NUREG-0661
Supplement No. 1

Safety Evaluation Report

Mark I Containment Long-Term Program

Resolution of Generic Technical Activity A-7

U.S. Nuclear Regulatory Commission

Office of Nuclear Reactor Regulation

August 1982

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ABSTRACT

When the NRC staff published "Safety Evaluation Report, Mark I Containment Long-Term Program" (NUREG-0661) in July 1980, four areas were identified where the technical issues had not been fully resolved. These were: (1) specification for condensation oscillation loads acting on the downcomers, (2) adequacy of the data base for specifying torus wall pressures during condensation oscillations, (3) possibility of asymmetric torus loading during condensation oscillations, and (4) effect of fluid compressibility in the vent system on pool swell loads. The first item, downcomer condensation oscillation loads, lacked an acceptable load definition. The remaining three items had acceptable specifications; however, NRC requested additional confirmatory information to justify the adequacy of the load specifications.

This supplement addresses the resolution of the four issues listed above. In response to NRC concerns expressed in NUREG-0661, the Mark I Owners Group conducted additional experimental and analytical studies. The experimental studies consisted basically of two additional condensation oscillation tests in the Full-Scale Test Facility (Norco, California). The staff has reviewed these efforts and has concluded that all technical issues connected with the generic Mark I Long-Term Program have been resolved.

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ACKNOWLEDGMENTS

The following individuals contributed substantially to this report:

C. I. Grimes, USNRC, Division of Licensing
J. D. Ranlet, Brookhaven National Laboratory
G. Maise, Brookhaven National Laboratory
R. L. Kosson, Brookhaven National Laboratory (Grumman Aerospace Corporation)
C. Brennen, California Institute of Technology
A. A. Sonin, Massachusetts Institute of Technology
G. Bienkowski, Princeton University

ACRONYMS AND INITIALISMS

BWR	boiling water reactor
DBA	design-basis accident
EPRI	Electric Power Research Institute
FSI	fluid-structure interaction
FSTF	Full-Scale Test Facility
GE	General Electric Company
IBA	intermediate-break accident
LDR	Load Definition Report
LLL	Lawrence Livermore Laboratory
LOCA	loss-of-coolant accident
LTP	long-term program
NRC	Nuclear Regulatory Commission
PSD	power spectral density
PUAAG	plant-unique analysis-applications guide
QSTF	Quarter-Scale Test Facility
RMS	root-mean-square
SBA	small-break accident
SER	Safety Evaluation Report
STP	short-term program

1 INTRODUCTION AND SUMMARY

The suppression pool hydrodynamic loads associated with a postulated loss-of-coolant accident (LOCA) were first identified during large-scale testing of an advanced design pressure-suppression containment (Mark III). These additional loads, which had not explicitly been included in the original Mark I containment design, result from the dynamic effects of drywell air and steam being rapidly forced into the suppression pool (torus). Because these hydrodynamic loads had not been considered in the original design of the Mark I containment, a detailed reevaluation of the Mark I containment system was required.

The historical development of the bases for the original Mark I design as well as a summary of the two-part overall program (i.e., Short-Term and Long-Term Programs) used to resolve these issues is in Section 1 of NUREG-0661, "The Safety Evaluation Report Mark I Long-Term Program" (SER) (Ref. 1). Reference 2 describes the staff's evaluation of the Short-Term Program (STP) used to verify that licensed Mark I facilities could continue to operate safely while the Long-Term Program (LTP) was being conducted.

The objectives of the LTP were to establish design-basis (conservative) loads that are appropriate for the anticipated life of each Mark I boiling water reactor (BWR) facility (40 years) and to restore the originally intended design-safety margins for each Mark I containment system. The principal thrust of the LTP has been the development of generic methods for the definition of suppression pool hydrodynamic loadings and the associated structural assessment techniques for the Mark I configuration. The generic aspects of the Mark I Owners Group LTP were completed with the submittal of "Mark I Containment Program Load Definition Report" (Ref. 3), hereafter referred to as LDR, and "Mark I Containment Program Structural Acceptance Guide" (Ref. 4), hereafter referred to as the PUAAG, as well as supporting reports on the LTP experimental and analytical tasks.

The Mark I containment LTP SER (Ref. 1) presented the staff's review of the generic suppression pool hydrodynamic load definition and structural assessment techniques proposed in the reports cited above. On the basis of the review of the experimental and analytical programs conducted by the Mark I Owners Group, the staff has concluded that, with one exception, the proposed suppression pool hydrodynamic load definition procedures, as modified by the NRC Acceptance Criteria in Appendix A of Reference 1, will provide a conservative estimate of these loading conditions. The exception is the lack of an acceptable specification for the downcomer condensation oscillation loads. In addition, the staff requested confirmatory programs to justify the adequacy of the load specifications in the following three areas: (1) adequacy of the data base for specifying torus wall pressures during condensation oscillations, (2) possibility of asymmetric torus loading during condensation oscillations, and (3) effect of fluid compressibility in the vent system on pool-swell loads. This report supplements the Mark I SER (NUREG-0661) by addressing the outstanding issues relating to the Mark I containment LTP, namely the downcomer condensation oscillation load definition and the confirmatory analyses and test programs that are intended to justify the adequacy of the load specifications.

A discussion of these issues can be found in Reference 1, as shown in Table 1. Also shown in Table 1 are the sections of this report where the supplemental reviews of these items are discussed.

Based on the above reviews, the staff has concluded that the improved load definition submitted by the Mark I Owners Group for downcomer condensation oscillation loads is acceptable. In addition, the staff has concluded that the load specification associated with the confirmatory experimental and analytical programs has been justified. Thus, the staff has concluded that the outstanding issues relating to the Mark I containment LTP have been resolved.

Table 1 Tabulation of Pertinent Mark I Outstanding Issues Documentation

Issue	NUREG-0661 SER Section	Supplement Section
Downcomer Condenstion Oscillation Loads	3.8.2	2.1
Condensation Oscillation Load Magnitude Confirmation	3.8	2.2
Confirmation of Condensation Oscillation Load Global Symmetry	3.8.1	2.3
Compressibility Effects in Scaled Pool Swell Tests	3.4	2.4

2 HYDRODYNAMIC LOAD EVALUATION AND CONFIRMATION

2.1 Downcomer Condensation Oscillation Loads

Condensation oscillation loads and chugging loads refer to the oscillatory pressure loads imparted to structures as a result of the unsteady, transient behavior of the condensation of the steam (released during a LOCA) occurring near the end of the downcomers. Because the nature of this unsteadiness has been found to be significantly different at high steam-flow rates than it is at low steam-flow rates, it is convenient to divide the phenomena into two types: (1) "condensation oscillations," which occur at relatively high vent-flow rates and are characterized by continuous periodic oscillations, with neigh boring downcomers oscillating in phase, and (2) "chugging," which occurs at lower vent-flow rates and is characterized by a series of random pulses that are typically a second or more apart. The classifications--condensation oscillation and chugging--are somewhat arbitrary because there is a continuous spectrum of unsteady condensation phenomena. However, they are convenient for the purposes of defining the nature of the various loading conditions.

When the NRC published NUREG-0661, all the loading specifications in the chugging regime were found acceptable. The concerns with periodic loads related only to those loads resulting from condensation oscillations. Thus, the downcomer loads discussed below, as well as the loads addressed in the next two sections, stem from condensation oscillations.

During the condensation oscillation phase of the blowdown, a harmonic pressure oscillation occurs at the exit of each downcomer. In all Mark I systems the downcomers are tied in pairs: a pair comprises the two downcomers on opposite sides of the vent header, tied together by a tie bar near the exit level (see Figure 2.1-2 in Ref. 1). An inphase harmonic pressure oscillation in the two downcomers of a pair will tend to make the pair oscillate vertically, with each downcomer flexing somewhat at its "knee" and in the region where the downcomer is joined to the ring header. An out-of-phase pressure oscillation will tend to make the pair oscillate in a lateral swinging motion, and this oscillation may give rise to more significant strains in the vent header region.

In the Mark I LTP SER (NUREG-0661), NRC expressed reservations about the then-extant load definition for tied downcomers, and concluded that an improved specification should be developed based on new supplemental experiments in the Full-Scale Test Facility (FSTF). The reservations centered on two concerns: first, that the original load definition lacked an out-of-phase driving force that could excite the swinging motion of a downcomer pair; and second, that more information was needed on the structural response frequencies and damping in the downcomer pair systems.

Based on the new series of tests that the Mark I owners carried out in the FSTF in response to NRC's request, a revised load definition was submitted

(Ref. 5). The new definition applies two superposed components of loading to the downcomers in a pair (see Figure 7-1 and Table 7-1 in Ref. 5) as follows:

(1) An internal pressure of the same magnitude in both of the downcomers in a pair. This tends to cause the vertical oscillation of the pair.

(2) An internal pressure differential between the two downcomers in a pair. This tends to set up the swinging motion of the pair.

These two load components (pressures) are applied synchronously. The load is presented in terms of sinusoids at three frequencies: a fundamental, a second harmonic at twice the fundamental, and a third harmonic at three times the fundamental (further harmonics were not deemed important because even the second and third harmonics contributed relatively little to the strains in the FSTF, which is typical of the Mark I systems). These three sinusoids, each split into components (1) and (2) as described above, are applied simultaneously to represent the total dynamic downcomer load. The amplitudes of the sinusoids were obtained by Fourier analysis from the worst case loading conditions observed in the FSTF tests. The frequencies are based on those observed in the FSTF, modified by an uncertainty band that conservatively accounts for frequency variability within and between tests. For a design-basis accident (DBA), for example, the fundamental is specified to be between 4 and 8 Hz. The actual fundamental frequency to be used in the load specification of a particular plant (the two higher harmonics follow once the fundamental is specified) is to be that frequency from within the uncertainty bands that produces the highest structural strains in the system.

Based on the FSTF data, separate load definitions are derived for DBA and intermediate-break accident (IBA) conditions. The IBA (see Table 7-2 in Ref. 5) has somewhat higher frequencies but lower load amplitudes.

The above discussion defines the dynamic load on a single tied downcomer pair. The FSTF data showed that the swinging motion of one downcomer pair, caused by the pressure differential in (2) above, can be either out-of-phase or inphase with the swinging motion of an adjacent downcomer pair, with no clear rule as to which may be expected. To cover the worst expected loading conditions of the Mark I vent header/downcomer system, eight different combinations of phasing are prescribed for the swinging motion of the various downcomer pairs between two vents. These eight load cases are defined in Figure 7-7 of Reference 5; they include the case in which all downcomers on one side of the header experience positive pressure differentials with respect to their pair-mates on the other side. The load specification calls for the evaluation of all eight load cases for each plant.

This revised load definition is acceptable. It derives primarily from worst case FSTF data and provides for frequency spreading to account for uncertainty. The staff has concluded that the definition addresses and resolves the concerns raised relative to the original specification. Worst case combinations of swinging motion of the various downcomer pairs associated with a bay are conservatively addressed via the eignt load cases that are part of the specification.

2.2 Condensation Oscillation Load Magnitude Confirmation

The condensation oscillations that occur at the ends of the downcomers, as described in Section 2.1, produce pressure fluctuations within the pool that are transmitted to the torus walls. This section addresses the adequacy of the data base used to define these wall pressure loadings. The condensation phenomenon involves an unsteady, turbulent, two-phase flow. No reliable analytical methods exist that allow the modelling of such flows. Furthermore, because of the apparently random element in the condensation phenomenon, no reliable and proven empirical engineering methods exist that would allow accurate assessment of either (1) the load magnitudes, (2) the parametric variation of the loads, or (3) the scaling of the loads. Consequently, the load definition must rely on a data base taken from experiments that model closely the conditions in an actual plant. For this reason, condensation oscillation loads for load definition were based on the results of tests conducted in the Full-Scale Test Facility (FSTF), which is a full-scale, 22.5 sector of a typical Mark I torus connected to a simulated drywell and pressure vessel (Ref. 6).

Ten tests were conducted, with parametric variations of break size and type (steam or liquid), submergence, initial pool temperature, and torus pressure (see Table 3.8-1 of Ref. 1). The complete series of tests simulated blowdowns over a range from small breaks to the design-basis accident.

The principal design parameters for the FSTF (vent-area-to-pool-area ratio and distance of the downcomer exit to the torus shell) were selected to produce conservative data from which the loads could be derived. Structurally the FSTF torus sector was a replica of the Monticello plant. (Monticello is considered to be structurally "average" in relation to the range of the Mark I design characteristics.) The FSTF was intended to be prototypical so that loads measured in that facility could be applied directly in the plant-unique analyses. However, condensation oscillation loads transmitted to the structure by the water in the pool have been found to be affected by fluid-structure interaction (FSI) effects. Because there are variations in the structures of different plants, and, consequently, between the individual plants and the FSTF, some analysis and identification of these effects in both the FSTF and individual plants are necessary to define appropriate plant loads.

To assess this effect, the Mark I Owners Group developed a coupled fluid-structure analytical model simulating the FSTF structure and suppression pool (Ref. 7). In this model an assumed oscillatory source applied at the end of each downcomer is varied until the wall pressures match the maximum amplitude pressures observed in the FSTF tests. The source function thus determined is used to derive an equivalent "rigid-wall" pressure transient. From these analyses, a global pressure load on the torus shell is generated. The detailed procedure is described in the LDR (Ref. 3) and summarized in the SER (Ref. 1).

The load specification proposed in the LDR was derived from selected periods of maximum-amplitude test data from the FSTF. The FSI model used to derive the pressure amplitude-frequency spectra incorporates assumptions that are not all necessarily conservative by themselves. However, the overall conservatism of this technique is demonstrated by comparisons of the predicted structural response using the load specification and the measured structural response in the FSTF (Ref. 8). The measured peak structural responses (stresses, displacements and column loads) in the FSTF facility were generally exceeded by the values computed according to the LDR procedure by 80% or more. This suggests that the load application procedure contains conservatisms that should lead to an overall conservative specification as long as the data base is adequate to establish a reasonable representation of the amplitudes of the pressure sources.

The maximum condensation oscillation loads in the FSTF were found to occur for the large-break, liquid blowdown test. Only one such test was conducted in the original test series (M8). The load definition is therefore based almost exclusively on this single blowdown. In view of the periodic nature of the condensation oscillations, as well as the stochastic nature of the complex condensation processes, the staff concluded that test M8 constitutes only a single data point. Consequently, statistical variance or load magnitude uncertainty cannot be established with any useful accuracy from this single test run, even when magnitudes from test runs at much lower vent-flow rates are factored into the analysis. Thus, although the staff accepted the M8 test conditions as both conservative and prototypical for the Mark I design, the information was considered insufficient to establish a reasonable measure of the uncertainty in the loading functions and, hence, to ensure margins of safety in the containment structure.

Nevertheless, the staff concluded that the loads derived from M8 are probably conservative (although the degree of conservatism cannot be quantified) and, therefore, form a sufficient basis to proceed with the implementation of the Mark I LTP. [illegible] letters dated October 2, 1979 (Ref. 9), the NRC advised each Mark I licensee that additional FSTF tests would be required to establish the uncertainty in each of the condensation oscillation loads and to confirm the adequacy of the load specifications.

In response, the Mark I Owners Group, with the staff's concurrence, conducted two additional large-break liquid blowdowns in the FSTF Facility (Ref. 5). One test, M11B (meant as a repeat of test M8), was performed under geometric and flow conditions as nearly identical to M8 as was practicable. The type and size of the break as well as the submergence were identical. The nominal initial pool pressure was also identical to M8, and the initial pool temperature was held at 70°F, as in test M8. Test M12 was performed at conditions nominally identical to M8 except that the initial pool temperature was 95°F. The overall blowdown parameters--such as drywell pressure history, flow rate, and wetwell pressure history--are in Reference 5. These parameters are similar for all three tests (M8, M11B, and M12) and do not differ significantly from one another, suggesting a high degree of repeatability of the tests.

The wetwell bottom center pressure, as well as the pressure averaged over all the wetwell transducer locations, shows sufficient similarity in the time history of amplitudes and the frequency content of the oscillations to conclude that condensation oscillations in the FSTF are repeatable phenomena with a dominant deterministic character. The overall amplitude (root-mean-square (RMS) value) of the averaged wetwell pressure in run M11B peaks at a value about 25% below the peak in run M8 that was used to establish the LDR value.

The frequency content is essentially similar, with a fundamental frequency of about 6 Hz as measured in run M8. In run M12 the peak RMS amplitude exceeds run M8 (and the LDR value) by about 15%. The fundamental frequency is shifted slightly from 6 Hz to 5 Hz, but there is no significant difference in the energy content in that frequency range. This is consistent with the model of larger bubbles oscillating at the downcomers as a result of the hotter pool temperature in M12. The major contribution to the increased overall (RMS) amplitude appears to arise from increased energy content in the 20-to-30-Hz range.

On the basis of this information, the Mark I owners conclude that the new tests demonstrate that condensation phenomena are highly repeatable and not overly sensitive to the parameters within their expected ranges. They further conclude that the LDR bounds all of the new pressure data below 20 Hz and is slightly nonconservative between 20 and 30 Hz. The owners further demonstrate (Table 2-11 in Ref. 5) that this slight nonconservatism is not significant because of the conservatisms introduced by the methodology when the loads are applied to the structure. The LDR load definition applied to the FSTF facility using the methodology that is to be applied to the Mark I plants yields peak structural stresses and loads that exceed those measured in M12 by at least 70% and by as much as 150%. The owners therefore conclude that the two supplementary tests confirm the adequacy of the data base used for the load definition in the LDR.

The staff has carefully reviewed the new data and concurs with the Mark I owners' conclusion. While it is difficult to quantify the degree of uncertainty in the results from three blowdowns, reasonably conservative estimates can be made by using 1-second RMS pressure values from all three runs between 22 and 30 seconds (24 points). On this basis, the mean RMS pressure at this high-mass-flow condition is about 2.1 psi, the standard deviation is about 0.5 psi, the LDR value is about 2.5 psi, and run M12 peaks at about 2.9 psi. Because of the high degree of conservatism introduced by the methodology when the loads are applied to the structures, the potential variation of the pressure loading from the LDR value is well within the demonstrated conservatisms for the structural loads. For example, the assumption of a pressure loading that is three standard deviations from the mean (3.6 psi RMS) but that has spatial and frequency distribution identical to run M12 would reduce the demonstrated margin on the hoop membrane stress from 1.7 to about 1.4, thus retaining a substantial conservatism.

The staff considers the condensation oscillation load definition acceptable because of (1) the demonstrated repeatability of the condensation oscillation pressure measurements on the wetwell boundary, (2) the conservative nature of the data base, and (3) the conservative methodology for applying the loads to the torus.

2.3 Confirmation of Condensation Oscillation Load Global Symmetry

The Mark I Containment Program Load Definition Report (Ref. 3) specifies only a symmetric loading of the torus during the condensation oscillation phase of a postulated LOCA. The methodology assumes uniform amplitudes of the sources (or rigid wall pressures) and identical inphase time histories along the circumferential direction of the torus. The FSTF measurements indicated that the amplitudes of the pressure oscillations within all of the instrumented downcomers were approximately the same and showed no discernible trend in the small variations. Comparison of pressure traces also tended to suggest that essentially inphase oscillation was occurring at all of the instrumented downcomers.

The staff concurred with the Mark I owners' specification of a symmetric loading (Ref. 1) subject only to confirmatory analysis verifying that no significant asymmetric loading could be inferred from FSTF data when they are applied to a full Mark I torus.

The staff's concern was based on the potential for a significantly different structural response arising from asymmetric loading coupled with the necessity to extrapolate data from a 22.5° sector (FSTF) data to a full 360 torus. The staff felt that the information on the amplitudes in the original series of FSTF tests (Ref. 6) was sufficient to conclude that no significant asymmetry in amplitude variation can be expected. Because of the need to extrapolate phasing information to a Mark I torus, the staff requested an additional analysis of phasing in the original FSTF data and the confirmation tests (Ref. 9).

The General Electric Company letter report of April 1981 (Ref. 5) responds to this request. The report presents data showing that only the dominant frequency (near 5 Hz) is correlated between the downcomers in the FSTF run M8. The higher frequency components appear more stochastic in character and show no correlation. Phase data for the pressure signals at downcomers spaced 5, 9, and 14 ft apart for the 5-Hz frequency component are presented from the peak condensation oscillation periods in runs M8, M11B, and M12. Phase angles between -16° and 44° are observed with no systematic trend observed in any single time period from a single run. The Mark I owners, therefore, conclude that an asymmetric torus shell load does not need to be specified.

The NRC staff has reviewed the new data and analysis and concurs with that conclusion. The staff examined the data presented for potential systematic variation of phase with distance between downcomers because of the potential consequences that such a trend might have on the extrapolation to a full torus. If all 12 tests are considered for each distance between downcomers, the plot of phase angle vs. distance shows a slightly increasing trend with distance. The statistical scatter, however, totally overwhelms this trend within any single run. In addition, pressure amplitudes at different vents, while similar to each other, do show some variation of a stochastic nature without any evident trend.

Although the data cannot be used to unequivocally conclude that the load at all times must remain symmetric on a full-scale torus, the evidence is very strong that any expected asymmetry will be small and strongly random in direction. The phasing and amplitude correlation information of Reference 5 is consistent with a picture of waves travelling through the venting system, causing phasing between the dominant oscillations at different vents. In addition, the smaller scale, higher frequency oscillations can be attributed to local phenomena occurring at each vent. Thus, the lack of any known mechanism to create a standing wave with some defined direction of asymmetry in the full-scale Mark I geometry, together with the data from Reference 5, provides a reasonable basis for assuming that asymmetries in the condensation load will be small and will be constantly shifting in direction.

The staff, therefore, concludes that there is no need to define an asymmetric condensation oscillation load on the torus shell.

2.4 Compressibility Effects in Scaled Pool-Swell Tests

The Mark I specification for torus upward and downward loads during pool swell is derived from scale model tests. One of the shortcomings of these tests is that the compressibility in the vent system was not properly scaled (acoustic waves in the model vents travel much too fast relative to the velocity of the water slug in the downcomers). As described below, this scaling deficiency could lead to modest underprediction (or overprediction) of the pool-swell loads in Mark I containments.

The general description of events during the pool swell is as follows: In the case of a postulated DBA, as described in SER Section 2.2.1 (Ref. 1), the drywell and vent system are pressurized, causing the water leg initially in the downcomers to be accelerated downward into the suppression pool. Immediately following downcomer clearing, air bubbles form at the exit of the downcomers. As these bubbles form, their presence is felt on the submerged portion of the torus walls as an increase in pressure. Consequently, the torus experiences a dynamic net downward load as the bubble pressure is transmitted through the suppression pool. At that time, the torus airspace has not yet sensed the effects of the transient. The air bubbles continue to expand and decompress, causing a ligament of solid water above the bubbles to be accelerated upward. As the water slug continues to rise, the wetwell airspace volume above the water in the torus is compressed, resulting in a dynamic net upward load on the torus. The pool swell continues until there is a breakup of the water ligament, and direct communication between the bubble and airspace is achieved.

The loading specifications associated with the pool-swell transient are based on the subscale results of the plant-unique test series conducted in the Quarter-Scale Test Facility (QSTF) (Ref. 10) and the Electric Power Research Institute (EPRI) 1/11.7-scale three-dimensional test facility (Ref. 11). The scaling relationships utilized for these tests were developed by Moody (Ref. 12) during the STP and are based on the method of similitude. These scaling relationships have been confirmed by the experimental study presented in Reference 13, as well as by the independent research studies performed for the NRC, as described in References 14 to 16.

Note, however, that all of these confirmations were between scale models of various sizes, with 1/4 scale as the largest. During preliminary calculations to provide justification for the scaled three-dimensional flow distribution in the EPRI 1/11.7-scale pool swell tests, it was discovered that compressibility effects could cause higher torus loadings at full-scale conditions than those loadings derived from scaled-up test data. The mechanism responsible for this stems from communication delays within the vent system. These are negligible in scale models but not in full-scale Mark I systems. These calculations indicated that prior to vent clearing, for example, the vent system exhibited a closed-pipe-type response to the drywell pressure ramp. In other words, acoustic waves travelled back and forth through the vent system during the downcomer clearing process, causing the pressure at the interface (between air and water) to oscillate above and below the instantaneous drywell pressure. Thus, at vent clearing, the pressure at the downcomer end (which is commumicated to the torus bottom) could conceivably be greater than the drywell pressure at that time. Because these effects were not considered in the original load by the above scaling definition (Ref. 3), the staff required that the Mark I Owners Group perform an assessment of compressible flow effects and justify the adequacy of the pool-swell-related loads. A discussion of this assessment, along with the staff's review, follows.

The Mark I Owners Group used the computer code described in Reference 17 to investigate the effects of compressibility on the scaled pool-swell loads. The pool-swell transient was analyzed by means of a one-dimensional, compressible vent-flow model that was coupled to a semi-empirical bubble/pool-swell model. The vent system was treated as a series of nodes connected by flow paths which are used to simulate the lengths, friction losses, and area changes associated with the effective vent and vent header areas that service a single downcomer in a prototype Mark I configuration. The describing equations for the vent flow model, which included both area change and friction, were cast into algebraic form by the use of an implicit backward differencing technique coupled with a linearization method. Of special interest is the semi-empirical bubble model that is used at the exit node of the vent system. The model uses a modified Rayleigh bubble formulation that includes two empirically determined constants. These constants are used to simulate the effects of side walls as well as bubble growth or rise velocity and must be calibrated against available test data. The calibration phase of the model evaluation consisted of benchmarking the model against QSTF test data to select optimal values of the model bubble parameters. Good overall agreement with the test data was obtained over a wide range of Δp (i.e., drywell-to-wetwell pressure differential) and submergence for the drywell pressure, wetwell airspace pressure, bubble pressure, load transients, and torus up and down loads. The parameters selected on this basis were utilized for all remaining calculations, with appropriate variations to account for different scales.

The verification of the computer code was separately performed for the vent system and combined vent-system/pool-swell models. The vent-system model was verified by demonstrating that it accurately describes various test cases with known analytic solutions. The test cases considered were isentropic nozzle flow, constant area Fanno flow, and a transient ramp pressure at the entrance to a dead-end pipe. The vent-flow model quickly converged to a steady state solution for each of the cases, and the resulting values agreed with the known solutions.

The combined vent-system/pool swell model, which had been calibrated using the QSTF data, was checked against available information that consisted of the EPRI 1/11.7-scale test data, the FSTF test data (run M8), and the compressible flow analysis of the EPRI data presented in Reference 18. The comparison of the model-predicted pressures with the EPRI test data showed good agreement, whereas the comparison with the FSTF data provided only a rough estimate of the pressure histories. However, the agreement with the FSTF test data was considered reasonable because of the limitations of the data because the FSTF tests were not pool swell tests and thus did not have the appropriate instrumentation to accurately define the phenomena. The comparison with the compressible flow analysis of Reference 18, which originally identified the possibility of compressibility effects, provided an important part of the program verification. The analyses were compared at both the EPRI 1/11.7-scale as-tested conditions and with correctly scaled compressibility. Both models gave generally similar results, with particularly good agreement in the prediction of the acoustic delays and pressurization rates before vent clearing.

In addition to the above comparisons, timestep and nodalization sensitivity studies were performed to ensure that timestep and node spacings were small enough to achieve reliable results for the purposes of the compressibility study. The approach utilized to assess the possible effects of compressibility consisted of comparing computer runs of: (1) an idealized or "perfect" QSTF simulation of pool swell, within the context of Moody scaling (orifices in vents and air at room temperature), and (2) a corresponding full-scale Mark I scaled down to 1/4 size for purposes of comparison. The "perfect" QSTF configuration is correct in terms of drywell pressurization rate, vent friction, vent volume, and flow resistance split but not in terms of compressibility. The full-scale configuration is correct in all respects, thereby enabling the quantification of the compressibility effects.

The quantities that are most important with regard to load specification are the maximum torus downward and upward vertical pressure loads, and these are used as a measure of the possible effects of compressibility. The calculations were performed using the drywell-to-wetwell pressure differential (Δp) as the variable parameter, with all other quantities kept constant at nominal Mark I conditions. The comparison of the peak downloads (i.e., the ratio of the full-scale download to the "perfect" QSTF download compared at quarter-scale) indicated that for water legs of 4 in. or greater the download is either virtually unaffected or mitigated by the effects of compressibility. For water legs less than 4 in., the peak download comparison affected by compressibility, with a maximum of 11% increase at full Δp. However, because the Mark I plant unique water legs are all greater than or equal to 6 in., no adverse effects as a result of compressibility are indicated. Similarly, the QSTF uploads are shown in Reference 16 to be conservative with respect to the full-scale values by as much as 18%. As a result of the above comparisons, it was concluded in Reference 16 that compressibility effects mitigate the pool-swell loads for operating Mark I conditions.

As stated earlier in this section, the oscillation of interface pressure in the downcomer is responsible for the dependence of the peak downloads on the length of the downcomer water leg. Later in the pool-swell transient, specifically during bubble expansion, mass-flow demands at the downcomer exit are delayed because of compressibility effects. This delay is due to the time required for an acoustic wave to communicate with the drywell or with any other mass-storing volume within the vent system. The delay in the full-scale mass-flow response is termed the compressible mass decrement; it is discussed in detail in Reference 17.

Additional analyses were performed in response to staff questions on the above issues, and the results are presented in Reference 19. The purpose of the calculations was to obtain a quantitative assessment of the compressible mass decrement through comparison of the QSTF "perfect" and full-scale prototype analyses. Mass defects ranging from 7.1% to 11.4% were obtained for several prototypical exit conditions. To estimate the effect of mass defect on peak upload and thereby verify the computer results of Reference 17, a simplified pool-swell analysis consisting of a slab bubble model was utilized. The analysis showed that a mass defect of 7% would yield a 20% upload reduction, which is consistent with the results of Reference 17.

The confirmatory analyses described above have been reviewed by the staff and found to satisfactorily address the concerns raised regarding compressible flow effects in scaled pool-swell tests. Consequently, the staff has concluded that the load definition procedures for the torus downward and upward vertical pressure loads, the torus pool-swell pressure distribution, the vent header pool-swell impact timing, and the vent header deflector impact timing, as modified by the NRC acceptance criteria in Appendix A of the SER, (Ref. 1), are acceptable for the present Mark I operating conditions. However, although the staff is in agreement with the Mark I Owners Group that compressibility effects mitigate the pool-swell loads, no quantitative credit should be taken for these mitigating effects without considerable additional justification. This justification would require a quantitatively correct three-dimensional model of the pool swell process in Mark I containments.

3. REFERENCES

References cited in this report are available as follows:

Those items marked with one asterisk (*) are available in the NRC Public Document Room for inspection; they may be copied for a fee.

Material marked with two asterisks (**) is not publicly available because it contains proprietary information; however, a nonproprietary version is available in the NRC Public Document Room for inspection and may be copied for a fee.

Those reference items marked with three asterisks (***) are available for purchase from the NRC/GPO Sales Program, U.S. Nuclear Regulatory Commission, Washington, D.C. 20555, and/or the National Technical Information Service, Springfield, Virginia 22161.

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16. ABSTRACT (200 words or less)

NUREG-0661 was originally issued in July 1980 with four open items which have now been resolved. The four open items consisted of the downcomer oscillation load definition and the confirmatory analyses and test programs which were intended to justify the adequacy of the load specification. The confirmatory efforts concern the assessment of compressible flow effects in the scaled pool swell tests and the confirmation of condensation oscillation load magnitude and global symmetry.

The staff has reviewed the improved downcomer condensation oscillation load definition provided by the Mark I Owners' Group and find it acceptable. The staff has also reviewed the confirmatory experimental and analytical programs conducted by the Mark I Owners' Group and have concluded that the adequacy of the various load specifications have been justified.

This Supplement No. 1 to NUREG-0661 therefore serves as the staff's final resolution of Unresolved Safety Issue A-7.

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