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RECOMMENDED PRACTICES IN ELEVATED TEMPERATURE DESIGN: A COMPENDIUM OF BREEDER REACTOR EXPERIENCES (1970-1986)

AN OVERVIEW[**]

B. C. Wei[*]
W. L. Cooper, Jr.[+]
A. K. Dhalla[o]

I. INTRODUCTION

Significant experiences have been accumulated in the establishment of design methods and criteria applicable to the design of Liquid Metal Fast Breeder Reactor (LMFBR) components. The Subcommittee of the Elevated Temperature Design under the Pressure Vessel Research Council (PVRC) has undertaken to collect, on an international basis, design experience gained, and the lessons learned, to provide guidelines for next generation advanced reactor designs.

The complete work consists of ten chapters and five appendices as follows:

Ch. 1. Introduction
2. Preliminary Design Procedures
3. Simplified Methods
4. Detailed Inelastic Analysis
5. Simplified Stress Classification Procedure
6. Elevated Temperature Design Codes
7. Fracture Mechanics
8. Nonlinear Collapse
9. Current Issues and Future Directions in Elevated Temperature Design
10. Summary

App. A. Breeder Reactor Components and Design Specifications
B. Capabilities of General Purpose Finite Element Computer Programs
C. Example of Detailed Inelastic Analysis of a Pressure Vessel Component
D. Example of Detailed Inelastic Analysis of a Piping System
E. Bibliography of Selected Elevated Temperature Design and Analysis Publications - 1970 and 1985

This paper shall present an overview and describe the highlights of the work. Given below are excerpts from works in Chapters 2-9.

II. PRELIMINARY DESIGN PROCEDURE

Experience in the LMFBR program has shown that, if early in the program, a viable preliminary design and analysis effort is not existent, serious technical problems might have been overlooked. When these problems are eventually recognized later, they can be most difficult, if not impossible, to solve. These problems result in cost overruns, schedule slippage, and, in the extreme, can jeopardize the success of the program. Many of these problems can be eliminated or minimized in their impact by a proper preliminary design effort.

In order to develop the preliminary design procedure for elevated temperature design, the following items are included as recommended practices:

- o Document Review
- o Developing Structural Evaluation Plan
- o Design and Analysis Guidelines
- o Load Controlled Elastic Analysis
- o Deformation Controlled Elastic Analysis

The second item will be discussed more in detail here. The purpose of the Structural Evaluation Plan (SEP) is to present the overall

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[*] B. C. Wei, U. S. Dept. of Energy, NE-54, Washington, DC, 20545, USA

[+] W. L. Cooper, Jr., Oak Ridge National Laboratory, P.O. Box Y, Oak Ridge, TN, 37831, USA

[o] A. K. Dhalla, Westinghouse Electric Corp., P. O. Box 158, Madison, PA, 15663, USA

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organizational plan used in the elevated temperature structural design and analysis. The SEP defines the necessary tasks to be performed in order to demonstrate that the component will comply with the structural and functional criteria of the Equipment Design Specification. The plan should be modified and updated as the design and analysis progress. A flow diagram for the various tasks under the SEP is shown in Figure 1.

III. SIMPLIFIED METHODS

During the last 15 years, a number of simplified or approximate inelastic structural analysis methods have been developed to evaluate the structural integrity of breeder reactor components. These methods have been effectively used: a) to optimize conceptual designs, b) to estimate design margins, c) to procure long lead structural forgings, d) to release fabrication drawings for final machining, and e) to identify critical areas for a detailed inelastic analysis. Being easy to use and less expensive than a detailed inelastic analysis, a simplified method is ideally suited to perform sensitivity studies of material and geometric parameters. The simplifications include idealization of complex geometric or material models of structural components and/or approximation of an LMFBR plant operating history. Consequently, careful selection of an appropriate simplified method is necessary for each application to avoid unconservative predictions.

This section provides a brief description of each of the simplified methods successfully used in the breeder reactor component design, and recommends correct usage by specific application examples. Verification of these simplified methods by comparison to detailed inelastic analysis and/or experimental data is also included.

The simplified methods are based upon numerical integration of classical elastic-plastic-creep differential equations formulated for an infinitely long thick cylinder and a finite length thin cylinder. These methods have been developed to accommodate the complicated mechanical and thermal loading histories encountered in breeder reactor plant operation; hence, they are applicable to LMFBR pressure vessel components whose geometries could be idealized as cylinders or cones. Typical elevated temperature failure modes investigated are: a) incremental ratchetting strain accumulation, and b) creep-rupture damage and fatigue damage accumulation due to cyclic thermal and mechanical loadings. Only geometric idealization of a thick or a thin cylinder is considered in the classical formulation.

A. Thick Cylinder Formulation

The thick cylinder formulation is appropriate to analyze a structural component which can be geometrically idealized as an infinitely long cylinder subjected to through-the-wall temperature gradient and to arbitrary time varying axisymmetric axial and pressure loads. The method is based upon an exact (classical) boundary value formulation of a thick cylinder. The two available boundary conditions at the inside and outside surfaces of the cylinder are used to solve for two basic variables which are conveniently selected to formulate two first order differential equations. The elastic-plastic-creep rate formulation is in terms of the deviatoric stress rates S_r and S_e in the radial and circumferential directions, respectively. Two basic governing differential equations are derived from the compatibility condition and the radial equilibrium condition.

1. Recommended Use of Thick Cylinder Formulation. The accuracy for design application is governed by the geometric and loading idealizations embedded in the thick cylinder formulation. The predictions are "exact" (within the bounds of numerical tolerances used in the computer program) for a thick cylinder under plane strain or generalized plane strain conditions. In design applications, the accuracy of predictions depends upon the simulated deviations from geometric and loading idealizations assumed in the thick cylinder formulation. The simplified method can be applied to structures when:

a. The geometry and loadings are axisymmetric.

b. The predominant thermal loading on the structure is through-the-thickness temperature variation, and the longitudinal variation of mechanical and thermal loading is small.

c. The longitudinal interaction between various portions of the structure is small, and the geometric variation of the simulated component is gradual.

d. The plastic regions are confined by surrounding elastic material; that is, gross through-the-wall plasticity is absent.

Conversely, the simplified method should <u>not</u> be used when:

a. The longitudinal variation of thermal or mechanical loading is significant.

b. The structural shape changes abruptly or three dimensional effects are significant. Examples include flange to shell junctions, tubesheets, and nozzle penetrations near flanged supports.

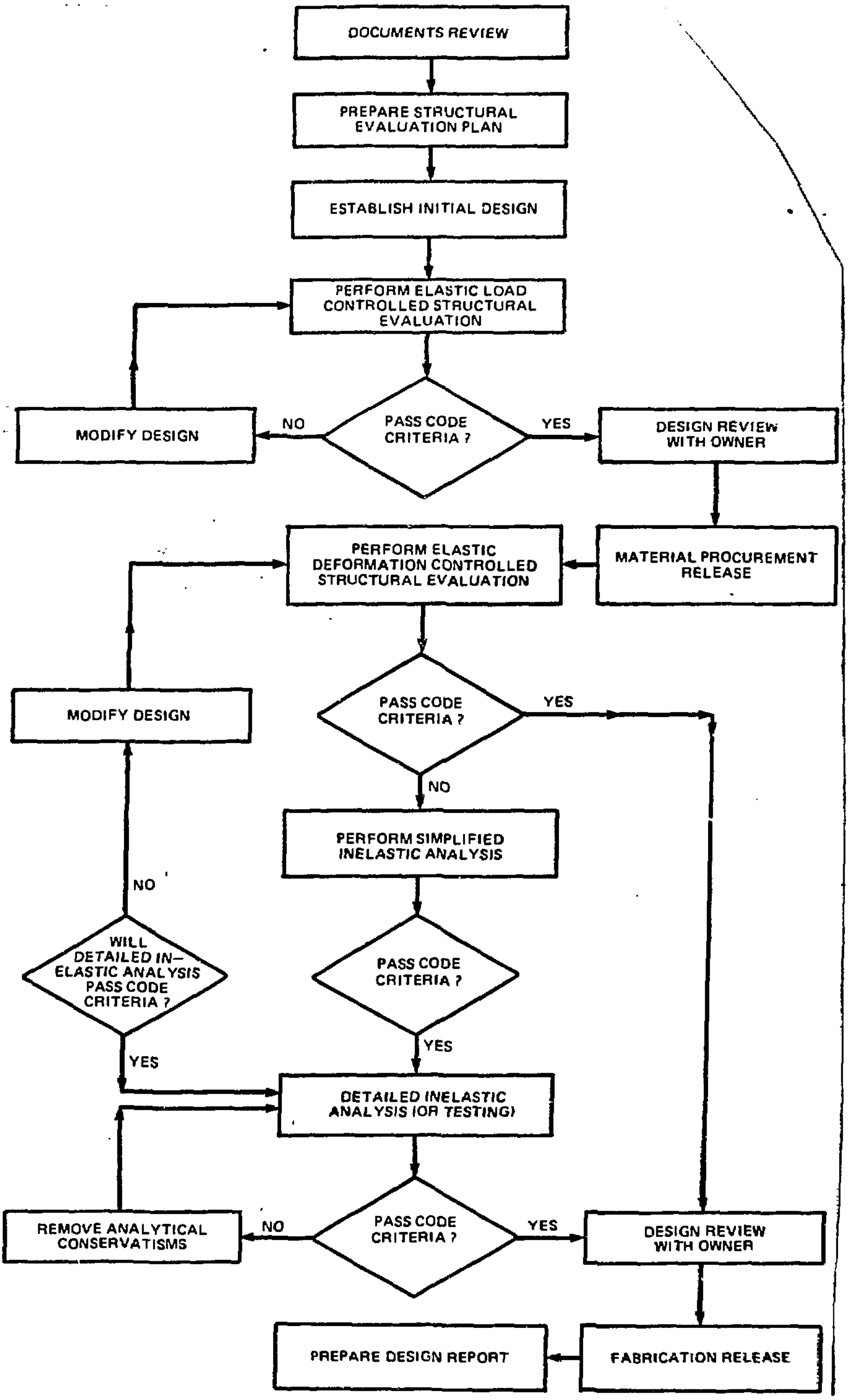

Figure 1. Structural Evaluation Plan Overall Approach to Elevated Temperature Design and Analysis

c. The mechanical loading imposes either an axisymmetric or an overall bending moment on the structure. Examples include vessel shell to head junctions, axisymmetric Y or Z junctions, and elbows which ovalize under external loadings.

B. Finite Length Thin Cylinder Formulation Axisymmetric Loading.

The rate formulation for a finite length thin cylinder is similar to the thick cylinder formulation. The thin cylinder formulation permits mechanical and thermal loads to vary with time along the length of the cylinder, this longitudinal variation was a major limitation of the thick cylinder formulation. However, thin cylinder formulation is not applicable to cases where the predominant thermal loading is due to a through-the-thickness temperature variation. The radial stress is neglected in this thin shell theory, and the two non-zero stress components σ_z and σ_θ are in the axial and hoop directions, respectively. Similarly, the three non-zero strain components are ε_z, ε_θ, and ε_r in the axial, hoop, and radial directions, and they are determined by inelastic constitutive relationships.

1. Recommended Use of Thin Cylinder Formulation. The thin cylinder formulation can be used to simulate gross structural discontinuity when:

a. The meridional or longitudinal temperature variation between a thick section (or support) and a thin shell introduces an axisymmetric meridional bending at the structural discontinuity.

b. Axisymmetric temporal history of constraints at the structural discontinuity can be obtained from elastic analysis of a detailed structural model.

c. The operational through-the-thickness temperature variation can be represented as a linear temperature gradient.

d. Through-the-thickness radial stress effects in a thin shell can be neglected.

Conversely, the thin cylinder formulation should <u>not</u> be used when:

a. The spread of plastic zones and ratchetting is caused primarily by through-the-thickness temperature distributions.

b. The temporal history of constraints at the structural discontinuity cannot be established by elastic analysis because the cross section undergoes large shear deformations and/or plastic stress redistribution.

C. Inelastic Buckling of Cylinders.

The buckling charts presented in Sections III and VIII of the ASME Boiler and Pressure Vessel Code are primarily based upon experimental and analytical investigations performed in the 1930's and the empirical correlations derived therefrom in the early 1950's. Since then, considerable progress has been made by Gerard who has presented various closed form solutions, based upon classical shell theory, to predict bifurcation buckling load in the plastic range. The available literature since 1950 indicates that Section III and VIII design charts are conservative for plastic local (shell) buckling of cylinders in axial compression and bending, but do not maintain the same degree of conservatism over the range of parameters addressed. The buckling rules for elevated temperature nuclear components are specified in Code Case N-47.

This section is to recommend a simple, verified method that can be used to predict local shell buckling load for cylindrical pressure vessel components subjected to axial compressive and bending loads. The local shell buckling mode has been found to be design limiting for loop type LMFBR pressure vessel components with radius-to-thickness ratio, r/t, in the range of 10 to 50. The length-to-radius ratio, L/r, for these components is generally less than 5; consequently, failure in the column buckling mode is not a consideration.

1. Recommended Use of Simplified Buckling Formula. Gerard's buckling formula is recommended for design use for cylindrical pressure vessels with L/r (length-to-radius) ratio less than 10 and r/t (radius-to-thickness) ratio between 10 and 50. Gerard's formula agrees with detailed nonlinear finite element analysis predictions and it generally provides a close lower bound estimate of experimental buckling loads. Experimental observations reported in the literature indicate that plastic buckling of a cylinder subjected to a bending moment is initiated in a bellows mode similar to the wrinkling or axisymmetric mode in axial compression. Thus, Gerard's axial buckling formula can also be used to conservatively predict the plastic buckling moment for a cylinder subjected to lateral loads. Although the simplified method was verified for idealized cylinders, the method will conservatively predict a lower bound buckling load for a cylindrical pressure vessel with varying thickness if the minimum thickness is used in the simplified formula.

The simplified plastic buckling formula is also recommended for predicting creep buckling times for cylinders if the instantaneous stress-strain curve (t = o hours) is replaced by an appropriate isochronous stress strain curve. The main report also describes the simplified inelastic analysis of 2-1/4 Cr-1Mo steam generator and the use of the simplified notched strength formula. For simplicity, these are omitted in this overview paper.

IV. DETAILED INELASTIC ANALYSIS

A. Introduction

The elastic design rules in the elevated temperature ASME Code Case N-47 (and possibly other international codes) are conservative. Consequently, the most highly stressed components operating at elevated temperature (above ASME Section III temperature limits) may not satisfy the Code design limits using only elastic analysis and/or simplified inelastic analysis. Therefore, to comply with the Code design limits it is sometimes necessary to perform detailed inelastic analysis of critical structural components.

Inelastic analysis methodology can be considered as a mature technology for application to future LMRs, although the current methodology has not been completely verified and validated by long-term tests at elevated temperature. Experience has shown that the inelastic analysis methodology is cost effective. For example, about forty detailed inelastic analyses were successfully performed on Fast Flux Test Facility (FFTF) structural components to qualify the design of critical areas in the Intermediate Heat Exchanger (IHX) and primary piping system. FFTF experience has shown that the inelastic analyses costs were about 13 percent of the total elevated temperature design/analysis costs, and total design/analysis costs were about 2.3 percent of total FFTF capital costs.

This section describes a procedure used in the U.S. to perform and evaluate inelastic analysis results and to document voluminous information generated by inelastic analysis in preparation of a final stress report. Table 1 shows an outline of a typical inelastic analysis stress report, which complies with the Structural Evaluation Plan (SEP).

Table I
AN OUTLINE OF FINAL STRESS REPORT

1.0 INTRODUCTION

- 1.1 Purpose
- 1.2 Scope
- 1.3 Background Documents

2.0 GENERAL REQUIREMENT AND ASSUMPTIONS FOR INELASTIC ANALYSIS

- 2.1 Recommended Method for Inelastic Analysis
- 2.2 Computer Programs
- 2.3 Material Properties
- 2.4 Load Histogram

3.0 NUMERICAL EVALUATION

- 3.1 General Procedure
- 3.2 Selection of an Accurate but Economical Mesh
- 3.3 Thermal Analysis
  - 3.3.1 Discussion of Heat Transfer Analysis Results
  - 3.3.2 Selection of Thermal Steps for Stress Analysis
- 3.4 Stress Analysis
  - 3.4.1 Elastic Analysis
  - 3.4.2 Inelastic Analysis
  - 3.4.3 Screening of Inelastic Analysis Results

4.0 DISCUSSION OF RESULTS

- 4.1 Stress-Strain Histories Excluding Thermal Strains

5.0 CREEP-FATIGUE DAMAGE AND STRAIN ACCUMULATION

- 5.1 Creep-Rupture Damage
- 5.2 Fatigue Damage
- 5.3 Strain Accumulation

6.0 CONCLUSIONS

7.0 RECOMMENDATIONS

8.0 REFERENCES

APPENDIX A Relevant Input Data Extracted from Equipment Specifications (E-Spec)

APPENDIX B Preliminary Elastic Analyses to Establish Adequacy of the Finite Element Mesh (Convergence Study)

APPENDIX C Selection of Material Properties and Component Specific Environment Effects

APPENDIX D Record of Analysis to Comply with Structural Evaluation Plan (SEP)

Table I (Contd.)

APPENDIX E	Temperature Contour Plots as Selected Steps in Heat Transfer Analysis
APPENDIX F	Stress and Strain Contour Plots at Selected Load Steps to Identify Highly Stressed Regions
APPENDIX G	Deformed Geometry Plots to Verify Boundary Conditions and Qualitatively Assess Analysis Results
APPENDIX H	Time History Plots of Temperature, Stress and Strain Variables to Evaluate Creep-Rupture Damage and Inelastic Strain Accumulation
APPENDIX I	Cyclic Stress-Strain History Plots to Evaluate Cyclic Strain Growth and Fatigue Damage

Typically, a breeder reactor structural component is subjected to cyclic thermal, mechanical, and seismic loadings postulated in the Equipment Specifications (E-Specs). It is preferable to describe incidental but essential details in Appendices of the final stress report, as illustrated in Table I. The relevant input data necessary for inelastic analysis should include geometry, boundary conditions, loadings, and material data. Details on the selection of adequate geometric and appropriate material models depend upon the numerical idealization required for specific computer program and material constitutive equation formulation.

B. Summary of the Recommended Method.

In summary, the recommended method for inelastic analysis is based upon the fundamental assumption that the total strain is the sum of the independent strain components: elastic, plastic, creep, thermal, and any other inelastic strain, such as irradiation swelling strain. Classical plasticity and creep theories are augmented by ad hoc rules to analytically simulate the experimentally observed creep-plasticity interaction in type 300 series stainless steel and 2-1/4 Cr-1Mo steel at elevated temperatures. The standard assumptions of the classical creep and plasticity theory of isotropic homogeneous material and small incompressible inelastic strains are included.

For elastic-plastic analysis the recommended constitutive equations are based upon the Von Mises yield criterion, its associated flow rule and classical non-isothermal kinematic hardening with the α-reset procedure for elastic-plastic time dependent analysis. The observed cyclic plastic hardening due to continuous thermal cycles and creep hold time postulated for reactor operation is accommodated through isotropic expansion of the yield surface to the tenth cycle stress-strain curve measured in a uniaxial continuous cycle test, without creep-hold period.

The virgin, as well as the tenth cycle, stress-strain curve is bilinearized such that the strain energy represented by the idealized curve is approximately the same as that observed under the measured curve. For simplicity, the bilinearization of the virgin stress-strain curve is based upon the maximum strain anticipated in monotonic loading; the bilinearization of the tenth cycle stress-strain curve is based upon one-half of the maximum strain anticipated in cyclic loading.

For time-dependent creep analysis the recommended constitutive equations are based upon the classical equation-of-state approach. A modified strain hardening approach is used to related components of creep strain rates to the deviatoric stress, temperature, and accumulated creep strain. Auxiliary rules, in the form of dual origins, are provided for determining the measure of strain hardening under reversed creep loadings. The effect of prior plasticity on subsequent creep is simulated through the B-option. That is, the creep strain accumulation (creep strain hardening) in cyclic loading is negated by an equal amount of prior (half-cycle) plastic strain accumulation.

The time-independent plasticity computations are performed independently of the time-dependent creep calculations. Therefore, in some reactor structural component analysis, the creep effects may have to be included during a few hours at the end of heat-up but before steady state conditions are reached. For example, the elapsed time between the end of heat-up and steady state operation may be as much as 20 hours when non-uniform longitudinal temperature differentials are encountered in pool-type reactor components such as a reactor vessel with a specified hot sodium level, relatively cold support flanges in thin-walled heat exchangers and steam generators, and fluid-head penetrations through cold concrete barriers. The calculated elastic stress intensity at the end of heat-up may be considerably higher than the stress intensity during steady state operation. To include creep effects before steady state conditions are reached, the analyst may perform a creep analysis for 20 hours after the end of heat-up and then switch to elastic-plastic analysis to calculate steady state stresses. The rest of the postulated creep hold time between thermal cycles can then be analyzed for full power steady state conditions. Thus, the higher creep-rupture damage at the end of heat-up can be captured in the structural evaluation.

V. SIMPLIFIED STRESS CLASSIFICATION PROCEDURE

A. Statement of Problem

The design criteria for Class 1 nuclear components are given in Section III of the ASME Boiler and Pressure Vessel Code supplemented by Code Case N-47 for elevated temperature service. The definitions of primary (load-controlled) and secondary (deformation-controlled) stresses for elevated temperature service in Code Case N-47-3213 are essentially the same as those presented for low temperature service in NB-3213 with one exception: the secondary stresses due to "...a large amount of elastic follow-up" are to be considered primary for elevated temperature service even if the deformation limits in Code Case N-47-3250 are satisfied. Although it is conservative to assume that stresses from thermal expansion and axial thermal gradient are primary for design calculations, in practice, it is seldom possible to comply with the code limits if such assumption is used.

This section presents a method to classify, into primary and secondary stress categories, the thermal stresses in piping systems and the bending stresses due to internal pressure in pressure vessels at structural discontinuities. The method uses a reduced elastic modulus procedure to classify clamp induced pipe stresses and extends to quantify elastic follow-up thermal stresses in elevated temperature piping systems. The method treats creep strains as time-independent inelastic strains by use of isochronous stress-strain curves. The proposed procedure has been verified by detailed creep analysis of a piping system subjected to thermal expansion and displacement.

B. Concluding Remarks

A stress classification procedure is described in this section to quantify the primary-secondary split of discontinuity stresses in piping systems and pressure vessels. Three illustrative examples are also presented. The method utilizes the concept of a reduced elastic (scant) modulus. The concept was developed to classify clamp induced stresses into primary and secondary categories as defined in the ASME Code. The proposed method is verified by comparing the predictions from reduced (secant) modulus elastic analyses to those predicted from detailed inelastic analyses.

VI. ELEVATED TEMPERATURE DESIGN CODES

A. The U.S. Structural Design Code

This section presents the rules and criteria for the design of elevated temperature nuclear components as presently used in the United States. The American Society of Mechanical Engineers Boiler and Pressure Vessel Code Section III Division 1 presents the rules for design of Class 1 pressure boundary components intended for nuclear service. In those instances where the operating temperatures exceed the temperatures for which allowable stresses are presented in Section III, Code Case N-47 is invoked for the design and analysis of Class 1 nuclear components in elevated temperature service.

1. Failure Modes. The basic philosophy of Code Case N-47 is to provide quantitative margins of safety by requiring analyses to be performed to demonstrate structural adequacy against the specified elevated temperature failure modes. The failure modes of concern in Code Case N-47 are based on the Section III failure modes and supplemented by the time dependent (creep) failure modes. The failure modes addressed by Code Case N-47 therefore include:

a. Ductile rupture from short-term loadings.

b. Creep rupture from long-term loadings.

c. Creep-fatigue failure.

d. Gross distortion due to incremental collapse and ratchetting.

e. Loss of function due to excessive deformation.

f. Buckling due to short-term loadings.

g. Creep buckling due to long-term loadings.

2. Load Categories. The load-controlled quantities are stress intensities which result from equilibrium with applied loads during plant operation. As in Section III, Code Case N-47 defines stress intensity as twice the maximum shear stress, and it is equal to the largest algebraic difference between any two of the three principal stresses. The load-controlled quantities are determined using linearly elastic material models. The most commonly encountered primary stress intensities are due to the applied pressure, deadweight, wind, seismic, and pipe loads.

Deformation-controlled quantities are stresses, strains, and deformations which result from load deflection and strain compatibility. These quantities may vary with both time and the applied loads, and creep effects may be a major time-dependent influence. Thus, accurate analytical evaluation of deformation-controlled quantities requires inelastic stress analysis when creep effects are significant.

In addition to differentiating between load controlled and deformation controlled quantities, Code Case N-47 utilizes the Section III design by analysis philosophy of categorizing load conditions as Design, Normal (Level A), Upset (Level B), Emergency Level (Level C) and Faulted (Level D).

3. Load Controlled Criteria. The basic feature of a load controlled stress is that, it is necessary to maintain equilibrium of the structure under the applied loads. As a result, deformations will not relieve load controlled stresses. These load controlled stresses are denoted as "Primary Stresses" in Code Case N-47.

The time independent primary stresses result from loads which have the capacity to cause structural failure in a single load application. The Code limits the average primary (membrane) stress intensity in any cross-section to the lower of:

a. 33.3 percent of the minimum specified ultimate tensile strength at room temperature.

b. 33.3 percent of the (tabulated) elevated temperature ultimate tensile strength.

c. 66.7 percent of the minimum specified yield strength at room temperature.

d. 66.7 percent of (tabulated) elevated temperature yield strength. For austenitic stainless steels the code permits 90 percent of the yield strength at temperature.

The first two quantities preclude plastic tensile instability. The last two quantities preclude gross plastic flow. The resulting stress limit is termed "S_m".

Code Case N-47 also defines load controlled stress limits based on the duration or time of the applied elevated temperature loading event. These are denoted as time dependent primary stress limits. The introduction of time dependent Code Case N-47 primary stress limits that depend on both the load duration and temperature provide important design flexibility for the conditions typical of LMFBR service. The Code time dependent primary stress allowable is denoted as S_t. The S_t values are the least of three quantities:

a. Two-thirds of the minimum stress to cause creep rupture in time t;

b. 80 percent of the minimum stress to cause the onset of tertiary creep in time, t, and

c. The minimum stress to produce one percent total strain in time, t.

Code Case N-47 defines the allowable stress limit S_{mt} as the lower of S_m and S_t at the particular time and temperature under consideration.

The specific Code Case N-47 load controlled primary stresses for the Design, Normal, Upset, Emergency, and Faulted Conditions are summarized in Figure 2. Code Case N-47 has two sets of primary stress allowables, one for Design Conditions, and the other for Operating Conditions.

To account for varying loads at variable times and temperatures, a linear damage use fraction approach is used by the Code. The linear damage use fraction is defined as follows:

$$\sum_i \left(\frac{t_i}{t_{ia}}\right) \le B$$

where:

t_i - the total duration of time at a particular stress level and temperature during the service life of the component

t_{ia} - the allowable time of operation at the same stress level and temperature

B - factor which is equal to unity or, alternately, it can be specified to be less than unity in the Design Specifications to account for nonlinearities in the use-fraction rule

B. Salient Features of Design Codes (France)

1. RCC-MR, French Code for FBR Components. The French Code is called RCC-MR, which means "Design and Construction Rules for Mechanical Components of Fast Breeder Reactor Nuclear Islands" and the first edition was published in June 1985. It is edited by Association Francaise pour les Regles de Conception et de Construction des Materials des Chaudieres Electro-Nucleaires (AFCEN).

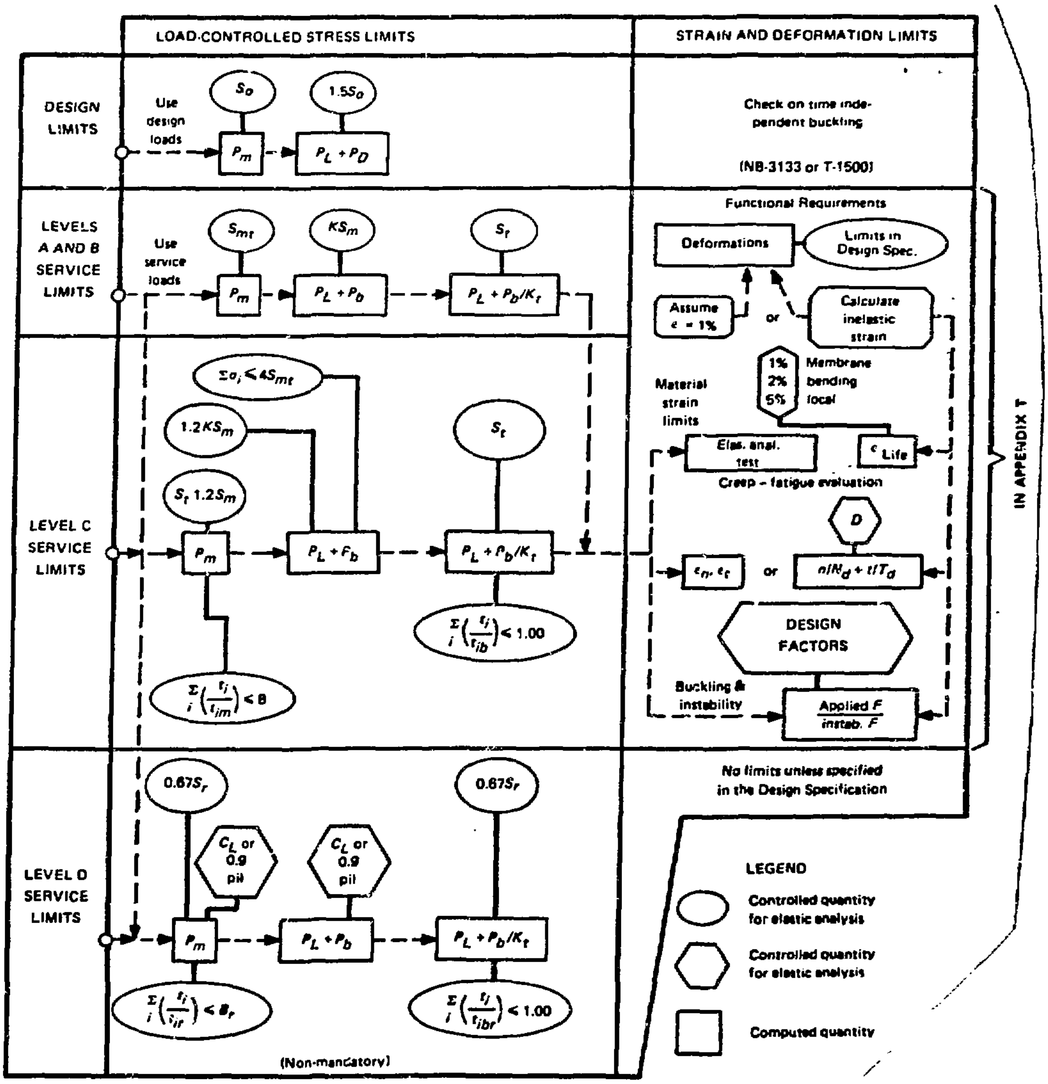

Figure 2. Code Case N-47 Elevated Temperature Analysis Flow Diagram

This code is the result of experience gained through design, manufacturing, erection, and operation of Rhapsodie, Phenix, and Super Phenix. A part of this experience is the large R&D program on Structural Mechanics launched as a part of the French LMFBR program.

Most of the design sections were written by a "tripartite committee" including experts from manufacturers, research organization, and utility. The publication of the first edition has not stopped this work and many additions and amendments are in preparation.

2. Direct Reference to Modes of Failure. Prevention of failures of various modes is clearly the aid of the design rules. For components of class 1, modes of failures are given in RB 3140. For instance, for level A criteria it is written as follows:

RB 3141 Level A Criteria

The aim of level A criteria is to protect the equipment against the following damages:

- Instantaneous or time-dependent excessive deformation,
- Instantaneous or time-dependent plastic instability,
- Time dependent fracture,
- Elastic or elastoplastic instability, immediate or time-dependent,
- Progressive deformation,
- Fatigue

RB 3111 P Type Damage

Types of damage referred to in this chapter by the expression "P type damage" are those which can result from the application to a structure of a steadily and regularly increasing loading or a constant loading.

RB 3111.1 Immediate Excessive Deformation

If we take a structure comprising an elastic, ductile material to which is applied a loading multiplied by a gradually increasing coefficient, the following behavior can be observed: with lower coefficient values, the structure behaves elastically and deformation is reversible. At higher values, irreversible plastic deformations occur such that if the loading were to be cancelled, the structure would not return to its original dimensions or shape. These plastic deformations are firstly contained by elastic zones which limit them and then, the plastic zones being sufficiently extended, yielding takes place easily. The overall permanent deformation of the structure thus increases faster the higher the loading coefficient. It is when the overall permanent deformation begins to increase rapidly that it is said to be excessive.

RB 3111.2 Immediate Plastic Instability

When, in the previous case, the loading continues to increase the behavior of the structure depends on any variations in its shape and the strain hardening increase of the yield strength of the material. These two effects rapidly become counteracting and any change in shape tends to weaken the structure whereas an increase in the yield strength of the material tends, on the contrary, to reinforce it. As long as the first effect is dominated by the second, the structure is deformed in a stable manner, when the first becomes dominant, deformation is unstable and fracture is not far behind if the loading is maintained.

RB 3111.3 Time-dependent Excessive Deformation

When a structure is subjected to loadings maintained for a sufficiently long time at high temperatures, deformations evolve with time and can consequently produce excessive deformation. This type of damage is called a time-dependent excessive deformation.

RB 3111.4 Time-dependent Plastic Instability

Although inducing no immediate damage when applied, a loading can, because of creep, induce plastic instability over a certain period of time. This type of damage is called time-dependent plastic instability.

RB 3111.5 Time-dependent Fracture

In certain conditions, changes in shape prior to fracture can be small. Sometimes considerable reduction in the elongation at the time of rupture means that this phenomenon must be taken into account both globally (under the effect of external forces) and locally (fracture before complete release of internal stresses).

RB 3111.6 Elastic or Elastoplastic Instability

Apart from the instabilities described above, other elastic or elastoplastic instabilities may occur, in which elastic deformation, by the changes in shape it induces, considerably weakens the strength of a structure and its ability to withstand the applied loading. The typical case of this type of damage is buckling.

RB 3112 S Type Damage

Types of damage described in this chapter by the expression "S type damage" are those which can only result from repeated application of loadings.

RB 3112.1 Progressive Deformation

When we consider a structure subjected to cyclic loading, at the end of the first cycle, the structure may show signs of permanent deformation. During the following cycles, two cases may arise:

- Either, after a few cycles, the overall permanent deformation is stable,
- or, the permanent overall deformation continues to increase as every loading cycle induces additional deformation and the structure gradually changes from its original shape. This behavior is called progressive deformation.

RB 3112.2 Fatigue (Progressive Cracking)

When the loading applied to a structure evolves with time, in particular in a cyclic fashion, the material is subjected to deformation variations. These variations, if sufficiently numerous and if of large amplitude, are capable of causing cracking. The damage here is defined by the appearance of small macroscopic cracks which do not compromise the strength of the structure with regard to the other types of damage to be considered.

When the temperature is sufficiently high, creep deformation occurs during each cycle thus accelerating the appearance of cracking.

RB 3113 Buckling

Buckling is a phenomenon which can occur in structures with an average centerline or average surface area. It consists of the development of deformation different from those which manifest themselves at low loading levels. They can lead to instability as well as considerable levels of deformation or exaggeration of variations in local deformation.

Buckling is not strictly speaking a type of damage but its appearance generally induces damage such as elastoplastic instability or excessive deformation or fatigue. Geometrical imperfections resulting from acceptable manufacturing tolerances are likely to accelerate and aggravate buckling.

RB 3113.1 Load Controlled Buckling

Buckling is said to be load controlled when it is the result of imposed loads which cannot be reduced by the deformations associated with buckling. The existence of other external (imposed displacements) or internal (temperatures) loadings, act simultaneously with the imposed loads to modify the imposed loading leading to buckling.

RB 3113.2 Strain Controlled Buckling

Buckling is said to be strain controlled only if the imposed loads, whatever their intensity, could not on their own produce it. In all other cases, buckling is said to be load controlled.

RB 3113.3 Time-dependent Buckling

At high temperatures, maintained loadings could cause time-dependent buckling chiefly because of the evolution of the properties of the material and the shape of the structures with time (amplification geometrical defects)

RB 3114 Fast Fracture

Fast fracture is any fracture which occurs without being preceded by an applicable global deformation. Two types of fast fractures are generally considered, one by ductile tearing, the other by fragile or semi-fragile tearing.

Ductile tearing is the result of a small volume of material being subjected to stresses inducing its fracture through instability whereas the rest of the structure still behaves elastically and is consequently liable to withstand these stresses.

VII. FRACTURE MECHANICS

A. Introduction

The assessment of the structural integrity of systems and components in elevated temperature service is one of the most important recommendations with respect to safety and economics for fast breeder reactors. To demonstrate the structural integrity, an extended evaluation is needed considering the behavior of flaws which are either accepted to be left in a structure after fabrication or postulated to be left undetected by final inspection.

Taking into account the relevant design, operating and loading conditions of LMFBR structures, fracture mechanics methods have to be extended into the elastic-plastic regime. The objective of fracture mechanics investigations is as follows:

- Demonstrate that initial defects far above sizes which can be detected by Nondestructive Examination (NDE) will not grow significantly during the service life of the structure.

- If significant crack propagation is postulated to occur - applying the specified design load cycles of the service life continuously - it should be shown that cracks will grow through the wall, its length remaining stable with respect to fracture mechanics stability criteria.

To be successful in the application of fracture mechanics methods, the following basic requirements should be fulfilled:

- Structural <u>materials</u> should be selected to be high-qualified. Its ductility should remain sufficiently high throughout the service life.

- <u>Design and</u> structural <u>analysis</u> should be performed in accordance with existing codes and standards (e.g. ASME-Code, RCC-MR), considering the special features and operating conditions of FBR's.

- A comprehensive <u>quality assurance</u> should exist throughout fabrication and installation.

Based on these requirements, the following failure modes should generally be excluded from design:

- Brittle fracture

- Ductile fracture by excessive plastic deformation

- Gross failure due to deficiencies during fabrication and installation.

Within the limits of these conditions, an extended evaluation of the structural integrity using elastoplastic fracture mechanics methods is recommended.

B. Application Techniques.

The design work for LMFBR's is based on the assumption that defects are not present in the structures being designed and specifications are defined to assure the quality of manufactured components. Although a large amount of results from fracture mechanics investigations is available, there exists no set of rules for its application in elevated temperature service. The principal items of fracture mechanics integrity evaluation are listed below:

- Establish the leak before break rationale as design basis for the coolant boundary.

- Demonstrate the structural integrity in case of postulated flaws and define design basis leakage areas.

- Decide if flaws which are detected during fabrication exceeding specified acceptance levels may be tolerated, provided that they are not harmful to the structural integrity.

Procedures to evaluate the structural integrity are somewhat different in various countries.

C. Industrial Practice in the United States.

The <u>leak before break rationale</u> has been accepted as design basis for FBR's. Sodium systems are considered as Moderate Energy Fluid Systems (MEFS) according to the U.S.-NRC Standard Review Plan. This position was accepted for the Clinch River Breeder Reactor Plant (CRBRP), stating that no sodium systems operate with any significant amount of internal fluid-stored energy.

A reference through crack length of about 100 mm is recommended based upon fatigue crack growth calculations and a leakage area of about 1 cm has been computed by crack opening considerations. The design basis leakage area has been established to be about 10 cm, using a safety factor of 10. The decision is also based upon a large amount of experimental investigations together with crack growth calculations.

<u>Crack Growth Analysis</u> was performed assuming hypothetical flaws at most highly-stressed areas. They are characterized by stress gradient over the wall thickness due to thermal transients and are generic in nature. Axial, circumferential and shear components of stresses were calculated in each piping run, using finite element programs. The maximum stresses were found to be at the elbow sections. The initial flaw parameters for the Fast Flux Test Facility (FFTF) and for the CRBRP were taken as follows:

	$\frac{a}{t}$	$\frac{a}{c}$
FFTF	0.22	0.164
CRBRP	0.25	0.167

where

a - crack depth
c - half crack length
t - wall thickness

They are regarded to be far above crack configurations which can be detected by NDE methods.

The results show that crack extension over the lifetime of the plants applying the design basis load cycles is not significant.

D. Industrial Practice in European Countries

The state-of-the-art reports are under preparation dealing with applications of fracture mechanics concepts to LMFBR components below the creep range and within the creep range. The major objectives are as follows:

- Review current methods and available theoretical and experimental work on a world-wide basis.
- Show how improved fracture mechanics methods can be of benefit to design engineers.
- Define materials data requirements.

The French approach with respect to fracture mechanics application can be summarized as follows:

Instability analysis:

Critical crack length are evaluated on flow-stress type criteria since the phenomenon is instability controlled rather than toughness controlled. This approach is being validated under complex stress situations. Comparison is made with other criteria like J-integral, tearing modulus concept and the CEGB R6 assessment procedure.

Fatigue analysis:

Fatigue is analyzed using strain intensity factor approach which results from the application of Green's function to a pseudo-elastic stress field related to total applied deformations. This approach is being validated for situations where sharp stress gradients exist like at the base of notches.

Creep analysis:

Presently, the analysis is conducted using net section and C* versus crack rate curves. Creep crack initiation and propagation has been studied recently on type 316 stainless steel. In general the following approach has been proposed:

- Prevention of defects by careful fabrication and control.
- Calculation of the extension of undetected defects during the service life.
- Demonstration of non-criticality of defects under seismic loads.
- Design of pool internals in such a way that critical cracks will not cause a catastrophic failure by fast fracture.

A joint French-German R&D program on fracture mechanics investigations has been initiated to validate theoretical methods by component tests.

The position in Germany is characterized by extended fracture mechanics investigations, which have partially been accepted for SNR-300. The results are being applied to propose a consistent concept in structural integrity for the demonstration plant SNR-2. The principal elements of the concept are as follows:

- Initial defects can be evaluated (e.g. 1 mm depth x 30 mm length) which are far above indications from nondestructive examination during and after fabrication. They will be shown to grow not significantly during the service life of the plant.
- If crack propagation is postulated to occur - applying the specific design load cycles of the service life continuously - cracks will be shown to grow through the wall, its length remaining stable with respect to fracture mechanics stability criteria.
- To demonstrate that at areas in which leak detection is not possible (e.g. internal structures of the pool vessel) the crack length of through wall cracks remain stable during the whole service life.

In the United Kingdom the structural integrity for the Commercial Demonstration Fast Reactor (CDFR) is demonstrated using fracture mechanics methods similar to other countries. Combined experimental and analytical programs are applied to show that tolerable defect sizes are well above the limits of detection by inspection methods used in both fabrication and service.

Analytical approaches were applied including the CEGB R6 method which has been shown experimentally to fulfill its aim of providing realistic failure prediction, and the British Standard Crack Opening Displacement Curve, which is a conservative method with safety factors built in.

These methods have been compared with an inelastic finite element analysis which shows that the R6 method agrees with the inelastic analysis but with a degree of conservatism.

Three point bend specimen tests were performed on welds and parent material to obtain fracture mechanics resistance curves. The analytical methods are also compared with a series of wide plate tests to determine the influence of residual stress on failure initiation. The experimental results are in reasonable agreement with predictions by fracture mechanics theory. They strongly support the leak before break concept for the coolant boundary.

VIII. NONLINEAR COLLAPSE

A. Introduction

The radius-to-thickness (r/t) ratios of typical pool type LMFBR reactor vessel and internals components range from 150 to 650. The corresponding r/t ratios for loop type LMFBR Structural Components in the primary and intermediate Heat Transport System (HTS) range from 10 to 50. The loop type LMFBR structural components operate in the creep range of the material, whereas the pool type LMFBRs experience temperatures in creep range only during accident conditions.

At elevated temperature operation thin-walled structural components may collapse (or due to the reduced yield strength of the material and creep deformation at elevated temperature. Thus, failed modes such as plastic and creep collapse and incremental collapse due to plastic or creep ratchetting require verified analysis procedures to assure the structural integrity of LMFBR plants for a 20 to 40 year design life. For simplicity, the word "collapse" is used here to designate only the post-buckling stable, gradual instability due to the interaction of both material and geometric nonlinearities; "buckling" is used generically to identify either gradual or catastrophic buckling with or without inelastic deformations at incipient geometric instability.

The structural components in LMFBR plants are significantly thinner than those designed for a Pressurized Water Reactor (PWR) plant. The thickness of PWR pressure vessel and piping components is primarily dictated by the internal pressure loading. In contrast, LMFBR pressure vessels and piping components operate at a very low pressure, hence their thickness is not dictated by internal pressure. Predominant operating loads on LMFBR components are due to temperature differentials between various portions of the structure. Theoretically, it is beneficial to design LMFBR structural components to be as thin as possible, to reduce through-the-wall temperature differentials and the corresponding thermal stresses. However, the relative thinness of LMFBR structures makes them more susceptible to buckling failure due to compressive seismic loads. Thus, the wall thickness of LMFBR pressure vessels is in some cases dictated by the buckling limits specified in the French Construction Code RCC-MR and the U.S. ASME Boiler and Pressure Vessel Code. In very thin LMFBR components ($r/t > 100$), thermally induced ratchetting, fluid structural interaction and flow induced vibrations complicate calculations of collapse load.

The buckling problems encountered in pool type LMFBRs are more complex than those encountered in loop type LMFBRs. The collapse load calculations in pool type LMFBRs are complicated by two principal factors: a) Imperfection sensitivity of the slender ($150 < r/t < 650$) pool type reactor vessel and internals as compared to relatively thick loop type pressure vessels and piping components ($10 < r/t < 50$), b) thermally induced progressive ratchetting and flow induced vibrations or fluid structural interaction in very thin structures ($r/t > 100$). The prediction of buckling or collapse load in such complex thin-walled slender shell structures is further complicated by discrepancies between an idealized response and the actual failure due to postulated accidental overloads. The discrepancies originate in the analytical idealizations which are different from the following realistic variations encountered in as-built structures: a) initial (geometric) fabrication imperfections, b) scatter in material properties at operating temperatures, c) residual stress introduced during fabrication, and d) variations in boundary conditions due to a fabricated connection and interactions among different shell structures during operation.

In addition to the inaccuracies introduced in the calculations of buckling or collapse loads, the evaluation of safety margins against unstable buckling failure is complicated by interaction between geometrically induced critical buckling deformation modes and material dependent failure modes such as creep-fatigue, ratchetting, and plastic instability. The evaluation of a margin of safety requires investigation of hypothetical behavior rather than actual behavior under postulated normal, upset, and accident conditions. Buckling is an instability phenomenon which sometimes occurs instantaneously (primarily in the elastic range) rather than gradually, as in plastic or creep collapse. Consequently, to assure structural integrity with an adequate margin of safety during plant operation, it is necessary to conservatively evaluate various hypothetical combinations and sequences of postulated loadings.

B. Recommended Buckling Analysis Procedures for Large Pool Type LMFBRs.

In the 1970's, nonlinear general purpose computer programs were developed to compute the buckling loads of complex structures in inelastic (plastic and creep) regime. However, detailed nonlinear collapse analysis of complex pool type LMFBR structures subjected to dynamic loading is expensive and time consuming. The calendar time required for detailed analysis makes it impractical for use in routine design of structural components. Simplified methods are needed, especially in the preliminary stages of design, for scoping the effects of design parameters and assessing alternate design configurations.

A simplified method is included in the French Construction Code RCC-MR. The method requires calculations of classical elastic bifurcation buckling load λ_e and the load λ_y at which a highly stressed location in a structure experiences plastic deformations. Design charts are provided to calculate the buckling load of real structures with a range of initial imperfections and material modifications introduced during fabrication. The method has been validated by comparing the simplified predictions to the experimentally observed collapse load of scaled models.

IX. CURRENT ISSUES AND FUTURE DIRECTIONS IN ELEVATED TEMPERATURE DESIGN

A. Key Technological Issues

During the past ten years, the high temperature technology development has been extensive, and the basic structural criteria and procedures adopted in the design of LMFBR components have generally been accepted as adequate during the licensing review process.

Based upon the international design experience, key structural technological issues may be divided into the following three categories:

- Stable and Defensible Design Methods. Three areas identified are weldments, flawed components and validation of inelastic analysis methodology.
- Improved Guidelines and Procedures for Design Application. Both the U.S. perspective and the European concerns are described in detail.
- Cost reduction of future LMFBR's. Four areas are identified and discussed. These include:
    1. Simplified Analysis Procedures.
    2. Application of Advanced Materials.
    3. Buckling Rules.
    4. Design Criteria for Non-Safety-Related LMFBR Components.

X. SUMMARY

When compared to conventional nuclear power plants, LMFBR primary structures can be characterized as relatively thin-walled shell structures (radius-to-thickness ratio ranging from 20 to 500), which contain liquid metal radioactive coolant as a heat transfer medium. These LMFBR structures experience elevated temperatures well above the creep range of the component material either during accident conditions or during normal operation. The relative thinness of LMFBR structures is mainly due to the small thickness required to contain low normal operating pressures, which are less than 1.4 MPa for loop-type primary heat transport system pressure vessel and piping system components, or hydrostatic pressures in both loop- and pool-type reactor vessels. Thin components are preferable not only for efficient and economical use of material, but also to reduce secondary stresses in structures due to severe thermal transients and temperature fluctuations encountered in LMFBRs.

Structural design for elevated temperature service is not a new concept as demonstrated by successful and reliable operation of petrochemical structures designed to Section VIII of the ASME Boiler and Pressure Vessel Code. Also, very thin-walled shell structures (200 r/t 2000) have been successfully designed for aerospace structures in the past. What is different about the LMFBR structures is the combination of geometry, loadings, environment, and stringent design criteria, which present new challenges not encountered in conventional nuclear and non-nuclear power and petrochemical plants or aerospace structures. Formalized and focused structural development programs in various countries were pursued to support design of large-scale LMFBRs. Direct technology transfer from other industrial practices was not feasible due to the following design considerations unique to LMFBRs:

1. Design for long-life operation (200,000 to 300,000 hours) sometimes at elevated temperature without continuous access to physical inspection, repair, or replacement of structural components.
2. Protection of public health and safety during accident conditions.
3. Assurance of structural integrity during seismic and other plant related postulated excursion events.
4. Consideration of dynamic response characteristics during fluid structural interaction.
5. Consideration of material and geometric nonlinearities with excessive deformations and loss of function of critical components.
6. Inclusion of material property variations during plant operation due to LMFBR specific environment and loading.

Although there are some differences in operating conditions among LMFBRs currently operating in various nations, the overall similarity of the above mentioned design considerations have resulted in the selection of generally similar materials of construction: stainless steel for primary and intermediate heat transport systems and chrome alloys for secondary systems.

Similarities among structural design and development programs pursued by various nations also confirm the commonality of purpose and consensus on the technology development needs over the past years. This consensus, although independently reached, has been fostered by formal and informal exchanges and contacts between various national programs and among individual participants. However, the design practice in various countries may differ in the emphasis placed upon design criteria to preclude anticipated failure modes, analysis approach used in ensuring structural integrity for long-term safe operation, and priority assigned to resolve structural design problems through additional testing and detailed numerical analysis.

Similarities in LMFBR primary heat transport system material selection and operating conditions facilitate documentation of current design practices. Therefore, much of the report is written from the U.S. viewpoint, which is consistent with international design practice. Significant differences in design practices due to emphasis on loop-or pool-type LMFBRs are appropriately addressed in the report. It should be recognized that technical opinions expressed in the report. It should be recognized that technical opinions expressed in the report are those of individual authors based upon individual perception and emphasis. Significant differences may well exist among different national practices and the recommendations in the report are not to be construed as universally accepted design practices for LMFBRs.

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