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METAL CONTAINMENTS: NATURE OF LOADS AND BEHAVIOR LIMITS

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SUMMARY

For present generation of nuclear reactors with the capacity of 3800 MWt and larger, metal containments are the viable concept. Development of new materials, namely steels SA 299 and SA 537, and the approval for their use on the MC components by the ASME Boiler and Pressure Vessel Code have overcome a traditional belief that the use of metal containments is limited to the smaller capacity reactors. — To meet the increasing demand for metal containments, NRC publications and Division 1 of the Code have developed general guidelines for loads, load combinations, and design allowables.

The objective of this paper is to interpret regulatory requirements, define more specifically loads and load combinations, and assist the reader with applications.

The paper further discusses the probabilistic analysis of the design loads and associated risks. Let us observe load combinations, consisting of dead, live, accident pressure, temperature, and earthquake loads, and examine the probability of their simultaneous occurrence. The primary load in containment is the internal pressure and temperature that develops after the Loss of Coolant Accident (LOCA). This is a postulated but highly improbable load with its peak occurring for a very short period of time. The probability of the occurrence of LOCA is estimated as 10^{-4} per reactor year. Another very important load for designing metal containments is earthquake. A reasonable estimate for the probability of ground motion in excess of an SSE of 0.2 g would appear to be 10^{-4} to 10^{-6} per reactor year. Additional dead and live loads will be acting on containment at all times, and therefore their probability is unity. A reasonable estimate that the loads described above would occur simultaneously would approximate the order of 10^{-8} to 10^{-10}.

Load allowables assigned to each load equation should be reflected by the probability of their simultaneous occurrence. The discussions on that subject are also given in the paper.

The paper further discusses the analysis of metal containments, with special emphasis on the analysis of local support zones. The equations are developed for spherical and cylindrical type containments, as the function of dead and pressure loads. The recommendations are then made for the length of local support zone effects. Design stress allowables recommended by the Code are also discussed.

It could be demonstrated that the pressure capacity of metal containment systems, designed for yield and ultimate stress levels, provides for significantly greater design margins than those required in modern concrete containment systems. As an illustration, let us consider a 195 ft dia spherical containment with 1.5 in. thick walls made of steel SA 516, grade 70. Neglecting the effects of discontinuity and the dynamic nature of loading, calculated safety factors against over-pressurization are: for the allowable stress conditions, 1.20; for yield, 1.98; and for ultimate, 3.99.

From materials presented in this paper, the reader will be able to better understand the potentials of metals used in containment structures. Steels with their great ductile properties, designed to their optimum capacities, are safe and economical. It is our belief that in the future, metal containments will have a leading role in the nuclear power plant applications.

1.0 OBJECTIVE

In the last several years, increased public demand for assurance as to nuclear power plant safety has brought about a need for quantitative assessment of acceptable risk levels for nuclear containment systems.

This paper looks beyond the undifferentiated listing of loads and load combinations found in regulations pertaining to the analysis of metal containment vessels. The paper emphasizes the nature of loads, their origins, and the probability of their occurrence.

Each load acting on the metal containment structure has an independent probability of occurrence. If considered together as a load category, the probability of the category's occurrence will be reduced by the combination of their individual probabilities.

Combined load occurrence probability lessens from Load Category A through Load Category D. This phenomenon can serve as a rational basis for setting the direction of stress limits for load categories.

2.0 LOADS AND LOAD COMBINATIONS

Loads and load combinations described in this section conform to the requirements of the ASME Code (1) and regulatory publications (2, 3, 4) as applicable to Pressurized Water Reactor (PWR) nuclear plants. For convenience, these loads are divided into five major categories.

CATEGORY A includes all those loads to which the containment vessel is exposed during normal plant operation and the Design Basis Accident (DBA) conditions for which the containment function is required. They are defined as follows:

D - Dead loads, including permanent equipment loads. These loads will be acting at all times and their probability of occurrence is unity.

L - Live loads, including any movable equipment loads which vary with intensity and occurrence. Probability of the occurrence of these loads is estimated as unity.

R_o - Pipe reactions during normal operation and shutdown conditions, based on the most critical transient or steady state condition. This type of load primarily occurs at the penetrations for which a cyclic type of analysis is required. Based on the maximum number of cycles estimated for the life of the plant, the containment shell is checked for the local effects. Their probability is also estimated as unity.

P_a - Design pressure load within the containment vessel generated by a DBA. A typical Loss of Coolant Accident (LOCA) which could result in the generation of maximum pressure in the containment vessel is a double-ended reactor coolant pipe break. To account for all the uncertainties and variations that may affect the final calculated pressure value, a mandatory minimum margin is added. Therefore, calculated maximum pressure, increased by that margin, is defined as a design pressure.

The median probability of a large LOCA (Event A) which could create a condition for the development of maximum pressure is assessed at 1×10^{-4} per reactor year. (4)

T_a - Thermal effects and loads, generated by a DBA. Temperature loads are associated with the pressure loads following a LOCA; therefore, their probability is also 1×10^{-4} per reactor year.

CATEGORY B includes the applicable loads in Category A, plus the additional loads resulting from natural phenomena, such as the earthquake load, for which the plant must remain operational.

E - Loads generated by the Operating Basis Earthquake (OBE) as defined in Reference (5). In recent years, a number of publications have dealt with the probability of the occurrence of earthquakes. If the magnitude of ground acceleration is known for the given site, the probability of an OBE exceeding this value can be found in Table II.

Information presented in Table II has been developed for regions in the eastern U.S.(7). However, the order of magnitude would not be greatly changed if the same information is used for sites in the western U.S.

P_e - Design external pressure. Negative pressure conditions may exist inside a containment vessel if heat removal systems, such as fan coil units or internal spray systems, are inadvertently initiated during normal operation of the plant. If such an event occurs, the vacuum relief system will be mechanically opened and will remain open until pressures are equalized inside the containment and the reactor building annulus. A primary concern in the case of external pressure is the buckling of the vessel. The probability of such an occurrence appears to be low, however quantitative assessments of its frequency are not available.

T_e - Thermal effects and loads under thermal conditions during events causing external pressure.

CATEGORY C includes the applicable loads of Category A, plus the additional loads on the containment vessel resulting from natural phenomena, such as the earthquake load, for which safe shutdown of the plant is required.

E' - Loads generated by a Safe Shutdown Earthquake (SSE) as defined in reference (5). Table II gives the probability of occurrence of earthquakes as a function of ground acceleration at a given site.

CATEGORY D includes the applicable loads in Categories A, B, and C, plus the additional loads which produce a localized effect on the containment vessel, such as impact forces from jet impingement and associated reactions.

Y_r - Equivalent static load on the structure generated by the reaction of the ruptured pipe during a pipe-rupture accident.

Y_j - Jet impingement equivalent static load on the structure generated by the ruptured pipe during the same pipe-rupture accident.

For the specific pipe, located in the immediate proximity of the containment vessel, the probability of an accident can be estimated from reference (4).

CATEGORY E includes the applicable loads during structural integrity or leak rate testing. These testing conditions are in addition to tests permitted by the ASME Code and include leak tests or subsequent hydrostatic or pneumatic tests.

P_t - Test pressure during structural integrity or leak rate testing.

T_t - Thermal effects and thermal loads during testing.

Since those tests are mandatory requirements of the ASME Code, probabilistic load analysis is not applicable.

Loads and load combinations of the five categories described above are shown in Table I.

3.0 BEHAVIOR LIMITS

Stress allowables and design limitations are described in references (1), (2), and (3). Their magnitude should be reflected by the probability of simultaneous load occurrence for each load category. Generally higher stress limits should be allowed for a load category when the joint load probability is smaller. However this is not true in all cases. Consider Load Combinations 2, 5, and 6 from Table I. Code specified allowables for load categories A and B are the same throughout. Nevertheless, the probability of simultaneous load occurrence in Combination 2 is not identical to that for Combination 5, as discussed below.

For Load Combination 2, the probability of load occurrence will be the probability of a single failure of reactor coolant piping. This value is set at 1×10^{-4} in reference (4).

Assessing the load probability of Combination 5 is much more difficult. However, for the purpose of this study, assumptions can be made to arrive at an order of magnitude value which will be meaningful. Assuming that the ground acceleration of a given site is 0.1g and that the plant will be founded on firm or average soil on the site in the eastern United States, the probability of an OBE can be estimated as 1.4×10^{-3} to 3.6×10^{-3}, respectively. Considering a single system failure definition for a LOCA, and using an earthquake as the initial failure mode causing damage to pipe in the reactor coolant system, the probability of the occurrence of Load Combination 5 should be corrected by a factor of 0.001 (8) to 1.4×10^{-6} to 3.6×10^{-6}.

Extending the same philosophy to an SSE of 0.2g, the load probability of Combination 6 can be estimated as 1.5×10^{-7} to 6.5×10^{-7}.

In Table IV, Code allowables are shown for primary membrane stress for Load Combinations 2, 5, and 6. It appears that allowable stresses are not consistent with the reduced load probability. This phenomenon raises again the question of the necessity for designing containment vessels for any earthquake other than an SSE (9).

The materials presently available for construction of metal nuclear containments are limited to SA-516, SA-537, and SA-299. An increase of 20 percent above S_m values for allowable membrane stresses in the case of an SSE will assure elastic response of containment for those materials. If the structure remains elastic under loads including an SSE, redundancy of Load Combination 5 is observed.

For further discussion, let us examine the load probability for Load Combination 8. Jet impingement loads are associated with the pipe rupture in the immediate proximity of the containment vessel; this could conceivably be the case if one of the large-diameter, high-energy pipes ruptures near its penetration inside the vessel. Let us assume that an SSE is the initial failure mode for damaging two systems: 1) reactor coolant piping, resulting in internal pressure and temperature; and 2) high-energy pipe, producing reaction Y_r and jet impingement Y_j. This probability can be assessed by combining the probability of an SSE and the probability of it damaging the two systems. Assuming that ground acceleration is 0.2g for an SSE, the probability of damaging two systems can be assessed from Table III as 3×10^{-5}. Therefore, total probability for simultaneous load occurrence in Combination 8 can be estimated as 2×10^{-8} to 4.5×10^{-9}. This is an extremely low probability; therefore, increase of stress allowables for faulted conditions is fully justified.

BUCKLING STRESS CRITERIA. Load Combinations 4 and 7 will require investigation of the compressive allowable of the metal containment vessel. Until more developmental work is made available, straight line interaction formulae can be used as shown below:

$$\frac{\sigma_D}{\sigma_{D\ all}} + \frac{\sigma_E}{\sigma_{E\ all}} + \frac{\sigma_{P_e}}{\sigma_{P_e\ all}} \leq \begin{cases} 1.0 & \text{When an OBE is considered (eq. (4) in Table I)} \\ 1.2 & \text{When an SSE is considered (eq. (7) in Table I)} \end{cases}$$

where: σ_D, σ_E, and σ_{P_e} - are membrane stresses in the vessel due to dead, earthquake, and external pressure loads, respectively.

$\sigma_{D\ all}$, $\sigma_{E\ all}$, and $\sigma_{P_e\ all}$ - are allowable compressive stresses obtained by reducing the corresponding buckling stress by the safety factory for dead, earthquake, and external pressure loads respectively.

New developmental work is required for the assessment of buckling load under dead and earthquake states of stress. Computer programs which can handle geometric nonlinearity and local imperfections should be investigated for that purpose.

LOCAL EFFECTS. Localized stress areas and containment vessel support zones will experience a high level of local stresses. Design maximum and peak stress length are specified in the ASME Code, but no guidelines are given for the maximum allowable length of containment support zones, where local stress criteria may be applied.

Combined action of several loads will impose different definitions of what is considered "local." In Fig. 1, major contributing loads for the metal containment vessel capacity are shown. Since internal pressure accounts for over eighty percent of vessel design capacity, a conservative estimate for the length of local support zones could be calculated based on the internal pressure requirements. In Appendix A, a calculation procedure for the local effects of membrane stresses in a spherical containment vessel is shown. Definition of local zone length of $4.277\sqrt{Rt}$ for spherical metal containment vessels is given in Fig. 2.

4.0 RISK ASSESSMENT

Risk is defined as the product of failure probability and the consequence of a failure as measured in terms of loss of life, injury, or property damage. Consequences of failure of safety-related nuclear power plant components were studied (4). The results of the study were analyzed and compared with the nonnuclear risks to which individuals in our society are already exposed.

In risk assessment analysis, the greatest attention was given to the analysis of reactor core melt-down, because consequences arising from such an event are the greatest. Containment failure risk assessment also warrants a thorough investigation. It is recognized, however, that with the present state of knowledge and probabilities, the lack of dependable data precludes a complete analysis with a desirable level of precision.

Containment failure probability can be defined as a product of the simultaneous load occurrence probability and the structural overstress probability. As an illustration, let us consider a 195-ft (59.4m) diameter spherical containment with 1.5-in. (3.8cm) thick walls made of steel SA-516, Grade 70 (10), subject to loads from Combination 6 of Table I. Neglecting the effects of discontinuity and the dynamic nature of the loading, the contribution of load effects to the containment vessel design capacity can be calculated as shown in Fig. 1. The likelihood that design loads from eq. 6 will occur simultaneously and exceed their magnitude was established as 1.5×10^{-7} to 6.5×10^{-7}.

For a dependable assessment of structural overstress probability, actual test data on a smaller scale model would be required. To this date, such data is not available. Using information from reference (4), an order of magnitude could be estimated as 1×10^{-4}. This would account for all deficiencies of design, materials and workmanship.

Finally, containment failure probability could be calculated, as defined, by combining load and structural overstress probabilities, as 1.5×10^{-11} to 6.5×10^{-11}.

This is an extremely low probability, and represents additional evidence of the margins of safety built in to metal containment structures.

5.0 CONCLUSIONS

Metal containment vessels are a valid containment concept and should be evaluated in any containment system selection program. Careful design, using state of the art techniques, coupled with proven excellence in steel material performance will assure maximum safety to the public and protection of the environment. The ASME Code should also recognize the need for the definition of local regions. Local primary membrane stresses, for load categories A and B should be allowed to exceed a stress intensity value of 1.0 S_m for the length of not more than $4.277\sqrt{Rt}$ in the meridional direction of spherical vessel containment.

Evidence presented in this paper shows that an increase of stress allowables in case of and OBE can be fully justified.

For the future, the ASME and the NRC should use the probabilistic methods outlined in this paper to a greater degree in formulating stress allowables.

6.0 ACKNOWLEDGMENTS

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APPENDIX A

LOCAL STRESS REGION IN SPHERICAL SHELL DUE TO INTERNAL PRESSURE

The solution for the stress resultants of a shell consists of the sum for the membrane solution and the edge load solution.

The particular membrane solution for a spherical shell subject to internal pressure is:

$$\left.\begin{aligned} N_\phi = N_\theta &= \frac{pR}{2} \quad \ldots\ldots \\ \psi^{p}_{(o)} &\equiv 0 \quad \ldots\ldots \\ \delta^{p}_{(o)} &= \frac{pR^2 \sin\alpha}{2Et}\,(1-\nu)\,.\;.\;. \end{aligned}\right\} \quad (1)$$

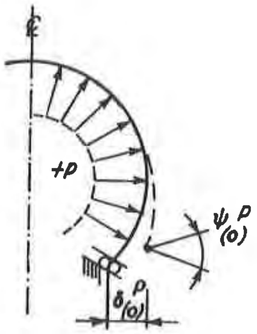

FIGURE A-1
MEMBRANE SOLUTION

The displacements at the edge are:

$$\left.\begin{aligned} \psi^{(h)}_{(o)} &= -\frac{4\lambda^3}{ERt} M_\alpha + \frac{2\lambda^2 \sin\alpha}{Et} H_\alpha \;.\;. \\ \delta^{(h)}_{(o)} &= \frac{2\lambda^2 \sin\alpha}{Et} M_\alpha - \frac{2R\lambda \sin\alpha}{Et} H_\alpha \;.\;. \end{aligned}\right\} \quad (2)$$

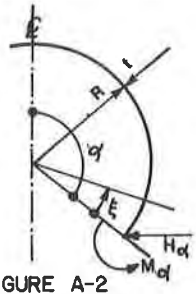

FIGURE A-2
EDGE LOADS

Constants H_α and M_α are found from the compatibility conditions as:

$$\left.\begin{aligned} M_\alpha &= \frac{pRt}{4}\sqrt{\frac{1-\nu}{3(1-\nu)}} \quad \ldots\ldots \\ H_\alpha &= \frac{pR(1-\nu)}{2\lambda \sin\alpha} \quad \ldots\ldots \end{aligned}\right\} \quad (3)$$

By adding the homogeneous solution for a spherical shell (11) to the membrane solution and then substituting the constants from eq 3 (preceding page), the total solution for membrane forces is:

$$N_\phi = \frac{pR}{2}\left[1 - \frac{(1-\nu)}{\lambda}\, e^{-\lambda\xi}\cot(\alpha - \xi)\cos\lambda\xi\right]$$

$$N_\theta = \frac{pR}{2}\left[1 - \sqrt{2}(1-\nu)e^{-\lambda\xi}\sin(\lambda\xi + \frac{\bar{\mu}}{4})\right]$$

Where period is $\frac{2\tilde{\mu}}{\lambda}$ and $\lambda = \sqrt[4]{(\frac{R}{t})^2\, 3\,(1-\nu)}$

Define local stress zone as shown on Figure A-3.

For N_ϕ ... $\xi_\phi = \frac{\tilde{\mu}}{2\lambda} + \frac{\tilde{\mu}}{\lambda} = 1.50\,\frac{\tilde{\mu}}{\lambda} = \frac{1.50\tilde{\mu}}{\sqrt{3(1-\nu^2)}}\sqrt{\frac{t}{R}}$ radians

or $L_\phi = R\xi_\phi = \frac{1.50\tilde{\mu}}{\sqrt{3(1-\nu^2)}}\sqrt{Rt}$ measured in the meridional direction

For N_θ ... $\xi_\theta = \frac{3\tilde{\mu}}{4\lambda} + \frac{\tilde{\mu}}{\lambda} = 1.75\,\frac{\bar{\mu}}{\lambda} = \frac{1.75\tilde{\mu}}{3(1-\nu^2)}\sqrt{\frac{t}{R}}$ radians

or $L_\theta = R\,\xi_\theta = \frac{1.75\tilde{\mu}}{\sqrt{3(1-\nu^2)}}\sqrt{Rt}$ measured in the meridional direction

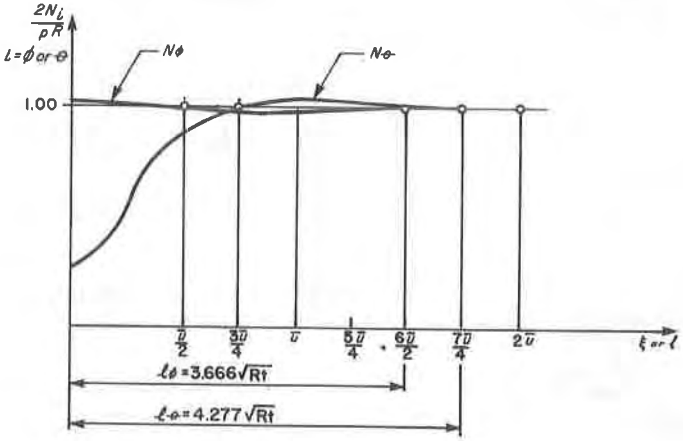

FIGURE A-3

Table I

LOAD COMBINATIONS - CONTAINMENT VESSEL

No.	LOAD COMBINATION	Cate-gory	D	L	P_t	P_e	P_a	T_t	T_o	T_e	T_a	E	E'	R_o	R_e	R_a	Y_j	Y_r
(1)	Normal Operations	A	1.0	1.0	-	-	-	-	1.0	-	-	-	-	1.0	-	-	-	-
(2)	Abnormal/Normal Operation		1.0	1.0	-	-	1.0	-	-	-	1.0	-	-	1.0	-	1.0	-	-
(3)	Severe Environmental	B	1.0	1.0	-	-	-	-	1.0	-	-	1.0	-	1.0	-	-	-	-
(4)	Severe Environmental/ External Pressure		1.0	1.0	-	1.0	-	-	-	1.0	-	1.0	-	-	1.0	-	-	-
(5)	Abnormal/Severe Environmental		1.0	1.0	-	-	1.0	-	-	-	1.0	1.0	-	-	-	1.0	-	-
(6)	Abnormal/Extreme Environmental	C	1.0	1.0	-	-	1.0	-	-	-	1.0	-	1.0	-	-	1.0	-	-
(7)	Extreme Environmental/ External Pressure		1.0	1.0	-	1.0	-	-	-	1.0	-	-	1.0	-	1.0	-	-	-
(8)	Abnormal Extreme Environmental/Jet Impingement	D	1.0	1.0	-	-	1.0	-	-	-	1.0	-	1.0	-	-	1.0	1.0	1.0
(9)	Test	E	1.0	1.0	1.0	-	-	1.0	-	-	-	-	-	-	-	-	-	-

Table II

Probability of Ground Acceleration per Year in the Eastern U.S. for Different Site Conditions

Ground Accel. (incremental)*	Soft	Average	Firm
0.1g	7.7×10^{-3}	3.6×10^{-3}	1.4×10^{-3}
0.2g	1.9×10^{-3}	6.5×10^{-4}	1.5×10^{-4}
0.5g	2.0×10^{-4}	4.6×10^{-5}	7.9×10^{-6}
1.0g**	3.5×10^{-5}	1.0×10^{-5}	6.9×10^{-7}

*The increment includes a band of accelerations around that specified, e.g., the probability at 0.1g is equal to the average of the two probabilities 0.05g to 0.1g and 0.1g to 0.15g.

**This entry encompasses accelerations greater than 1.0g.

Table III

Probability of Producing Failure for Given Earthquake

Ground Acceleration	Prob. of Damage Single System	Prob. of Damage Two Systems
0.2g	.001	3×10^{-5}
0.5g	.02	3×10^{-3}
1.0g	.1	3×10^{-2}

Table IV

Load Combination	Load Category	Joint Load Probability	Code Allowable Membrane
(2) Abnormal/ Normal Operation	A	1×10^{-4}	S_m
(5) Abnormal/ Severe Environmental	B	1.4×10^{-6} to 3.6×10^{-6}	S_m
(6) Abnormal/ Extreme Environmental	C	1.5×10^{-7} to 6.5×10^{-7}	$1.2\ S_m$

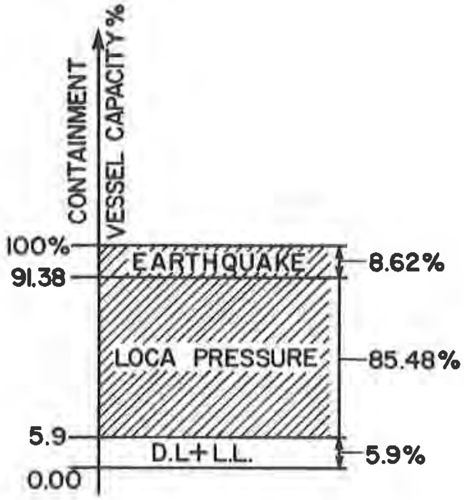

FIGURE 1

METAL CONTAINMENT VESSEL DESIGN CAPACITY

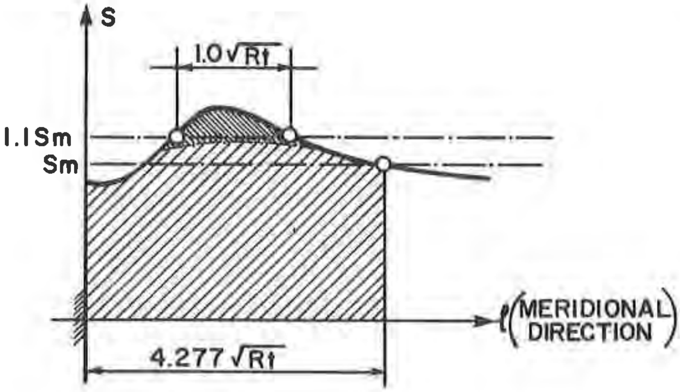

FIGURE 2

LOCAL STRESS REGION FOR SPHERICAL CONTAINMENT

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