TELEDYNE ENGINEERING SERVICES

BACKGROUND OF THE FACTORS OF SAFETY USED IN DIVISIONS 1 OF SECTIONS III AND XI OF THE ASME RULES FOR NUCLEAR VESSELS

Prepared for the ASME Section XI Special Working Group on Operating Plant Criteria by Dr. W. E. Cooper, Teledyne Engineering Services, October 1984

1.0 INTRODUCTION

During the September 10, 1984 meeting of the Special Working Group on Operating Plant Criteria, the Chairman requested the writer to prepare a discussion of the background of the factors of safety used in the various Code rules as an aid to the Working Group. This document was prepared in response to that request on the basis of the long-time participation of the writer in Code activities and should be interpreted as his, individual, viewpoint on the matters under discussion. While ths viewpoint is not known to be at odds with the viewpoints of other individuals who have been similarly involved, there may be many different veiwpoints which lead to consensus. Further, the writer has not performed an exhaustive search of his own files, believing that the purpose of the request was for a quick summary of the background.

The discussion is limited to Class 1 pressure vessels, such as the Reactor Pressure Vessel (RPV). First, this is the subject with which the writer is most familiar; second, there are some differences for other components; and, third, the major interest of this WG, at least at present, is with the RPV.

The general approach followed is to cite basic reference documents, to lead the reader to the more important aspects which are pertinent to the

subject material, and to provide a viewpoint on additional rules which might be either needed or desirable. After a discussion of the differences between Sections III and XI in categorizing the loadings to be considered, the sequence of consideration is as follows:

(1) The rules of the Code which control initial construction, Section III, Division. (Construction = materials + design + examination + testing + inspection + certification)

(2) The rules of Section III which specifically affect operation, Appendix G, which forms the basis of the pressure-temperature limits of the Technical Specifications

(3) The rules of Section XI as they affect "Acceptance by Examination" and "Acceptance by Evaluation"

(4) The special considerations of:

a. Limits for Emergency and Faulted Conditions
b. Elastic-Plastic Fracture Mechanics
c. Low Upper-Shelf Energy (USE) Materials
d. Pressure Thermal Shock (PTS)

With respect to the latter considerations, the writer has tended to restate some of his previous suggestions on these matters and has not adequately covered the proposals of many others. The reader, and particularly those with alternative proposals, must recognize this document for what it is and what it is not. It clearly is not intended to be THE (or perhaps not even A) definitive proposal on these newer considerations.

2.0 DEFINITION OF DESIGN AND SERVICE CONDITIONS

Section XI rules for "Acceptance by Evaluation" define criteria for "Normal Conditions" and for "Emergency and Faulted Conditions." Section

III presently defines loadings and limits in terms of Design, Test and Service, with four categories of the latter (Levels A, B, C and D). Prior to 1976, Section III provided rules with respect to "Normal," "Upset," "Emergency," and "Faulted" Conditions in addition to Design Conditions. The relationship between the two Sections appeared to be much clearer at that time, because Section XI clearly states that their rules for "Normal Conditions" include "Upset Conditions." However, the apparent clarity actually contributed to the misuses of the Section III rules which necessitated the Section III revisions. Specifically, as a component Code, Section III intended that the definition of "normal" refer to the normal function of the component, not the normal function of the system. For example, consider a valve in the ECCS system which is required to function during ECC. The normal operating condition for that valve is a faulted plant condition, but Section III intended that those conditions be considered under what are now Service Level A Limits, not under Service Level D Limits. It is not clear to the writer that a similar revision should not be made in Section XI, but it is not a change which he would advocate without further study. This is another reason for restricting this document to the RPV, because even the Section III revision was not required for that component.

A more important consideration may be the reasons why Section III considered it desirable to identify more than one combination of loadings for design. More than one was not considered necessary for fossil boilers (Section I) or for process vessels (Section VIII). These vessels are, essentially, designed to withstand a specific Design Pressure with the allowable stresses dependent upon the Design Temperature. While it is true that these older Sections contain a more inclusive list of loadings, there were no specific criteria in the Code except that they be considered. In most cases, the consideration became a matter of the experience of the designer with similar vessels. Further, it was not clear until the Winter 1979 Addenda to Section VIII that only the effect of these additional loadings on the membrane (average) stress through the thickness of the vessel required consideration.

In summary, these changes came about because of the assignment to a Special Committee to Review Code Stress Basis (1955-1967) to determine the requirements which would permit the nominal factor of safety on the ultimate tensile strength to be reduced from 4 to 3. This effort identified a need to provide explicit consideration of the loadings which would be applied to the vessel, including the number of times these loads would be applied in order to permit evaluation of the fatigue resistance of the vessel. This same effort also identified a need to improve the criteria related to prevention of brittle fracture.

Once a need to consider various loadings was established, it became necessary to define the loadings which could be applied and to reach a judgement as to the significance of each load in order that acceptance criteria could be established. The most simply conceived such condition is that where, for whatever reason, the Code-required pressure relief system is operable and the pressure builds up to the permitted 110% of Design Pressure. Based on the fact that this was an occasional load, the committee quickly agreed that a different set of allowable values was to be permitted (10% higher basic allowable) in order that this event not be THE basis for sizing the vessel. Going further it was agreed that since this condition was one which had to be considered to occur, the fatigue effects would have to be evaluated. However, it was also agreed that the fatigue effects did not have to be considered for every possible loading.

Continuing on this train of thought lead to the concept of providing for a Design Condition and for more than one level of Service Condition, and lead to agreement as to what the basic differences in load definition and in criteria should be. Specifically:

(1) The evaluation of the Design Loadings (Design Pressure and Design Mechanical Loads at the Design Temperature) was to assure that the vessel was sufficiently strong. The definition of the Design Pressure was to include those expected during "normal

operation" and the Design Mechanical Loads were to include such aspects as pipe reactions and "normal" seismic effects. "Normal Operation" meant all those operations required to achieve the generation of power.

(2) Off-normal conditions expected to occur during operation were to be considered, along with normal operation, in evaluating the primary plus secondary stresses and the peak stresses. These are the stresses of concern with respect to fatigue, and are the present Service Levels A and B.

(3) Abnormal or postulated conditions were to be considered, but it was recognized that these were not pertinent with respect to fatigue. The 1971 Edition of Section III provided a criterion for separation between this category and that covered by the fatigue analysis: the total number of postulated occurrences for all specified Service Level C Conditions for which fatigue analysis is not required shall not cause more than 25 cycles of alternating stresses exceeded the allowble value at a million cycles. The consequences of operation at the high stresses permitted provided the mean of distinguishing between the two sets of allowable stresses:

a. Use of the Service Level C (Emergency) Limits may necessitate removal of the component from service for inspection or repair of damage to the component or support.

b. Use of the Service Level D (Faulted) Limits may require removal of the component from service.

3.0 INITIAL CONSTRUCTION

The basic information is provided in the ASME criteria document (7.1). Unfortunately, that document is dated 1969, and a later revision

has not been prepared and is not expected. As originally conceived these rules were written under the assumption that other requirements would ensure that the material was in a ductile state. This aspect is discussed in more detail in later sections of the present document.

3.1 Design Condition

The Design Conditions establish the overall dimensions of a vessel and establish its gross strength characteristics.

As indicated in the previous discussion, Section III has a nominal factor of safety of three. Specifically, this means that at room temperature, where the required material properties are specified, the allowable membrane stress intensity value S_m does not exceed one-third of the specified ultimate tensile strength. Also, at elevated temperatures the allowable value does not exceed one-third of the ultimate tensile strength obtained from a specific "trend curve" procedure. The procedure results in a true factor of safety on the minimum expected elevated temperature ultimate tensile strength of about 2.7, a value consistent with common European practice which requires testing to determine elevated temperature properties.

As described in Appendix III to Section III, the allowable value is also restricted by consideration of the yield strength of the material, with the numerical coefficient dependent upon the strain hardening characteristics of the material and previous service experience. For the ferritic materials used in the RPV, two-thirds of the yield strength is permitted, so the allowable value obtained using the factor on the ultimate tensile strength controls.

It is very important to note, however, that these allowable values are those to be used with an elastic stress analysis and that less restrictive requirements apply if a plastic analysis is performed. Particulary, these limits need not be satisfied if either:

a. A Limit Analysis demonstrates that the specified loadings do not exceed two-thirds of the lower bound collapse load calculated using a yield strength of 1.5 S_m, or;

b. A plastic analysis demonstrates that the specified loadings do not exceed two-thirds of the plastic analysis collapse load.

The reader is cautioned to refer to NB-3228 and the referenced Section III contents to assure that his understanding of these words is consistent with the intent of the Code.

What, then, is the expected ratio of the failure pressure of a Class 1 vessel to the Design Pressure? The answer is dependent upon the design procedure followed, but the ratio is certainly no less than 1.5 and is probably closer to, or in excess of, 3.0. Is the answer to this question of practical interest? Probably not, because the pressure relief system is designed to keep the pressure below 110% of the Design Pressure (except, of course, for sharp pressure peaks which do not result in relief actuation nor in failure pressures directly relatable to the static design pressure) and because mechanical joints, such as the main closure, will almost certainly leak before the pressure reaches levels which are significant with respect to bursting. While it is true that the vessel is subject to a construction-stage pressure test at 125% of Design Pressure, mechanical closures may be modified for the performance of the test.

3.2 Service Levels A (Normal) and B (Upset)

The criteria associated with these loadings may result in modification of local structural details in response to fatigue considerations.

The data obtained from strain-cycling tests, or stress-cycling tests at very high numbers of cycles, is first corrected for the maximum

possible effects of "mean" stresses (7.1). This correction is required in all welded structures because of the difficulty in computing and evaluating the effects of residual stresses. The resulting curve is then shifted to the left by a factor of 20 on cycles and shifted downward by a factor of two on stress. The resultant Design Fatigue Curve is then drawn as a lower envelope of these two curves.

This process does not result in the use of a factor of safety of 20 on the number of cycles to failure. The factor of 20 is intended to make the small, polished specimen data applicable to real vessels, and includes the following considerations:

Scatter of data	2.0
Size effect	2.5
Surface finish, atmosphere, etc.	4.0

The available test data (7.1) indicate that the actual factor of safety on cycles probably ranges between one and five, with a mean value of about three. Since these data defined failure as the appearance of a visual crack, about 3/16" long, this should be considered a factor of safety on initiation - not on failure.

Should this fatigue design procedure be relied upon with respect to fatigue crack initiation or propagation in-service? No! This is one of the main reasons we have Section XI. Neither the operating conditions nor the number of cycles defined in the Design Specification are sufficiently detailed to justify the application of the Section III analyses, positive or negative, to the establishment of the service life to be expected or to be permitted. The purpose of these requirements is to improve the design.

3.3 Service Levels C (Emergency) and D (Faulted)

The intent was to provide two sets of primary stress limits which would assure safe shutdown, with one (Emergency) providing reasonable

assurance that operation could continue following shutdown for inspection and for needed, but limited, repairs. The other (Faulted) was conceived as a last-ditch barrier to safety, but further operation was not anticipated.

In practice, the first of these is seldom used (except possibly for ATWS considerations) and the second is considered to be sufficiently conservative as to permit continued operation following shutdown for inspection and needed, but limited, repairs. The difference between intent and practice is probably the result of the Regulatory practices with respect to postulated events being much more conservative than originally anticipated.

As a somewhat simplified but not unreasonable description, the Service Level C limits permit the loadings to approach those which would result in gross deformation, and the present Code requires that the total rated relieving capacity for system Emergency Conditions be such that this stress limit is satisfied. Service Level D limits permit the loadings to reach 70% of those which would result in gross failure. However, at least for the RPV, the system Faulted Conditions of major interest do not result in significant increases of primary stresses, but do result in temperatures sufficiently low to raise questions concerning the validity of the assumption that the material is ductile.

4.0 SECTION III, APPENDIX G

Additional evaluation and limitations on operation are required in order to ensure the correctness of the Section III assumption that the criteria need only be those appropriate to ductile materials. The requirement is in NB-3211(d): "Protection against non-ductile fracture shall be provided. An acceptable procedure for non-ductile failure prevention is given in Appendix G." The purpose of the Code Appendix B was to establish pressure-temperature limits during initial operation for the as-constructed vessel (7.2), recognizing that vessel fabrication and examination will not be and need not be perfect.