reflect material degradation due to such effects. No credit shall be taken, however, for environmental effects which tend to enhance material properties above those obtained from unirradiated specimens.

4.3 PRIMARY STRESS CALCULATIONS

In computing the intensity of primary stresses for the purpose of satisfying the primary stress intensity limits prescribed hereunder, the calculations shall be made on an elastic basis.

4.4 ALLOWABLE PRIMARY STRESSES

4.4.1 GENERAL PRIMARY MEMBRANE STRESS INTENSITY

(a) The general primary membrane stress intensity, P_m , is the average primary stress intensity computed across the section due to pressure and other specified mechanical loads, but excluding the effects of discontinuities and stress concentrations. The maximum allowable value of this stress is the basic stress intensity limit, S_m .

$$P_m \leq S_m \quad . \quad . \quad . \quad . \quad . \quad (1)$$

(b) The value obtained by summation of the life fractions associated with the general primary stress intensities for all primary design loading conditions shall not exceed 0.75.

$$\sum_i \left(\frac{t_i}{t_{im}} \right) \leq 0.75 \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where, t_i = total duration of the design loading condition during the component lifetime, $\bar{t}$

t_{im} = the allowable loading duration obtained by entering the $\bar{S}_m$ -versus-time graph for the material at temperature at a value equal to the general primary membrane stress intensity calculated for each primary design loading condition, P_{mi} . The $\bar{S}_m$ -versus-time graph for 304SS is given in Figure 4.1, and for 316SS in Figure 4.2.

FIGURE 4.1 $\bar{S}_m$ -versus-time curve for 304SS

FIGURE 4.2 $\bar{S}_m$ -versus-time curve for 316SS

4.4.1 GENERAL PRIMARY MEMBRANE STRESS INTENSITY Continued

When the intensity of stress associated with a given primary design loading condition varies with time, the corresponding life fraction summation may be evaluated by the application of Equation (2a).

$$\sum_i \left(\frac{t_i}{t_{im}} \right) + \sum_j \left[\int \left(\frac{dt}{t_m} \right) \right]_j \leq 0.75 \quad . \quad . \quad . \quad . \quad . \quad (2a)$$

4.4.2 LOCAL PRIMARY MEMBRANE STRESS INTENSITY

The local primary membrane stress intensity, P_L , is the average primary stress intensity computed across the section due to pressure and other specified mechanical loads, inclusive of the effects of discontinuities, but excluding the effects of stress concentrations. The maximum allowable value of this stress is 150% of the basic stress intensity limit, S_m .

$$P_L \leq 1.5S_m \quad . \quad . \quad . \quad . \quad . \quad (3)$$

4.4.3 PRIMARY MEMBRANE PLUS BENDING STRESS INTENSITY

(a) The primary membrane plus bending stress intensity, P_b , is the sum of the local primary membrane stress intensity, P_L , and the moment-generated bending-type stress due to local buckling effects computed across the wall of the pipe or component, P_L' . This stress category excludes the effects of discontinuities and stress concentrations. The maximum allowable value of this stress is the basic stress intensity limit, S_m , multiplied by a temperature-dependent factor, K .

$$P_b = P_L + P_L' \leq KS_m \quad . \quad . \quad . \quad . \quad . \quad (4)$$

$$\text{where, } K = 1.5 - \left(\frac{T - T_C}{200} \right) \left(0.17 + 0.33 \frac{P_L}{S_m} \right)$$

$$\text{for } T_C \leq T \leq T_C + 200F$$

$$K = 1.33 - 0.33 \left(\frac{P_L}{S_m} \right) \quad \text{for } T > T_C + 200F$$

$$K = 1.5 \quad \text{for } T < T_C$$

$$T_C = 800F \text{ for the materials covered by the provisions of Paragraph 2.2}$$

4.4.3 PRIMARY MEMBRANE PLUS BENDING STRESS INTENSITY Continued

NOTE 1 - In evaluating the moment-generated bending-type stress due to local buckling effects, the forces and moments induced by thermal expansion shall be taken into account if the component under investigation is judged to act in restraint of thermal expansion -- eg, a branch connection, and certain types of pipe supports

NOTE 2 - The values for K as defined above may be subject to change

(b) The value obtained by summation of the life fractions associated with the primary membrane plus bending stress intensities for all primary design loading conditions shall not exceed 0.75.

$$\sum_i \left(\frac{t_i}{t_{ib}} \right) \leq 0.75 \quad . \quad . \quad . \quad . \quad . \quad (5)$$

where, t_i = total duration of the design loading condition during the component lifetime, $\bar{t}$

t_{ib} = the allowable loading duration obtained by entering the $\bar{S}_m$ -versus-time graph for the material at temperature at a value equal to the primary membrane plus bending stress intensity calculated for each primary design loading condition, P_{bi} , divided by K (ie, P_{bi}/K)

When the intensity of stress associated with a given primary design loading condition varies with time, the corresponding life fraction summation may be evaluated by the application of Equation (5a).

$$\sum_i \left(\frac{t_i}{t_{ib}} \right) + \sum_j \left[\int \left(\frac{dt}{t_b} \right) \right]_j \leq 0.75 \quad . \quad . \quad . \quad . \quad . \quad (5a)$$

4.5 DISCUSSION

The provisions of Paragraph 4.4 are essentially the same as those adopted for FFTF applications in FRA-152 (17). They are generally consistent with those of the nuclear codes and their high-temperature Code Cases with respect to primary stresses, except for the inclusion of the life-fraction rules of 4.4.1(b) and 4.4.3(b). This new provision attempts to account for duration of loading, which has been recognized as having a deleterious effect on material properties at elevated temperatures.

4.5 DISCUSSION Continued

To offset the more rigorous requirements of these provisions, it is permitted to take advantage of higher allowable stresses when the design lifetime, $\bar{t}$, of a component is less than the arbitrary 100,000 hours required by the nuclear codes. It should be noted, however, that this relief may not be taken in the case of piping which is to be code stamped.

5 SECONDARY STRESSES

Reference 21 has defined a secondary stress as " ... a stress developed by the self-constraint of a structure. It must satisfy an imposed strain pattern rather than being in equilibrium with an external load. The basic characteristic of a secondary stress is that it is self-limiting since minor distortions can satisfy the discontinuity conditions or thermal expansions which cause the stress to occur".

The essential difference between a primary stress and a secondary stress, then, is in the mechanisms which induce them. Whereas a primary stress is caused by a load and is thereby stress-controlled, a secondary stress is caused by a limited deflection of the structure and is therefore strain-controlled.

Another characteristic of a secondary stress in a piping system is that it is always cyclic in nature. The imposed strain patterns therefore change from one end of a loading cycle to the other, as well as from one cycle to the next.

The nuclear codes have established limits on cyclic secondary stresses such that, when the causative loads are repetitively applied, the induced stresses fluctuate between the compressive and tensile yield strength of the material at temperature. Under these conditions the stresses can then be said to cycle within the elastic range: a favorable pattern of residual stresses is established, and "shakedown" to elastic action is attained.

The limits imposed on secondary stresses should not be thought of as providing protection against some mode of failure in the usual sense: rather, they are intended only for the purpose of ensuring that shakedown will occur, and that consequently there will be no progressive distortion, or monotonic strain accumulation, in the structure. They also serve to validate the use of elastic analysis, since elastic action is thereby demonstrated.

In the presence of creep at elevated temperatures, the residual stress patterns attained in the elastic shakedown state may be modified or erased with time. Since at elevated temperatures relaxation of stresses will occur at load levels below the yield strength of the material if the load is maintained for a sufficient period of time, it is the relaxation strength, rather than the yield strength, which dictates whether a shakedown state is reached. This is the principle on which the rules given below are based. Its rationale is further discussed in Paragraph 5.3.1.

5.1 SECONDARY STRESS CALCULATIONS

In computing the range of secondary stress intensity due to thermal expansion (ie, constraint of free end displacement), for the purpose of satisfying the criterion of Paragraph 5.2, the calculations shall be made on an elastic basis.

5.2 ALLOWABLE SECONDARY STRESS INTENSITY RANGE

The secondary stress intensity range, P_s , is the absolute value of the range of stress intensity due to a cyclic loading condition. A cycle is defined as a change in temperature, pressure, or live load, or a combination of these, from some initial value to another higher (or lower) value and back again to the initial condition. It includes the effects of discontinuities, but not stress concentrations. The maximum allowable value of the secondary stress intensity range is the sum of the relaxation strengths, S_r , of the material at the temperatures prevailing at each extreme of the loading cycle. The relaxation strengths shall be selected with due consideration for the duration for which the temperature at each extreme of the loading cycle is to be maintained.

$$P_s \leq S_{r1} + S_{r2} \quad . \quad . \quad . \quad . \quad . \quad (6)$$

where, S_{r1} , S_{r2} = relaxation strengths of the material associated with the temperatures at the "cold" and "hot" ends of the loading cycle, respectively, with due consideration for the duration for which those temperatures are to be maintained.

5.3 DISCUSSION

The significant differences between the criterion given above and those of existing practices are, (1) the introduction of relaxation into the shakedown criterion; (2) the removal of thermal transient stresses from the secondary category; and, (3) the deletion of the secondary membrane plus bending category. These innovations call for further discussion.

5.3.1 RELAXATION

Relaxation is defined as the reduction in stress in a body under load due to the replacement of initial elastic strain by plastic (creep) strain. Under constant load this phenomenon is known as creep, and the strain accumulates at a more-or-less constant rate. Under conditions of controlled strain, however, the strain rate tends towards zero as the strain condition is satisfied by relaxation, and the stresses reduce with time.

5.3.1 RELAXATION Continued

Typically, plots of stress relaxation versus time at temperatures T_1 , T_2 , T_3 , etc, are characterized by the curves shown in Figure 5.1.

FIGURE 5.1 Typical Relaxation Curves

While Figure 5.1 implies that relaxation curves may be plotted for any initial stress (time, $t = 0$), both below and above the yield strength, for the purposes of demonstrating shakedown the relaxation strengths, S_{r1} , S_{r2} , are taken from curves plotted from an initial stress equal to the yield strength of the material at temperature. At sub-creep temperatures, where relaxation effects are negligible, it will be apparent that the plot will be a virtually horizontal line, entering the stress ordinate of the graph at the yield stress, S_y .

Utilizing an idealized elastic-perfectly-plastic model of the stress-versus-strain relationship of structural materials, Reference 21 clearly demonstrates $2S_y$ as the borderline between loads which, when repetitively applied between fixed strain limits, allow the structure to shake down to elastic action every time they are applied, and loads which monotonically produce some plastic action every time they are applied. It is self-evident that some plastic action will necessarily occur at stresses between S_y and $2S_y$, and it is essential to the acceptance of this rationale that in the range between S_y and $2S_y$ a favorable pattern of residual stresses will have been established after a few load cycles, such that shakedown is assured. The theory of limit analysis gives rigorous proof of this.

Figure 5.2, which is based on a similar diagram from Reference 21, shows the strain history for a secondary stress cycle below the creep range when the elastic stress, $S_e = 2S_y$.

5.3.1 RELAXATION Continued

FIGURE 5.2 Strain History, $S_e = 2S_y$, for Fixed-Strain Cycle, $0-\epsilon_1-0$. (No Creep).

Figure 5.2 shows the initial strain cycle, from 0 to ϵ_1 and back to 0. On loading, plastic strain occurs when the yield stress, S_y , is reached (A), and ceases when the strain limit, ϵ_1 is reached (B). On unloading through the same strain range, ϵ_1 to 0, no further plastic strain is incurred, and the residual stress at the end of the cycle (C) will be $-S_y$. It will be seen that all subsequent cycles within the same, or smaller, strain ranges will be accompanied by purely elastic behavior, and no additional plastic strain will take place. Shakedown to elastic action has consequently been accomplished.

We will now consider the case where the temperature is in the creep range, and relaxation can occur at each end of the cycle, as shown in Figure 5.3(a). Depending upon the stress intensity and the duration of hold-time at the completion of loading (B), the yield stress will relax by some amount ΔS_{ra} to the appropriate relaxation stress, S_{r1} . Unloading now takes place, and some plastic strain, $\Delta \epsilon$, will be incurred before unloading is completed (D). Again, depending upon the hold-time in the unloaded state, further relaxation, ΔS_{rb} , occurs, to a relaxation stress, S_{r2} . This point (E) is now the starting condition for any subsequent loading cycle, and it will be seen that further plastic action will take place, and shakedown has not been reached.

5.3.1 RELAXATION Continued

FIGURE 5.3 Strain History in Creep Range, with Relaxation.
 (a) at $S_e = 2S_y$; (b) at $S_e' = S_{r1} + S_{r2}$

Consideration of Figure 5.3(b), however, shows that there will be an elastic stress range, S_e' ($< S_e$), and an associated strain range, ϵ_1' ($< \epsilon_1$), such that shakedown will be assured. It will be seen that this stress range must be equal to the sum of the relaxation stresses at each end of the thermal cycle, $S_{r1} + S_{r2}$. This is the limit of the secondary membrane stress intensity range, P_s , given by 5.3.2, Equation (6).

(It is to be noted that the above discussion ignores the strain-hardening characteristics of LMFBR candidate materials. If advantage is taken of strain-hardening, it can be shown in a very similar fashion that shakedown may be achieved at a somewhat higher strain range than indicated here. However, this can be effectively demonstrated only by inelastic analysis. The criterion of Equation (6) permits the use of purely elastic analyses. If some further relief is sought, the designer may resort to inelastic methods -- see Chapter 8).

5.3.2 THERMAL TRANSIENT STRESSES

As was mentioned in Chapter 3, a study has been conducted by Braun into the characteristics of thermal transient stresses (22). It was concluded from this study that the inner fibers of the pipe wall act in virtually complete suppression of radial and circumferential expansion, and that these stresses therefore more properly belong in the peak stress category.

Figure 5.4 shows the results of the thermal transient analysis of a 30-inch diameter pipe with 0.75-inch wall subjected to a transient rate of 35F/sec for 6 seconds, followed by 2F/sec for a further 45 seconds, from an initial temperature of 800F. The initial state of stress was about 10,800 psi. The graph shows equivalent elastic stress versus time at stations through the pipe wall 0.125-in apart, Station 1 being the inside surface and Station 7 the outside surface. Although plastic strains are evidenced at the inner and outer surfaces, none are seen in the middle half of the pipe wall. The peak effects have a maximum duration of less than one minute, and the effects of the transient have dissipated in less than three minutes, leaving only a small residual stress pattern.

The longitudinal thermal expansion stress associated with thermal transients must, of course, be included in the secondary membrane stress category. And the contribution of thermal transient stresses towards a possible ratcheting mechanism must also be evaluated, as discussed in Chapter 6.

5.3.3 SECONDARY MEMBRANE PLUS BENDING STRESSES

The thermal expansion loads imposed locally on components (tees, support attachments, etc) have been included in the primary membrane plus bending stress category (see 4.4.3, Note 1). There is thus no justification for considering them in the secondary stress category.

FIGURE 5.4 Equivalent Elastic Stress Versus Time
for a Severe Thermal Transient

6 THERMAL STRESS RATCHET

Under certain combinations of sustained primary stress and superimposed cyclic secondary stress, a ratcheting mechanism may result. The nuclear codes draw attention to this possibility, and Section III, paragraph N-417.3, contains a criterion for determining the maximum cyclic thermal stress which, when combined with steady-state internal pressure, will ensure that ratcheting is prevented. This criterion is not applicable in the creep range, since it does not account for the effects of stress relaxation. The criterion presented in Paragraph 6.1 below is appropriate for conditions in the creep range, and is an extension of the Section III criterion. Its derivation is discussed in Paragraph 6.2.

The criterion below is not a limit. If it cannot be satisfied, it means only that the designer is obligated to show, by inelastic analysis, either that no ratcheting will occur, or that the limit on total equivalent strain will not be exceeded (see Chapter 8).

6.1 SPECIAL PROVISION AGAINST RATCHETING

The absence of ratcheting is demonstrated if the following criterion is satisfied.

$$\bar{P}_L \leq \frac{S_{r1} + S_{r2}}{2} - \frac{\bar{P}_s}{4} - \frac{(S_{r1} - S_{r2})^2}{4\bar{P}_s} \quad . \quad . \quad . (7)$$

where, $\bar{P}_L$ = maximum local membrane stress intensity coincident with the cyclic secondary condition being investigated

$\bar{P}_s$ = secondary stress intensity range, including the stress resulting from the equivalent linear portion, ΔT_1 , of a radial thermal gradient, if any. ΔT_1 is defined in Figure 6.1 below

FIGURE 6.1

6.2 DISCUSSION

Figure 6.2 illustrates the temperature-versus-time relationship for the duration of a typical thermal transient cycle, AE. From an initial temperature of, say, 1100F, the temperature is dropped rapidly at a rate of, say, 30F/sec for 10 seconds, to 800F. After a period of time, BC, during which the temperature is held steady, the temperature is raised slowly back to the initial temperature (CD). The temperature is maintained at 1100F for a further period of time, DE, after which a new thermal cycle is initiated. The total duration, AE, represents one complete thermal cycle. It will be assumed that the pressure and live load was constant throughout the cycle, but this need not always be the case.

FIGURE 6.2

At some time during the rapid transient, AB, the temperature distribution across the pipe wall will be such as to result in a maximum value of ΔT_1 , with an actual profile similar to that shown in Figure 6.1. Although the change in fluid temperature in this case is 300F, the maximum ΔT across the pipe wall will probably be quite a bit less (say 200F), its value being a function of the wall thickness, the fluid velocity, and the thermal diffusivity of the material.

Calculated elastically, the thermal stress across the pipe wall due to ΔT_1 would be as shown in Figure 6.3.

FIGURE 6.3

6.2 DISCUSSION Continued

The maximum value of this thermal stress, σ_s , is tensile on the inside surface and compressive on the outside surface. When this elastically computed stress pattern is combined with the sustained primary stress, σ_p , the distribution pattern will be as shown in Figure 6.4(a). The net area under the curve is $\sigma_p t$ (where t is the wall thickness), and the slope of the curve, θ , is $2\sigma_s/t$.

FIGURE 6.4(a)

The distribution shown in Figure 6.4(a) will not develop if the value of $\sigma_p + \sigma_s$ exceeds the relaxation strength of the material, σ_1 , that is appropriate for the duration of the transient and the mean temperature at the time the maximum ΔT_1 was experienced. Instead, the distribution during the transient will be as shown in Figure 6.4(b). The area under the curve must remain $\sigma_p t$, and the slope of the elastic portion of the curve will remain $2\sigma_s/t$.

FIGURE 6.4(b)

Upon completion of the transient (B in Figure 6.2), the stress distribution will have again changed, to that shown in Figure 6.5. The new distribution will be the pattern of Figure 6.4(b) minus that of Figure 6.3. The area remains $\sigma_p t$, and the slope of the elastic portion is still θ . The maximum stress is now σ_2 , and this pattern will be held as the temperature slowly returns to 1100F provided that σ_2 is no greater than the relaxation strength of the material which is appropriate for the 1100F temperature and the elapsed time to the end of the cycle (E in Figure 6.2).

6.2 DISCUSSION Continued

FIGURE 6.5

During the next cycle of this same transient, the stress σ_1 shown in Figure 6.4(b) may drop to a somewhat lower relaxation value since the duration will now be twice as long as it was for one cycle. This in turn would cause σ_2 to be somewhat greater. On the other hand, strain hardening would tend to offset further relaxation. However, there is a limiting condition which is reached when the stress σ_1 drops to the relaxation strength, S_1 , that is appropriate for the mean temperature at the time the maximum ΔT_1 is experienced and the duration is the duration of the transient, AB , multiplied by the number of cycles anticipated, with the further condition that σ_2 is equal to the relaxation strength, S_2 , that is appropriate for 1100F at a duration equal to the time, DE , that the pipe is to be held at that temperature, multiplied by the anticipated number of cycles. The stress patterns for this limiting condition are represented by the two curves of Figure 6.6.

FIGURE 6.6

7 PEAK STRESSES AND FATIGUE

Low cycle fatigue is the failure mode which is of primary concern in LMFBR piping. High cyclic peak stresses induced by severe thermal transients, particularly in regions of stress concentrations such as structural or metallurgical discontinuities or notches, may be expected to initiate surface cracks which naturally present the potential for early failure.

Present code practice is to compute peak stresses by analysis, and then to determine the service life of the component by performing a fatigue evaluation. No changes in this procedure are contemplated for the Design Guide. It is, however, proposed to extend them to incorporate a procedure for taking into account the effects of creep-fatigue interaction, utilizing the provisions of FRA-152 (17).

7.1 PEAK STRESSES

A peak stress is defined as that increment of stress that is additive to the primary and secondary stresses by reason of local discontinuities or local thermal stresses, including the effects of stress concentrations, if any. The basic characteristic of a peak stress is that it does not produce any appreciable distortion, which is virtually suppressed by constraint of the section or structure. It is objectionable only as a possible source of a fatigue crack.

The peak stress intensity is derived from the highest value of the combination of all primary, secondary, and local thermal stresses, produced at any point across the thickness of a section by specified operating pressures, mechanical loads, thermal expansion, and radial thermal gradients, including the effects of gross and local structural and metallurgical discontinuities. The allowable value of peak stress intensity is dependent upon the range of the stress difference from which it is derived, and upon the number of times it is to be applied.

The stress report shall show that the evaluation of peak stress intensities, and the determination of allowable peak stress intensities, are in accordance with all applicable provisions of ANSI B31.7.

7.2 CREEP-FATIGUE INTERACTION

The stress report shall demonstrate that the life fraction summation (creep and fatigue) does not exceed the limits given hereunder at any point in the piping system.

7.2 CREEP-FATIGUE INTERACTION Continued

The limit of the creep-fatigue life fraction summation shall be obtained from the following relationship.

$$\sum_{i=1}^n \left(\frac{t_{\sigma}}{t_r} \right)_i + \sum_{j=1}^m \left(\frac{t_{\epsilon}}{t_r} \right)_j + \sum_{k=1}^p \left(\frac{N}{N_f} \right)_k \leq D \quad . \quad . \quad . \quad . \quad . \quad (8)$$

where, t_{σ} = total duration of a load which is primary in nature and thus does not relax due to plastic or creep deformation

t_r = allowable duration for the stress, σ , at temperature, obtained from Figure 7.2(a) for 304SS or Figure 7.2(b) for 316SS

$\frac{t_{\epsilon}}{t_r}$ = creep-rupture usage factor associated with a relaxing load. It may be evaluated using the integral $\int \frac{dt}{t_r}$ determined for the time-dependent stress level

$\frac{N}{N_f}$ = fatigue usage factor evaluated using the procedures of N-415.2 of Section III and the fatigue curves of Code Case 1331-4

D = life fraction summation limit, obtained from Figure 7.1

In general the creep portion of the creep-fatigue life fraction summation should be evaluated using primary plus secondary stress intensities, but ignoring peak stresses. Where elastic analysis is used the loading shall be assumed to be constant and the (t_{σ}/t_r) ratio shall be used unless experimental or analytical evidence applicable to the particular situation exists which clearly proves otherwise. It shall be assumed that compressive stresses cause damage at the same rate as tensile stresses unless other behavior can be demonstrated.

The strain concentration factor, K_{ϵ} , of Code Case 1441 shall be applied to both the creep and fatigue portions of the life fraction summation.

(a) Assumed Interaction

(b) Resulting Value of D

FIGURE 7.1 Creep-Fatigue Interaction

FIGURE 7.2(a) Values of t_r for 304SS

FIGURE 7.2(b) Values of t_r for 316SS

8 INELASTIC ANALYSIS

The emphasis in the philosophy and criteria presented in this Technical Report has been on elastic analysis, and means have been devised to extend the validity of elastic methods into the creep range. This course is judged an expedient one, because inelastic methods of analysis are not yet sufficiently developed to permit the implementation of fully inelastic criteria. It is believed that the procedures described in the preceding chapters represent the best that can be attained with today's technology. It is nevertheless also believed that only fully inelastic criteria and analysis methods will provide an entirely satisfactory basis for the design of LMFBR piping, and it is strongly recommended that the development of these methods be urgently pursued. The progress already made in this direction is encouraging, and there is every reason to expect the early attainment of this objective.

The utilization of elastic methods, however, should not be discouraged. Their inherent simplicity, their familiarity to those already experienced in piping stress analysis, their availability, and their relatively low cost, are all factors which suggest that they be used wherever possible. There will certainly be many instances in LMFBR piping design analysis where elastic methods may be used to advantage.

Inelastic analysis methods -- elastic-plastic-creep analyses which properly account for the behavior of structural materials subjected to plastic action and creep effects -- may be used as an alternative to elastic analyses in satisfying any of the criteria of the LMFBR Piping Design Guide. There is no real justification for using these means for primary stresses alone, since these must in any case remain elastic. In all other cases it may be anticipated that inelastic methods will give the designer some relief from the restrictions imposed by purely elastic criteria.

The shakedown criterion of Chapter 5, Equation (6), and the ratchet criterion of Chapter 6, Equation (7), are not limits in the usual sense of the word: they merely indicate the extent to which elastic analyses are valid. Both these criteria are actually based on concepts of strain rather than stress, and only an inelastic analysis can predict the true patterns of residual strains (and hence stresses) which exist after a component has yielded plastically. Thus in these instances inelastic analysis offers the designer the opportunity to go beyond the elastic bounds, with the possibility of proving the integrity of a structure which would otherwise have proven unacceptable.

8.1 LIMIT ON TOTAL EQUIVALENT STRAIN

In lieu of satisfying the shakedown and ratcheting criteria of Chapters 5 and 6, the structure may be considered satisfactory if the total accumulated plastic strain, expressed as effective equivalent strain (22,23), at any point does not exceed 1.0% (.01 in/in). The inelastic analysis shall show that all other requirements of the Design Guide have been met in full, including peak stress and fatigue limits, and creep-fatigue interaction life fraction summation limits.

9 CONCLUDING REMARKS

It is a matter of record that tens of thousands of piping systems have been designed, built, and successfully operated in recent years, using present-day techniques, for conditions which for the most part are at least as severe as those envisioned for the LMFBR. Higher temperatures, and considerably higher pressures, are commonplace, and the piping engineering community is well equipped to deal with them.

Perhaps the only condition unique to the LMFBR is the severe thermal transients. Unfortunately there is very little quantitative data concerning their effects, and while theoretical analyses have been developed to predict the consequences of severe thermal transients, they lack verification. A program to ascertain these consequences and obtain verifying data is urgently needed.

In the preceding chapter the recommendation was made for the development of inelastic methods, to enhance the degree of confidence which the designer can enjoy in the integrity of LMFBR piping. At the same time, the greatest possible utilization of existing elastic methods was just as strongly urged. These objectives are not in conflict, since the alternative methods must serve to complement each other. The designer should be cautioned however, that inelastic analyses will not prove to be a panacea for all his problems. Indeed, he may well find they give him no relief at all in some instances. The remedy in such cases will have to lie in his experience and ingenuity in seeking and finding engineering solutions whereby the causative conditions are removed or reduced to acceptable levels. Above all else it is essential that the prescribed loading conditions are realistically defined from the start. In particular, thermal transient rates and their frequency of occurrence must be established on a rational basis.

The development, over the next few years, of the technology needed to fill the gap between what we do know about the design of LMFBR piping and what we do not know, should be pursued in an objective fashion, following a carefully-conceived course of action addressed to solving real problems. The disorderly burgeoning of an unplanned and unneeded technology -- no matter how scientifically sound -- can only hinder the timely development of the fast breeder reactor on a commercial scale.

10 BIBLIOGRAPHY

- 1 The Development and Verification of a Design Guide for LMFBR Sodium Piping, C F Braun & Co, Technical Report 100, July 23, 1969
- 2 ASME Boiler and Pressure Vessel Code, Section III, Nuclear Vessels, 1968 Edition, ASME, New York, NY, 1968.
- 3 ANSI Standard Code for Pressure Piping, B31.7, Nuclear Power Piping, 1969 Edition, ASME, New York, NY, 1969.
- 4 LMFBR System Requirements for Sodium Piping, C F Braun & Co, Technical Report 110, October 25, 1968.
- 5 A Study of Failure Theories as Related to LMFBR Piping Systems, C F Braun & Co, Technical Report 210, January 31, 1969.
- 6 A Review of Piping Failure Experience, C F Braun & Co, Technical Report 214, March 28, 1969.
- 7 A Review of Piping and Pressure Vessel Code Design Criteria, C F Braun & Co, Technical Report 217, April 18, 1969.
- 8 A Review of Fabrication and Installation Requirements for LMFBR Piping, C F Braun & Co, Technical Report 220, June 6, 1969.
- 9 A Study of Heating and Insulation Methods for LMFBR Sodium Piping, C F Braun & Co, Technical Report 223, February 28, 1969.
- 10 A Review of LMFBR Piping Materials, C F Braun & Co, Technical Report 228, May 22, 1970.
- 11 A Study of LMFBR System Interfaces, C F Braun & Co, Technical Report 231, March 28, 1969.
- 12 A Study of Scale Model Testing Methods Applicable to LMFBR Piping Design, C F Braun & Co, Technical Report 234, May 6, 1969.
- 13 A Study of Dynamic Analysis Methods as Related to LMFBR Piping Systems, C F Braun & Co, Technical Report 237, May 14, 1969.
- 14 A Study of Instability Analysis Methods as Related to LMFBR Piping Systems, C F Braun & Co, Technical Report 240, February 13, 1969.
- 15 A Review of In-Service Surveillance Methods Applicable to LMFBR Sodium Piping, C F Braun & Co, Technical Report 243, January 7, 1970.

10 BIBLIOGRAPHY Continued

- 16 Summary of Research and Development Recommendations for LMFBR Piping, C F Braun & Co, Technical Report 518, May 1, 1970.
- 17 Supplementary Structural Design Criteria for FFTF Applications, Westinghouse Electric Corporation, Power Systems Division, FRA-152, Revision 2, July 31, 1970.
- 18 Liquid Metal Fast Breeder Program Plan, LMFBR Program Office, Argonne National Laboratory, AEC R&D Report WASH-1101, August, 1968.
- 19 HTS Piping Design Criteria, Westinghouse Electric Corporation, Power Systems Division, BDR-362, March, 1970.
- 20 Interpretations of ASME Boiler and Pressure Vessel Code, Case 1331-4, ASME, New York, NY, August 15, 1967.
- 21 Criteria of Section III of the ASME Boiler and Pressure Vessel Code for Nuclear Vessels, ASME, New York, NY, 1964.
- 22 Gascoyne, J W and G R Graves, An Elastic-Plastic Transient Strain Analysis for LMFBR Sodium Piping, Second Annual Information Meeting, Studies in Applied Solid Mechanics, ORNL, April 2, 1970.
- 23 Lubahn, J D and R P Felgar, Plasticity and Creep of Metals, John Wiley and Sons, New York, NY, 1961.