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ATTACHMENT 1

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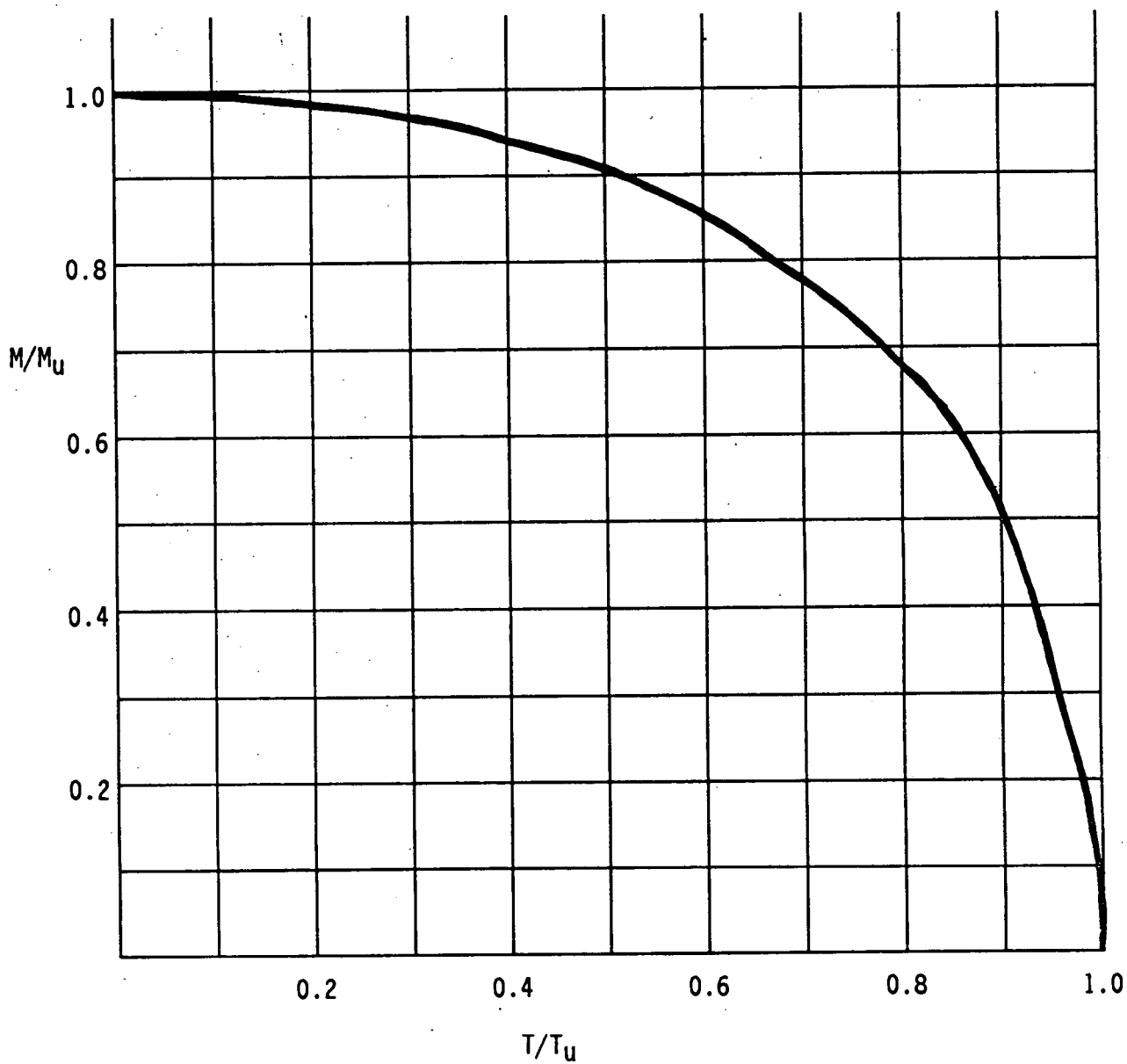
Figure 1

Effect of Torsion on Limit Moment

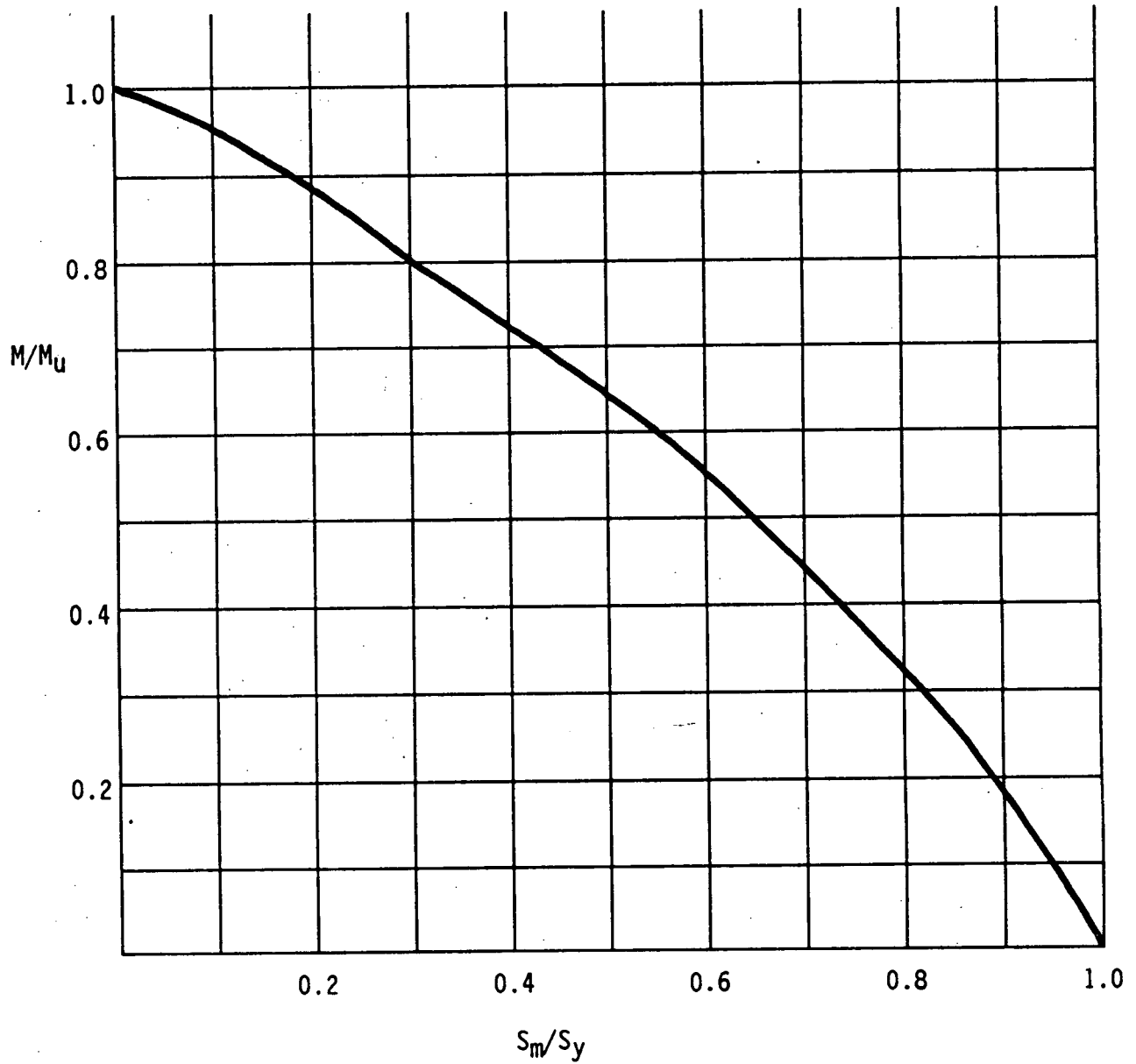(Reference 10)

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Figure 2

Effect of Internal Pressure on Limit Moment
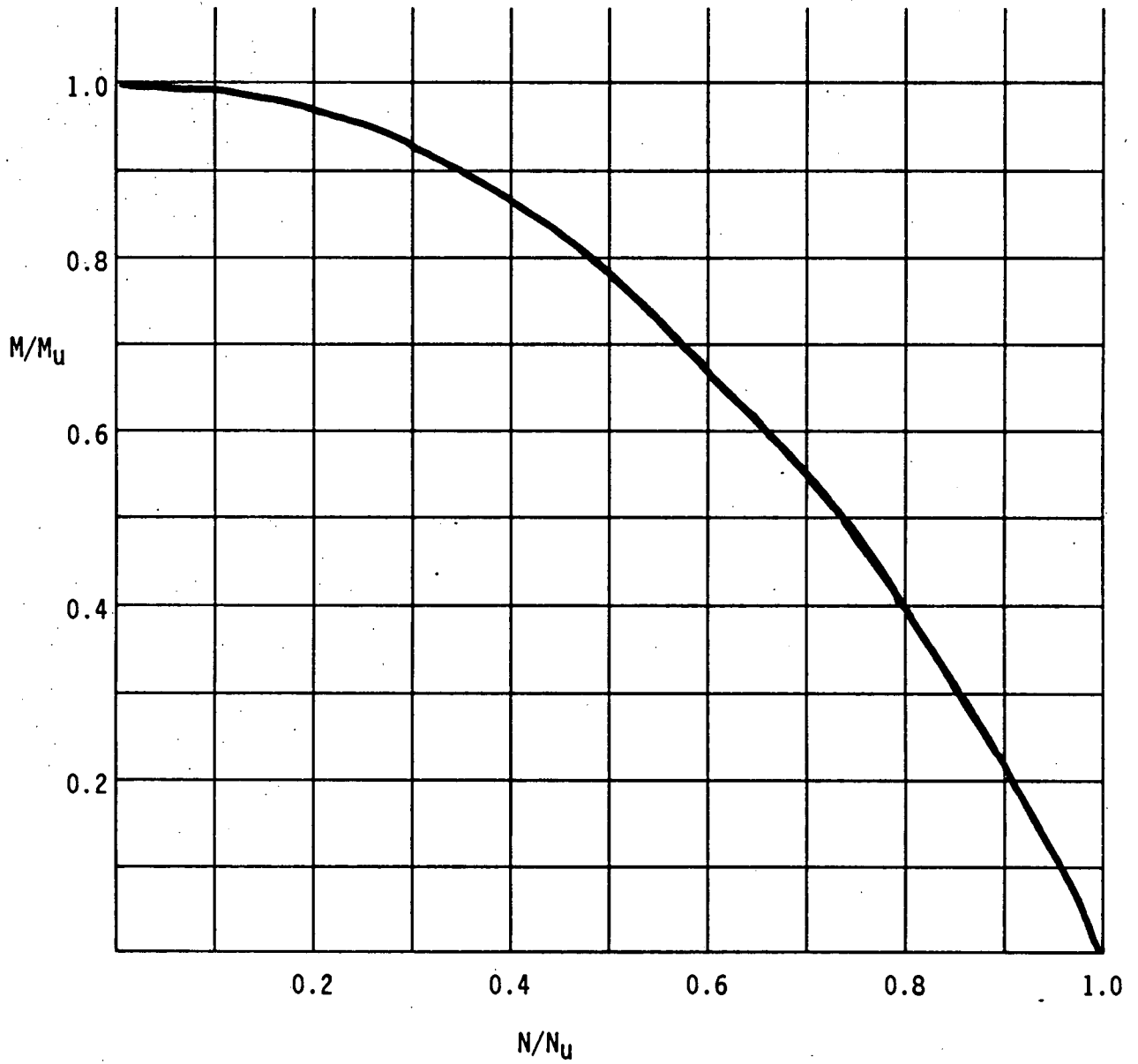
(Reference 10)

Figure 3

Effect of Axial Load on Limit Moment

(Reference 10)

SLI-8904

DOCUMENTATION OF METHODOLOGY USED FOR COMBINATION OF MOMENTS FOR PIPING CONSTRUCTED TO THE USAS B31.1-1967 POWER PIPING CODE

ACKNOWLEDGEMENT

TABLE OF CONTENTS

1.0 INTRODUCTION

This report has been prepared at the request of Fluor Daniel. A study was made of the methodology which Fluor Daniel used for calculating the stresses due to occasional loads acting on piping systems. The methodology was reviewed from the standpoint of (a) compliance with and proper interpretation of USAS B31.1.0-1967 and (b) the technical adequacy of USAS B31.1.0-1967. It is the purpose of this report to provide the results of this study.

The USNRC has questioned whether Fluor Daniel correctly interpreted the intent of USAS B31.1.0-1967 when the original piping design and analysis was performed for the Prairie Island and Kewaunee Nuclear Power Plants. The issue to be resolved is whether torsional moments were correctly left out of calculations to determine piping stresses due to sustained and occasional loads, including earthquake. It is our understanding that compliance with Paragraph 102.3.3 of USAS B31.1.0 was accomplished by meeting the requirements of the following equation:

$$S_L = \frac{Pd^2}{Do^2 - d^2} + \frac{i \sqrt{Mi^2 + Mo^2}}{Z} < 1.2 \, S_h$$

where,

> Mi and Mo = in-plane and out-of-plane moments due to weight and
> operational basis earthquake (OBE).

In the summer 1973 Addendum to B31.1, an equation similar to the one above was provided for occasional loads except it included torsional moments under the radical and used 0.75i instead of 1.0i. This change to B31.1 was the basis for the NRC to pose these two questions:

1)   First, for a project designed to the 1967 Edition of B31.1, was it a correct interpretation of the Code to use just the two bending moments in calculating pipe stresses due to weight and earthquake?

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2)   Was the Code in error, even though the interpretation was correct?

The report contained herein will show that the exclusion of torsional moments was an adequate interpretation of the 1967 Code and that piping analyzed to the 1967 Edition of B31.1 is acceptable.

2.0   EVALUATION OF CODE ANALYSIS REQUIREMENTS (MOMENT LOADINGS)

The basic Code rules for piping stress evaluation were derived from the work of A.R.C Markl and others beginning in the 1940's (see References 1, 2, and 3). The concept of stress intensification (i) factors came from a series of fatigue tests by Markl in which the fatigue life (under cyclic moment loading) of various piping products were compared to that for a reference item. Markl's work shows that the use of these "i" factors was intended for application to bending moments and were to be used for calculation of expansion stresses. The concern for longitudinal (primary) stresses was primarily from pressure and deadweight. The designer was told to calculate longitudinal stresses due to these loads, but no specific guidance was given on how to do this. The lack of specific guidance in primary stresses continued from the 1955 to the 1973 Editions of the Code. Finally, in the summer 1973 Addenda to B31.1, explicit equations to be used for calculating primary stresses were provided. With this change, the Code allowed the use of all three moments to calculate longitudinal stress. This change is probably what initiated questions on the correctness of the use of two moments in primary stress calculations performed to earlier codes.

The complete discussion on the evolution of Code primary stress calculations is presented in Appendix A. This Appendix clearly shows that use of the two bending moments to calculate longitudinal primary stresses is entirely consistent with the intent of the 1967 Edition of the Code and earlier work to support the Code rules. The technical justification and

historical bases for use of two bending moments is further discussed in Sections 3 and 4.

3.0 TECHNICAL DISCUSSION

The use of two bending moments to calculate longitudinal stresses is consistent with the historical information on the basis of Code rules and the requirements delineated in the 1967 Code, as was discussed in Section 2 of this paper. However, technical information available in other literature and the changes made to the Code and Section III itself also shed light on the matter.

As a preface to this discussion, one should bear in mind the Foreword to the 1967 Code (Reference 5) which states:

> *"There are many instances where the Code serves to warn a designer, fabricator, or erector against possible pitfalls; but the Code is not a handbook, and cannot substitute for education, experience, and sound engineering judgment."*

The philosophy behind the statement is part of all of the Codes referenced in this report. The 1967 Code allowed the use of two bending moments to calculate longitudinal stress. However, it was still up to the designer to use "sound engineering judgment."

3.1 Use of Bending Moment to Calculate Longitudinal Stress

The 1967 (Reference 5) Code is specific in its requirement that longitudinal stresses due to pressure, weight, other sustained loads, and occasional loads be calculated. One question, regarding the reasonableness of using bending moments to calculate longitudinal stresses has been posed by the NRC.

This is a reasonable approach. To begin with, the classic definition of stresses due to bending moments in beams and similar structural items (like

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pipe) results in the moment being resisted by longitudinal stresses across the section of the beam. It is also interesting to note that this interpretation is also used by the power industry. For example, Reference 10 is a report on NRC funded work to evaluate "End Effects on Elbows Subjected to Moment Loadings." Reference 10 notes that longitudinal stress is calculated using $(M_1 + M_2)^{1/2}$ where M_1 and M_2 are the out-of-plane and in-plane bending moments, respectively (Reference 10 also notes that the actual maximum stress found in the elbow is less than that predicted by the SRSS sum of all three moments). Reference 11 is a similar report regarding nozzles in pressure vessels and piping. Reference 11 specifically defines bending moment, M_b as $(M_1 + M_2)^{1/2}$. Reference 12 notes that bending stress as defined by B31.3 is

$$S_b = [(i_i M_i)^2 + (i_o M_o)^2]^{1/2} / Z$$

Again, this is based on two bending moments.

Therefore, calculation of longitudinal stress based on bending moments is reasonable and meets the stated requirements of Reference 5.

3.2 Code Changes

In Section 2 we discussed that, in the summer 1973 Addenda, the Code changed to allow the use of all three moments. This strongly suggests that use of three moments is a deviation from past practice. This is discussed further in Paragraph 4.2.2.

The moment portion of the primary stress calculation changed from

$$\frac{\sqrt{(i \, M_{bp})^2 + (i \, M_{bt})^2}}{Z} \quad \text{to} \quad \frac{0.75i \, M_A}{Z} + \frac{0.75i \, M_B}{Z}$$

where: M_{bp} is in-plane bending moment

M_{bt} is out-of-plane bending moment

M_A is resultant moment due to sustained loads

M_B is resultant moment due to occasional loads

Several changes are evident:

1.   Resultant moment rather than bending moment "may" now be used.

2.   Moments for sustained loads are separated from those for occasional loads.

3.   0.75i is now used in place of i.

The change to use of 0.75i was made for several reasons. It was recognized that the stress intensification factor "i" was derived from fatigue tests, and may be in error by as much as a factor of 2 in predicting stresses. This can be seen in the data presented in References 1, 2, and 3 and is discussed further in NC-3673.2(b) of Reference 8, which notes that i is approximately $C_2 K_2/2$ (C_2 and K_2 are stress indices defined in Subarticle NB-3680 of Section III). This is discussed in more detail in Reference 13. According to NB-3680 (Reference 8), the index B_2, which is for primary stress calculation is equal to $0.75 C_2$. Therefore, the change to 0.75i was made to approximate B_2 by the use of 0.75i.

The change to the use of all three moments was probably made for several reasons. First, there was a desire to ease bookkeeping. Since ASME Class 1 rules had always required the use of resultant moment, it was deemed advisable to require this for Class 2 and 3 piping. Second, there was a desire to maintain consistency between ASME Class 2 and 3 rules and B31.1. Also, ASME Section III is tending to make the Class 2 and 3 piping design rules more like Class 1 by requiring the use of stress indices, rather than the "i" factors. This also required the use of resultant moments. The history of this change is discussed further in Subsection 4.2. Note that

currently, the ASME Code (Reference 9) does use the B_2 index, rather than 0.75i for primary stress calculations in piping.

Because of the change of ASME to the B_2 indices for primary stress, B31.1 initiated a study of the conservatism of B31.1 compared to Section III (Reference 19). This study showed that in most cases, the B31.1 rules were significantly more conservative than Section III in the determination of maximum allowed moment. The few instances of non-conservatism were found to be small and the authors of Reference 19 concluded that there was no immediate safety concern with the B31.1 rules. In fact, the authors recommended a modification to the 0.75i term and a possible increase in allowable stress to 1.5 S_h from the current 1.2 S_h.

Finally, Table 3-1 shows a compilation of computed stress indices and the B_2 index for several piping products. Note that for the welding elbow and welding tee, the B_2 index currently required by the ASME Code is approximately 1-1/2 times higher than the i factor required by Reference 5 and twice 0.75i required by Reference 7. This again shows another technical issue in which the Codes have evolved to new criteria over a period of time. One should not interpret designs made to these earlier codes to be wrong, and the same interpretation should apply to primary stress calculations performed to Reference 5. In other words, the integrity of the original Design Code should be recognized as intended by Section III (NCA-1140) and Section XI (IWA-7210).

Therefore, the changes made to the analysis requirements of B31.1 and Section III were based on an evolution of knowledge and data on how to calculate primary stresses. The codes evolved to their current forms regarding stress calculations and enumerable other requirements because of this evolution and not because of explicit errors.

TABLE 3-1

ITEM	SIZE	T	R_1	r_2	h	i B31.1-67	0.75i B31.1b-73	B2 ASME-86
	2"/80	.218	3	1.078	.5628	1.32	.99	1.91
WELD	8"/40	.322	12	4.15	.2244	2.44	1.83	3.52
	8"/80	.5	12	4.06	.3640	1.77	1.32	2.55
ELBOW	12"/40	.375	18	6.17	.1773	2.85	2.14	4.12
	12"/80	.687	18	6.03	.3401	1.85	1.39	2.67
	16"/80	.5	24	7.58	.2089	2.56	1.92	3.69
	24"/80	1.218	36	11.39	.3380	1.85	1.39	2.68
	2"/80	.218	−	1.078	.8898	.97	.73	1.45
WELD	8"/40	.312	−	4.15	.3308	1.88	1.41	2.81
	8"/80	.5	−	4.06	.5419	1.35	1.02	2.02
TEE	12"/40	.375	−	6.17	.2674	2.17	1.63	3.23
	12"/80	.687	−	6.03	.5013	1.43	1.07	2.13
	16"/80	.5	−	7.58	.2902	2.05	1.54	3.06
	24"/80	1.218	−	11.39	.4705	1.49	1.12	2.22
SOCKET WELD	ALL	−	−	−	−	1.30	1.575	1.50

Note: These are calculated values of i and B_2. B_2, i, or 0.75i are not to be taken as less than 1.0 in calculations.

3.3 Significance of Torsional Moments

Even though we have seen that Reference 5 did not require the use of torsional moments in primary stress calculations, what is the practical difference between including the torsional moment and leaving it out? If this comparison is made, it ought to be between the requirements of the 1967 Code using 1.0i and the summer 1973 addenda, which uses 0.75i (where 0.75i > 1.0).

To check equivalence let

$$\frac{i \, (M_o^2 + M_i^2)^{1/2}}{Z} = \frac{0.75i \, (M_o^2 + M_i^2 + M_t^2)^{1/2}}{Z}$$

assuming i has not changed (not true for socket welds)

$$(M_o^2 + M_i^2)^{1/2} = 0.75 \, (M_o^2 + M_i^2 + M_t^2)^{1/2}$$

$$M_o^2 + M_i^2 = .56 \, (M_o^2 + M_i^2 + M_t^2)$$

$$\frac{0.44 \, (M_o^2 + M_i^2)}{0.56} = M_t^2$$

$$M_t = .88 \, (M_o^2 + M_i^2)^{1/2}$$

Therefore the torsional moment needs to be 88% of the resultant bending moment to match the stresses calculated using the 1967 Code. Torsional moments smaller than this would result in calculation of stresses lower than calculated using the resultant bending moment in the 1967 Code.

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If one were to ignore the "0.75i" factor as part of the change, one might ask what is the effect of torsion when combined with bending stresses? Figure 1.5.3.5 of Reference 14 is an interaction diagram for circular tubes with bending and torsional load. For a torsional moment of 50% of the total allowable torsion moment, the resulting bending stress can still be 85% of the allowable stress in pure bending. This shows that low to moderate levels of torsional moments do not significantly lower the bending capacity of straight pipe.

Figure 1 of the Foreword to Reference 15 has a similar interaction diagram for pipe under high internal pressure (membrane stress = S_m). This figure also shows that low to moderate levels of torsional moment do not significantly lower bending capacity. This is also shown in Reference 20, which investigated the effects of pressure, moment, axial force and torsion on tubes. Figure 10 of this paper shows that a torsional moment equal to 40% of the ultimate torsional moment only reduces the bending capacity of the pipe (tube) by about 12%.

4.0   HISTORY OF CODE CHANGES

This discussion concerning the intent or correctness of the early piping Code (Reference 5) would not be complete without an historical perspective from those who were responsible for writing these specific Code rules, for they are the ones best suited to interpret what their interest was. Of the authors of this paper, one (R. F. Petrokas) was a member of the ASME Code Committee for Nuclear Piping and attended meetings of this group beginning around 1974. The other (E. O. Swain) was a long-time member of the ASME Code Committee for Nuclear Piping and is a long-term member of B31. The discussions which follow in Subsections 4.1 and 4.2 relate historical information on interpretation of the intent of the early piping codes from two individuals who were present at the time. One of these individuals is a co-author of this report. The other, Sam E. Moore, has been a long-term participant on the ASME Working Group on Piping.

4.1   Individual Contact - S. E. Moore

Conversations took place with Mr. Sam Moore of Oak Ridge National
Laboratory. Mr. Moore has a long history in research into the behavior of
piping and piping products. He is a co-author of References 10 and 11.
Mr. Moore's discussion revealed his opinion that B31.1.0-1967 (Reference 5)
was based on the maximum stress theory and its evaluation requirements did
not include all stresses. With the publication of B31.7-1969 (Reference
15), evaluation criteria for Class 1 piping were based on the maximum shear
stress criteria which required the evaluation of all three principal
stresses (which in turn requires the use of all three moments). Later
changes to nuclear piping rules imposed the use of 0.75i rather than the i
factor to calculate primary stresses as a way to approximate the B_2 stress
index, but still allow the use of "i" factors (which were so familiar to
designers of B31.1 and ASME Class 2 and 3 piping). The Code was not
entirely correct in the way primary stresses were handled, and this was
changed like a lot of other information in the Code. He felt there were
plenty of other conservatisms available to cover any concerns these changes
may have caused. Among these are:

- Adding [peak] pressure and moment coincidentally in time. This
  only briefly occurs during an earthquake.

- Maximum stress vectors do not all occur at the same point in a
  fitting.

- Use of minimum properties for material strength.

- The Codes have recently begun to discover that dynamic loads
  like earthquakes do not behave like static loads anyhow.

The fact that changes were made to analysis requirements does not
invalidate work done to the old Code. In fact, ASME Section III, NCA-1140,
recognizes the legitimacy of the original Code of Construction. Finally,
Mr. Moore philosophically agreed that there was probably not much practical
difference between using two moments with an "i" intensification and three
moments with "0.75i".

4.2   B31.1 Code Changes

The following discussion is based on the B31 participation of E. O. Swain.

4.2.1   Reason for B31.1 Changes

As can be seen from References 17 and 18, E. O. Swain initiated and led the effort to introduce the equations that define the longitudinal primary stresses due to sustained and occasional loads into B31.1. The principal and perhaps only reason for the addition of these equations to the Code was to answer the many questions and problems that arose on how the Code criteria was to be interpreted and applied. There was never a feeling that changes were needed to correct Code error or unsafe criteria. The motivations for placing these equations in the Code are discussed below.

- Most of the piping being designed, analyzed, and installed in nuclear power plants in the late 1960's and early 1970's was B31.1 piping. Because of the many Quality Assurance and NRC regulatory requirements it was important to have reasonable consistency throughout industry on how the stress criteria of B31.1 was being applied. Experience at the time showed there was a wide difference in how the B31.1 criteria was being applied. The equations were aimed at providing that consistency.

- Because of the large number of nuclear plants being designed and constructed and the large amount of piping in each of these plants, there was a demand for very large numbers of piping engineers. Many of the new engineers entering the piping field had little piping analysis experience and limited experience in working with piping codes. General criteria were not always enough under these circumstances. Detailed requirements of the type supplied by the stress equations provided a way to get more uniform interpretations of the Code by these many new piping engineers.

The large amount of complex stress analysis, particularly earthquake analysis, required that nuclear piping analysis be done on computers. The computers perform the analysis in two basic steps. First, a structural or flexibility analysis is made on the piping system to determine the forces, moments and deflections from each of the external loading conditions. Second, the moments are used to calculate pipe stresses for comparison with allowable stresses and allowable stress ranges. The Code committees had to provide clear, consistent, and easily understood requirements so computer programs, stress reports, and licensing documents would be reasonably consistent throughout the industry.

4.2.2 Reason for Use of Resultant of Three Moments

The equations added to B31.1 allowed, but did not require[1], the use of the resultant of three moments rather than longitudinal bending stresses that excluded torsional effects. The Code Committee was careful not to change the Code wording of the criteria itself. The written criteria in Paragraphs 102.3.2(D) "Longitudinal Stresses" and 102.3.3 "Limits of Calculated Stresses Due to Occasional Loads" still use the expression "longitudinal stresses."

There were two reasons the resultant of three moments was allowed. First, the resultant of three moments was easier for the computer to calculate and easier for the analyst to interpret. Nuclear piping was generally defined by global coordinates and conversion of global moments to moments about a local axis was often confusing and a source of error, particularly for piping running on a skewed axis. The second reason was to provide consistency with B31.7 and with ASME III.

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(1) Paragraph 104.8.4 A of Reference 7.

4.2.3 Some Recent Code Actions Regarding Primary Stress Equations

There has recently been a large amount of testing throughout the world that shows earthquake or any other building filtered loads do not create a collapse failure mechanism in piping. EPRI and the NRC have recently sponsored an extensive and comprehensive series of high level tests of piping components and piping systems to examine the failure mode of piping subjected to vibratory loads many times more powerful than earthquake and other dynamic design loads. These tests, as well as many tests performed by others, show the failure mode to be one of fatigue or fatigue ratcheting, not collapse (see Reference 21). Although there are several reasons why collapse, the primary stress failure mode, did not occur, it is clear that the inertia loads reverse in direction so rapidly there is not time for a collapse of the piping system to occur.

The main purpose of Equations 11 and 12 in ANSI B31.1 (Reference 7) and Equation 9 in NX3600 of Section III (Reference 8) is to provide protection against collapse. Because the many test results show earthquake does not produce a collapse failure mode, Section III has passed two Code Cases (Code Cases N-451 and N-462) covering Class 1, 2 and 3 piping that allows earthquake and other building filtered loads to be excluded from Equation 9 for Service Level B loads (References 22 and 23).

Because of this new understanding of piping response to cyclic loadings such as earthquake, the method of moment combination in the primary stress equations is becoming of second or third order importance.

4.3 Archival Information

Other documentation that has come to light also reinforces the opinion that combining two bending moments met the intent of B31.1.0-1967.

Reference 16 is an update of the document which was prepared to provide guidance on mechanical design to members of the 831 Committee. The stated purpose of this nonmandatory document *"is for guidance purposes to help establish a unanimity of engineering logic and mechanical design criteria among the various B31 Committees."* In the portion of Reference 16 which discusses the flexibility factor and stress intensification factor (i) for each piping product, the intensification factor for torsion is always noted as being unity (also noted in Reference 13). This is consistent with the application in Equation 2, above, the equation required for expansion stress evaluation. No specific requirements on the methodology to be used for determination of primary stresses are given except as discussed in the following sentence, although the stresses due to weight and other sustained loads are specifically stated as being longitudinal stresses. It is especially important to note that Reference 16, page 4, notes *"in determining the longitudinal stress due to weight, stress intensification factors need not be applied."* This shows that the B31 Committee did not intend for the "i" factors to be applied to primary stresses, leading one to conclude that analyses were conservative when "i" factors were applied to primary bending moments. It would therefore be a correct interpretation of the 1967 Edition of B31.1 to omit the stress intensification factor as well as torsional moments.

References 17 and 18 are Code Correspondence from around the time of discussion of the summer 1973 rules. Reference 17 notes that torsional moments can probably be excluded from primary stress calculations, but that this is not stated in the Code. Reference 18, in discussing the proposed (summer 1973) new Code rules, notes that there are currently questions on how to combine moments.

5.0 CONCLUSIONS

From the discussion contained herein, the following conclusions can be drawn:

1. USAS B31.1.0-1967 did not require that torsional moments be considered when calculating longitudinal stresses in accordance with Paragraph 102.3.2(D), "Additive Stresses" and Paragraph 102.3.3, "Limits of Calculated Stresses Due to Occasional Loads."

2. USAS B31.1.0-1967 did not require the application of stress intensification factors when calculating longitudinal stresses in accordance with Paragraph 102.3.2(D), "Additive Stresses" and Paragraph 102.3.3, "Limits of Calculated Stresses Due to Occasional Loads."

3. The equations for calculating primary stresses for sustained and occasional loads were added (Reference 7) for clarification and consistent Code application throughout a rapidly growing power piping industry. The equations were not added to correct an error or deficiency in the Code.

4. The interpretation of the 1967 Edition of B31.1 as defined in the equation below is acceptable.

$$S_L = \frac{Pd^2}{Do^2 - d^2} + \frac{i \sqrt{Mi^2 + Mo^2}}{Z} < 1.2 \, S_h \qquad \text{(OBE)}$$

where,

   Mi and Mo = in-plane and out-of-plane moments due to weight and earthquake.

5. It is the policy of the Code Committees to not require design or analysis performed to one edition of the Code to be updated to later revisions of the Code.

6. It is now widely recognized that earthquake and other similar cyclic loadings do not cause primary stress failures (collapse) in piping

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systems. Showing that stresses due to earthquake comply with present
primary stress limits is unnecessarily conservative and may lead to
excessive seismic restraints and undesirable loss of piping
flexibility.

Therefore, use of the SRSS sum of the two bending moments to calculate
stresses due to sustained and occasional loads meets the requirements of
USAS B31.1.0-1967.

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APPENDIX A
EVOLUTION OF CODE ANALYSIS REQUIREMENTS (MOMENT LOADINGS)

Much of the bases of B31.1 (Code) and ASME Section III (Section III) have their roots in the work of A.R.C. Markl in the late 1940's and early 1950's (References 1, 2, 3). Markl's work and the resulting Code design rules were based on the premise that *"Cyclically varying bending moments resulting from thermal expansion and contraction, from pressure pulsation, or from vibrations"* (Reference 3) needed to be evaluated to appraise the safety of piping. The concept of *"occasional loads"* (defined in subsequent piping codes) is not mentioned as being a factor or concern in Markl's work as documented in References 1, 2, and 3. Note that an actual set of proposed Code design rules is attached to Reference 3. These rules were produced by a B31 working group consisting of Messrs. Markl, Spielvogel, Blair, and Wallstrom.

Reference 1 is Markl's paper which first discusses the need to predict the fatigue life of piping. He recognized the need to predict the behavior of piping products (e.g. fittings and flanges) as well as the straight pipe itself. Markl talks about the use of allowable stress range as the failure criterion in effect in B31 at the time. Reference 1 also describes initial set of tests on 90° elbows and mitre bends. The specimens were tested to failure by cyclic bending in and out of the plane of curvature to the point of failure (a crack). The concept of stress intensification associated with bending stresses was introduced. Finally, Reference 1 attempts to develop several failure criteria which match the test data. One of these criteria uses torsional (shear) stress as part of the formulation. No mention is made regarding concern for occasional loads.

Reference 2 greatly extends the information available in Reference 1 and appears to be about five years farther along in time. This paper reports on a number of tests of straight pipe, welded pipe, elbows, mitre bends, tees and intersections. Fatigue test data for these fittings are compared

to a reference. The fatigue life of the fitting is compared to that of the reference, which was chosen to be a piece of straight pipe with a girth butt weld. The fatigue life of each item was determined to be approximately related by

(1) $i\,S = 245{,}000\ N^{-0.2}$

where i =   stress intensification factor
       N =   number of cycles of stress reversal to failure
       S =   stress amplitude corresponding to N cycles

It should be emphasized that the reference (base) case ($i = 1$) is a butt welded pipe. If an unwelded piece of pipe had been used as a base case, data showed that i for that case should be approximately 0.5. This should indicate that use of "i" to calculate primary (longitudinal) stress is not entirely accurate. In reading Reference 2, note that data regarding the fatigue strength of all fittings was derived from tests using bending moments. Torsional loadings were not used. In summary, Reference 2 itself states that *"the primary use of the data is to provide design constants for the analysis of stresses caused in piping systems by thermal expansion."*

Reference 3 follows on Markl's work by applying the test results from the first two references to the flexibility analysis of piping systems. In Reference 3 we see the development of proposed rules which were incorporated into ASA B31.1-1955 (Reference 4). In fact, Appendix 1 of Reference 3 is the proposed text for what was to become of the design rules of Reference 4 (e.g. equations 13 and 14) produced by a B31.1 working group in which Markl participated. Note that Appendix 1 is still talking about expansion stresses with the formula:

(2) $S_E = \sqrt{S_b^2 + 4\,S_t^2}$

where $S_b = i \, M_b/Z$

$S_t = M_t/2Z$

i = stress intensification factor defined in Eq. (I), above

M_b is the resultant bending moment and is distinguished from the torsional moment M_t. Note that the "i" factor is only used with the bending stress in keeping with its derivation from bending test data. It is of further interest to note that Markl, in Appendix 1 of Reference 3, talks about the need to design and space supports to assure that longitudinal stress due to weight and pressure does not exceed the hot allowable stress, S_h. Apparently this is the beginning of the separate set of Code requirements to protect against collapse due to primary stress. However, as mentioned earlier, the concern that drove Markl's work and the resulting code rules, including the concept of stress intensification factors, was cyclic stresses due primarily to expansion.

As discussed above, part of Markl's and the B31 working group's work was suggested Code rules for piping evaluation. These were incorporated into the 1955 Edition of B31.1 (Reference 4). Starting with this Code, we can trace the development of Code rules for the evaluation of the expansion stress range and longitudinal (primary) stresses due to external loads (including pressure). Table A-1 summarizes the evolution of Code and Section III rules for the evaluation of primary stresses in piping.

Table A-1 shows that the early (1955) Code was primarily interested in expansion stress and provided an explicit equation for calculating it using both bending and torsional moments. The designer is told to calculate longitudinal stresses due to weight, pressure and other sustained loads. No specific guidance on how to do this is given, but the requirement for longitudinal stress leads one to conclude that bending stresses (due to bending moments) should be used. The 1967 Code still does not provide an

CODE EVOLUTION OF PRIMARY STRESS CALCULATIONS

CODE	EXPANSION STRESS	DEFINITION	STRESS INTENSIFICATION	PRIMARY STRESS	MOMENT USED IN PRIMARY STRESS	OCCASIONAL LOAD LIMIT	COMMENT
ASA B31.1-1955 (Ref. 4)	Par. 622: $$S_E = \sqrt{S_b^2 + 4S_t^2}$$ $$\leq S_A$$	$$S_b = i\,M_b/Z$$ $$S_t = M_t/2Z$$	"i" applied to M_b only in S_E	"The sum of longitudinal stresses due to pressure, weight and other sustained loads shall not exceed S_h"	Not directly specified but "longitudinal stress" suggests using S_b	Up to 20% increase to S_h for pressure and temperature	S_B = Resultant bending stress
USAS B31.1.0-1967 (Ref. 5)	Par. 119.6.4: $$S_E = \sqrt{S_b^2 + 4S_t^2}$$ $$\leq S_A$$	$$S_b = \frac{\sqrt{(i\,M_{bp})^2 + (i\,M_{bt})^2}}{Z}$$ $$S_t' = M_t/2Z$$	"i" applied to in-plane & out-of-plane bending moments (M_{bp} & M_{bt})	"The sum of longitudinal stresses due to pressure, weight and other sustained loads shall not exceed the allowable stress in the hot condition S_h"	Not directly specified but "longitudinal stress" suggests using S_b as defined[b]	Up to 20% increase to S_h for pressure, live and dead loads and occasional loads	Resultant bending moment defined for first time
ANSI B31.1-1973 (Ref. 6)	Par. 119.6.4: $$S_E = \sqrt{S_b^2 + 4S_t^2}$$ $$\leq S_A$$	$$S_b = \frac{\sqrt{(i\,M_x)^2 + (i\,M_y)^2}}{Z}$$ $$S_t = M_t/2Z$$	"i" applied to in-plane & out-of plane bending moments (M_x & M_y)	"The sum of longitudinal stresses due to pressure, weight and other sustained loads shall not exceed the allowable stress in the hot condition S_h	Not directly specified, but "longitudinal stress" suggests using S_b as defined[b]	Up to 20% increase to S_h for pressure, live and dead loads and occasional loads	No significant change
ANSI B31.1b-1973 (Ref. 7	Par. 4.8.1: $$S_E = \frac{i\,M_C}{Z} \leq S_A$$	M_C = Range of Resultant Moment due to thermal Expansion M_A = Resultant Moment due to sustained loads M_B = Resultant Moment due to occasional loads	"i" only applied to M_C 0.75 applied to M_A & M_B	$$\frac{PD_o}{4t_n} + \frac{0.75\,i M_A}{Z}$$ $$+ \frac{0.75\,i M_B}{Z}$$	M_i "may be calculated" as $$(M_x^2 + M_y^2 + M_z^2)$$	$k S_h$, where k = 1.15 or 1.2	Changed to more closely agree with Section III methodology. Note 0.75i used with three moments

CODE	EXPANSION STRESS	DEFINITION	STRESS INTENSIFICATION	PRIMARY STRESS	MOMENT USED IN PRIMARY STRESS	OCCASIONAL LOAD LIMIT	COMMENT
ASME Section III 1977 Edition (Ref. 8)	NC-3650: $S_E = \dfrac{i\,M_C}{Z} \leq S_A$	M_C = Range of Resultant Moment due to thermal expansion M_A = Resultant Moment due to sustained loads M_B = Resultant Moment due to occasional loads	"i" only applied to M_C 0.75 applied to M_A & M_B	$\dfrac{P_{MAX}D_o + 0.75i(M_A + M_B)}{4t_n}$	$M_j = [Mx_j^2 + My_j^2 + Mz_j^2]^{1/2}$	1.2 S_h	Not Significantly different from B31.1
ASME Section III 1986 Edition (Ref. 9) A-5	NC-3650: $S_E = \dfrac{i\,M_C}{Z} \leq S_A$	M_C = Range of Resultant Moment due to thermal Expansion M_A = Resultant Moment due to sustained loads M_B = Resultant Moment due to occasional loads	"i" only applied to M_C B_2 (see NB-3680) applied to M_A, M_B B_1 (see NB-3680) applied to pressure stress	$\dfrac{B_1 P_{MAX} D_o}{2t_n} + \dfrac{B_2(M_A + M_B)}{Z}$	$M_j = [Mx_j^2 + My_j^2 + Mz_j^2]^{1/2}$	1.8 S_h, but not greater than 1.5 S_y	Major change: "i" no longer used for primary stress

explicit equation for longitudinal stress, but again the requirement leads one to use bending moments. The 1967 Code is clear in defining bending stress as one based on the SRSS sum of the in-plane and out-of-plane bending moments. This consistency is maintained up to the 1973 edition, which continues to define bending stress as being based on the SRSS sum of two bending moments. Finally, in the summer 1973 addenda to the Code, the requirements for primary stress calculation have been specifically stated and an equation is given for calculation of pressure and sustained and occasional loads. For the first time, the Code suggests that the resultant moment required (see Table A-1) be the SRSS of all three moments, including torsion. Also, note that instead of using "i" for stress intensification, "0.75i" is used.

Finally, it is worthwhile to note that changes beyond what occurred in B31.1 have taken place. For example, in the 1986 Edition of Section III (Reference 9) we see that "i" factors are no longer used in calculating primary stresses in Class 2 piping. They are used strictly for expansion stresses (which is why they were originally derived). Now the B_1 and B_2 stress indices from NB-3680 are used for primary stresses. These indices are more representative of the actual state of stress in the fitting than are the use of "i".

In summary, the use of the two bending moments for calculation of longitudinal piping stress as required by USAS B31.1.0-1967 is correct and consistent with changes made to later editions of the Code. The later introduction of all three moments in the summer 1973 addenda to B31.1 was part of the continuing evolution of the Code and similar rules in Section III.