UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

APR 25 1980

MEMORANDUM FOR: Harold R. Denton, Director
Office of Nuclear Reactor Regulation

FROM: Robert J. Budnitz, Director
Office of Nuclear Regulatory Research

SUBJECT: RESEARCH INFORMATION LETTER # 88 , "DESIGN CRITERIA FOR CLOSELY-SPACED NOZZLES IN PRESSURE VESSELS"

This memorandum transmits the results of completed research dealing with the establishment of design criteria for closely-spaced nozzles in pressure vessels and the resulting change to the ASME Code rules (Appendix A). Seven reports (Appendices B through H) issued in the process of this research are enclosed. The eighth and final report (Appendix I) is in the process of publication and will be submitted upon completion.

1.0 Introduction

The results described herein were generated in a research program whose objectives were to investigate the state-of-stress at reinforced openings (nozzles) in cylindrical pressure vessels operating at temperatures below the creep range, such as for light water reactor (LWR) vessels, and to assess the rules and criteria that govern the design and qualification of isolated and closely-spaced nozzles in reactor vessels. Two of the more important parameters investigated are the maximum stresses in the nozzle-vessel region and the minimum distance between nozzles or between a nozzle and other structural discontinuity. These must be limited to acceptable values to assure that the vessel will not develop failure mechanisms from excessive peak stresses (initiation of fatigue cracks) and from high local membrane stresses (excessive distortion due to material yielding). Although the ASME Boiler and Pressure Vessel Code, Section III, Nuclear Power Plant Components, contains clear instructions for designing nozzle penetrations including geometric details, reinforcement rules, stress indices, and spacing requirements, there was concern that the Code rules for computing maximum stresses (stress indices) and for maintaining an appropriate distance between nozzles to prevent excessive interaction of stress fields were inadequate, at least over some range of the geometric parameters covered by the rules. There was also a desire to reduce the minimum spacing distances in the event that the present criteria are overly conservative.

2.0 Discussion

In order to investigate these questions, ORNL developed and validated two special purpose finite-element stress analysis computer programs, CORTES and MULT-NOZZLE, for analyzing pressure vessels with a single (isolated) nozzle or with two or more closely-spaced nozzles, under loading conditions of internal pressure and/or force and moments applied to the end(s) of the nozzle(s). These computer programs were used to conduct parametric studies of the ASME Code endorsed nozzle designs over a wide range of dimensionless geometric parameters. Work was carried out to correlate the calculated maximum stress data developed with experimental data and to compare these correlations with the ASME Code calculated stress indices. The information developed as described above led to the establishment of a new criterion for defining an "isolated nozzle condition." And finally, the work carried out led to the development of proposed alternate criteria, both for computing the maximum stress intensity (not to be confused with the stress intensity of fracture mechanics terminology) for a given nozzle design and loading condition and for limiting the minimum distance between nozzles. These criteria are given in a form that can be introduced into the ASME Code to replace the present rules.

3.0 Results

Results of the studies (see Appendix G) show that the Code stress index for computing the maximum design stress intensity at the inside corner of the nozzel-vessel junction can be unconservative for values of the parametric relation:

$$\eta = (d_i/D_i)^{0.133} (D_i/T)^{0.18} > 1.1 \qquad (1)$$

where d_i = inside diameter of nozzle

D_i = inside diameter of vessel

T = actual wall thickness of vessel minus corrosion allowance.

The degree of this unconservatism is dependent upon the amount and placement of nozzle reinforcement material allowed by the latitude permitted by Code reinforcement rules. Since many (or most of the reactor vessel designs of current interest have values of the parameter η, less than 1.1, it is recommended that use of the current Code indices be limited to values of $\eta < 1.1$. This is somewhat more restrictive than the present Code limit of:

$$\rho = (d_i/D_i)\sqrt{D_i/T} < 0.8 \qquad (2)$$

For nozzle designs with $\eta > 1.1$, such as occur routinely in piping applications, more elaborate stress index formulas were developed for both internal pressure and applied moment loadings to replace the present Code indices. These recommendations, in the form of proposed Code rule revisions, have been presented to the ASME Boiler and Pressure Vessel Code Committee and are summarized in Appendix A.

Results of the studies addressed to the question of nozzle spacing (see Appendix I - to be supplied at a later date) indicate that the Code rules are inadequate in several respects, primarily due to the lack of a sufficient data base. Nozzle spacing rules as given in various portions of the Code are not consistent. Of more importance, however, is the fact that a given rule may be conservative in one respect, such as for nozzles spaced around the circumference of a vessel, but unconservative in another respect, such as for nozzles spaced in a longitudinal plane or in some nonorthogonal plane. Further, the Code rules may be unconservative for smaller nozzles with all the required reinforcement placed in the nozzle wall but excessively conservative for larger nozzles with a significant portion of the reinforcement in the form of increased vessel wall thickness.

To resolve these problems two items were needed: (1) an acceptable definition of the isolated nozzle condition in terms of the dimensional extent of the region in which the nozzle has a significant influence on the primary membrane stresses in the vessel, and (2) a computational rule for limiting the minimum distance between nozzles so that their local primary membrane stresses regions do not interact significantly. To define the isolated nozzle condition, the criterion that a primary membrane stress intensity greater than 10 percent above nominal would be considered significant, and that the directional distance from the nozzle centerline to the 1.1 T_{nom} contour would be considered the boundary of the isolated nozzle region was adopted. The region was then further defined in terms of the dimensional parameters of the nozzle and vessel, the directional orientation of the nozzles, and a vessel-wall reinforcement parameter, based on analytical results obtained from the finite-element parameter studies and existing experimental data.

A new nozzle spacing rule based on the additional condition that no two nozzles should be closer than the sum of the distances to the boundary of their respective isolated nozzle has been formulated. This new rule is being proposed as a replacement for the four or more rules in current use. Figure 1, extracted from Appendix I (report not yet available) shows a comparison between the longitudinal spacing requirement of the new rule and the current rules for Class 1 nuclear pressure vessels (and piping) as a function of the nondimensional parameter.

$$\lambda = (d_1 + d_2)/\sqrt{R_i T_r} \qquad (3)$$

where d_1, d_2 = inside diameters of nozzles

R_i = inside radius of the vessel (or pipe)

T_r = minimum vessel wall thickness required by Code to resist design pressure.

The new rule, which includes the influence of the additional nondimensional parameters D_i/T_a, t_n/T_a and T_a/T_r, where D_i is the inside diameter of the vessel, T_a is the actual vessel wall thickness, and t_n is the nozzle wall thickness, is illustrated for parametric values of $D_i/T_a = 10$ and 100 and $T_a/T_r = 1$ and 2. This range effectively brackets the range of current pressure vessel design. Values of t_n/T_a were chosen to satisfy the Code rules for 100 percent reinforcement specified in paragraph NB-3338 of Section III of the Code.

Figure 1 (enclosure 1) shows that although the current rules are simpler, since they are expressed only in terms of the one parameter λ, they are somewhat unconservative for values of $\lambda < 2.75$ (which includes most nuclear applications) when $T_a/T_r = 1$. On the other hand, when the nozzle course of the vessel is thicker than the minimum required, i.e., $T_a/T_r > 1$ and/or when $\lambda > 2.75$ (which includes most piping installations), the current rules tend to be excessively conservative. Thus, application of the new rule will not only contribute to an increase in effective margins of safety but will also allow for design options that are not available under the current rules without detailed and expensive analyses.

4.0 Recommendations and Conclusions

The proposed Code revisions for nozzle spacing and for stress indices for nuclear Class 1 vessels [NB-3300, NB-3338.2(d)(3) and NB-3339.1(f)] and nuclear Class 1 piping branch connections [NB-3600 and NB-3683.8] are enclosed as Appendix A. The latter are given in the proposed complete rewrite of the present ASME Code paragraph NB-3683 and stress index table [Table NB-3681(a)-1].

The impact of this research program, leading to better design rules for vessel-nozzle, piping-branch design, does not require any reexamination of existing configurations. Such configurations have been traditionally designed with wall thicknesses in excess of Code minimums and, where they have been designed to Code minimums, the resultant modest decrease in safety factors, as shown in this program, does not compromise the safety of the structures in question. This is due to the large inherent factors of safety built in the Code directly, particularly as apply to stress limits for the approved vessel, nozzle and piping material.

Robert J. Budnitz, Director
Office of Nuclear Regulatory Research

Enclosures:
1. Figure 1
2. Appendices A-H
   (see attached sheet)

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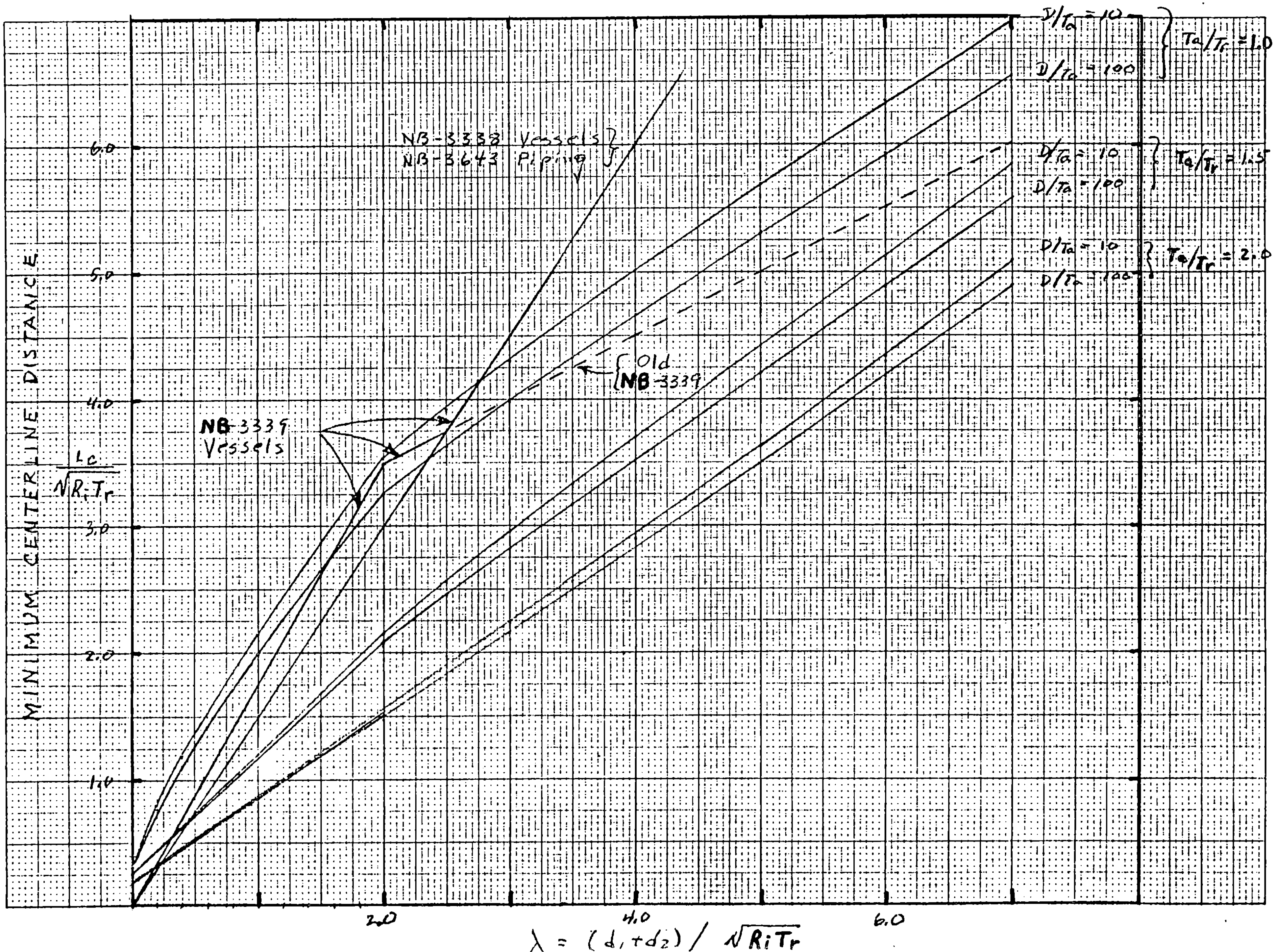

Fig. 1. Proposed minimum normalized center line-to-center line distance $L_c/\sqrt{R_i T_r}$ between nozzles in a longitudinal plane of a nuclear class 1 cylindrical pressure vessel or straight pipe as a function of the dimensionless sum-of-inside-diameters parameter $\lambda = (d_1 + d_2)/\sqrt{R_i T_r}$, where L_c is the centerline distance measured along the inside surface of the shell, R_i is the inside radius of the vessel (or pipe), T_r is the minimum required wall thickness of the vessel computed by the equations given in Code paragraphs NB-3324.1 or NB-3641.1. The lines identified by parametric values, e.g., $D/T_a = 10$, $T_a/T_r = 1$ are plots of the proposed rule for various values of the vessel inside diameter-to-actual wall thickness ratio D/T_a and the excess vessel thickness parameter T_a/T_r. The lines identified by Code paragraph number, NB-3338, NB-3339, and NB-3643 are plots of the current rules under the subject paragraph. The dashed line (old NB-3339) is the so-called 2 1/2 $\sqrt{RT}$ rule given in the Code prior to the 1977 edition.

Appendices

A. Proposed Revisions to ASME Boiler and Pressure Vessel Code, Section III, Paragraphs NB-3300, NB-3338.2(d)(3), NB-3339.1(f), NB-3600, NB-3683.8 and Table NB-3681(a)-1

B. B. R. Bass, J. W. Bryson, and S. E. Moore, "Validation of the Finite Element Stress Analysis Computer Program CORTES-SA for Analyzing Piping Tees and Pressure Vessel Nozzles," Pressure Vessels and Piping Computer Program Evaluation and Qualification, PVP-PB-024, pp. 9-25, ASME (1977)

C. J. W. Bryson, W. G. Johnson, and B. R. Bass, "Stresses in Reinforced Nozzle-Cylinder Attachments Under Internal Pressure Loading Analyzed by the Finite-Element Method - A Parameter Study," ORNL/NUREG-4 (October 1977)

D. F. K. W. Tso et al., "Stress Analysis of Cylindrical Pressure Vessels with Closely Spaced Nozzles by the Finite-Element Method, Volume 1. Stress Analysis of Vessels with Two Closely Spaced Nozzles Under Internal Pressure," ORNL/NUREG-18/V1 (Ncvember 1977)

E. F. K. W. Tso and R. A. Weed, "Stress Analysis of Cylindrical Pressure Vessels with Closely Spaced Nozzles by the Finite-Element Method, Volume 2. Vessels with Two Nozzles Under External Force and Moment Loadings," NUREG/CR-0123, ORNL/NUREG-18/V2 (August 1978)

F. F. K. W. Tso and R. A. Weed, "Stress Analysis of Cylindrical Pressure Vessels with Closely Spaced Nozzles by the Finite-Element Method, Volume 3. Vessels with Three Nozzles Under Internal Pressure and External Loadings," NUREG/CR-0507, ORNL/NUREG-18/V3 (May 1979)

G. E. C. Rodabaugh and S. E. Moore, "Stress Indices and Flexibility Factors for Nozzles in Pressure Vessels and Piping," NUREG/CR-0778, ORNL/Sub-2913/10 (June 1979)

H. J. W. Bryson, W. G. Johnson, and B. R. Bass, "Stresses in Reinforced Nozzle-Cylinder Attachments Under External Moment Loadings Analyzed by the Finite-Element Method - A Parameter Study," NUREG/CR-0506, ORNL/NUREG-52 (August 1979)

I. S. E. Moore and J. L. Mershon, "Design Criteria for the Spacing of Nozzles and Reinforced Openings in Cylindrical Class 1 Nuclear Pressure Vessels," (Draft)

4.0 Recommendations and Conclusions

The proposed Code revisions for nozzle spacing and for stress indices for nuclear Class 1 vessels [NB-3300, NB-3338.2(d)(3) and NB-3339.1(f)] and nuclear Class 1 piping branch connections [NB-3600 and NB-3683.8] are enclosed as Appendix A. The latter are given in the proposed complete rewrite of the present ASME Code paragraph NB-3683 and stress index table [Table NB-3681(a)-1].

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Robert J. Budnitz, Director
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1. Figure 1
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