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COMPARISON OF A
TWO-DIMENSIONAL HYDRODYNAMICS CODE (REXCO)
TO EXCURSION EXPERIMENTS FOR
FAST REACTOR CONTAINMENT

by

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ABSTRACT

The Reactor Excursion Containment Code System (REXCO) is a tool that has been developed at Argonne National Laboratory to predict the effects of excursions originating at the core upon the components and on the containment system of Liquid Metal Fast Breeder Reactors. The codes include hydrodynamic and inelastic material behavior depending on the magnitude of the excursion treated. The physical phenomena computed by the codes involve the shock wave, the sodium momentum, and the early stages of the gas bubble.

ANL-7911 compared experimental excursion data with REXCO computations, with emphasis upon the comparison of computed pressure loads with directly measured pressure data. This supplement makes further comparisons, but with emphasis upon the deformations produced by the pressure loads. The results of these comparisons verify the capability of the REXCO Code System to predict the response of containment structures and of the primary system components to the excursion pressure waves.

Computations of the deformation of the containment vessel wall caused by pressure loads generated by high-explosive charges are compared with experiments conducted by the Naval Ordnance Laboratory. The computation of deformations in the upper vessel region resulting from coolant slug impact are verified by comparison with the SL-1 accident data.

I. INTRODUCTION

Comparison with small-model experiments, reported in ANL-7911, has demonstrated the capability of the REXCO-H code to predict the early-time pressure loadings generated by chemical high-explosive charges. In the experiments, hypothetical core-disassembly accidents are simulated by the detonation of small explosive charges. As a result of the energy release, a certain fraction of the energy will promptly transfer to the local coolant, changing the phase from liquid to vapor. The initial abrupt rise in pressure will produce compression waves. The impingement of the waves upon structural members, in particular the containment-vessel wall, will produce a sudden impulsive pressure loading; the pressure will rise sharply upon reflection, and then sharply drop with the following rarefaction. The REXCO-H computations of the compression-wave shock loads produced directly from the initial sudden vapor-pressure rise are consistent with the experimental data (see, e.g., Fig. 6, for the British UKAEA tests, ANL-7911).

In addition to the shock-wave impulsive loads, more gradual pressure loads will build up in those spaces into which the liquid coolant is driven. For example, as the coolant is driven upward, the gas in the space above the coolant will compress. The consistency of the REXCO-H computation with experiment is shown in Fig. 12 (ANL-7911). If the containment vessel should rupture, as in the NOL rupture-model tests, the pressure will rise in the containment chamber receiving the escaping coolant. In this case, the REXCO-H code computes the rupture sequence for the vessel (see, e.g., Fig. 21, ANL-7911) and the consequent chamber pressure buildup as shown in Fig. 19, ANL-7911.

A third type of pressure loading can be created when slugs of the liquid coolant are driven against structural elements by the progressive expansion of the vapor bubble. For the Cadarache experiment (Fig. 16, ANL-7911), the peak pressure generated by the slug impact upon the top plate was consistent with the REXCO-H computed value. However, the response of the instrumentation system was not sufficiently fast to record the details of the pressure fluctuations created by the impingement of the liquid sodium. Further, the pressure trace was complicated by the arrival of the shock wave reflected from the vessel bottom. Because of the importance of this "water-hammer" type of compression-wave loading, further verification of the capability of REXCO-H to compute pressure loads due to slug impact is reported in this Supplement to ANL-7911. It is first shown that the known analytical results for a postulated hypothetical slug-impact model are consistent with REXCO-H computations. It is then shown that for the SL-1 accident the actual damage to the upper vessel compares with that predicted by the REXCO-H computation. The very close agreement of the computed and observed deformation confirms the capability of the code to predict not only the impact loading, but also the resultant vessel deformations.

In ANL-7911, emphasis was placed upon verification of the pressure-loading predictions as computed by the REXCO-H code. In this supplement to ANL-7911, the capability of the REXCO-H code to compute the vessel deformations resulting from the pressure loads is demonstrated. The verifying comparisons are made with the above-mentioned SL-1 vessel deformation caused by slug impact, and also with explosion containment data from experiments performed at the U.S. Naval Ordnance Laboratory.¹³ The NOL tests were for small-scale models of nuclear reactor vessels, while, of course, the SL-1 observations were for a full-scale accident.

II. ANALYTICAL VERIFICATION OF THE REXCO-H CAPABILITY TO TREAT WATER-HAMMER PHENOMENA

Before the computation of the SL-1 vessel deformation caused by slug impact, the REXCO-H treatment of water-hammer phenomena was verified by an independent computation. One-dimensional water-hammer

Fig. 22. Theoretical Slug-Impact Model.
ANL Neg. No. 900-1655 Rev. 1.

compression waves are easily described analytically. The hypothetical slug-impact model shown in Fig. 22 represents such a one-dimensional case. The slug-velocity distribution is assumed uniform in the horizontal (transverse) direction. By limiting the discussion to the case of a rigid-walled container, variations can occur only in the axial z -direction. The model is then reduced to a spatially one-dimensional problem. In an actual case, the wall will deform, so that wave disturbances in the radial r -direction are produced. In this case the analytical treatment must be extended to employ a two-dimensional code such as REXCO-H. However, because the one-dimensional case is so well established analytically, it can serve as an appropriate special case to check the performance of the more general REXCO-H code.

From the Rankine-Hugoniot conditions, the impact pressure exerted upon the stationary vessel head is given by

$$p = \rho UV,$$

where ρ and V are the undisturbed sodium-slug density and velocity, and U is the velocity of the compression shock wave traveling back into the undisturbed coolant. For a sodium-slug density of 0.8288 g/cm^3 and velocity

of 2960 cm/sec, the impact pressure is 541.4 bar. After slug impact, the shock wave travels back from the head zone, shown in Fig. 22 at axial location 28, down through the coolant, passing first axial location 24, and then axial location 21. Finally, the shock wave will reach the end of the slug, where the pressure unloads. An unloading rarefaction wave will next travel back up the coolant column, successively relieving the pressure, until finally the compression pressure pulse at the head drops to zero. The total time of 4.89 msec for the loading and unloading waves to traverse the slug length of 540 cm is determined analytically from the wave velocities.

The analytical results for both the delay times and pressure magnitudes compare with the REXCO-H computations shown in Fig. 23. The

Fig. 23. Rigid-wall Water-hammer Impulse for Theoretical Slug-Impact Model. ANL Neg. No. 900-905 Rev. 1.

small downward slope is due to the motion of the head arising from stretching of the hold-down bolts. If the head had been perfectly stationary, the pulse would have been square-shaped.

The effect of wall flexibility is to relieve the impact pressure. When the top of the cylinder wall deflects outward, a rarefaction wave will travel radially inward, relieving the compression-wave pressure directly under the head. The time for this unloading wave to traverse the radial distance of 300 cm is 1.38 msec, and at this time, at the center point (radial zone 2, axial

zone 28, shown in Fig. 22), the compression-wave pressure should drop to zero. This analytical result is consistent with the REXCO-H two-dimensional computation for a flexible wall shown in Fig. 24.

Fig. 24

Effect of Flexible Wall upon Pressure Unloading. At zone 28, theoretical time to unload is 1.38 msec.

The above results demonstrate that the REXCO-H code correctly computes the water-hammer type of compression waves generated by slug impact. In the SL-1 accident, the upper reactor vessel was damaged by slug impact; the observed deformations will be compared with results of REXCO-H computations.

III. VESSEL DEFORMATION CAUSED IN THE SL-1 ACCIDENT BY SLUG IMPACT

A. Description of the Slug-impact Data

On January 3, 1961, a sudden energy release of some 130 MW-sec occurred, apparently as the result of an accidental withdrawal of a control rod in the SL-1 reactor. The results of the accident are given in the Final Report of the SL-1 Recovery Operation.¹⁴ The heat released promptly to the coolant produced an abrupt coolant vaporization, driving the coolant mass upward above the core. The air space between the water level and the top head was estimated to be $2\frac{3}{4}$ ft at the time of the accident. Just prior to impact with the top head the reported velocity of the water was 159 fps. The mass of the water slug driven upward was 200 slugs. The total mass of the reactor vessel was about 1100 slugs, including the vessel, internals, and the water. By the conservation of momentum, a completely unrestrained vessel velocity would be 29 fps. The corresponding unrestrained vessel rise would be about 13 ft, compared to the reported estimated rise of 9 ft for the actual restrained vessel.

Proctor¹⁵ has estimated, on the basis of a 60-MW-sec prompt energy release and an isothermal expansion process for the vapor bubble, that the water column should reach a peak velocity of 161 fps. From the conservation of momentum, the unrestrained vessel velocity for inelastic collision should be 29.3 fps, raising the vessel to a height of 13.3 ft. By comparison, Proctor showed that for a prompt energy release of 50 MW-sec, the slug velocity for an isothermal vapor bubble expansion would be 147 fps, the vessel velocity 26.7 fps, and the unrestrained vessel rise 11.1 ft.

B. Computation of the Vessel Deformation

For the REXCO-H computation the actual configuration was somewhat idealized and is shown in Fig. 25. The vessel data for the computational model are based upon the engineering drawing of the ALPR Reactor.¹⁶ The outside diameter of the SL-1 pressure vessel was 4.5 ft. The $\frac{3}{4}$ -in. vessel wall was Type SA-212 carbon steel, clad inside with $\frac{3}{16}$ -in. stainless steel. The outside was insulated with 3-in. magnesia blocks. The top flange consisted of a 6-in.-thick ring section, and a 4-in. tapered transition section changing from 2 to $\frac{15}{16}$ in. The ring section was $5\frac{7}{8}$ in. high. The top head was $7\frac{9}{16}$ in. thick and was fastened to the top flange by forty-eight $1\frac{3}{4}$ -in.-dia bolts.

Fig. 25. Slug-Impact Model of SL-1.
ANL Neg. No. 900-1659.

strain-rate hardening of the vessel material was not considered. The velocity of the water slug was taken as 130 fps, the velocity relative to the vessel, assuming the vessel was moving at 29 fps, and the absolute velocity of the slug was 159 fps. It is recognized that this velocity may be questionable, and the strain-rate effects may be significant, but the important point is that the deformed shape of the upper vessel is accurately predicted. Variations in the vessel strength or in the slug momentum can be expected to change the amplitude, but should have substantially less influence upon the mode of the deformation.

The good correlation between the predicted vessel deformation, shown in Fig. 26, and the actual measurements proves the capability of the REXCO-H code to compute both the water-hammer phenomena and the coupled vessel strains produced by the resulting compression waves.

The REXCO-H computations of pressure loadings for high-explosive tests in small models have already been verified. The SL-1 comparison validates the computation of a full-scale accident, involving a much slower and lower-intensity pressure excursion. The computation includes both pressure loading and vessel deformation.

The values of the yield stress, ultimate stress, and ultimate elongation of the SA-212 carbon steel are based upon the average values of four unstrained specimens taken from the recovered vessel:

yield stress = 47,100 psi;

ultimate stress = 70,600 psi;

ultimate elongation = 0.26 in./in.

The average yield strength and tensile strength of the A193 type B14 bolt material were 126,000 and 140,000 psi, respectively.

For this model, the vessel deformation computed by REXCO-H is shown in Fig. 26, compared with the observed vessel deformation. For this computation, the

Fig. 26. Comparison of Computed Vessel Deformation with Actual Measurements of Deformed SL-1 Profile. ANL Neg. No. 900-1652.

IV. REXCO-H COMPARISONS WITH THE NAVAL ORDNANCE LABORATORY MODEL TEST PROGRAM FOR CONTAINMENT-VESSEL DEFORMATIONS

A. Comparison of the Maximum Terminal Radial Strains

To determine the effects of explosions upon containment vessels, the U.S. Naval Ordnance Laboratory¹³ performed an extensive series of small-scale model tests during the period 1956-1964. Two of the tests were chosen for comparison with the REXCO-H code. The selection of the representative tests were based upon the recommendations of J. F. Proctor of the Naval Ordnance Laboratory. For both tests, the vessels were 10-in.-high, right-circular cylinders with a 5-in. inside diameter. The vessels were centrifugally cast, Type 304 stainless steel, with rigid end-enclosures as shown in Fig. 27. The pentolite charges were detonated at the center of the cylinders.

Fig. 27. Comparison of REXCO-computed Vessel Deformation for NOL Experiments. ANL Neg. No. 900-1745 Rev. 1.

To determine the relationship between vessel strength and containment capacity, the vessel wall thickness was varied in the NOL test series. For an 1/8-in.-thick wall the maximum charge size that was contained without vessel wall rupture was 18 gm. For a 19-gm charge marginal rupture occurred. The measured maximum terminal radial strain for the 18-gm charge was 0.352 and is referred to as the marginal containment strain. Doubling the wall thickness from 1/8 to 1/4 in. raised the containment capability of the vessel to withstand an energy release of a 50.5-gm charge without rupture. To check the test reproducibility, the 50.5-gm-charge test was repeated, and in one test the vessel remained intact with a marginal containment strain of 0.354; in the other test, a marginal rupture occurred with a maximum radial strain of 0.385. Another test was run with a slightly smaller charge of 50.1 gm, which was contained without rupture, but the maximum radial strain was 0.375, unexpectedly higher than that for the 50.5-gm charge.

The observed variability of terminal strains for the same reported charge size indicates that experimental variations of roughly 10% in the maximum radial strain measurements may be expected at marginal containment conditions.

Table II summarizes the NOL test results and compares them with the REXCO-H computations for the maximum terminal strains for the 18- and 50.5-gm charges. For the 18-gm charge, the REXCO-H computation yields a maximum terminal strain of 0.388, which is higher than the observed test value of 0.352, but compatible with the estimated 10% experimental variation indicated above. It is possible that the explosive yield was somewhat less than the theoretically expected yield, accounting for the lower observed terminal strain. This possibility is indicated by the lower measured incident pressure. For the 50.5-gm charge, the REXCO-H computed maximum terminal strain of 0.366 falls within the measured strains for the repeated tests. The conclusion to be reached is that the experimentally observed strains are consistent within experimental variations, and the REXCO-H capability to predict vessel deformations is verified.

TABLE II. REXCO Two-dimensional Computations
Compared with Selected NOL Tests

	Charge Weight, gm	Wall Thickness, in.	Incident Pressure, kbar	Peak Wall Pressure, kbar	Max Circumferential Vessel Strain, cm/cm
NOL Test (Wise-Proctor)	18	1/8	3 (cylindrical charge)	-	0.352 (marginal containment)
REXCO Computation	18	1/8	-	9.187	0.388
One-dimensional Computation (Sternberg-Walker)	18	1/8	3.7 (spherical charge)	9.25 (reflection factor of 2.5)	-
NOL Test	50.5	1/4	-	-	0.354 to 0.375 (marginal con- tainment)
					0.385 (marginal rupture)
REXCO Computation	50.5	1/4	5.6	14.42	0.366

B. The Strain-rate Effects

The terminal radial deformation of the cylinder wall is strongly dependent upon the material strength of the Type 304 stainless steel. The material strength, in turn, depends upon the initially high strain rates of the wall. This dependence is illustrated by the following empirical equation¹⁷ relating the strain rate and dynamic yield stresses:

$$\sigma_{\text{dynamic}} = \sigma_{\text{static}} \left[\left(\frac{\text{strain rate}}{40.4} \right)^{0.2} + 1.0 \right].$$

The strain rates computed by REXCO-H were found to be as high as 4000 sec^{-1} . For such very high strain rates, the static yield stress can be increased by a factor as high as 3.5. Steichen¹⁸ indicates that for strain rates of this magnitude, the maximum stress could reach values in excess of 120,000 psi. Accurate test data for this influence of strain-rate effects in the range of 4000 sec^{-1} appear to be lacking in the literature. A literature survey compiled by Garner¹⁹ includes data only for strain rates below 1000 sec^{-1} . Some very limited data are given by Johnson *et al.*²⁰

The REXCO-H-computed terminal strains are based upon an assumed maximum stress of 120 kips. To illustrate the dependence of the final vessel deformation upon the material strength, a computation was made for the 18-gm charge based upon a lower maximum stress value of 105 kips. The change in the material property of the steel increased the computed terminal strain from 0.388 to 0.452. This sensitivity computation shows that a decrease in the maximum stress of 12.5% causes an increase in the maximum terminal strain of 16.5%. On this basis, since the REXCO-H-computed strain of 0.388 is higher than the observed strain of 0.352, it is conceivable that the maximum stress is higher than the assumed 120 kips.

The computed strain rate of 4000 sec^{-1} appears to be reasonably consistent with the experimentally measured strain rate. The strain rates were measured with a framing camera operating at 25,000 fps, or one frame per 40 μsec , over a range of 15 frames. For a 5-in.-dia vessel, the strain rate of 4000 sec^{-1} is too fast to catch the peak speed accurately. However, for a 10-in.-dia vessel the slower peak strain rates were measured to be 1970 sec^{-1} , which by scaling laws should correspond to 3940 sec^{-1} , very close to the computed values for the smaller vessel of the subject comparisons.

C. The Generated Charge Pressure

The REXCO-H-computed peak pressure at the cylinder wall for the 18-gm charge was 9.187 kbar. The detonation process was simulated by the constant-burn energy-release method of computation that was successfully used for the earlier comparisons of ANL-7911 (see p. 65). For this computation, a relatively coarse grid was used. The explosive charge was represented by a cylinder, two grid cells high, with only a single grid spacing in the radial direction. The detonation energy of the cell was increased at a rate proportional to the volume engulfed by the actual detonation front advancing at the assumed constant Chapman-Jouguet burning velocity. This method yields good results provided the vessel wall is not too close to the charge. For the 18-gm charge, the 5-in.-dia vessel wall is 4.6 charge radii from the detonation center. The peak pressure at the wall was computed to be 9.187 kbar.

Because the vessel wall is relatively close to the charge, the adequacy of the constant-burn method was checked against an independent

computation by Sternberg and Walker.²¹ Their computation indicated that at 4.6 charge radii the free-field charge pressure should be 3.7 kbar. This computation was based upon a one-dimensional, spherically symmetric code, starting from the Taylor similarity solution for the charge. Applying a rigid-wall reflection factor of 2.5 (see Cole,²² p. 56), the theoretical peak pressure at the wall should be 9.25 kbar. This rigid wall value compares closely with the REXCO-H value of 9.187 kbar, especially upon consideration that the 9.25 kbar should be reduced slightly because of the compressibility of the actual steel wall.

The computed peak pressure is also consistent with recent measurements by Hantel and Davis.²³ In their experiments, because of the very close proximity to the charge, within 3.5 charge radii, the measurements were by necessity made indirectly by optical methods. They used a rotating-mirror streak camera to measure the near-field shock velocity, and from the known equation of state of water the corresponding pressure was computed.

An accurate direct measurement of the peak-reflected shock pressure at a wall so very close to the charge is extremely difficult to accomplish. An attempt was made¹³ to measure the pressure for the 18-gm charge. A separate test was performed in a special overstrong control vessel. The incident pressure, 1/4 in. away from the wall, was found to be 3 kbar when corrections for instrument lag time were made. This pressure measurement is somewhat lower than the theoretical 3.7 kbar predicted by the Sternberg-Walker computation, and the discrepancy is most probably due to the instrumentation difficulties. The gage positioned a small distance from the wall is subjected to severe diffraction and wall-interaction effects. There is, however, some possibility that the charge did not develop its full theoretical Chapman-Jouguet detonation process, consequently lowering the interface pressure match between the charge and the water.

For the 50.5-gm charge the vessel wall was only 3.27 charge radii from the detonation center. In this case the charge was too close to treat the detonation by the constant-burn method. For the coarse grid, in which the charge is only one grid cell wide, the emergent shock will move radially outward as a cylindrical wave and will strike the wall before the proper attenuation due to spherical divergence occurs. An accurate computation for regions so close to the charge requires a detailed description of the distribution inside the detonation-product gas bubble, as well as in the immediate surrounding water. Because of the very high gradients involved at the charge interface for the intense high-explosive detonation, a fine grid spacing is required to compute a sufficiently detailed distribution. It should be noted that similar high gradients would not occur for the slower pressure buildup expected from an actual reactor excursion, and such a fine grid would not be required. A very fine computational grid requires a correspondingly large computer storage and a lengthy computer run.

Computer time can be saved by taking advantage of the approximately spherical symmetry existing around the charge center at the instant the emergent shock wave is just incident upon the cylinder wall. At later times as reflection processes occur, the spherical symmetry is destroyed, and the full two-dimensional REXCO-H code must be used. The most efficient computational procedure to follow is to use first a one-dimensional spherically symmetric computational procedure with a very fine grid spacing, up to the instant the shock wave is incident upon the wall. Then the one-dimensional code output will provide the input to the two-dimensional REXCO-H code. Following this procedure, the REXCO-H input conditions were provided by the Sternberg-Walker, Naval Ordnance Laboratory, WUNDY spherical symmetry code. The gas sphere was divided into 50 grid zones and the water into 250 zones. Since the number of zones increases as the square, an equivalently fine grid for a two-dimensional code would require 90,000 individual zones rather than 300.

The one-dimensional computation of the initial conditions to the REXCO-H code starts from the Taylor similarity distribution in the detonation-product gases. The Taylor assumption is that the independent spherical radius r and time t can be replaced by a single independent similarity variable r/t , i.e., that conditions behind the detonation front are unique functions of r/t . As a result the partial differential, fluid-mechanic conservation equations are transformed to ordinary differential equations. The system of ordinary differential equations are solved numerically by a predictor-corrector method, in which the initial values are determined from a Runge-Kutta procedure. The free-field pressure incident at the wall at 3.27 charge radii was computed to be 5.6 kbar. This computed incident pressure distribution provided the input conditions to REXCO-H. The ensuing motions of the fluid, and of the deformations of the cylinder wall under the pressure loading, were then calculated by REXCO-H. The computed peak reflected pressure was 14.42 kbar. The rigid-wall reflection factor, from Cole,²² for the 5.6-kbar incident pressure is 2.65, so the rigid-wall-reflected pressure should be 14.84 kbar. The REXCO-H-computed value is lower than the rigid-wall value because the pressure is lowered by initial response of the actual wall.

V. SUMMARY AND CONCLUSIONS

In this supplement to ANL-7911, further comparisons of REXCO-H computations are made with experimental data from model excursion tests. Also, a comparison is made with observations from the full-size SL-1 accident. The emphasis in this supplement is upon the verification of the capability of the REXCO-H code to predict vessel deformations. The results of the comparisons demonstrate that REXCO-H computations of deformations and pressure loadings for reactor excursions are consistent with the actual phenomena.

The upper-vessel deformation from the SL-1 accident was caused by the water-hammer pressure impulse produced by slug impact. The comparison in Fig. 26 shows very close conformity of the REXCO-H-computed upper-vessel deformation with measurements of the actual deformation.

The results of the comparison of REXCO-H computations with the Naval Ordnance Laboratory containment vessel tests are shown in Table II. For both 18- and 50.5-gm charges the maximum computed terminal vessel strains are consistent, within experimental variations, with the measured test results. A sensitivity computation indicated that the maximum terminal strain is strongly dependent upon the yield strength of the steel vessel. A comparative computation for the 18-gm charge illustrated that a reduction in yield strength from 120 to 105 kips increased the terminal strain from 0.388 to 0.452. The yield strength is influenced by the strain rates. It can be concluded that some uncertainty is introduced into the interpretation of maximum terminal strains in small-scale model tests using high-explosive charges when high strain rates occur. In the NOL tests, the peak strain rates were of the order of 4000 sec^{-1} , much higher than most of the available reported experimental investigations into the effects of strain rates upon material properties.

While further research is indicated to establish dynamic material properties, the results of the comparisons of the REXCO-H-code computations with experimental test results demonstrate that the structural response to a postulated hypothetical accident can be predicted.

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