# DESIGN AGAINST BUCKLING OF NUCLEAR COMPONENTS

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## SUMMARY

This paper evaluates the buckling design rules for nuclear power plant components. These rules are given in Section III and Code Case 1592 of the ASME Boiler and Pressure Vessel Code. The buckling design rules given in Section III are valid for applications in which the time-dependent phenomena are insignificant. The rules which consider time dependence are given in Code Case 1592.

Section III rules are presented by means of design charts which apply to spherical and cylindrical shells with or without stiffening rings. With the only limitation being the maximum allowable imperfections, the design curves as given in these charts are independent of the actual geometric imperfections. Therefore, no design advantage can be taken if significantly lower imperfections were assured in a structure. In addition, in Section III, no guidance is provided to guard against strain-controlled buckling or buckling of other than cylindrical and spherical shapes.

For applications at elevated temperatures, where time-dependent processes become important, design limits for time-independent and time dependent buckling are given in Appendix T of the Code Case 1592. The design limits are provided in terms of design factors for load-controlled buckling. One factor is provided on load; a second design factor is provided on time at actual load. A design factor is also provided on strain for strain-controlled buckling. These rules may be applied to any structure with any known (or postulated) amount of geometric imperfection. The structure may be subjected to any loading conditions. Further discussion in the paper is related to an evaluation of the rules in Code Case 1592 with respect to their validity, difficulty in use and the possibility of alternatives.

The various uncertainties involved in geometry, loading and material characterizations and analytical procedures are illustrated. The severity of these uncertainties, usually assessed from practical experience, determines the magnitude of the design factors. In choosing a set of criteria and design factors one attempts, by a limited number of calculations, to cover all of the uncertainties involved.

Since these rules are still in a state of development, it is important to study some of the difficulties in their use as well as their validity. Many terms such as load and strain require clarification. For example, since Code Case 1592 includes loads for design, normal, upset, emergency and faulted conditions, it is not clear as to which load should be considered and how. Another difficulty arises from meeting the time design factor requirement. This is so because creep buckling analyses for an exact load histogram is usually prohibitive in cost. Furthermore, the time dependent material properties for long time applications are obtained from relatively short time material data extrapolation.

In terms of material variability, some results of a specific study are presented. These relate to the effects of the scatter in the time dependent material properties on the buckling characteristics of a thin cylindrical shell subjected to external pressure. The remainder of the body of the paper presents and indicates some justification for a simpler alternative to the time design factor for load controlled buckling. The suggested criterion is a load increase factor, which would be applied on the load histogram throughout the design life time. The background study that led to the above proposal is discussed in the paper and is described briefly below.

The study relates to the Elastic-Plastic-Creep Buckling analysis of a Thin Cylindrical Shell with initial ovality that is subjected to external pressure. From a limited study, it was found that the buckling time of the shell at a given temperature could be explicitly expressed in terms of the ratio of sustained load to the initial buckling load. This has significance since the representation does not explicitly depend on the geometric factors and the form of creep relation used. It was further found that if one simply increased the sustained load by a factor of about 1.3, the buckling time reduced consistently by a factor of 10, for the various geometric parameters and temperatures considered in the study.

## 1.0 SECTION III BUCKLING RULES

The buckling design rules of Section III of the ASME Boiler and Pres-pressure Vessel Code [1] are valid for applications in which time-dependent phenomena are not significant. These rules are presented in Section III by means of design charts which apply to spherical and cylindrical shells with or without stiffening rings. These are shown in Appendix VII for various materials. The loading conditions covered by these charts are: external pressure on both spherical and cylindrical shells and axial load on the cyl-indrical shell. These charts are based on an evaluation of the general pri-mary membrane stresses and hence guard only against gross structural buckling. A general primary membrane stress, $P_m$, is defined in Section III of the ASME Code as one which is so distributed in the structure that no redistribution of load occurs as a result of yielding. It is an average across the section and does not include discontinuities and concentrations. Also, it is only produced by mechanical loads. Thus Section III rules do not provide protec-tion against local buckling and strain controlled buckling.

In order that a structure satisfy the Section III buckling rules, the design conditions must meet the limits provided by the design charts. Among operating conditions, only Emergency, Testing and Faulted Conditions require a buckling evaluation. For these operating conditions, compared to a design value of 1.0, the allowable loads are:

| | | |
|---|---|---|
| Emergency | 1.20 | |
| Faulted | 1.50 | (in general) |
| | 2.50 | if $\delta_0{}^* \leq 1\%$ |
| Testing | 1.35 | |

The design charts do not show any explicit consideration of the initial geometric imperfections. However, the temperature effects on the stress-strain curves are accounted for in these design charts. There are also buck-ling design rules for flanges, columns and other support structures in Sec-tion III.

## 2.0 CODE CASE 1592 BUCKLING RULES

For applications at elevated temperatures, at which creep becomes impor-tant, design limits for time-independent and time-dependent buckling are given in Appendix T of Code Case 1592 [2]. These design limits are provided in terms of design factors. These rules may be applied to any structure sub-jected to any loading conditions. The effects of all geometric imperfections either initially present or induced during service must be considered.

Code Case 1592 distinguishes between load controlled buckling and strain controlled buckling. Load controlled buckling is characterized by continued application of an applied load in the post buckling regime leading to catastrophic failure. Strain controlled buckling is characterized by the immediate reduction of strain induced load due to initiation of buckling, and the self limiting nature of the resulting deformation.

For load controlled buckling, one set of limits is provided on load and another set of limits on time. A load design factor is defined as the "load which would cause instant instability if applied at time, t, divided by the expected load at time, t". A load design factor of 3 is required when time-independent buckling is completely elastic whereas a factor of 2.5 is required when the buckling is associated with a fully plastic cross-section. The time design factor is defined as the "time to instability of the expected load history during service life, or some reasonable approximation thereof, is repeatedly applied; divided by the expected service life". A time design

* ovality, $\delta_0 = \dfrac{D_{max} - D_{min}}{D_{nominal}} \times 100\%$

factor of 10 is required.

For time-independent strain controlled buckling, a design factor of 1.67 on strain is provided. A time-dependent evaluation of strain-controlled buckling is not required.

The above buckling rules are based exclusively on an evaluation of Operating Conditions. There is no requirement for evaluation of Design Conditions. There is also no explicit distinction between the Normal, Upset, Emergency, Faulted and Testing Conditions. There are various difficulties encountered in meeting the buckling rules. A major difficulty arises from the time•design factor requirement. This is so because creep buckling analyses for an exact load histogram for ten times the service life are expensive. In addition, this time design factor requirement also poses an important technical problem. This relates to the choice of material properties to be used in the analysis beyond one service life time. The Code Case rule states that appropriate primary and secondary creep properties should be used. It is not clear, however, what is appropriate for ten times life.

## 3.0 PROPOSED NEW BUCKLING RULES FOR ELEVATED TEMPERATURE APPLICATIONS

The Working Group on Creep Analysis of the Subgroup on Elevated Temperature Design of the ASME Boiler and Pressure Vessel Code Committee has been working towards modifying the current rules. A set of new rules has been prepared which is awaiting final approval of various Code committees. In essence, the following fundamental changes have been incorporated in the new rules.

1) All types of loading conditions - Design and Operating (Normal, Upset, Emergency, Faulted and Testing) are individually considered with separate factors for each.

2) In terms of a load factor, no distinction between the elastic or the elastic-plastic case is made. For both cases, the load factor for time-independent load controlled buckling is 3.0.

3) The time design factor has been replaced by a load increase factor of 1.5 by which the Normal, Upset and Emergency Conditions of the load histotram is multiplied. The numerical value of the load increase factor is 1.25 for Faulted Conditions.

The first change in the buckling rules described above makes the elevated temperature buckling rules consistent with the other parts of the Section III and Code Case 1592 of the ASME Code. The second change is essentially a conservative simplification. The last change is more basic. Some of the background studies that led to this last change are described below.

## 4.0 BACKGROUND STUDIES

In an elastic-plastic creep buckling study of a thin cylindrical shell previously reported [3], it was shown that the creep buckling time can be expressed in terms of the ratio of the sustained load to the initial instantaneous buckling load ($q/q_o$). The study involved a thin cylindrical shell made of type 304 stainless steel with a prescribed initial ovality subjected to external pressure at elevated temperature. The effects of variations of geometrical parameters, applied pressure, exposed temperature level, creep rule, etc. on buckling load and creep buckling time were examined in the study. For the specific shell configuration, material, and range of parameters considered in this study it was observed that there exists almost a linear relationship between $q/q_o$ and creep buckling time, represented on a semi-log scale plot. Figure 1, extracted from [3] shows this linear relationship. It also shows that a reduction of q by a factor of 1.5 increases the buckling time by a factor of about 30. To test further the validity of such an equivalent load increase factor, the elastic-creep buckling solutions reported by Hoff [4] for plates and shells were considered. A steady state creep relation is used therein to represent the creep behavior of the type

$$\varepsilon_c = A \sigma^n t \tag{1}$$

where $\varepsilon_c$ is the creep strain, A and n are material constants, $\sigma$ is stress and t is time. Solutions for the following problems were given:

1) A rectangular plate under edgewise compression
2) A circular cylinder under axial compression
3) A circular cylinder under constant bending moment
4) A circular cylinder under external pressure

In all except the last problem the creep exponent, n, was assumed to be arbitrary. The last problem was solved only for n = 3.

The creep buckling solutions given in [4] are all of the form:

$$t_m = \frac{1}{\sigma^n}\left(1 - \frac{\sigma}{\sigma_0}\right) F \qquad (2)$$

in which
$\sigma$ = sustained stress (load)
$\sigma_0$ = initial buckling stress (load)
$t_m$ = buckling time corresponding to $\sigma$
$F$ = a function of stress enhanced geometry and material properties

In order to relate a load increase factor to the time design factor, consider a sustained stress level of $\sigma_1$ with a corresponding buckling time of $t_{m1}$. A load increase factor $\sigma_2/\sigma_1$ would cause a stress $\sigma_2$ and a corresponding buckling time of $t_{m2}$. The related time design factor is then $t_{m1}/t_{m2}$. By the use of eq. 2 the time design factor and load increase factor may be related by the expression:

$$\frac{t_{m1}}{t_{m2}} = \left(\frac{1-\sigma_1/\sigma_0}{1-\sigma_2/\sigma_0}\right)\left(\frac{\sigma_2}{\sigma_1}\right)^n \left(\frac{F_1}{F_2}\right) \qquad (3)$$

The ratio $(F_1/F_2)$ is generally greater than but not much different than 1. Assume it to be 1. This will mean that in general, the time design factor will be slightly underestimated. The region of greatest interest is that of the highest sustained stress. This occurs for $\sigma_1/\sigma_0 = 1/3$. With this value of $\sigma_1/\sigma_0$, and a load increase factor of 1.5, the values of time design factor are presented in Table I for various values of n.

The creep exponents, n, of materials for nuclear applications as per the Code Case 1592 lie above 5. It is therefore indiacted from this study that the proposed load increase factor of 1.5 to replace the time factor of 10 is valid.

## 5.0 UNCERTAINTIES AND DESIGN FACTORS

The design factors specified in Code Case 1592 for the creep buckling design problems were largely based on engineering judgement. The basic idea was that the specified factors should give safeguards against uncertainties in the design. Variations from their nominal values used for the design cal culation may occur in various parameters such as:

1. Geometric uncertainties in shape, size, seam mismatch, etc.
2. Loading uncertainties in magnitudes, histogram and sequencing.
3. Material uncertainties in isotropy, homogeneity, material modelling, etc.
4. Analytical procedure uncertainties in theoretical assumptions, numerical analysis, etc.

In the discussion which follows, a limited study of three specific items in regard to their uncertainties is presented. These studies pertain only to the buckling time evaluation of a circular cylindrical shell subjected to external pressure. The three items are: initial ovality, $\delta_0$; thickness to radius ratio, h/a; and creep property variability.

A circular cylinder will have some ovality at the time it is put into service. The calculations of buckling time are based on some specific (nominal) value listed in the design specifications. There is always a chance that this nomimal value may have underestimated the actual value. Table 2 lists various levels of uncertainty in initial imperfection. The uncertainties are indicated in terms of percent underestimation relative to the nominal value. The magnitude of the time design factor that is required to cover this underestimation is shown in the second column of Table II. The third column lists the equivalent load increase factor. The results in Table II have been extracted from the study presented in [3] for nominal value of $\delta_0 = 10\%$. Similar results, also extracted from [3], are given in Table III for overestimation of h/a from its nominal value of 0.1.

The effects of creep property variability on creep buckling of a cylinder subjected to external pressure are studied in Reference [5]. Some results were extracted from this study and are presented in Table IV. Shown therein are values of the time design factor and the load increase factor that are required to cover various levels of underestimation in the primary and secondary creep behavior.

The results shown in Tables II, III & IV were all obtained from a particular creep buckling analysis of circular cylindrical shell subjected to external pressure. A limited number of materials, temperature, uncertainties, etc. were utilized. Even if the entire range of possibilities was considered, more information and techniques are required in order to arrive at a satisfactory Design Factor. One must use probabilistic methods to study the individual behaviors of each parameter as well as techniques to determine the combined effects. One thing to remember, however, is that the current design practices generally assume a set of conversative numbers as the nominal values of the design parameters. Therefore it may be unwarranted to assume a large uncertainty of these parameters from their nominal values, for the purpose of determining the design factor.

## 6.0 CLOSURE

From the limited study conducted it appears that the proposed modifications in the Code Case 1592 rules are valid, The specified design factors seem reasonable. The proposed modifications substantially simplify the creep buckling evaluation. The rules are also consistent with the other relevant parts of the ASME Boiler and Pressure Vessel Code.

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TABLE I

CREEP EXPONENT VS. TIME FACTOR

$[\sigma_2/\sigma_1 = 1.5 \text{ AND } \sigma_1/\sigma_0 = 1/3]$

| n | $\frac{t_{m_1}}{t_{m_2}}$ |
|---|---|
| 4 | 6.8 |
| 5 | 10.1 |
| 6 | 15.2 |
| 7 | 22.8 |

TABLE II

UNCERTAINTY IN INITIAL IMPERFECTION

VS. TIME DESIGN FACTOR AND

EQUIVALENT LOAD INCREASE FACTOR

| % Underestimation Relative to Nominal | Time Design Factor | Equiv. Load Increase Factor |
|---|---|---|
| 25 | 4 | 1.16 |
| 50 | 10 | 1.30 |
| 75 | 21 | 1.45 |
| 100 | 40 | 1.59 |

TABLE III

UNCERTAINTY IN h/a

VS. TIME DESIGN FACTOR AND

EQUIVALENT LOAD INCREASE FACTOR

| % Overestimation Relative to Nominal | Time Design Factor | Equiv. Load Increase Factor |
|---|---|---|
| 5 | 2 | 1.08 |
| 10 | 6 | 1.22 |
| 15 | 15 | 1.38 |
| 20 | 40 | 1.59 |

TABLE IV

UNCERTAINTY IN PRIMARY AND SECONDARY

CREEP VS. TIME DESIGN FACTOR AND

EQUIVALENT LOAD INCREASE FACTOR

| CREEP COMPONENT | % Underestimation Related to Nominal | Time Design Factor | Equiv. Load Increase Factor |
|---|---|---|---|
| Primary | 100 | 1.34 | 1.03 |
| | 200 | 1.95 | 1.07 |
| | 300 | 2.70 | 1.11 |
| Secondary | 100 | 2.10 | 1.08 |
| | 200 | 3.20 | 1.13 |
| | 300 | 4.00 | 1.16 |

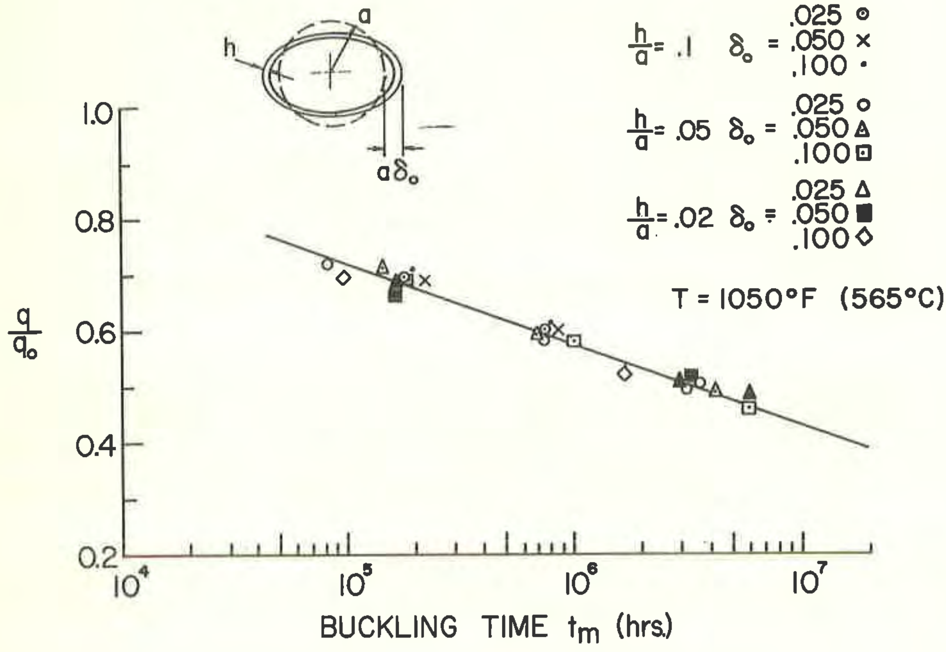


FIGURE 1 LOAD-BUCKLING TIME EQUIVALENCY
$q$ = Sustained Pressure
$q_o$ = Initial Buckling Pressure
$t_m$ = Buckling Time