PRELIMINARY SAFETY EVALUATION OF THE CAPACITY OF THE PRIMARY CONTAINMENT VESSEL OF THE ADVANCED BOILING WATER REACTOR (ABWR)

I. INTRODUCTION

In Appendix 19F to Chapter 19 of the ABWR Standard Safety Analysis Report (SSAR), GE discussed the ultimate capacity of its primary containment vessel, also referred to as a reinforced concrete containment vessel (RCCV). The staff's evaluation of the adequacy of the RCCV to withstand the postulated design basis loads is discussed in Sections 3.8.1 and 3.8.2 of the Final Safety Evaluation Report (FSER). The purpose of this evaluation is to assess if the containment performance goals of the ABWR RCCV under severe accident loadings are consistent with the deterministic containment performance goal of SECY-90-016, "Evolutionary LWR Certification Issues and their Relationship to Current Regulatory Requirements."

In SECY-90-016 dated January 12, 1990, the staff recommended that the Commission approve a conditional containment failure probability (CCFP) of 0.1 or a deterministic containment performance goal that offers comparable protection in the evaluation of evolutionary ALWRs. The staff recommended a general criterion for containment performance during a severe accident challenge for evolutionary ALWRs in place of a CCFP:

> The containment should maintain its role as a reliable leaktight barrier by ensuring that containment stresses do not exceed ASME Level C Service Limits for a minimum period of 24 hours following the onset of core damage and that following this 24 hour period the containment should continue to provide a barrier against the uncontrolled release of fission products.

In the staff requirements memorandum (SRM) dated June 26, 1990, the Commission approved the use of a 0.1 CCFP as a basis for establishing regulatory guidance for evolutionary ALWRs. The Commission further encouraged the staff to review suitable alternative, deterministically established, containment performance objectives that provide comparable mitigation capability, if submitted by applicants.

The staff has evaluated the RCCV performance objectives submitted by the applicant for the ABWR. The staff evaluated the RCCV internal pressures that establish the containment performance objectives using the deterministic criterion in SECY-90-016 (i.e., Level C Service Limit for the first 24 hours and assurance of no uncontrolled release after 24 hours). The details of the staff's evaluation are discussed below.

II. EVALUATION

The ABWR's RCCV is a right, cylindrical structure of the steel-lined, reinforced concrete design with a steel torispherical upper drywell head

Enclosure

(STUDH). In order to establish the ultimate capacity of the containment, the applicant discusses in Appendices 19E and 19F of its SSAR (Ref. 1) the scale model testing of the RCCV performed in Japan, provides the calculated capacity of the RCCV STUDH, and discusses the potential leak path under pressures and temperatures that could represent the environment inside the containment during severe accident conditions. In a letter dated April 24, 1992 (Ref. 2), the applicant revised its SSAR to incorporate the effects of increasing the STUDH thickness from 2.54 cm to 3.175 cm (1 in. to 1¼ in.). The preliminary review by the staff generated a number of questions (Ref. 3) which were transmitted to the applicant by a telefax on May 6, 1992. The applicant's responses to the questions were received by the staff on June 3, 1992 and June 27, 1992 (Ref 4). This evaluation is based on a review of the information provided in References 1, 2, and 4.

In the information provided to the staff, the applicant arrives at the following four conclusions regarding the structural capability and functionality of the RCCV:

1. The modified STUDH of the RCCV will have an internal pressure capacity of 668.8 kPa (97 psig) at 260° C (500° F) when the allowable stresses in the steel drywell head are limited to the Level C Service Limit of the ASME Code Section III, Subarticle NE-3220.

2. The pressure capacity of the STUDH at the median fragility (as defined by the conditional failure probability at 50 percent confidence level) is determined to be 923.9 kPa (134 psig).

3. The ultimate capacity of the concrete portion of the RCCV is 1241.1 kPa (180 psig).

4. The total leak area through various penetrations at 827.4 kPa (120 psig) is estimated to be 67.55 cm^2 (10.47 in^2).

The acceptability of the applicant's four conclusions are discussed and evaluated by the staff in the following sections:

A. Level C Service Limit

The first part of the deterministic criterion of SECY-90-016 limits the containment stresses to Level C Service Limit as provided in the ASME Boiler and Pressure Vessel Code (hereafter referred to as the "ASME Code") Section III, Paragraphs NE-3221 for stress intensity and NE-3222 for buckling. The following paragraphs discuss compliance of this aspect of the containment performance goals for the steel torispherical upper drywell head and the concrete portion (including the steel liner).

1. STUDH

a. Membrane Stress Intensity

On the basis of NASTRAN analysis and the stress intensity criterion provided in the ASME Code, Section III, Paragraph NE-3221, the applicant stated that the general primary membrane stress controls the design at the Level C Service Limit for an internal pressure of 730.8 kPa (106 psig) at 171° C (340° F). At 260° C (500° F), the allowable internal pressure at the Level C Service Limit for membrane stress intensity was found to be 668.8 kPa (97 psig). To verify the applicant's results of the stresses using the NASTRAN computer code, the staff independently calculated the membrane stresses using the ALGOR computer code. The staff's comparison (Table 1) confirmed the applicant's conclusion.

b. Buckling

Galletly (Ref. 5) developed a simple parametric equation to calculate limiting internal pressure that would prevent buckling of steel torispherical heads based on the actual test data. Based on the equation and the analysis of the data in Reference 6, the applicant calculated a best estimate internal pressure value of 1737.5 kPa (252 psig) and an lower bound value of 1144.5 kPa (166 psig) as values corresponding to test buckling failure of torispherical heads.

When test data are used to establish the ASME Code Section III, NE-3222 allowable buckling stress, it is appropriate to use the best estimate test data. Accordingly, when the best estimate test data values are used in NE-3222, the allowable internal pressure at the Level C Service Limit for buckling stress is 695 kPa (101 psig). An alternate method of computing the allowable buckling stress is provided in ASME Code, Section III Code Case N-284. The factor of safety at the Level C Service Limit in the Code Case N-284 (1.67) is less than that of NE-3222 (2.5). However, the factor of safety has to be applied to the lower bound test data. When the lower bound test data are used in Code Case N-284, the allowable internal pressure at the Level C Service Limit is 685.3 kPa (99 psig).

From the above three limiting pressure values of 668.8 kPa (97 psig) based on membrane stress intensity criterion, 695 kPa (101 psig) from buckling criterion of NE-3222, and 685.3 kPa (99 psig) from buckling criterion of N-284, the staff finds that because the 668.8 kPa (97 psig) is the least of the pressure values, it controls the internal pressure capacity of STUDH corresponding to ASME Level C stress criterion. Thus, the staff finds the proposed internal pressure of 668.8 kPa (97 psig) as an acceptable value for the STUDH in establishing the deterministic Level C Service Limit criterion as stated in SECY-90-016.

2. Concrete

The first part of the deterministic criterion of SECY-90-016 does not provide an explicit criterion for concrete containments since the Level C Service Limit criterion is applicable to only steel containments. However, for the concrete portion of the RCCV, the staff considers the factored load acceptance standards of ASME Code Section III, Division 2, Article CC-3000 as an appropriate acceptable criterion. It should be noted that in applying the criterion, a factor of 1.0 (instead of 1.5) should be substituted in the abnormal load category in Table CC-3230-1 for the internal pressure generated by severe accidents. The staff believes that this criterion satisfies the intent of the first part of the deterministic criterion of SECY 90-016. Compliance with the criterion for the concrete portion of the RCCV is discussed in the subsequent paragraphs:

In Appendix 19E2.3.2, in reference to compliance with 10 CFR 50.34(f), the applicant discusses the use of the factored load acceptance standards to establish the internal pressure capability of the concrete portions of the RCCV at 552 kPa (80 psig). In addition, in Appendix 19F, the applicant discusses the ultimate capacity of the concrete portion of the RCCV on the basis of model testing. The staff reviewed the information in the Appendices to evaluate the maximum internal pressure value that could satisfy the factored load acceptance standards of Article CC-3000 of the ASME Code, Section III, Div. 2.

At 620.5 kPa (90 psig), the reinforcing bar strains in the general shell area vary between 0.1 percent and 0.15 percent and those in the discontinuity areas (junctions of walls and slabs, around containment openings) vary between 0.15 percent and 0.22 percent. The allowable strains for the reinforcing bars (assuming ASTM A615, Grade 60 reinforcing bars) would be 0.2 percent in the general shell area, and 0.4 percent around the discontinuities. By linearly extrapolating the strains from 620.5 kPa (90 psig) to 668.8 kPa (97 psig), the staff finds that the allowable strain value for the reinforcing bars would not be exceeded. Since there was no liner plate in the model, it is expected that, in the general shell areas, the liner strains will be approximately equal to the strains in the reinforcing bars near the inside face. At the penetration openings and other discontinuities, the liner strains will depend upon the material of the liner and actual details of liner-anchorage construction. Thus, a definite conclusion cannot be made regarding the actual liner strains in this area. However, based on the general deformation curves provided in Fig. 6-1 (Ref. 4), it can be judged that the onset of the non-linear behavior will be between the pressure range of 586.1 kPa (85 psig) and 689.5 kPa (100 psig) in the areas near openings and large discontinuities. Assuming that the strains in the inside reinforcing bars and the liner plate will be similar in the pressure range between 568.1 and 689.5 kPa (85 and 100 psig), the staff finds that the strains in the plate will not

exceed the factored load acceptance criteria of the ASME Code, Section III, Division 2, Article CC-3000 at 668.8 kPa (97 psig).

Thus, the staff finds the proposed internal pressure of 668.8 (97 psig) an acceptable value for the STUDH, as well as for the concrete portion of the RCCV, satisfying the intent of the first part of the deterministic criterion of SECY-90-016.

B. Median Fragility Level for RCCV

The objective of the second part of the deterministic criterion of SECY-90-016 is to assure that the uncontrolled leakage does not occur from the containment. The staff considers the median fragility of the containment structure (RCCV) as an adequate criterion for satisfying this objective, provided the total leakage from penetrations and other bypasses are within the definition of controlled leakages.

1. STUDH

The applicant stated that the limit pressure for plastic deformation was found to be 839.1 kPa (121.7 psig) at 260° C (500° F) by Shield and Drucker's proposed equation (Ref. 6). The minimum yield strength of material SA-516, Gr. 70 as specified in Appendix I of ASME Section III was increased by 10 percent for the realistic estimate of the structural strength. Thus, the applicant determined the limiting internal pressure of 923.9 kPa (134 psig) at 260° C (500° F).

In a telefax transmitted to the staff on June 1, 1992, regarding the RCCV STUDH buckling capability, the applicant predicts a best estimate internal pressure value of 1737.5 kPa (252 psig) and lower bound value of 1144.5 kPa (166 psig) as values corresponding to buckling failure of the STUDH. These values are based on the results of the tests (Ref. 6) performed on stainless steel and carbon steel torispherical heads fabricated using pressed and spun (PS) technique as well as crown and segment technique (CS). Out of 43 tests, six data points were from the actual failure internal pressure of the carbon steel CS heads. These are the most relevant data for the RCCV drywell head. The lower bound value is estimated 1144.5 kPa (166 psig). As these values are based on a limited data base and they correspond to actual buckling failure of the heads, use of these values to arrive at the actual median fragility internal pressure for the RCCV drywell head should be made with some margin on the lower bounds. Providing a knockdown factor of 1.2 (arbitrary), the internal buckling pressure of median fragility level can be derived as 951.5 kPa (138 psig). However, the applicant adopts median fragility value of 923.9 kPa (134 psig) due to axisymmetric yielding of the head as calculated from Reference 6.

Based on the staff's evaluation and by taking the above factors into account, the staff considers the median fragility value for drywell head of 923.9 kPa (134 psig) to be reasonable.

2. Concrete

The applicant has described in detail the results of 1/6-scale global model test and 1/10-scale top slab test of the RCCV. The 1/6-scale global model test was terminated at the average internal pressure of 620.5 kPa (90 psig) (2 times the design pressure, $2P_d$). In the 1/10th scale local test of the top slab, the test was carried out until the rupture of the vertical reinforcing bars at the joint of the pool girders and cylindrical wall. The slab shear failure occurred at about 1172.1 kPa (170 psig) and the vertical reinforcing bars ruptured at about 1241.1 kPa (180 psig). The applicant identified the portion near the lower drywell access tunnel as the weakest region in determining the ultimate capacity of the RCCV (concrete portion). The applicant considered the reinforcing bar strains measured in this region, and by extrapolating the strains for higher internal pressure using elastic analysis determined that the hoop bars in this region would rupture at about 1241.1 kPa (180 psig). This type of analysis verified the applicant's assumption that the ultimate capacity of the concrete portion of the RCCV is approximately to 1241.1 kPa (180 psig). The staff has a number of concerns related to the proposed ultimate capacity value as well as any internal pressure value higher than 689.5 kPa (100 psig) as the median fragility value.

In order to complete its review, the staff requires that the applicant address the concerns discussed below:

a. The 1/6-scale model test of the RCCV was performed using rubber liner, and by pressurizing the containment with water. Such a model testing does not provide sufficicnt evidence regarding the functional failure (vs. structural failure) pressure of the RCCV (i.e., the pressure at which the leak rate exceeds the pressurization rate). The ultimate pressure capacity of the 1/6 scale model of reinforced concrete containment test performed at Sandia National Laboratory was limited by such a functional failure. Therefore, the ABWR RCCV test, while provides evidence of structural strength, does not address the leaktightness at higher pressures.

b. Figure 19F.2.22 (strain diagram near lower opening) indicates that the strains in the diagonal bars at 620.5 kPa (90 psig) internal pressure are slightly higher than 0.2 percent which is at about the elastic yield of the bar material. The measured surface cracks (Figure 19F.2.25) in this area were about 0.0559 cm (0.022 in.) and in the general shell area the cracks were about 0.0254 cm (0.01 in.). These observations would indicate some reduction in the stiffness of the shell at 620.5 kPa (90 psig). This stiffness reduction is likely to progress rapidly with increasing pressure. Thus, extrapolating the capacity from 620.5 kPa (90 psig) to 1241.1 kPa (180 psig) using an elastic

model could not provide reliable results. The applicant should use the cracked concrete, non-linear model to extrapolate the test results beyond 6895.5 kPa (100 psig).

c. The absence of liner plate in the model tests is discussed by the applicant in 19F.3.2.1. However, the applicant assumes: (1) the liner will experience the same strain as the inside reinforcing bars, and (2) that the liner anchor failure does not occur. The applicant should address: (1) the basis for the above assumptions, and (2) the effects of strain concentrations at the junction of the thicker-to-thinner liner plate and consequent high forces that could be developed in the stud anchor (Ref. 7).

The staff's concerns could be addressed by realistic model tests, or by improved analytical codes (Ref. 8) which explicitly considers the possibilities of various failure modes of reinforced concrete containment, and in particular, tearing of liner plate due to strain concentration.

C. Leakage

In Section 19F.3.2.2, the applicant discusses the leakages through various RCCV penetrations under severe accident temperatures and pressures. The assumptions and rationale used in the discussions by the applicant depend upon the experimental work performed at SNL and Argonne National Laboratory (ANL). Up to 620.5 kPa (90 psig), the estimate of leak area (i.e., 5.85 in^2), is based on; (1) relatively small strains (<0.2 percent) around the equipment hatch (minimizing the chances of ovalization), and (2) credible assumption regarding pressure unseating penetrations. This is acceptable to the staff. However, after 620.5 kPa (90 psig), the estimated leakage area values are subjected to large uncertainties. The applicant should provide the assessment of potential leakage from these penetrations up to the internal pressure value of 923.9 kPa (134 psig).

III. SUMMARY AND CONCLUSION

Based on the review of the information provided by the applicant and the staff's evaluation as discussed above, the staff comes to the following conclusions regarding the consistency of the containment performance goals of the ABWR RCCV under severe accident loadings with the deterministic containment performance goals of SECY-90-016.

1. If the containment internal pressure during the first 24 hours after the onset of a core-damage accident is limited to 668.8 kPa (97 psig), then the staff considers that the ABWR containment structure meets the first part of the deterministic criterion of SECY-90-016. It should be noted, however, that according to the applicant's estimation, the leakage areas through penetrations would be higher than 37.7 cm^2 (5.85 in^2).

2. As discussed in II.B of the evaluation, the staff considers the median fragility of the RCCV as an adequate criterion for satisfying the second part of the deterministic criterion of SECY-90-016. The following conclusions addresses the consistency with this part of SECY-90-016:

   a. The applicant has assessed the median fragility value for the STUDH of the RCCV to be 923.9 kPa (134 psig). The staff's evaluation indicates that this is a conservative value, and should ensure that the STUDH would provide a reliable barrier against uncontrolled release of fission products as long as the internal pressure generated by a severe accident event does not exceed this value, and the accompanied temperature does not exceed 260°C (500°F).

      However, as stated in Sections II.B.2 and II.C of the evaluation, additional information is needed to support this value for the concrete portion of the RCCV.

   Thus, establishing the consistency with the second part of the deterministic criterion of SECY 90-016 remains an open item.

References:

1. General Electric Nuclear Energy, Advance Boiling Water Reactor Standard Safety Analysis Report (Up to and including Amendment 21).

2. Letter from P. W. Marriott of General Electric Nuclear Energy to NRC Document Control Desk (Attn. Robert C. Pierson), Docket No. STN 52-001, dated April 24, 1992. Subject: Revision to Appendices 19F and 19E for Containment Ultimate Strength and 100 percent Metal-Water Reaction.

3. Telefax from V. McCree (NRC) to J. Fox (GE), transmitting RAI from Goutam Bagchi to Robert Pierson, dated April 12, 1992.

4. Telefaxes from Jack Fox of General Electric Nuclear Energy to Goutam Bagchi and Chet Poslusny of NRC, Docket No. STN 52-001, dated June 1, 1992, and June 26, 1992. Subject: Containment Ultimate Strength Evaluation. (Proprietary)

5. Galletly, G. D. "A Simple Design Equation for Preventing Buckling in Fabricated Torispherical Shells under Internal Pressure," ASME Journal of Pressure Vessel Technology, Vol. 108, November 1986.

6. Shield, R. D., Drucker, D. C. "Design of Thin-Walled Torispherical and Toriconical Pressure-Vessel Heads," Transactions of ASME, June 1961.

7. NUREG/CR-5476, "Posttest Analysis of a 1:6-Scale Reinforced Concrete Reactor Containment Building," Sandia National Laboratory, February, 1990.

8. NUREG/CR-5341, "Round-Robin Analysis of the Behavior of a 1:6-Scale Reinforced Concrete Containment Model Pressurized to Failure: Posttest Evaluations," Sandia National Laboratory, October 1989.

TABLE 1

GE ABWR Drywell Head
Comparison of Membrane Stresses

75 psig internal pressure, 1.25" thickness, 340° F

	Hoop	Longitudinal	Intensity	Remarks
NASTRAN	-14,725	8,640	23,365	5° Wedge
ALGOR*	-14,650	8,420	23,070	5° Wedge 1st Quadrant
ALGOR*	-13,475	8,630	22,105	10° Wedge Full model

From NASTRAN,

Stress intensity, P_m: 23,365 psi @ 75 psig and 340°F

Yield strength (S_y) (SA-516, Gr. 70): 33,300 psi @ 340°F
30,700 psi @ 500°F

Allowa stress intensity (S_{mc}) (SA-516, Gr. 70): 19,300 psi

Level C Service Limit Criteria (NE-3221): $P_m \leq$ max. $(1.0S_y, 1.2S_{mc})$,
$P_m \leq$ 33,300 psi @ 340°F
$P_m \leq$ 30,700 psi @ 500°F

Allowable pressure = (75)*(33,300)/(23,365) = 106 psig @ 340°F
=(106)*(30,700)/(33,300) = 97 psig @ 500°F

* ALGOR has been used by the staff for its independent evaluation.