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Final Report on:

**Seismic Decoupling of an Explosion Centered in a
Granite Chimney Rubble -- Scaled Experiment Results**

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by

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1.0 SUMMARY

The question was raised during a TROIKA panel review of verification technologies (Reference 1) as to the possible seismic decoupling of a nuclear explosion if it were to be sited in a coarse, strong rubble such as exists in a collapsed chimney above a shot point of a previous event in granite. The effect of an air-filled porosity on the seismic signature of an explosion is well measured (Reference 2). the effect of an air-filled cavity has also been well studied. The question was whether the crush of the large air void of a strong rubble could dissipate the explosion energy so as to significantly reduce the seismic signal. The concern was that such a decoupling mechanism was readily available at Soviet test sites or mining regions. It is inexpensive, since no excavation is required, and it is difficult to detect by overhead surveillance that such a test is in progress, because the tunnels exist for chimney access from the original explosion experiment.

This report describes the small scale evaluation of the feasibility of significant decoupling by siting an explosion in granite rubble. The chimney characteristics scaled to laboratory dimensions were those of the PILE DRIVER event. The scaled charges were of 1 KT and 8 KT in the PILE DRIVER chimney. The measure of the effect was the velocity field history in the granite outside the chimney volume with the chimney rubble and with no rubble (e.g., solid granite). A number of chimney sizes and shapes were studied. The explosion process was modeled via two-dimensional, finite-difference methods used for predictions of velocity histories at the Nevada Test Site (NTS).

The result was that both the spectral shape and the magnitude of the transmitted shock wave were drastically altered. The chimney geometry was as important as the rubble characteristics. By comparison of the calculational results and the measurements under a variety of circumstances, it is shown that the effective energy transmitted to the seismic ranges is 90 percent less with the granite rubble than for the same charge fully tamped in solid granite. It was discovered that the shock velocity in the rubble was only one-third that of the granite and hence a very large shear deformation is produced in the solid granite as compared to the more typical spherical motion. The reason was that the rebound had occurred on the equatorial plane of the chimney, before the shock in the rubble had reached the ends of the chimney.

The net effects of these processes were as follows:

1. The effective energy source is reduced by a factor of ten.
2. The frequency spectrum is extremely depressed (1/10 to 1/100) in the high frequencies, enhanced in the mid frequencies ($\sim 2x$) and somewhat depressed (1/2 to 1/4) in the low frequencies.
3. The peak velocity is reduced fivefold.
4. The permanent displacement is reduced to nearly zero.
5. The effect is strongly influenced by the chimney shape and size.

These effects were measured in very small scale HE experiments at SRII and interpreted with the help of 2-D calculational models at SAIC (PacTech).

The small scale of the experiments prohibits measurement of real seismic coupling or the effect of an asymmetric source geometry (e.g., siting the explosion off center in the chimney). Phase 2 of the experimental series is to be done in a granite quarry at a larger scale and with seismic monitors. A plan for that test has been developed by SEA. The full scale decoupling is probably larger than that measured in the laboratory because of the possible asymmetry and surface interaction effects. The proof is the experiment, but the decoupling mechanism is probably more effective than an empty cavity for reasons discussed in this report.

2.0 INTRODUCTION

The problem of monitoring nuclear explosions around the world has led to many suggested methods. The most popular method is probably the seismic method for a variety of reasons that do not need to be repeated here. The ability to monitor explosions world wide by measurement of the resulting seismic energy coupled to the earth requires a thorough understanding of not only the normal situation but also the situations which might be engineered to avoid seismic detection. The extent to which the seismic source term can be affected by near source conditions has been long examined. The effects of geologic site, depth of burial, void space around the nuclear charge, multiple sources, etc. have been calculated and measured. It has become clear that some factors such as air-filled porosity and medium strength are strong modifiers of seismic signals. The comparison of nuclear signatures with the seismic result of "natural" or non nuclear seismic sources such as earthquakes and chemical explosions is necessary to discriminate them from nuclear explosions. This whole study of source characteristics and transmission path effects has led some people to believe that clandestine nuclear tests or treaty threshold violations are detectable.

In a review of seismic measurement techniques conducted by a group called the TROIKA panel, it was suggested that all possible methods of evading seismic detection had been examined and had been found to be impractical, because they were too expensive, easily detected by satellite, or other means, or they were not effective. However, one technique was suggested (by the author) which had not been examined. That is the siting of a nuclear explosion in a granite chimney rubble. Granite chimneys are abundant in some regions. Emplacement of a nuclear device from existing nearby tunnels could not be detected. No construction is required. The question remaining is whether the situation can lead to a significant reduction of the seismic signal, or a significant perturbation, so as to avoid the limits of a treaty. If so, what yield is still detectable and what are the characteristics of the seismic signal?

The reason that granite rubble chimneys are of special interest compared to the many other chimneys formed above collapsed nuclear explosion cavities is that the granite rubble has a relatively large air-filled pore space and the rubble is strong. In fact the pore space exists because the strong rock is not smashed back to its original density by the fall to the bottom of the cavity. At low yields (less than 1 KT) even weak rock (e.g., tuff of Rainier Mesa) can maintain a relative uncompacted rubble state. But at 10 KT, the Rainier Mesa chimneys in tuff are compacted to near their original density before the collapse.

The effect of the yield on the air void of the rubble is also seen in granite in the series of SHOAL, HARDHAT, and PILE DRIVER. The pore space is less with increased yield, but it ranges over the large values of 25 to 19 percent.

The effect of a strong porous material is that it requires a larger amount of work to crush the pore space. The integral of PdV is much larger than for a weak rock (low P) or a low open porosity (low dV). That work of crushing can be left in the rock as waste heat. Hence the energy transmitted to seismic distances is potentially much less.

The other mechanism found to be significant for an explosion in a chimney is the shape of the shock wave driving the granite outside the rubble region. The normal tamped event in an approximately homogeneous medium produces an approximately spherical shock wave. This is a critical feature for discriminating against a shallow earthquake source. The shock velocity in the rubble is much less than that of the native granite. Consequently, the shock wave traveling in the rubble drives the surrounding competent rock in a most peculiar nonspherical manner.

The solid granite near the explosion is driven early. The shock traveling slowly to the top of the chimney arrives long after the shock in the granite initiated at the explosion horizon. Another consequence is that the shock traveling upward to the surface, the cause of the spall process, is greatly affected in timing and amplitude.

It is quite likely that the peculiar source shock geometry would change the partition of the energy between shear and longitudinal waves, change the effect of spall on the seismic signature and reduce the total energy transmitted. The purpose of the proposed series of experiments was to measure the effect of a chimney rubble on the small scale of laboratory tests. If those effects were judged significant, the scale could be increased, until all aspects of the effect could be measured. The comparison with calculational predictions could be instructive if the source was drastically changed in its character. For example, if spall was eliminated as a part of the source term, does it produce the expected effect on the seismic record? One of the difficulties of analysis of actual nuclear test experience is that it occurs under very similar scaled conditions with few known efforts to deceive the monitoring community. These measurements are therefore of special interest if the rubble effect is large.

This statement of the problem has been expanded by the experience of these measurements. The initial simple objective was to measure the transmitted shock wave with and without a rubble surrounding the charge.

3.0 APPROACH

Science and Engineering Associates, Inc. proposed to DARPA a three-phase experimental series to measure the effect of siting an explosion in a granite chimney rubble. The first phase (reported herein) is a very small scale HE experimental series allowing relatively inexpensive parameter variations to explore the general question of whether the concept produces any significant effect. To be significant, the effect must exceed the normal seismic measurement uncertainty in the size of an explosive source. Stanford Research Institute International was selected to perform the HE experiments using a technique developed for the Defense Nuclear Agency and used for previous DARPA experiments in fractured granite (Reference 3).

3.1 Experiment Design

The experiment geometry is shown in Figure 1. A small HE charge (3/8 gram PETN) is located in the center of the granite core. Thin concentric wires are located on the equatorial plane surrounding the charge. When those wires are displaced by the shock wave from the charge, their

(a) Meridional cross section

(b) Plan of lower cylinder

Figure 1. Sierra White granite specimen for tamped experiments.

motion in a uniaxial magnetic field (provided by an outer coil) provides a voltage history directly proportional to the velocity history of the rock adjacent to the wire. Hence each concentric wire provides a detailed particle velocity history at the range of the wire from the charge. Due to symmetry and the uniaxial field, only the radial velocity component is measured, but that is the total spherical or cylindrical velocity vector, if the experiment is symmetric about the equatorial plane.

The experiment plan was to model three material geometries (Figure 2):

1. The charge fully tamped in solid granite.
2. The charge centered in a small crushed granite rubble-filled chimney.
3. The charge centered in a larger chimney.

Since the charge was always the same size, the smaller chimney is either a smaller scale equivalent of a larger charge or simply a small chimney site with the same scaled charge.

When it became clear that the effect depended upon both the geometry and the material properties of the chimney, a spherical chimney was added to the series to separate the geometry effects from the material effects on the velocity histories measured outside the chimney.

The chimney sizes were picked so as to fit within the granite core, 24.9-cm diameter by 30.0-cm height. The model chimneys are presumed to be scaled versions of the PILE DRIVER (64 KT) chimney shown in Figure 3 (Reference 4). The HARD HAT chimney, shown in Figure 4, shows that in granite the chimney radius is approximately the same as the cavity radius. The two measured chimney shapes led us to select 40 meters (~131 feet) as the appropriate PILE DRIVER chimney radius. This leads to a small model chimney ($R = 1.65$ cm) scale factor of 2424 and a large model chimney ($R = 3.18$ cm) scale factor of 1258.

The model HE charge of 3/8 gm PETN is equivalent to about 0.483 gm TNT. That scales to about a 0.9 KT TNT charge in the large chimney and a 6.9 KT TNT charge in the small chimney. However, the 3/8 gm PETN produces a .6 cm radius when tamped in Sierra White granite. That implies, with the experience of $R_{cav} = 11 W^{1/3}$ meters in granite, that the effective TNT yield of the PETN is .54 gm versus the energy equivalent value of .483 gm. This slightly greater efficiency of the charge leads us to ascribe a nominal 1 KT and 8 KT to the charges used in the large and small scale chimneys respectively. But, we kept the linear scaling to the PILE DRIVER chimney.

Figure 2. Sierra White granite specimen for tamped and chimney experiments.

Figure 3. Chimney shape resulting from PILEDRIVER event.

Figure 4. Chimney shape resulting from HARDHAT event.

This means that for simple comparisons, that the fully tamped small PETN charge is a scaled 1 KT charge when compared to the large chimney (1 KT in a 64 KT chimney) and that the tamped charge is 8 KT when compared to the small chimney (8 KT in a 64 KT chimney). These simple scaling rules must be considered approximations for such large scale factors.

The simple experiment purpose is to compare the transmitted shock wave of a tamped shot in granite with that of a tamped shot in granite rubble. The granite rubble must have a particle size and size distribution appropriate to a scaled version of the PILE DRIVER rubble. The PILE DRIVER rubble distribution was measured as reported in Reference 5. By good fortune, the particle size distribution of a crushed and screened Sierra White granite is only slightly larger than the scaled particle size of PILE DRIVER (Figure 5). Loading tests of the granite rubble simulate showed it to be much "softer" than Monterey sand (see Appendices of Appendix A for the crush curves).

Figure 5. Grain size distribution of the granite rubble used and the scaled PILEDRIIVER rubble.

There was some concern that the HE gas flow into the scaled rubble could be significantly different than that of a nuclear cavity gas into a PILE DRIVER rubble. However, the gas flow from a shot in solid granite is small at either scale. The loss must also be slow compared to the initial shock propagation. Nevertheless, this aspect of the full scale test could be important by the time of full cavity growth. At the extremely high strain rates of the small scale test, it is expected to be less important. If the gas flow is beneficial to decoupling, it may not be seen on the small scaled comparisons. This subject is addressed in the discussion of results.

The porosity of the model rubble was set at 20 percent to fit within the range of 25-19 percent of the several nuclear chimneys measured. The uncompacted model rubble had a porosity of about 30 percent. This required that the rubble be pressed into the chimneys to the required density for a 20 percent porosity. The process is described in Appendix A. The chimney rubble was pressed into each half of the chimney. The charge was inserted into an indentation in the pressed rubble and the two halves were glued together. The wires for velocity measurement were glued into machined grooves on the midplane. An important fact is that the top and bottom halves were symmetric about the midplane. Hence the measured motions on the midplane are expected to be radial and horizontal only.

The fully tamped charge was located in a machined hemisphere in the two solid core halves. The spherical chimney and the fully tamped charge are the only two geometries with essentially spherical motion until reflection from the outer surface of the granite core.

The other diagnostics of the coupling of the charge into the granite were pressure gauges located in the water surrounding the granite core. That water was pressurized to 1000 psi to provide reasonable confinement of the solid granite equivalent to a deep site in the middle of the PILE DRIVER chimney. The scaled rubble confinement is only that produced in the pressing/compaction operation. We do not know the state of confinement of the rubble in the PILE DRIVER chimney. At the top of the chimney is a void, so there the confinement is very little. At depth, the confinement is probably greater than half the rubble depth weight per unit area. Since the scaled rubble is well packed, it should be very similar to the full scale condition as it affects the shock response

The other differences between a small HE charge and a nuclear charge are worth considering for their effect on the measurements. The HE charge replaces about one-fourth of the final cavity volume. Hence the rock vaporized and melted by the nuclear charge is not included in the scaled HE test. That should lead to a greater expected energy loss for the nuclear case than for the HE

test. However, the experimental comparison of HE tests should reduce the significance of that difference. Because of the greater work done on a crushable material, the volume of melt on a nuclear test should be greater in a rubble. There may be no melt with the HE charge, so the rubble's effect as an energy sink may be underestimated with the HE model.

3.2 Calculation Approach

It has been found in the experience with scaled model testing that the experiment design and the interpretation of the results is greatly enhanced by a parallel calculational modeling effort. The PacTech division of SAIC was selected to perform a series of predictive calculations for comparison with the measurement results. One purpose of the modeling effort is to estimate the properties of the rubble as they affect shock propagation. A second purpose is to use the model results to "look" at the material behavior in those regions where measurements cannot be made (e.g., off the equatorial plane). The quality of the modeling effort is judged by comparing the detailed wave shapes calculated to those measured for all the different geometries.

The calculators were included in the experiment design phase to assure that the data needed would be provided and to advise on the probable effects of the various aspects of the construction techniques. Initial predictions were then calculated for comparison with the measurements. Differences from the measured results led to questions of the data quality (as is often the case), but there was little doubt about the measurement methods, since they have been well-tested before. Then the calculators adjusted their rubble model, particularly the sonic velocity, until they could better reproduce the measured results. The normalized model was then used to produce calculations of the chimney/granite system behavior and to estimate the total energy attenuation of the several chimney geometries.

The spherical chimney was added to the experiment to separate geometric effects of the chimney shape from the material effects on the measured results. This greatly aided the development of a better equation of state for the rubble.

The primary parameter for comparison was the velocity history at the measured ranges. The parameter of special interest was the vector velocity field calculated which showed the detailed response of the solid granite to the complex loading from the shock traveling in the chimney rubble.

Both the measured results and the calculated results of velocity histories were integrated for displacement histories and the data were transformed to reduced displacement potential histories as is commonly done for seismic propagation analysis. The decomposition of the data into the frequency domain provided additional insight into the effect of the rubble on the seismic source.

The calculational models used and the algorithms used for the transforms are described in Appendices A and B, the detailed reports of SRII and PacTech.

Since all measurements are necessarily near the source, the entire study is limited to effects of the chimney rubble upon the source rather than upon the seismic signal. The questions were:

1. How does the rubble affect the velocity wave shape and spectral content?
2. What processes are important to the full three-dimensional character of the source?
3. What might be done to further enhance the effect on the seismic signal?
4. What might one expect to use for seismic discrimination of such an explosion site?
5. What is the effective yield of an explosion located in a chimney rubble as a function of the size of the chimney and the yield of the explosion?

A related question not addressed is whether current practices would detect a nuclear test of this kind conducted by a country not a party to the verification treaty. What kind of site might be used in place of a nuclear explosion chimney in granite?

4.0 RESULTS

The results of this research are summarized in this section and the detailed data records are presented in the appendices. The kinds of results which support the conclusions presented here are.

1. Velocity histories at several ranges from the charge in the various test geometries
2. Integration of those histories and spectral analysis of the records
3. Predicted velocity histories, displacement histories and analysis of those.
4. Pressure histories measured in the water surrounding the granite cores.
5. Measurements of granite rubble characteristics.
6. Comparisons of measured and calculated velocity histories.
7. Examination of the rock cores, with and without chimneys, after the test.

The difference between shock waves transmitted in each of the four geometries is shown clearly in Figure 6 which is a plot of the velocity history measured at 5 cm from the charge center.

Figure 6. Comparison of velocity histories at the 5-cm range for the tamped and chimney experiments.

The sharp shock for the tamped case is typical. The small chimney and the spherical chimney show a large delay of the shock arrival, a much lower peak pressure, a broader wave form, and a much larger rebound than the tamped charge. The larger chimney produced an even larger effect of the same kind. It is interesting to see the broadened wave form for the small cylindrical chimney as compared to the spherical chimney wave form.

The complete set of velocity records for each geometry are shown in Figures 7 through 10. The reproducibility of the records is shown in Figures 11 A and B. It is an excellent set of data. It is important to remember that only the tamped shot and the spherical chimney shot are expected to have the same motion in all other radial directions. The records are deliberately truncated at the time of reflection from the outer granite core surface.

The velocity histories were integrated to provide the displacement histories. The comparison at 5 cm is shown in Figure 12. The individual data sets are shown in Figures 13 through 16. From Figure 12, the tamped shot seems to have developed a permanent displacement whereas the chimney shots probably do not. The trend is clear, but record truncation denies us the proof. However, the rubble apparently attenuates the shock so that it does not permanently deform the solid granite. That conclusion is supported by the calculations described later and also by long term oscillations about zero displacement not shown in the truncated record.

The long delay of the shock arrival for the rubble shots was due to the slow shock velocity in the rubble. Therefore, in the case of the cylindrical chimneys, the shock first reaches the solid granite at the equator of the chimney and then initiates a faster shock in the solid granite. Later, the shock in the rubble reaches the solid granite at higher and higher elevations in the chimney. Likewise in the downward direction, so that the shock wave in the solid granite is being driven by a pair of toroidal sources moving vertically away from the midplane. Eventually, the shock in the rubble reaches the top and bottom of the chimney at the same time. The velocity vectors of the 2-D calculations shown in Figure 17 show the slow-moving shock in the rubble (the velocity vectors nearer the source have been suppressed for clarity). By this time (25 μ s), the shock in the solid granite has traveled to the bottom of the chimney (the dashed enclosure) and is imploding the bottom of the chimney before the shock in the rubble has arrived. It is also noteworthy that the solid granite on the equator has already rebounded toward the charge. The result is that the solid granite is undergoing the nonspherical motion, described by the large curved arrow, between the midplane and the position of the shock in the chimney. It is also clear that the motion measured on the midplane of the chimney is not the same as that at

Figure 7. Particle velocity histories in tamped experiment in Sierra White granite, Test 574.

Figure 8. Particle velocity histories measured at the midplane of Sierra White granite in 3.3-cm-diameter spherical chimney experiment, Test 582.

Figure 9. Particle velocity histories measured along midplane in Sierra White granite in 3.3-cm-diameter cylindrical chimney experiment, Test 575.

Figure 10. Particle velocity histories measured along midplane in Sierra White granite in 6.35-cm-diameter cylindrical chimney experiment, Test 570.

Figure 11A. Comparison of particle velocity histories at the 3-cm range in two tamped experiments.

Figure 11B. Comparison of particle velocity histories at the 3-cm range in two spherical chimney experiments.

Figure 12. Comparison of displacement histories at 5-cm range in Sierra White granite for the tamped and chimney experiments.

Figure 13. Displacement histories measured in Sierra White granite in lamped experiment, Test 574.

Figure 14. Displacement histories along midplane in Sierra White granite in 3.3-cm-diameter spherical chimney experiment, Test 582.

Figure 15. Displacement histories along midplane in Sierra White granite in 3.3-cm-diameter cylindrical chimney experiment, Test 575.

Figure 16. Displacement histories along midplane in Sierra White granite in 6.35-cm-diameter cylindrical chimney experiment, Test 570.

Figure 17. Velocity vectors show nonspherical motion.

45° or 90° below that plane. The upper half of the chimney is the mirror image of Figure 17. Therefore, the two toroidal shock geometries are reflected on the equator and may produce the largest displacement on that plane. The comparison of the spherical chimney displacement at 5 cm with that of the small cylindrical chimney displacement at 5 cm (Figure 12) shows the enhanced motion on the equator of the cylindrical geometry.

An interpretation of the data is provided by SRII in Appendix A as though the geometry were not known and therefore is an assessment of the data as though the source were spherical. If measurements were made out of the equatorial plane, different conclusions may be obtained for the cylindrical source geometries.

The 2-D calculations were very helpful in evaluating the measurements on the equatorial plane. The calculations will be described more hereafter.

The comparison of the tamped source results to the spherical chimney results is a good measure of the effect of the rubble alone. Comparing the spherical chimney results to the small cylindrical chimney results is a measure of the geometry effects on the midplane only.

The reduced displacement potentials (RDP) for the two spherical geometries were developed from the displacement histories. They are shown in Figures 18 (tamped) and 19 (spherical chimney). It is suspected that the scatter of the plots is a result of the double integration of imprecise data records, but the trend is toward a slightly lower peak and a much lower permanent RDP for the chimney shot.

The spectral contents of the velocities of the two spherical shots and the small chimney shot are shown in Figures 20, 21 and 22. The ratio of the spectral plots in Figures 23 and 24 show how the spherical chimney and the small cylindrical chimney compare to the tamped shot. The high frequencies are clearly damped by the rubble, but the surprise was that the low frequencies were also depressed. If one used a spectral ratio between .01 and .03 MHz, as a discriminator, the result might be misleading. (Note: simply scaled, .001 Hz is about 2 Hz on the PILE DRIVER scale. But such scaling is best done for less extreme scale factors.)

The spectra and spectral ratios are shown for the RDP's in Appendix A. Appendix A also describes the procedures used to derive the reduced potentials and the spectral contents.

Figure 18. Reduced displacement potentials (RDP) in Sierra White granite for the tamped experiment, Test 574.

Figure 19. Reduced displacement potentials (RDP) in the 3.3-cm-diameter spherical chimney experiment, Test 582.

Figure 20. Spectral amplitudes of velocity histories in the tamped experiment, Test 574.

Figure 21. Spectral amplitudes of velocity histories for the 3.3-cm-diameter spherical chimney experiment, Test 583.

Figure 22. Spectral amplitudes of velocity histories for the 3.3-cm-diameter cylindrical chimney experiment, Test 575.

Figure 23. Comparison of spectral ratios (spherical chimney/tamped) of velocity histories at different ranges.

Figure 24. Comparison of spectral ratios (small cylindrical chimney/tamped) of velocity histories at different ranges.

The development of the calculational model is described in Appendix B. The comparison of the calculated and measured velocity histories is shown in Figure 25 (the small cylindrical chimney) and in Figure 26 (the large chimney). These are 2-D calculations. The 1-D calculation of the tamped event compares much better with the measurements (Figure 27). The differences between the model and the measurements of the 2-D geometries are partly from the model of the rubble properties but also from the 2-D effects of the rubble model or the 2-D numerics. However, the modeling effort was judged good enough to provide a good estimate of the motions off the measurement midplane. The calculations were also used to estimate the total energy transmitted beyond 6 cm and 10 cm from the source as a measure of how much the rubble could reduce the energy transmitted to seismic distances. These estimates are best for relative effects than for absolute energy transmissions.

The calculated effect of the rubble was very large. In the half space of the tamped case, roughly 3.5×10^8 ergs out of 1.0×10^{10} ergs is transported beyond 6 cm. Of the 3.5×10^8 , 2.5×10^8 ergs is transmitted beyond 10 cm. Comparing the energy transported beyond 6 cm, roughly seven times more energy is transmitted in the tamped case than in the small chimney case. Ten times more energy is transmitted in the tamped case than in the large chimney case. In the case of the 10 cm boundary, the tamped case transmits 10 times more energy than the small chimney case and 20 times more than the large chimney case. Clearly the chimneys lead to a marked reduction in energy transmitted to the far-field.

The measurements were also used to estimate the apparent transmitted kinetic energy differences based upon the midplane velocities. Those are described in Appendix A and support even larger differences than the calculations, but because the midplane velocities are not representative of those in other directions, the result is of limited value. This particular measurement is best done at a much greater distance on a larger scale experiment.

Spectral analysis of the calculated results was performed and generally supported the analysis of the measurements.

5.0 DISCUSSION OF THE RESULTS

The effect of the rubble was very large for several reasons. The attenuation in the rubble is large and the chimney's cylindrical geometry greatly distorted the shock velocity field and also utilized the rubble throughout the chimney for shock energy absorption.

Figure 25. Comparison of computed 2-D small cylindrical chimney velocity histories (solid line) with measured results (dashed line).

Figure 26. Comparison of computed 1-D large spherical chimney velocity histories (solid line) with computed 2-D cylindrical chimney results (dashed line).

Figure 27. Comparison of measured (dashed) and computed (solid) velocity histories for the tamped granite case.

The experiments were necessarily axisymmetric and symmetric about a midplane because of the requirements of the velocity measurement system. That does not allow one to assess the effect of asymmetries of both kinds. Those are best measured in phase 2 (yet to be funded). However, it seems quite likely that the vertical velocity component above the device could be reduced so much as to eliminate the usual spall.

The effect of gravity is not included in the small scale tests. As described previously, the effect of gas flow into the rubble may not be realistically large in the small scale test, but there are some reasons why the small cavities may decay too rapidly due to gas flow (e.g., the large surface to volume ratio). This effect may account for the lack of a permanent displacement with the chimney shots.

Some of these secondary effects are easily tested in larger scale events. One must also be careful of the effects due to the differences between HE and a nuclear source. Some of those differences such as charge equivalence have been addressed, but the difference in cavity gases, residual pressures, cavity gas quenching (e.g., steam versus HE products) and other differences can be evaluated better than possible under this contract.

The results so far suggest that the rubble is very effective in reduction of the seismic signal. Attempts have been made to compare the decoupling to that of an empty cavity, but there is not much to be gained from that in that a rubble filled cavity is much less expensive and much easier to hide. The block fall mining technique is a common practice to rubble ore bodies underground.

Clearly, the utility of the method depends upon the size of the strong rubble volume and the size of the device to be tested. The required chimney for a 150 KT device is not commonly available, but an adequate chimney is common for a 1 to 10 KT device. There was no effort to determine with this first experiment the smallest or largest chimney needed for a particular degree of decoupling. It was shown that a rubble of 30 percent porosity (uncompacted) produced a larger effect than a 20 percent porosity (Appendix A). The test of a saturated rubble was attempted, but difficulties with keeping high pressure water out of the charge prevented a successful test within the available funding.

6.0 RECOMMENDATIONS

The second phase proposed to DARPA overcomes many of the disadvantages of the very small scale test. The phase 2 test proposed is in a granite quarry of the same Sierra White granite

with a 1000 fold larger charge ($\sim 1/2$ Kg). The gauges can be reused in the proposed experiment to measure the energy transmitted from the same WP location so as to overcome the questions of a different site and different gauge emplacement. The test would include long distance geophone measurements of the transmitted signal. The source can be located off axis for a measure of that effect. Surface reflections would be realistic, even if spall was not.

Because of the success of the associated calculational effort, it should be included again. SEA CALIP stress gauges (recalibratable in place) would add to the data from accelerometers and geophones. The velocity measurement method used is not, unfortunately, applicable to a field scale event, but the experience from the small scale test assures better results in a somewhat more expensive quarry scale test.

If the quarry tests support the conclusions of this phase 1 effort, the next test would logically be a large HE charge in the PILE DRIVER chimney emplaced via the same access used for reentry.

There is also a question of how well the rubble decoupling might work in other types of rock more characteristic of those found in mining regions around the world, where earthquakes may be common and the need exists for clandestine testing.

The perversion of the seismic signal observed may be a useful clue to recognition of this method of decoupling. But, the better test may be in the ratio of shear to longitudinal waves or some other parameter not measured on this first experiment. That can be done on the next test.

7.0 CONCLUSIONS

This first in a series of three proposed experiments has shown the possibility of an exceptionally large energy decoupling and a possible unusual mix of shear and compressional wave forms for an explosive source. This experiment was planned to treat the question of whether such a proposed effect is actually possible.

The transmitted energy is probably reduced by more than 90 percent. The spectral content is altered from that of a common tamped spherical source even though the experiment was axially and plane symmetric. The calculational results suggest a variety of changes to enhance the effect.

The decoupling method becomes much easier to achieve at yields below 10 KT. But decoupling of large yields may be useful.

To the extent that seismic monitoring is expected to detect nuclear tests, it seems reasonable that this decoupling or disguising method should be evaluated at a larger scale. It seems possible to develop a normal rubble in a mining region with HE and then to exploit that rubble for decoupling purposes to a degree heretofore unappreciated.

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APPENDIX A

DECOUPLING OF UNDERGROUND EXPLOSIONS BY RUBBLE-FILLED CAVITIES

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ABSTRACT

This project was performed in support of the Defense Advanced Research Projects Agency (DARPA) Nuclear Monitoring Program to investigate evasion of a Limited Test Ban Treaty by the detonation of nuclear devices in chimneys. The investigation consisted of performing laboratory experiments in which small spherical explosive charges were detonated in cylindrical cores of granite and measurements were made of the resulting particle velocities. Four source conditions were examined: (1) tamped, (2) spherical chimney, (3) small cylindrical chimney, and (4) large cylindrical chimney. In each case, the particle velocity records were processed to provide displacements, reduced velocity and displacement potentials, spectra, velocity and displacement attenuations, and radiated kinetic energy.

The main conclusion, based on the experimental results for the tamped and small cylindrical chimney source conditions in which all the particle velocity measurements were in the midplane through the charge, is that yield can be underestimated by factors of 4-8 depending on the criteria used. Yield underestimation is even greater according to the large cylindrical chimney source results.

SUMMARY

This project was performed in support of the Defense Advanced Research Projects Agency (DARPA) program on nuclear monitoring to investigate evasion of a Limited Test Ban Treaty by the detonation of nuclear devices in chimneys. Chimneys are cavities created by nuclear explosions that fill with rubble from late-time collapse of the fragmented material above the cavity.

The investigation consisted of performing laboratory experiments in which small spherical explosive charges were detonated in cylindrical cores of Sierra White granite. The charges were 1 cm in diameter and consisted of 3/8 g of pentaerythritol tetranitrate (PETN) powder packed to a density of 1 g/cm³, which provided a total chemical energy of 2181 J. The granite cores were nominally 25 cm in diameter and 30 cm high. Measurements consisted of particle velocities at various ranges in the midplane of the configuration symmetry.

Four source conditions were examined: (1) a tamped charge (no chimney), (2) a charge located at the center of a spherical chimney, (3) a charge located at the center of a small cylindrical chimney, and (4) a charge located at the center of a large cylindrical chimney. The chimneys were packed with crushed Sierra White granite to provide a porosity of 20%, except for one small chimney experiment in which the porosity was 30%. The cavity dimensions and rubble size distribution were based on observations made of the PILEDRIVER underground nuclear test performed in granite at the Nevada Test Site. The nominal diameters of the chimneys were 3 and 6 cm, and the heights were three times the diameters.

The particle velocity records were processed to provide displacements, reduced velocity and displacement potentials, spectra for these quantities, attenuation plots of the maximum velocities and displacements, and the radiated kinetic energy. The calculation of potential and radiated kinetic energy based on spherical wave propagation for the cylindrical chimney source conditions is included to obtain the conclusions an observer would draw from midplane records if the source was assumed to be tamped.

The main conclusions, from comparison with the tamped source results, are that in the chimney experiments

- (1) The radiated kinetic energy was lower by a factor of 4 for the spherical and small cylindrical chimneys, so the yield would be underestimated by this factor (Table 4); when the rubble porosity is increased from 20 to 30% in the small cylindrical chimney, the underestimation factor is about 8.
- (2) The radiated kinetic energy was lower by a factor of 30 for the large chimney, so the yield would be underestimated by this factor (Table 4).
- (3) Maximum velocities (midplane) were lower by over a factor of 4 for the spherical and small cylindrical chimneys, which could lead to a yield underestimation factor of about 20 in granite (Figure 32). The maximum velocities (midplane) were lower by over a factor of 8 for the large cylindrical chimney, which leads to a very large yield underestimation factor.
- (4) Maximum displacements (midplane) were unaffected, which gives a good yield estimation (Figure 33).
- (5) All spectra showed a big loss of high-frequency content.
- (6) The "drop-off" in the displacement spectra occurred at a frequency an order of magnitude higher (higher "corner" frequency) for the spherical and small cylindrical chimneys.
- (7) A chimney's natural frequency forms a peak in the spectra (tamped spectra much more uniform); this property is a good signature for identifying a chimney shot.
- (8) Low-frequency amplitudes of velocity and displacement spectra are lower by a factor of 2 for the small cylindrical chimney, leading to an underestimation of yield by a factor of 8 if the source is assumed to be tamped; when the rubble porosity is increased from 20 to 30%, the underestimation factor is about 64.

PREFACE

This research was conducted under Contract No. 90-477/2 issued by Science and Engineering Applications, Inc. (SEA). The technical monitor at SEA was Carl E. Keller. The SEA prime contract was sponsored by DARPA. The technical monitor at DARPA was Dr. Robert R. Blandford.

The authors are indebted to E. M. Oyola for preparation and performance of the experiments, and M. A. Merritt for instrumentation.

Conversion factors for U.S. Customary to metric (SI) units of measurement

MULTIPLY $\longrightarrow$ BY $\longrightarrow$ TO GET
 TO GET $\longleftarrow$ BY $\longleftarrow$ DIVIDE

angstrom	1.000 000 X E -10	meters (m)
atmosphere (normal)	1.013 25 X E +2	kilo pascal (kPa)
bar	1.000 000 X E +2	kilo pascal (kPa)
barn	1.000 000 X E -28	meter ² (m ²)
British thermal unit (thermochemical)	1.054 350 X E +3	joule (J)
calorie (thermochemical)	4.184 000	joule (J)
cal (thermochemical)/cm ²	4.184 000 X E -2	mega joule/m ² (MJ/m ²)
curie	3.700 000 X 3 +1	*giga becquerel (GBq)
degree (angle)	1.745 329 X E -2	radian (rad)
degree Fahrenheit	$t_F = (t_C + 459.67) / 1.8$	degree kelvin (K)
electron volt	1.602 19 X E -19	joule (J)
erg	1.000 000 X E -7	joule (J)
erg/second	1.000 000 X E -7	watt (W)
foot	3.048 000 X E -1	meter (m)
foot-pound-force	1.355 818	joule (J)
gallon (U. S. liquid)	3.785 412 X E -3	meter ³ (m ³)
inch	2.540 000 X E -2	meter (m)
jerk	1.000 000 X E +9	joule (J)
joule/kilogram (J/kg) (radiation dose absorbed)	1.000 000	Gray (Gy)
kilotons	4.183	terajoules
kip (1000 lbf)	4.448 222 X E +3	newton (N)
kip/inch ² (ksi)	6.894 757 X E +3	kilo pascal (kPa)
kta ²	1.000 000 X E +2	newton-second/m ² (N-s/m ²)
micron	1.000 000 X E -6	meter (m)
mil	2.540 000 X E -5	meter (m)
mile (international)	1.609 344 X E +3	meter (m)
ounce	2.834 952 X E -2	kilogram (kg)
pound-force (lbs avoirdupois)	4.448 222	newton (N)
pound-force inch	1.129 848 X E -1	newton-meter (N·m)
pound-force/inch	1.751 268 X E +2	newton/meter (N/m)
pound-force/foot ²	4.788 026 X E -1	kilo pascal (kPa)
pound-force/inch ² (psi)	6.894 757	kilo pascal (kPa)
pound-mass (lbm avoirdupois)	4.535 924 X E -1	kilogram (kg)
pound-mass-foot ² (moment of inertia)	4.214 011 X E -2	kilogram-meter ² (kg·m ²)
pound-mass/foot ³	1.601 846 X E +1	kilogram/meter ³ (kg/m ³)
rad (radiation dose absorbed)	1.000 000 X E -2	**Gray (Gy)
roentgen	2.579 760 X E -4	coulomb/kilogram (C/kg)
shake	1.000 000 X E -8	second (s)
slug	1.459 390 X E +1	kilogram (kg)
torr (mm Hg, 0°C)	1.333 22 X E -1	kilo pascal (kPa)

*The becquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.

**The Gray (Gy) is the SI unit of absorbed radiation.

A more complete listing of conversions may be found in "Metric Practice Guide E 380-74," American Society for Testing Materials

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Section 1

INTRODUCTION

A potentially effective technique for avoiding compliance with a Limited Test Ban Treaty is to detonate the nuclear device in a cavity filled with rubble. Such cavities, called chimneys, exist at nuclear test sites as a result of past underground nuclear tests. Science and Engineering Applications (SEA) proposed a research program in three consecutive parts to investigate the effectiveness of this evasion technique: (1) laboratory experiments, (2) quarry field tests, and (3) an underground nuclear test. The first part of this program has been completed. The laboratory experiments were performed at SRI, and this report consists of a description of the experiments, presentation of the results, and interpretation. A coordinated computational study was conducted by Science Applications International Corporation (SAIC) and presented in a separate report.*

The experiments were performed with cylindrical cores of Sierra White granite. A small spherical explosive charge was installed at the center of the granite to generate divergent waves. The source conditions consisted of a tamped charge in contact with granite, a spherical chimney with a centrally located charge surrounded by packed rubble, and two cylindrical chimneys with centrally located charges and filled with packed rubble. In all cases, the configurations had a plane of symmetry through the center of the charge and perpendicular to the axes of the granite core and chimneys. In this midplane, radial particle velocities were measured at various ranges. The cores were sealed and placed in a pressure vessel, which was filled with water and pressurized to represent the overburden pressure. Pressure transducers were installed in the water in the midplane and below the core on the axis. A description of the design and technique of the experiments comprises Section 2.

The particle velocity histories were integrated temporally to obtain the particle displacements. Reduced velocity potentials (RVPs) and reduced displacement potentials (RDPs) were then determined. The determination of RVPs and RDPs is not applicable to cylindrical chimney source conditions, but we followed the procedure to play the role of an observer who is unaware that the explosive was detonated in a chimney. The particle velocities, displacements, RVPs, and RDPs

* M.B. Fogel and D.L. Kilb, "Theoretical Studies of Small Scale Explosions in Granite Chimneys," SAIC Report 90-7057 to SEA (23 August 1990).

were given spectral representations. The particle velocity records were also used to calculate the radiated kinetic energy. One experiment was performed in which the rubble porosity was increased. The results, comparisons, and implications for energy coupling comprise Section 3.

Conclusions on the chimney effect based on the midplane particle velocities are contained in Section 4. The main conclusions, from comparison with the tamped source results, are that in the chimney experiments

- (1) The radiated kinetic energy was lower by a factor of 4 for the spherical and small cylindrical chimneys, so the yield would be underestimated by this factor (Table 4); when the rubble porosity is increased from 20 to 30% in the small cylindrical chimney, the underestimation factor is about 8.
- (2) The radiated kinetic energy was lower by a factor of 30 for the large chimney, so the yield would be underestimated by this factor (Table 4).
- (3) Maximum velocities (midplane) were lower by over a factor of 4 for the spherical and small cylindrical chimneys, which could lead to a yield underestimation factor of about 20 in granite (Figure 32). The maximum velocities (midplane) were lower by over a factor of 8 for the large cylindrical chimney, which leads to a very large yield underestimation factor.
- (4) Maximum displacements (midplane) were unaffected, which gives a good yield estimation (Figure 33).
- (5) All spectra showed a big loss of high-frequency content.
- (6) The "drop-off" in the displacement spectra occurred at a frequency an order of magnitude higher (higher "corner" frequency) for the spherical and small cylindrical chimneys.
- (7) A chimney's natural frequency forms a peak in the spectra (tamped spectra much more uniform); this property is a good signature for identifying a chimney shot.
- (8) Low-frequency amplitudes of velocity and displacement spectra are lower by a factor of 2 for the small cylindrical chimney, leading to an underestimation of yield by a factor of 8 if the source is assumed to be tamped; when the rubble porosity is increased from 20 to 30%, the underestimation factor is about 64.

Additional experimental and theoretical information is contained in four appendices. Appendix A describes the properties of the rubble. Appendix B shows representative particle velocity records to demonstrate the degree of reproducibility of the experiments. Appendix C contains pressure records from the transducers installed in the water on the midplane and on the axis below the granite core. Appendix D is an outline of the theory of spherical elastic waves to show our treatment of the RVP, RDP, spectrum, and radiated kinetic energy.

Section 2

DESCRIPTION OF EXPERIMENTS

TECHNIQUE AND CONFIGURATIONS

Figure 1 shows a granite specimen under preparation for an experiment with a tamped spherical explosive charge. The specimen starts out as a core 24.8 cm in diameter and slightly longer than 29.8 cm. The end surfaces are ground flat and perpendicular to the cylinder axis. The core is cut into two equal pieces, and the cut surfaces are ground flat, again perpendicular to the axis, then smoothed. When the halves are brought together later in the preparation, the height is 29.8 cm. Hemispherical cavities are milled at the center of each smoothed face for the spherical charge. A diameter of 1 cm provides a tight fit for the charge container. In the smooth surface on the lower half of the specimen, concentric circular grooves are milled for insertion of insulated copper wire conductors to form the particle velocity gages. Not shown in Figure 1b are radial grooves for the conductors to allow construction of the electrical circuits. In the upper half specimen, a hole is drilled on the axis to allow insertion of the charge assembly.

The spherical charge consisted of 3/8 g of pentaerythritol tetranitrate (PETN) explosive powder packed to a density of 1 g/cm³ and contained in a spherical shell of Lucite with an outside diameter of 1 cm and a wall thickness of 0.05 cm. The charge was attached to a strand of mild detonating fuse (MDF) contained in a stainless steel tube. The tube was threaded through the axial hole in the upper half specimen until the spherical charge container fit snugly in the hemispherical cavity. Once the charge assembly was in place, the two halves of the specimen were joined and cemented around the perimeter of the midplane. The entire outer surface was then sealed with an impermeable membrane.

Figure 2a shows the specimen with the tamped charge prepared for insertion into the experimental apparatus. Figure 2b through 2d shows specimens with a spherical, small cylindrical, and large cylindrical chimney, respectively.

For preparation of the specimens with chimneys, the cavities in each half were packed with granite rubble to a porosity of 20% except for one test in which the porosity was 30%. The stainless steel tube for the MDF was fixed in place in half the specimen during compression of the rubble. The punch had a hemispherical shape to form the cavity for the charge container.

(a) Meridional cross section

(b) Plan of lower cylinder

RM-8205-39

Figure 1. Sierra White granite specimen for tamped experiments.

RM-8205-40

Figure 2. Sierra White granite specimen for tamped and chimney experiments.

The cylindrical specimen was lowered into a solenoid within a pressure vessel. Figure 3 shows the experimental arrangement. The nominal diameter and height of the solenoid were 32 and 34 cm, respectively. The internal diameter and height of the pressure vessel were 33 and 35.5 cm, respectively. The overburden or confining pressure of 10.3 MPa (1500 psi) was applied for filling the remaining volume with water and pressurizing.

The sequence of operations consisted of applying the overburden pressure, turning on the solenoid current to create a steady axial magnetic field in the specimen, and detonating the charge. The particle velocities were obtained by applying Faraday's law. The voltage measured for a loop was equal to the product of the magnetic field strength, the loop length, and the wire velocity. Typically, the field strength generated was $B = 0.15$ T, so a loop of radius $r = 0.01$ m ($l = 2\pi r$) expanding at a velocity of $v = 1$ m/s gave a potential difference of $V = Blv = 94$ mV.

CHIMNEY SIZE SELECTION

As an experimental and calculational simplification, we chose a cylindrical shape for the chimney. On the basis of observations made by SEA of the HARD HAT and PILEDRIIVER underground nuclear tests performed in granite, the chimney aspect ratio was chosen as height/diameter = 3. A spherical chimney was introduced into the experimental series to produce results that preserved the spherical symmetry. These results allow an evaluation of the effect of a chimney by one-dimensional calculations and analyses of the waveforms by comparison with the tamped charge results. By making the radius of the spherical chimney, the same as that of the small cylindrical chimney, we could compare the particle velocities on the specimen midplanes to assess the effect of chimney shape caused by increased volume of rubble.

Our spherical charge consisted of 3/8 g of PETN in a thin spherical Lucite container of 0.5 cm outside radius and 0.05 cm wall thickness. On the basis of the heats of explosion for PETN and TNT of 1390 and 1080 cal/g, the charge was equivalent to $w = 0.483$ g of TNT. If the charge represents an underground nuclear test with a yield equivalent to 64 kt of TNT, our scale factor according to cube root scaling is

$$\lambda = (W/w)^{1/3} = 5100$$

In our experiments, the charge created a cavity of radius $r = 0.65$ cm in Sierra White granite. At the Nevada Test Site (NTS), a yield equivalent to 64 kt of TNT in granite created a cavity of $R = 40$ m, which scales down to $r = R/\lambda = 0.78$ cm. Comparing the cavity radii gives one measure of the extent to which we were approximating an underground nuclear test.

MM-8392-1K

Figure 3. Experimental arrangement (tamped case shown).

A comparison of the cavity radii is more favorable in NTS tuff. For an underground test with a yield of $W = 64$ kt in tuff, the cavity radius is $R = 13.72 W^{1/3} = 55$ m, which scales down to $r = R/\lambda = 1.08$ cm. Our past experiments in cores of NTS tuff gave cavities with radii in close agreement with this value.

In our cylindrical chimneys, the radius was taken as the cavity radius and the remaining chimney volume was considered late-time roof collapse, which provided the rubble.

If a chimney of radius $r = 1.56$ cm in granite is assumed to represent the scaled-down cavity caused by a yield of $W = 64$ kt, the scale factor is $\lambda = 2550$ and we need 3.86 g of TNT, that is, 3 g of PETN. Our charge in the chimney is 3/8 g of PETN, which represents 8 kt of TNT when the scale factor is $\lambda = 2550$.

If a chimney of radius $r = 3.12$ cm in granite represents the scaled-down cavity caused by a yield of 64 kt, the scale factor is 1275 and we need 30.9 g of TNT, that is, 24 g of PETN. Our charge now represents 1 kt of TNT when the scale factor is 1275.

To represent the above two cases, we chose cylindrical chimneys with radii of 1.65 and 3.18 cm and heights of 9.9 and 19 cm. For the spherical chimney, we chose a radius of 1.65, the same as that of the smaller cylindrical chimney.

RUBBLE CHARACTERIZATION

The rubble consisted of crushed Sierra White granite compacted to provide a porosity of 20% for most of the experiments. On the basis of SEA observations of the PILEDRIVER chimney, a matching particle size distribution was provided by sieve analysis. Various mechanical properties such as the mean stress/volume change relationship were found by compressing the rubble contained in a thick-walled steel cylinder. The piston load and area gave the axial stress, and strain gages on the cylinder gave the radial stress. The results are approximate to the extent that friction along the inner walls caused some resistance to compaction. Porosity was calculated from measurements of grain density and rubble sample dry weight and volume.

The results of the rubble characterization tests are given in Appendix A.

EXPERIMENTS PERFORMED

Table 1 lists the test numbers, source conditions, particle velocity gage radii, and water pressure transducer standoff distances for the ten experiments performed. The pressure transducer locations are shown in Figure 4. At the location marked A in Table 1, the pressure is that reflected from the bottom of the pressure vessel on the axis of the configuration. At the locations marked B₁

Table 1
EXPERIMENTAL DATA

Source Condtions	Test Numbers	Particle Velocity Gage Ranges (mm)								Pressure Gage Standoff (mm)			
										A ^a	B ₁ ^b	B ₂ ^b	
Tamped	566	10	20	30	40	50	65	80	7.2	5.1	4.2		
	574	10	20	30	40	50	65	80	14.0	2.8	3.8		
Spherical chimney	582	20	30	35	40	50	65	80	8.0	3.9	5.7		
	583	20	30	35	40	50	65	80	8.0	6.4	4.0		
Small cylindrical chimney	569	20	30	35	40	50	65	80	95	7.0	8.8	5.6	
	575	20	30	35	40	50	65	80	95	18.0	2.5	6.1	
	581 ^c	20	30	35	40	50	65	80	95				
Large cylindrical chimney	567				35	40	50	65	80	95	13.0	2.7	6.1
	570				35		50	65	80	95	13.0	4.5	6.1

a. Reflected pressure.

b. Incident pressure.

c. Rubble porosity increased from 20 to 30%.

and B₂, the pressure transducers are probes that measure incident pressure in a water layer 19 mm thick. The pressure transducers were included to provide additional data for calculational comparisons. The pressure transducer in the base of the pressure vessel has the added importance of being the only measurement not on the midplane of symmetry. Consequently, it provides information on the effect of the cylindrical chimneys on the wave propagation on axis.

RM-8205-1

Figure 4. Experimental configuration for tamped and cylindrical and spherical chimney experiments in Sierra White granite.

Section 3

EXPERIMENTAL RESULTS

Because of the excellent reproducibility of the records, as demonstrated in Appendix B, the results for one of the repeat tests are presented. They consist primarily of particle velocities and displacements, reduced velocity and displacement potentials, spectral distributions, peak velocity and displacement attenuations, and radiated kinetic energy comparisons. Spherical wave treatments of the midplane particle velocities for obtaining RVP, RDP, and kinetic energy were performed for the cylindrical source condition to provide results and interpretations for an observer who assumes that the source is tamped. The water pressure records are included in Appendix C, but a discussion of the results is located toward the end of this section, which ends with the results of the single experiment performed in a cylindrical chimney containing rubble of higher porosity. Conclusions and recommendations are summarized in Section 4.

PARTICLE VELOCITIES

Figures 5 through 8 show the sets of particle velocities for the tamped, spherical chimney, small cylindrical chimney, and the large cylindrical chimney source conditions. The rubble was dry and had a porosity of 20%. The particle velocities in Figure 5 are typical of those generated in a hard rock by a tamped charge. The velocity rises almost instantaneously to its peak value, decays rapidly to form a short pulse of outward motion, and finally reverses direction and describes a rebound. The pulse duration remains fairly constant at about 5 μ s during propagation. The rebound velocity (toward the source) stays below 5 m/s.

Figure 6 shows the particle velocities generated by the 1-cm-diameter spherical source in a 3.3-cm-diameter spherical chimney. A comparison with Figure 5 shows that the chimney had the effect of reducing the outward velocities, and increasing the rise time, outward velocity pulse duration (9 μ s), and rebound velocity. The later arrival times at the gage ranges are a consequence of the slower wave speed through the rubble.

Figure 7 shows the particle velocities generated by the 1-cm-diameter spherical charge located at the center of a small cylindrical chimney 3.3 cm in diameter and 9.9 cm high. The velocities are measured in the specimen midplane throughout the charge, and during the outward motion and the start of the inward motion they are comparable to those associated with a spherical chimney (Figure 6). During the later stage of the rebound, differences are apparent. The rebound

RA-8205-2

Figure 5. Particle velocity histories in tamped experiment in Sierra White granite, Test 574.

RA-8205-3

Figure 6. Particle velocity histories measured at the midplane of Sierra White granite in 3.3-cm-diameter spherical chimney experiment, Test 582.

RA-8205-4

Figure 7. Particle velocity histories measured along midplane in Sierra White granite in 3.3-cm-diameter cylindrical chimney experiment, Test 575.

RA-8205-5

Figure 8. Particle velocity histories measured along midplane in Sierra White granite in 6.35-cm-diameter cylindrical chimney experiment, Test 570.

duration has almost doubled to about 21 μs (c.f. 12 μs in Figure 6). Subsequent velocity oscillations are smaller. The differences are attributed to the chimney shape; the resistance to the rebound is less when the cavity is cylindrical than when it is spherical and of equal diameter. Another reason, perhaps with a more important influence, is that the pressure pulse from the charge traveling upward and downward in the chimney produced delayed cylindrically outward velocities above and below the midplane region to counteract the rebound in the midplane region through shearing action.

Figure 8 shows the particle velocities generated by the 1-cm-diameter spherical charge located at the center of a large cylindrical chimney 6.35 cm in diameter and 19 cm high. The velocities were measured in the specimen midplane through the charge. The maximum outward velocities are about half those at the same range for the spherical and small cylindrical chimneys (Figures 6 and 7). The duration of outward motion is much longer (25 μs c.f. 9 μs). Because of the chimney diameter relative to the specimen diameter, the record period unaffected by wave reflections from the cylindrical boundary was too short to capture the whole rebound phase of the motion, even with the innermost velocity gage at the 35-mm range. An interesting feature of the velocity records is the gradual (relative to the other records) increase in velocity to the maximum value. This dispersive effect appears because the minimum rubble thickness (2.67 cm) that the wave passes through is enough to spread the wave noticeably. Once a gradual rise is established, spherical divergence exaggerates this feature as the wave expands.

As an aid to comparing velocity wave shapes, Figure 9 shows the particle velocities at a range of 50 mm for the four cases of tamped, spherical chimney, small cylindrical chimney, and large cylindrical chimney source conditions. The differences described above can be seen clearly.

The wave motions associated with the cylindrical source conditions are axisymmetric and will be very different from those recorded at the midplanes.

PARTICLE DISPLACEMENTS

Figures 10 through 13 show the sets of particle displacements for the tamped, spherical chimney, small cylindrical chimney, and large cylindrical chimney source conditions. The displacements were obtained by integrating the velocities shown in Figures 5 through 8.

Figure 10 shows the displacements for the tamped source. The general trend is a rise to the maximum displacement and a relatively gradual decay to an asymptotic positive value, which indicates that the cavity created by the explosive has undergone permanent expansion. In fact, the cavity diameter measured after the test was 1.3 cm, an increase of 30%.

RA-8205-10

Figure 9. Comparison of velocity histories at the 5-cm range for the tamped and chimney experiments.

RA-8205-15

Figure 10. Displacement histories measured in Sierra White granite in tamped experiment, Test 574.

RA-8205-16

Figure 11. Displacement histories along midplane in Sierra White granite in 3.3-cm-diameter spherical chimney experiment, Test 582.

RA-8205-17

Figure 12. Displacement histories along midplane in Sierra White granite in 3.3-cm-diameter cylindrical chimney experiment, Test 575.

Figure 13. Displacement histories along midplane in Sierra White granite in 6.35-cm-diameter cylindrical chimney experiment, Test 570.

Figure 11 shows the displacements around the spherical chimney. These displacement histories are much smoother than those of the tamped charge test. The maximum displacements at the various ranges are comparable to those of the tamped charge test. Overall, the wave behavior is predominantly elastic. In fact, late-time records (not shown in Figure 11) showed oscillations around a zero displacement.

Figure 12 shows the displacements in the midplane generated by the source in a small cylindrical chimney. As in the case of the spherical chimney test, the displacement histories are smooth and the magnitudes are similar. The durations of the outward displacements are longer because of the cylindrical shape of the chimney (see discussion of Figure 7). Again, the wave behavior is essentially elastic.

Figure 13 shows the displacements in the midplane generated by the source in a large cylindrical chimney. The maxima at 35 and 50 mm are below those for the small cylindrical chimney but comparable at larger ranges. Although the return to zero displacement is beyond the recording window, the records indicate longer pulses of outward displacement.

A comparison of the displacement histories at a range of 50 mm for the four source conditions can be seen in Figure 14. The characteristics described above are evident. The main points are that the maximum displacements are comparable, the tamped test produced a permanent displacement, and the cylindrical chimney tests produced longer pulses than the spherical chimney test (Figure 14).

REDUCED VELOCITY POTENTIALS

The definition and derivation of the integral form of the RVP can be found in Appendix D. The RVP curves in Figures 15 through 17 were generated by substituting the particle velocities of Figures 5 through 7 in (D-18) for weighted integration at each fixed range.

Figure 15 shows the RVP at each range for the tamped source condition. The curves vary little from range to range, which implies that the wave motion is predominantly elastic. The values are mostly positive, which means that the motion was mainly outward; this shape is consistent with small rebounds and permanent displacements resulting from permanent cavity expansion.

Figure 16 shows the RVP at each range for the spherical chimney source condition. The curves vary little from range to range, which implies that the wave motion is predominantly elastic. The curve shapes differ from those of the tamped test in that they are far more oscillatory, which is consistent with an elastic behavior throughout, including the region next to the chimney.

Figure 14. Comparison of displacement histories at 5-cm range in Sierra White granite for the tamped and chimney experiments.

RA-8205-24

Figure 15. Reduced velocity potentials (RVP) in Sierra White granite for the tamped experiment, Test 574.

Figure 16. Reduced velocity potentials (RVP) for 3.3-cm-diameter spray
chimney experiment, Test 582.

RA-8205-42

Figure 17. Reduced velocity potentials (RVP) for 3.3-cm-diameter small cylindrical chimney experiment, Test 575.

Figure 17 shows the RVP at each range for the small cylindrical chimney source condition. The curves are similar in shape and magnitude to those in Figure 16 for the spherical chimney and indicate elastic motion throughout. The durations of the negative portions of the curves are longer ($21\text{ }\mu\text{s}$ c.f. $13\text{ }\mu\text{s}$), as one would expect from a comparison of the particle velocities in Figures 6 and 7.

REDUCED DISPLACEMENT POTENTIALS

The definition and derivation of the integral form of the RDP can be found in Appendix D. The RDP curves in Figures 18 through 20 were generated by substituting the displacements of Figures 10 through 12 in (D-12) for weighted integration at each fixed range.

Figure 18 shows the RDP at each range for the tamped source condition. Qualitatively, the curves are of similar shape, each tending to the same asymptotic value given by (D-19). Strictly speaking, the recording period was not long enough to demonstrate this value, but it was enough to indicate the trend, especially for the shorter ranges. At ranges of 20 and 30 mm, the final displacements in Figure 10 are 25 and $12\text{ }\mu\text{m}$, which give the RDP asymptotes of 10 and 11 mm^3 . Differences between the overall curve shapes are attributed to insufficient experimental accuracy, because the process of calculating RDPs requires two integrations of the particle velocity data.

Figure 19 shows the RDP at each range for the spherical chimney source condition. Qualitatively, the curves are of similar shape, each tending toward damped oscillations about the abscissa, which indicates that no permanent displacement occurred. Again, differences between the curves are attributed to insufficient experimental accuracy for the double integration process.

Figure 20 shows the RDP at each range for the small cylindrical source condition. The curves are similar in shape and magnitude to those in Figure 19 for the spherical chimney source. If the calculation is performed over a longer time and if we neglect the influence of the outer boundary of the specimen, we obtain an extended RDP that shows damped oscillations around a zero value, indicating that no permanent deformation occurred.

Despite the differences in RDP curves in the chimney cases, the curves are close enough to allow the generation of generic RDPs, one for each case.

PARTICLE VELOCITY SPECTRA

The theory for determining the distribution of the amplitudes among the frequencies of a function is outlined in Appendix D. The spectral distributions are plots of $|F(v_n)|$ given by (D-33),

RA-8205-21

Figure 18. Reduced displacement potentials (RDP) in Sierra White granite for the tamped experiment, Test 574.

Figure 19. Reduced displacement potentials (RDP) in the 3.3-cm-diameter spherical chimney experiment, Test 582.

RA-8205-41

Figure 20. Reduced displacement potentials (RDP) for 3.3-cm-diameter cylindrical chimney experiment, Test 575.

where $F(v)$ is the Fourier transform of the function $f(t)$. In our case, the function is the particle velocity, displacement, RVP, or RDP. Formulas (D-31) and (D-32) give the coefficients determined from the discrete data needed in (D-33).

Figure 21 shows the spectra at six ranges of the particle velocities (Figure 5) measured in the tamped charge test over three frequency decades. The distributions are similar and show a relationship $|F_i| = (r_i/r_j)^{1.45} |F_j|$, where r_i and r_j are ranges. Hence, the velocity pulse (Figure 5) maintains its shape and decreases in amplitude during propagation, as in elastic wave propagation. With increasing frequency, each curve rises to a maximum amplitude at a frequency of about 40 kHz, then falls more rapidly in an overall monotonic manner. A yield of 64 kt gives a scale factor of 5100, and this frequency becomes 7.8 Hz (15.6 Hz for 8 kt).

Figure 22 shows the spectra at four ranges of the particle velocities (Figure 6) measured in the spherical chimney test over three frequency decades. The curves are similar in shape. As in the case of the tamped charge test, the spectra indicate elastic wave propagation. At each range, the lowest decade of frequency contains equal amplitudes. The middle decade of frequency contains amplitudes that rise to a peak at about 45 kHz, then fall. The highest decade of frequency contains amplitudes that fall to relatively low values. Sierra White granite with a spherical cavity of radius "a", Poisson's ratio ν , and a wave velocity c_p has a damped oscillation of frequency $f = (1 - 2\nu)^{1/2} c_p / 2\pi(1 - \nu)a$ when a pressure is suddenly applied to the cavity wall. If we take $a = 1.65$ cm, $\nu = 0.2$, and $c_p = 0.52$ cm/ μ s (from arrival times), we obtain a natural frequency of $f = 49$ kHz, which is close to the frequency at the spectrum peak and probably accounts for the relatively narrow band of frequencies having the greatest amplitudes.

Figure 23 shows the spectra at six ranges of the particle velocities (Figure 7) measured in the midplane of the small cylindrical chimney test over three frequency decades. The curves are similar in shape throughout, and they resemble those in Figure 22 for the spherical chimney test. The frequency with the maximum amplitude is lower, about 30 kHz compared with 45 kHz, which is probably due to the cylindrical shape of the chimney exciting a lower natural frequency than a spherical chimney of the same radius.

In Figure 24, the spectral ratios, $|F_{sc}(\nu_n)|/|F_T(\nu_n)|$, are shown for the particle velocity transforms, where $F_{sc}(\nu_n)$ is for the spherical chimney, $F_T(\nu_n)$ is for the tamped source, and ν_n is the frequency. The plots show that amplitude differences greater than an order of magnitude occur at frequencies above 300 kHz. Figure 25 shows the corresponding spectral ratios, $|F_{sc}(\nu_n)|/|F_T(\nu_n)|$, for the small cylindrical chimney from which we draw the same conclusions. In other words, the chimneys have the effect of drastically reducing the high-frequency content of the tamped source spectrum.

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Figure 21. Spectral amplitudes of velocity histories in the tamped experiment, Test 574.

RA-8205-29

Figure 22. Spectral amplitudes of velocity histories for the 3.3-cm-diameter spherical chimney experiment, Test 583.

Figure 23. Spectral amplitudes of velocity histories for the 3.3-cm-diameter cylindrical chimney experiment, Test 575.

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Figure 24. Comparison of spectral ratios (spherical chimney/tamped) of velocity histories at different ranges.

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Figure 25. Comparison of spectral ratios (small cylindrical chimney/tamped) of velocity histories at different ranges.

ARTICLE DISPLACEMENT SPECTRA

Figure 26 shows the particle displacement spectra over three decades of frequency obtained from the particle velocity records at a range of 30 mm for the tamped, spherical chimney, and small cylindrical chimney source conditions. The chimney curves lie below the tamped curves over most of the frequency range, but above them at frequencies near the natural spherical and cylindrical cavity frequencies (30 and 45 kHz). Above these natural frequencies, the steep declines in the spectral content of the two chimney cases are similar and tend toward an order of magnitude less than the tamped case content as the frequencies approach 1 MHz. The amplitudes start diminishing at frequencies of about 5, 45, and 30 kHz for the tamped, spherical chimney, and small cylindrical chimney cases, respectively. The low-frequency amplitude levels are 1000, 300, and 450 $\mu\text{m}/\text{MHz}$. Because the low-frequency amplitudes for small cylindrical chimneys are half those for a tamped source of the same yield, a 3/8 g PETN charge placed in a 3.3-cm-diameter cylindrical chimney will produce the same amplitude levels at low frequency as a tamped 3/64 g PETN charge; the yield estimate based on a tamped charge would be low by a factor of 8.

Figure 27 shows the amplitude ratios over the frequency domain at a range of 30 mm for the spherical and small cylindrical chimney cases. As in the case of the particle velocities, the chimney suppresses the high-frequency content of the tamped source displacement spectra, especially above 300 kHz.

VP SPECTRA

Figure 28 shows the RVP spectra at a range of 30 mm for the tamped, and spherical and small cylindrical chimney source conditions. In the spherical and cylindrical chimney cases, amplitudes have similar distributions with corner frequencies at about 45 and 30 kHz, and the amplitudes above 300 kHz are lower by more than an order of magnitude than those in the tamped case.

Figure 29 shows the spectral ratio obtained from the spectra of Figure 26 and reinforces the above observations about RVP spectra.

RDP SPECTRA

Figure 30 shows the RDP spectra at a range of 30 mm for the tamped, and spherical and small cylindrical chimney source conditions. In the spherical and cylindrical chimney cases, amplitudes have similar distributions with corner frequencies at about 40 and 30 kHz, and the

RA-8205-43

Figure 26. Spectral amplitude of displacement histories for tamped, spherical chimney, and small cylindrical chimney experiments at 3-cm range.

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Figure 27. Spectral ratios of displacement for spherical chimney/tamped and small cylindrical chimney/tamped at 3-cm range.

Figure 28. Comparison of spectral amplitudes of reduced velocity potentials (RVP) for tamped and 3.3-cm-diameter spherical and cylindrical chimneys at range of 3 cm.

RA-8205-37

RA-8205-38

Figure 29. Spectral ratios of RVP for spherical chimney/tamped and small cylindrical chimney/tamped at 3-cm range.

RA-8205-53

Figure 30. Spectral amplitudes for RDP histories in tamped, spherical chimney, and small cylindrical chimney experiments at 3-cm range.

amplitudes above 300 kHz are lower by more than an order of magnitude than those of the tamped case. At the low-frequency ends of the spectra, the amplitudes of the spherical and cylindrical cases are lower than those of the tamped case by over a factor of 2 (350 c.f. 800 mm³/MHz).

Figure 31 shows the spectral ratios obtained from the spectra of Figure 30 and reinforces the above observations about the RDP spectra.

In Appendix D, we show that the spectral ratios for the particle velocities and RVPs should be identical. This property is confirmed by Figures 24, 25, and 29.

P-WAVE ATTENUATION

Generally, the decrease in particle velocity and displacement with increase in range is caused by energy dissipation in the material and spherical divergence. Hence, the attenuation of peak velocity and displacement, or preferably the entire wave, is a measure of coupling. The entire wave tells us how much of the source energy the material allows to radiate in the form of kinetic energy of an elastic spherical wave beyond some range called the elastic radius. In our experiments, the elastic radii are close to the tamped charge and at the chimney wall, so the waves being monitored are elastic.

Figures 32 and 33 show the attenuation plots for peak velocity and displacement. The velocity plots form three distinct families. The highest velocities were generated by a tamped charge. The next highest velocities were generated by the charge in a spherical or small cylindrical chimney (midplane only). The lowest velocities were generated by the charge in the large cylindrical chimney (midplane only). The attenuation slopes are similar, as we would expect from elastic wave propagation. Figure 33, however, shows that the source condition had no effect on the maximum displacements. For convenience, values of the maximum particle velocities and displacements are listed in Tables 2 and 3.

RADIATED KINETIC ENERGY

The radiated kinetic energy is considered here as a coupling criterion. The theory and procedure for determining the radiated kinetic energy are outlined in Appendix D. The formula derived is (D-42), which requires an integration at each station with respect to the time after the arrival of the wave at the station. In the integrand, we need the particle velocity, the displacement, and the RVP. Scatter should be expected in the calculations because of the integrations needed to obtain the displacements and RVPs, squaring of the integrand, and another integration.

RA-8205-54

Figure 31. Spectral ratio of RDP histories for spherical chimney/tamped and small cylindrical chimney/tamped at 3-cm range.

RA-8205-55

Figure 32. Attenuation of peak particle velocity for tamped and spherical, small, and large chimney experiments.

RA-8205-56

Figure 33. Attenuation of peak displacement in tamped and spherical, small, and large cylindrical chimney experiments.

Table 2
MAXIMUM VALUES OF PARTICLE VELOCITY^a

Range (mm)	Source Conditions							
	Tamped		Spherical Chimney		Small Cylindrical Chimney		Large Cylindrical Chimney	
	#574	#566	#582	#583	#575	#569	#570	#567
10	162	138						
20	62	62	12.8	13.5	15.5	17.5		
25	59	52	8.5	8.8	11.0	11.5		
30	41	36	6.7	7.5	8.5	8.5		
35			6.1	6.5	6.5		2.5	2.4
40	24.5		4.8	5.8	5.6	5.0		1.8
50	15	22	3.9	5.0	4.3	2.5	1.6	1.7
65	9	14	2.9	4.0	2.5	1.6	1.1	1.4
80	5	8.5	2.0		2.0	1.4	0.8	0.8
95					1.5		0.7	0.7

Velocities in meters per second.

Table 3
MAXIMUM VALUES OF PARTICLE DISPLACEMENT^a

Range (mm)	Source Conditions							
	Tamped		Spherical Chimney		Small Cylindrical Chimney		Large Cylindrical Chimney	
	#574	#566	#582	#583	#575	#569	#570	#567
10	152	180						
20	62	96	59	64	63	70		
25	46	59	43	47	49	51		
30	36	48	33	36	39	41		
35			28	30	33		24	23
40	24		23	22	29	28		17
50	20	32	16	18	20	13	16	14
65	13	26	12	13	13	9	11	10
80	9		9		9	7	9	7
95					7		7	6

a. Displacements in micrometers.

The radiated kinetic energy in units of Joules calculated at several ranges for the tamped, spherical chimney, and small cylindrical chimney source conditions is listed in Table 4. The overall average of the energy for the tamped charge case is 154 J. The kinetic energy radiated from the source in a spherical chimney is 42 J, which is about one quarter of this value. Our charge contains 2181 J of chemical energy (heat of explosion), so the tamped and spherical chimney source conditions are associated with radiated kinetic energies that are 7.1 and 1.9% of the charge energy. If the kinetic energy were assumed to radiate from a tamped charge although it was contained in a spherical chimney, we would underestimate the yield by a factor of 3.7.

The theory does not apply to a cylindrical chimney, but if measurements of particle velocity were made in the midplane and we assumed that the explosive was tamped, we would again underestimate the yield, this time by factors of 4.5 and 30 for the small and large chimneys, according to the kinetic energies listed in Table 4. An increase in rubble porosity from 20 to 30% in the small chimney leads to an underestimation factor of 8.6.

WATER PRESSURE MEASUREMENTS

The results of the water pressure measurements described in Section 2 are given in Appendix C. The records provided additional data for correlation with calculational results and showed that the part of the wave propagating in the axial direction of a cylindrical chimney is different in shape and magnitude from that part of the wave propagating in the midplane, as expected. Reference is given to the pressure measurements by agreement with simple estimates based on the behavior of elastic waves as they propagate in granite, through an interface, and into the water to reach the pressure transducer (see Table C-1).

RUBBLE POROSITY

An experiment was performed (Test 581 with rubble having porosity of about 30%) in a small cylindrical chimney to examine the influence of porosity on the particle velocities and hence the other results derived from them.

Figure 34 shows the midplane particle velocities obtained in this test, and Figure 35 shows the displacements calculated by temporal integration. A representative comparison of the effect of rubble porosity on the particle velocities is seen in Figure 36 for the 20-mm range (see also Figure 11). The overall shapes are similar. The wave arrival time is later, and the maximum velocity is lower (about half at this range). The rebound velocities, however, are comparable. A comparison of the displacements for the 20-mm range is shown in Figure 37 (see also Figure 12). The maximum displacement is about two-thirds of that for the 20% porosity case.

Table 4
RADIATED KINETIC ENERGY^a

Range	Source Condition											
	Tamped					Spherical Chimney		Small Cylindrical Chimney		Small Cylindrical 30% ^b	Large Cylindrical	
	#563	#564	#565 ^c	#566 ^c	#574 ^c	#582	#583	#569	#575	#581	#567	#570
10	127	135	165	174	171	-	-	-	-	-	-	-
15	164	179	128	-	-	-	-	-	-	-	-	-
20	186	192	163	157	112	35	48.5	41.5	32	16	-	-
25	189	179	263	141	120	37	49.2	33.7	35	19.1	-	-
30	220	232	-	129	104	41	48.5	32	36	18.5	-	-
35	-	-	-	-	-	45.1	44.9	34.7	35.1	-	3.9	4.9
40	116	117	-	-	83.3	40.5	40.2	30.2	34.0	-	4.7	-
50	-	-	-	126	64.6	37.5	40.1	-	26.1	-	5.4	5.4
Avg.	167	171	180	145	109	39.4	45.2	34.4	33	17.9	4.7	5.2

a. Measured in Joules.

b. Rubble porosity.

c. Tests from S.A. Miller and A.L. Florence, "Particle Velocity Experiments on (JVE) Analog Rock," SRI Technical Report PYU-6645 to DARPA, October 1990.

Figure 34. Particle velocity histories measured in small cylindrical chimney experiment with 30% initial rubble porosity, Test 581.

Figure 35. Displacement histories measured in small cylindrical chimney experiment with 30% initial rubble porosity, Test 581.

Figure 36. Comparison of velocity histories for 20% and 30% initial rubble porosities in small cylindrical chimney experiments at the 2-cm range.

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Figure 37. Comparison of displacement histories for 20% and 30% rubble porosities in small cylindrical chimney experiments at the 2-cm range.

Figures 38 and 39 show the RVP and RDP at three ranges. The similarity of the shapes from range to range indicates elastic wave propagation. The shapes are similar to those in Figures 7 and 20 for the case of 20% rubble porosity in the small cylindrical chimney. The difference is primarily in magnitude, as we would expect from comparisons of the particle velocities.

Figures 40 and 41 show the spectra of the velocities and displacements. The curves are similar to those shown in Figures 23 and 26 corresponding to 20% rubble porosity. The main difference is found in the velocity spectra at the lower frequencies, where the amplitudes are lower by a factor of 2. At the chimney natural frequency (~ 30 kHz), the magnitudes in Figures 23 and Figure 40 are comparable.

Figure 38. Reduced velocity potentials measured in small cylindrical chimney experiment with 30% initial rubble porosity, Test 581.

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Figure 39. Reduced displacement potentials measured in small cylindrical chimney experiment with 30% initial rubble porosity, Test 581.

RA-8205-63

Figure 40. Spectral amplitude of velocity histories for small cylindrical chimney experiment with 30% initial rubble porosity, Test 581.

RA-8205-64

Figure 41. Spectral amplitude of displacement histories for small cylindrical chimney experiment with 30% initial rubble porosity, Test 581.

Section 4

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The conclusions address the effects of chimneys on the particle velocities, displacements, RVPs, RDPs, spectral distributions, and radiated kinetic energies associated with a tamped source and the relevance of the effects to yield estimation.

Chimneys lower the particle velocities and extend the duration of the outward motion. The extent of the decrease is seen clearly in the peak velocity attenuation plots in Figure 32. The decrease in velocity and increase in duration leave the maximum displacements unaffected, as we see in the attenuation plot of Figure 33. Comparisons of the velocity and displacement histories are shown in Figures 9 and 14 at the 50-mm range. Chimneys smooth the pulses and so remove the highest frequencies, and they emphasize a natural frequency.

A nuclear test site is characterized for peak particle velocity attenuation in the form

$$v = k/\bar{r}^n$$

where v is the peak particle velocity, k and n are site constants depending on the geologic material, and $\bar{r}$ is the scaled range given by

$$\bar{r} = r/W^{1/3}$$

where r is the range and W is the explosive yield. From our laboratory experiments (Figure 32), we obtain

$$v = 4907/\bar{r}^{1.35}$$

where v is in meters per second, r is in meters, and W is in kilo-tons. If we measure a peak velocity v_c at a given range r_c , the assumption that the charge is tamped gives a yield of

$$W_c = (v_c/k)^{3/n} r^3$$

If, in fact, the velocity from a tamped charge at the same range should be v_T , the yield is

$$W_T = (v_T/k)^{3/n} r^3$$

and the yield estimate is

$$W_c = (v_c/v_T)^{3/n} W_T$$

Taking $v_c = v_T/4$ and $n = 1.35$, the estimate is low by a factor of about 22.

Chimneys have the effect of introducing large oscillations in the RVPs (Figures 16 and 17). In our experiments, the material surrounding the chimney remained elastic, so the RDPs had a damped oscillatory behavior tending to a zero value.

Chimneys cause the spectral amplitudes of the particle velocities to peak around the natural frequency of the chimney cavity (Figures 22 through 25). In a relatively narrow band around this natural frequency, the amplitudes exceed those of the tamped source spectrum. The higher frequencies are suppressed, and the low-frequency amplitudes are lowered by a factor of about 2. The effect on the spectral amplitudes of the displacements is to increase by an order of magnitude the corner frequency where the amplitudes begin to diminish substantially with increasing frequency (Figure 26). The flat low-frequency part of the spectrum is lowered by about a factor of 2 (Figure 27). Relative to the tamped case, the spectral ratios exceed unity around the cavity natural frequency, as in the case of particle velocities.

The peaking of the velocity and displacement spectra around a preferred frequency appears to be an important signature for revealing a chimney shot.

Use of the low-frequency part of the displacement spectra for chimney source conditions and the assumption that the source is tamped result in an underestimation of yield by a factor of 8.

The RVP and RDP spectra show properties similar to those discussed above for the velocity and displacement spectra. In Appendix D, we prove that the spectral ratios for the velocities, displacements, and RVPs should be identical (Figures 24, 25, 27, and 29).

When the explosive source is detonated in a chimney, the radiated kinetic energy is drastically reduced (Table 4). In our experiments, with a source chemical energy of 2181 J, the tamped, spherical chimney, small cylindrical chimney, and large cylindrical chimney source conditions had radiated kinetic energies of 154, 42, 34, and 5 J, respectively. The cylindrical chimneys are based on midplane observations and the assumption that the observer thinks the shot is tamped. Yield estimates based on radiated kinetic energy are therefore low by factors of 3.7, 4.5, and 30.8, if we assume the source is tamped.

An increase in rubble porosity in the small cylindrical chimney from 20% to a value of 30% (rained particles) lowered the outward velocities by about half and the maximum displacements by about one-third. Apart from magnitudes, the wave shapes, potentials, and spectra remain similar

to those of the chimney cases with 20% rubble porosity. The radiated kinetic energy drops from 34 J to a value of 18 J, thus substantially improving the degree of decoupling and causing a lower yield estimate (factor of 8.6).

RECOMMENDATIONS

We recommend that more laboratory experiments be performed with sources in chimneys. The waves emanating from the cylindrical chimneys were monitored only in the midplane of symmetry passing through the source. A much more comprehensive description of the wave would be acquired by measurements made off the midplane. Because the material surrounding the chimney remains elastic for chimney cavities that are large enough, experimentation incorporating a volumetric distribution of particle velocity sensors would be facilitated by the use of a hard rock simulant. This substitution would obviate cutting up geologic cores for sensor installation, which introduces potential contamination of records caused by local interfaces off the specimen midplane. More laboratory experiments would increase the range of parameters of interest, such as charge location within the chimney. The data would also be invaluable for validating continuum code calculations and source characterization using seismological techniques.

Appendix A

RUBBLE PROPERTIES

Sierra White granite was crushed, subjected to sieve analysis to partition the sample by grain size ranges, and recombined by a proportionate selection from each range to obtain the rubble size distributions shown in Figure A-1.

The graded rubble was rained into a thick-walled steel cylinder. The dry density of the rubble at this stage was 1.84 g/cm^3 . From separate measurements to find the weight of water displaced by a specific weight of rubble, we calculated a grain density of 2.64 g/cm^3 , which corresponds to a porosity of 30.3%, according to

$$\phi = 1 - (\rho_d/\rho_g) \quad (\text{A-1})$$

in which ϕ is the porosity, ρ_d is the dry density (1.84 g/cm^3), and ρ_g is the grain density (2.64 g/cm^3). The rubble was then compressed axially by a steel piston. During compression, the piston load and displacement were recorded. The axial stress applied to the rubble was taken to be the load divided by the piston area. Frictional resistance was ignored. The axial strain was taken as the piston displacement divided by the starting height of the rubble (engineering strain). Because the steel container remains elastic and the strains are fairly large, the axial strain is equal to the volumetric strain. The result of this compression test is shown in Figure A-2. The shape of the loading/unloading curve is typical of those obtained for granular materials. Because Monterey sand was a candidate rubble material at the beginning of the program, compression tests were performed and the result is shown in Figure A-2. The same test results are shown in Figure A-3, but the volumetric strain has been converted to porosity through a change of dry density in equation (A-1).

The radial stress on the granular material is estimated by means of circumferential strain gage measurements. Because the steel container remains elastic, we can readily obtain from these measurements the radial inner traction acting on the thick wall. If the axial stress on the rubble is σ_z and the radial stress is σ_r , the mean stress is $\sigma_m = (\sigma_z + 2\sigma_r)/3$ and the deviatoric stress is $\sigma_z - \sigma_r$. Figure A-4 shows the mean stress-volume strain relationship, and Figure A-5 shows the failure envelope, $\sigma_z - \sigma_r$ versus σ_m .

The data provide rubble properties at the low end of the stress range and the compression needed to pack the rubble in the chimneys to provide a porosity of 20%.

Figure A-1. Grain size distribution of the granite rubble used and the scaled PILE-DRIVER rubble.

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Figure A-2. Axial stress-strain behavior of different chimney rubble. The granite aggregate was used in the chimney experiments.

RA-8205-67

Figure A-3. Porosity as a function of axial stress for rubble materials.

RA-8205-68

Figure A-4. Mean stress-volume strain for rubble materials.

Figure A-5. Stress difference-mean stress behavior of rubble materials.

Appendix B

REPRODUCIBILITY

Four examples are provided to demonstrate the reproducibility of the experiments. Figure B-1 shows the particle velocity records at a range of 30 mm obtained in the two tamped charge tests 566 and 574. Figure B-2 shows the records for the spherical chimney in repeat tests 582 and 583. Figure B-3 shows the records for the small chimney in repeat tests 569 and 575. Figure B-4 shows the records at a range of 35 mm for the large chimney in repeat tests 567 and 570.

In all cases, the reproducibility is excellent.

Figure B-1. Comparison of particle velocity histories at the 3-cm range in two tamped experiments.

Figure B-2. Comparison of particle velocity histories at the 3-cm range in two spherical chimney experiments.

Figure B-3. Comparison of particle velocity histories at the 3-cm range in two small cylindrical chimney experiments.

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Figure B-4. Comparison of particle velocity histories at the 3.5-cm range in two large cylindrical chimney experiments.

RA-8205-73

Appendix C

WATER PRESSURE MEASUREMENTS

In each experiment, pressures were recorded at three stations in the water surrounding the granite specimen. The locations of the gages are given in Figure 4 and Table 1. Two of the three gages were located to measure incident pressure in the midplane of the specimen (horizontal plane throughout the charge), and the third gage was installed in the steel base plate of the pressure vessel on the axis of symmetry to measure reflected pressure. The measurements were made to supplement the particle velocity data for computational comparison, and in the cases of the cylindrical source condition, the on-axis gage provides information on the departure of the wave from spherical symmetry. Unfortunately, the gage malfunctioned in both tests with the small cylindrical chimney. However, a record was obtained in Test 567 with the large cylindrical chimney.

Figures C-1, C-2, and C-3 show the reflected pressure pulses measured by the on-axis gage at the base of the pressure vessel for the tamped, spherical chimney, and large cylindrical chimney source conditions, respectively. The recording period before the wavefront returns to the gage after two transits through the base water layer varies between 9 and 18 μ s, depending on the water layer thickness A listed in Table 1.

Figures C-4 through C-7 show the incident pressure pulses measured by the gages in the midplane for the tamped, spherical chimney, small cylindrical chimney, and large cylindrical chimney source conditions. The recording periods vary according to the gage locations in Table 1 from 17 to 22 μ s before reflections arrive from the solenoid former.

Table C-1 shows a comparison between simple theoretical estimates of the pressures and recorded pressures. The estimates were obtained by extrapolating the peak velocity attenuation curves in Figure 28 to the range of the specimen boundary, assuming the maximum radial stresses are given approximately by $\sigma = \rho c_p u$, and using the granite/water plane wave transmission coefficient. The theoretical and experimental pressures are in good agreement.

Table C-1
MAXIMUM WATER PRESSURES (MPa)

<u>Source Conditions</u>	<u>Test Numbers</u>	<u>Pressure</u>		<u>Gage</u>	
		<u>A^a</u>		<u>B^b</u>	
		<u>Theory</u>	<u>Experiment</u>	<u>Theory</u>	<u>Experiment</u>
Tamped	574	7.87	8.61	5.25	5.30
Spherical	582/583	3.93	4.48	2.36	2.76
Small cylinder	569/575	-	c	2.36	2.03
Large cylinder	567	-	3.45	1.05	0.98

- a. Reflected pressure on axis.
b. Incident pressure in midplane.
c. Gage malfunction.

In all cases, except for the on-axis reflected pressure in the large cylindrical chimney experiment, the midplane incident pressure pulses and the on-axis reflected pressure pulses have the expected shapes, as shown at the beginning of the records in Figures C-1, C-2, and C-4 through C-7. However, Figure C-3 for the large cylindrical chimney experiment shows that the wave propagating downward has small magnitudes of the physical quantities, such as stress, and a shape different from the midplane shape. Complete characterization of the effect of a chimney on the wave propagation off the midplane requires a combination of continuum mechanics code calculation and further experimentation with sensors located off the midplane.

RA-8205-45

Figure C-1. Reflected water pressure history for tamped experiments.

RA-8205-46

Figure C-2. Reflected water pressure history for spherical chimney experiments.

RA-8205-47

Figure C-3. Reflected water pressure history in large cylindrical chimney experiment, Test 567.

RA-8205-48

Figure C-4. Water pressure history from two gages along specimen midplane in tamped experiment, Test 574.

RA-8205-49

Figure C-5. Water pressure history from two gages along specimen midplane in spherical chimney experiment, Test 582.

RA-8205-50

Figure C-6. Water pressure history from two gages along specimen midplane in small cylindrical chimney experiment, Test 575.

RA-8205-51

Figure C-7. Water pressure history from two gages along specimen midplane in large cylindrical chimney experiment, Test 570.

Appendix D

SPHERICAL ELASTIC WAVES

INTRODUCTION

An outline of the treatment of elastic spherical waves is provided here to show how the experimental data are processed and interpreted. The data consist of radial particle velocities at several ranges. Radial displacements are obtained by temporal integration of the particle velocity histories. We show how we obtain the reduced velocity and displacement potentials (RVP and RDP), the spectra of the velocities, displacements, and reduced potentials and the energy transmission. Interpretation is focused on the coupling of the explosive energy with the surrounding rock and the effect of chimneys on the coupling.

FORMULATION

In spherical coordinates (r, θ, ϕ) , a spherically symmetrical elastic field has a radial displacement ξ , strains ϵ_r and $\epsilon_\theta = \epsilon_\phi$, and stresses σ_r and $\sigma_\theta = \sigma_\phi$ that depend only on the radial coordinate, r , and the time, t . The kinematic relations are

$$\epsilon_r = \frac{\partial \xi}{\partial r} \quad \epsilon_\theta = \frac{\xi}{r} \quad (D-1)$$

and Hooke's law is

$$\sigma_r = (\lambda + 2\mu) \epsilon_r + 2\lambda \epsilon_\theta \quad \sigma_\theta = \lambda \epsilon_r + 2(\lambda + \mu) \epsilon_\theta \quad (D-2)$$

where λ and μ are the Lamé constants (μ is the shear modulus). In terms of Young's modulus, E , and Poisson's ratio, ν ,

$$\lambda = \frac{E\nu}{(1+\nu)(1-2\nu)} \quad \mu = \frac{E}{2(1+\nu)} \quad \lambda + 2\mu = \frac{(1-\nu)E}{(1+\nu)(1-2\nu)} \quad (D-3)$$

The equation of motion of an element of material is

$$\frac{\partial \sigma_r}{\partial r} + \frac{2}{r} (\sigma_r - \sigma_\theta) = \rho \frac{\partial^2 \xi}{\partial t^2} \quad (D-4)$$

in which ρ is the material density. Substitution of the stresses [Equation (D-2)] and then the strains [Equation (D-1)] changes Equation (D-4) to

$$\frac{\partial^2 \xi}{\partial r^2} + \frac{2}{r} \frac{\partial \xi}{\partial r} - \frac{2\xi}{r^2} = \frac{1}{c^2} \frac{\partial^2 \xi}{\partial t^2} \quad (D-5)$$

in which $c^2 = (\lambda + 2\mu)/\rho$, c being the P-wave speed. Differentiation of Equation (D-5) with respect to time t shows that the radial particle velocity $u = \partial \xi / \partial t$ satisfies the same equation.

To find the solution to Equation (D-5), we let $\phi(r, t)$ be a displacement potential, so

$$\xi = \frac{\partial \phi}{\partial r} \quad (D-6)$$

Then, Equation (D-5) becomes

$$\frac{\partial^2 (r\phi)}{\partial r^2} = \frac{1}{c^2} \frac{\partial^2 (r\phi)}{\partial t^2} \quad (D-7)$$

which is the standard form of the wave equation. The solution of Equation (D-7) that describes P-waves propagating outward from a spherical source of radius $r = a$ is

$$\phi = \frac{1}{r} \psi \left(t - \frac{r-a}{c} \right) \quad (D-8)$$

The function ψ is the reduced displacement potential. If the wave starts from the source at radius $r = a$ at time $t = 0$, the wave arrival time at radius r is $t_a = (r-a)/c$, so the RDP applies at this radius only when $t > t_a$. Let $\tau = t - (r-a)/c$ be the time measured from the time of arrival. Then,

$$\phi = \frac{1}{r} \psi(\tau) \quad \tau = t - (r-a)/c \quad (D-9)$$

According to Equations (D-6) and (D-9), the displacement is related to the RDP by

$$\xi = -\frac{\dot{\psi}(\tau)}{rc} - \frac{\psi(\tau)}{r^2} \quad (D-10)$$

where the dot indicates differentiation with respect to the argument, τ . The choice of the displacement potential value at the wavefront given by $\phi(0)$ is arbitrary, so we choose $\phi(0) = 0$. Also, the displacement at the wave front is zero, so $\partial \phi / \partial r = 0$ at $\tau = 0$. Hence, from Equations (D-9) and (D-10) we have

$$\psi(0) = 0 \quad \dot{\psi}(0) = 0 \quad (D-11)$$

The solution to Equation (D-10), giving the RDP at the radius, r , where the displacement history is measured, is simply

$$\psi(\tau) = -cr e^{-c\tau/r} \int_0^{\tau} \xi(r, \tau') e^{c\tau'/r} d\tau' \quad (D-12)$$

An analogous expression for the RVP is derived in the same way. The particle velocity, u , satisfies Equation (D-5) and when a velocity potential, χ , is introduced through the definition

$$u = \frac{\partial \chi}{\partial r} \quad (D-13)$$

we find that $r\chi$ replaces $r\phi$ in the standard wave Equation (D-7). For outgoing waves,

$$\chi = \frac{1}{r} \gamma\left(t - \frac{r-a}{c}\right) \quad (D-14)$$

or

$$\chi = \frac{1}{r} \gamma(\tau) \quad \tau = t - (r-a)/c \quad (D-15)$$

and $\gamma(\tau)$ is the RVP. Consequently, the particle velocity is related to the RVP by the equation

$$u = -\frac{\dot{\gamma}(\tau)}{rc} - \frac{\gamma(\tau)}{r^2} \quad (D-16)$$

The value of the velocity potential is arbitrary at the wavefront so, we choose $\chi(0) = 0$. However, the value of the particle velocity at the wavefront: need not be zero and we have

$$\gamma(0) = 0 \quad \dot{\gamma}(0) = rcu(r,0) \quad (D-17)$$

where $u(r,0)$ is the jump in velocity at the wavefront. The solution to Equation (D-16) with $\gamma(0) = 0$ gives the RVP in the form

$$\gamma(\tau) = -cr e^{-c\tau/r} \int_0^{\tau} u(r, \tau') e^{c\tau'/r} d\tau' \quad (D-18)$$

If a pulse in a cavity causes permanent deformation around the spherical cavity, we let the radius $r = a$ be the radius beyond which the material remains elastic. In these cases, the final displacement in the elastic region will not be zero; the final particle velocity will still be zero. Let the final displacement, $\xi_{\infty}(r)$, be established at radius $r > a$ at time τ_d . The formula [Equation (D-12)] then gives

$$\psi(\tau) = -cre^{-c\tau/r} \int_0^{\tau_d} \xi(r, \tau') e^{c\tau'/r} d\tau' - r^2 \xi_{\infty}(r) \{ 1 - e^{-c(\tau-\tau_d)/r} \}$$

for $\tau > \tau_d$, so $\psi(\infty) = \psi_{\infty}$ is

$$\psi_{\infty} = -r^2 \xi_{\infty}(r) \quad (D-19)$$

A similar treatment of formula [Equation (D-18)] gives $\gamma_{\infty} = 0$ because $u_{\infty}(r) = 0$.

FREQUENCY SPECTRA

The exponential form of the Fourier series for a function $f(t)$ in the interval $0 < t < T$ is

$$f(t) = \sum_{n=-\infty}^{\infty} c_n e^{i\omega_n t} \quad (D-20)$$

where the coefficients are

$$c_n = \frac{1}{T} \int_0^T f(t) e^{-i\omega_n t} dt \quad (D-21)$$

and the angular frequencies of the components are $\omega_n = n\omega = 2\pi n/T$; the frequencies are $\vartheta_n = \omega_n/2\pi = n/T$. The lowest frequencies are $\omega_1 = \omega = 2\pi/T$ and $\vartheta_1 = \omega_1/2\pi = 1/T$ (except for $\omega_0 = \vartheta_0 = 0$).

Let $f(t)$ be approximated by another function $\hat{f}(t)$ represented by a finite number of components

$$\hat{f}(t) = \sum_{n=-m}^m c_n e^{i\omega_n t} \quad (D-22)$$

The value of this function at N data points, t_α , ($N \geq m$) is

$$\hat{f}(t_\alpha) = \sum_{n=-m}^m c_n e^{i\omega_n t_\alpha} \quad (D-23)$$

Minimization of the residual

$$\eta^2 = \sum_{\alpha=0}^{N-1} \{ f(t_\alpha) - \hat{f}(t_\alpha) \}^2$$

with respect to the coefficients c_n is satisfied by

$$c_n = \frac{1}{n} \sum_{\alpha=0}^{n-1} f(t_\alpha) e^{-i\omega_n t_\alpha} \quad (D-23)$$

The sampling interval is T/n , and the n^{th} frequency is $\omega_n = n\omega = 2\pi n/T$ ($\vartheta_n = \omega_n/2\pi = n/T$). The function $\hat{f}(t)$ approximating $f(t)$ in Equation (D-20) is then given by Equation (D-22), when the coefficients are as in Equation (D-23) when N data points are provided.

If $m = N - 1$, the function

$$\hat{f}(t_\alpha) = \sum_{n=- (N-1)}^{N-1} c_n e^{i\omega_n t_\alpha} \quad (D-24)$$

passes through all the data points, and

$$c_n = \frac{1}{N} \sum_{\alpha=0}^{N-1} f(t_\alpha) e^{i\omega_n t_\alpha} \quad n = 0, 1, 2, \dots, N-1 \quad (D-25)$$

This series [Equation (D-25)] is called the discrete Fourier transform (DFT). The highest frequency represented is $\omega_N = 2\pi N/T$ ($\vartheta_N = N/T$). If the sample spacing is $\Delta T = T/N$, we have $\omega_N = 2\pi/\Delta T$ ($\vartheta_N = 1/\Delta T$).

If we let the sampling window be NT with T as the sample spacing, we set $t_\alpha = \alpha T$, $\omega = 2\pi/NT$, $\omega_n = n\omega = 2\pi n/NT$, $n\omega t_\alpha = 2\pi n\alpha/N$, and $\vartheta_n = n/NT$, so

$$c_n = \frac{1}{N} \sum_{\alpha=0}^{N-1} f(t_\alpha) e^{-2\pi i n\alpha/N} \quad n = 0, 1, 2, \dots, N-1$$

If the data $f(t_\alpha)$ are given at t_α in the range $0 < t < T$ so that $f(t_\alpha) = 0$ when the t_α are in the range $\bar{T} < t < T$, the coefficients of the Fourier series [Equation (D-20)] are

$$c_n = \frac{1}{T} \int_0^T f(t) e^{-i\omega_n t} dt \quad (D-26)$$

The Fourier transform of a function $f(t)$ that is zero outside the range $0 < t < T$ is

$$F(\omega) = \int_0^{\bar{T}} f(t) e^{-i\omega t} dt \quad (D-27)$$

and the values of the transform at specific frequencies $\omega_n = 2\pi n/T$, ($\vartheta_n = \omega_n/2\pi$), are determined by Equation (D-27) to be

$$F(\omega_n) = \int_0^{\bar{T}} f(t) e^{-i\omega_n t} dt \quad (D-28)$$

The relationship between the Fourier coefficients, c_n , given by Equation (D-21), and the Fourier transform [Equation (D-28)] at the same frequencies is therefore

$$F(\omega_n) = c_n T \quad (D-29)$$

For the discrete data points, t_α , in the range $0 < t_\alpha < T$ ($t_\alpha = \alpha\Delta T = \alpha T/N$), the coefficients are given by Equation (D-25). Hence, Equation (D-29) provides the required amplitude spectrum

$$F(\omega_n) = c_n T = \frac{T}{N} \sum_{\alpha=0}^{N-1} f(t_\alpha) e^{-i\omega_n t_\alpha} \quad n = 0, 1, 2, \dots, N-1 \quad (D-30)$$

The fundamental frequency is $\omega_1 = 2\pi/T$, and the maximum frequency is $(N-1)\omega_1$. For a fixed data spacing ($\Delta T = T/N$), the larger the window size T , the greater the spectral density.

The spectrum is presented as the variation of $|F(\omega_n)|$ or $|F(\vartheta_n)|$ versus the frequency ω_n or ϑ_n . Therefore, we need $|c_n|$. Write f_α for $f(t_\alpha)$. Then, from Equation (D-25),

$$a_n = \frac{1}{2} (c_n + \bar{c}_n) = \frac{1}{N} \sum_{\alpha=0}^{N-1} f_\alpha \cos \omega_n t_\alpha \quad (D-31)$$

$$b_n = \frac{i}{2} (c_n - \bar{c}_n) = \frac{1}{N} \sum_{\alpha=0}^{N-1} f_\alpha \sin \omega_n t_\alpha \quad (D-32)$$

$$c_n = a_n - ib_n \quad |c_n| = (a_n^2 + b_n^2)^{1/2}$$

where $\omega_n = n\omega_1$, $\omega_1 = 2\pi/T$, $t_\alpha = \alpha T/N$, $\omega_n t_\alpha = 2\pi\alpha n/N$, $\vartheta_n = \omega_n/2\pi = n/T = n\vartheta_1$, and $\vartheta_1 = 1/T$. That is,

$$|F(\vartheta_n)| = |c_n|T = (a_n^2 + b_n^2)^{1/2} T \quad (D-33)$$

where a_n and b_n are given by the series in Equations (D-31) and (D-32).

SPECTRAL RATIO

Starting with the Fourier transform definition [Equation (D-27)] and using $u = \dot{\xi}$ and Equation (D-16), we have the following relationship among the transforms U , Ξ , and Γ of u , ξ , $\xi(\bar{T})$, and γ :

$$\xi(\bar{T}) + i\omega \Xi(\omega) = U(\omega) = -\frac{1}{r} \left(\frac{i\omega}{c} + \frac{1}{r} \right) \Gamma(\omega)$$

If we denote the quantities for the tamped and chimney sources with subscripts T and C, we have the following relationships among the spectral ratios:

$$\frac{\Xi_c(\omega)}{\Xi_T(\omega) - i \xi_T(\bar{T})/\omega} = \frac{U_c(\omega)}{U_T(\omega)} = \frac{\Gamma_c(\omega)}{\Gamma_T(\omega)}$$

in which $\xi_c(\bar{T})$ is absent, because in our experiments, $\xi_c(\bar{T}) = 0$. Hence, the spectral ratios for the particle velocity and the RVP are identical. The spectral ratio for the displacements relative to the final displacement tends toward the other two spectral ratios as the frequency increases [$\xi_T(\bar{T})/\omega \rightarrow 0$].

RADIATED ENERGY

The rate of work (power) per unit area performed on the region outside a sphere of radius r is

$$J = \sigma_r u$$

where σ_r is the compressive radial stress and u is the radial particle velocity. If we measure time from the time of arrival of outgoing incident P-wave at radius r , the work done on the external medium is

$$W(r) = \int_0^{\infty} J(r, \tau) d\tau = \int_0^{\infty} \sigma_r u d\tau \quad (D-34)$$

Because the medium is elastic, Hooke's law gives the radial stress in terms of the contractual strains, ϵ_r and ϵ_θ , as

$$\sigma_r = \rho \{ c_p^2 \epsilon_r + 2 (c_p^2 - 2 c_s^2) \epsilon_\theta \} \quad (D-35)$$

in which c_p and c_s are the P-wave and S-wave velocities determined by

$$c_p^2 = (\lambda + 2\mu)/\rho \quad c_s^2 = \mu/\rho \quad (D-36)$$

ρ being the material density.

In Equation (D-36), λ and μ are the Lamé' material constants (μ is the elastic shear modulus). For convenience, we give λ and μ in terms of Young's modulus, E , and Poisson's ratio, ν :

$$\lambda = \frac{2\nu\mu}{1 - 2\nu} = \frac{\nu E}{(1 + \nu)(1 - 2\nu)} \quad \mu = \frac{E}{2(1 + \nu)}$$

$$\lambda + 2\mu = \frac{2(1 - \nu)}{1 - 2\nu} \cdot \mu$$

The strain components are

$$\epsilon_r = -\frac{\partial \xi}{\partial r} \quad \epsilon_\theta = -\frac{\xi}{r} \quad (D-37)$$

where ξ is the outward radial displacement at radius, r . These strains are obtained as functions of time from the particle velocity records of the laboratory experiments. Briefly, the procedure is to integrate the particle velocity record at each gage station to obtain the displacement histories. The circumferential strain history $\epsilon_\theta(r, \tau)$ is simply the displacement history divided by the radius where it is obtained, as indicated in Equation (D-37). The radial strain history requires the spatial gradient at selected times. Hence, from the displacement history at each radius, crossplots are made at each time t to produce the displacement at each time as a function of range r . From these plots, approximate spatial derivatives are obtained. With closely spaced gages, this process gives reasonable approximations to the radial strain except at a wavefront with a rise time comparable to the wave transit time between gage stations. To cope with this case, we give the wave a linear rise at radius r , so that

$$u = \bar{u}\tau/\bar{\tau} \quad \xi = \bar{u}\tau^2/2\bar{\tau}$$

where $\bar{\tau}$ is the time to achieve the maximum velocity, $\bar{u}$. The elastic wave solution then provides the strain components

$$\epsilon_r = \left\{ \frac{r}{c_p^2} (1 - e^{-c_p \tau/\bar{\tau}}) + \frac{\tau^2}{r} \right\} \frac{\bar{u}}{\bar{\tau}}$$

$$\epsilon_\theta = \bar{u}\tau^2/2\bar{\tau}r$$

The work done on the external medium expressed by Equation (D-34) is the same as the radiated energy only if the final displacement $\xi(r, \infty) = 0$. If the final displacement at radius r is not zero, the elastic strain energy stored in the external medium is

$$U(r, \infty) = 8\pi r \{ \xi(r, \infty) \}^2 \mu \quad (D-38)$$

and the radiated energy K is simply

$$K = W - U.$$

The work done can be expressed in terms of the reduced displacement potential by substituting

$$u = \frac{\partial \xi}{\partial \tau} = -\frac{\ddot{\Psi}}{rc_p} - \frac{\dot{\Psi}}{r^2}$$

$$\frac{\sigma_r}{\rho} = 4c_s^2 \left\{ \frac{\Psi}{r^3} + \frac{\dot{\Psi}}{r^2 c_p} \right\} + \frac{\ddot{\Psi}}{r}$$

in the work integral [Equation (D-34)] and performing the integration. The result is

$$W = 4\pi\rho \left\{ 2c_s^2 \Psi_\infty^2 \frac{1}{r^3} + \frac{1}{c_p} \int_0^\infty \ddot{\Psi}^2 d\tau \right\} \quad (D-39)$$

The first term is identical to Equation (D-38) and so represents the stored elastic energy. The second term is the radiated energy. The expression [Equation (D-39)] is useful if a convenient analytical form can be found to represent the RDP.

The radiated kinetic energy can be expressed in terms of the particle velocity, particle displacement, and reduced displacement potential obtained from our measurements of particle velocity. The time derivative of the displacement formula [Equation (D-10)] is

$$u(r,t) = -\frac{\ddot{\Psi}(\tau)}{rc} - \frac{\dot{\Psi}(\tau)}{r^2} \quad (D-40)$$

From Equations (D-10) and (D-40),

$$\ddot{\Psi}(r,t) = -rc_p u + c_p^2 \left(\xi + \frac{\Psi}{r^2} \right) \quad (D-41)$$

Hence, from Equation (D-39),

$$K(r) = 4\pi\rho c_p r^2 \int_0^{\tau_d} \left\{ -u + \left(\xi + \frac{\Psi}{r^2} \right) \frac{c_p}{r} \right\}^2 d\tau \quad (D-42)$$

in which τ given by Equation (D-9) is the time measured from the arrival of the wave at radius r .

APPENDIX B

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SECTION 1

EXECUTIVE SUMMARY

The purpose of the work performed by SEA, SRII and SAIC was to study the effects of detonating an explosive in a chimney. In particular, we sought to answer the question: is it possible to disguise the yield of nuclear shot by firing it in a chimney of rubbleized material? This phase of the effort addressed this question through small scale experiments and numerical simulations of them.

The small scale experiments performed by SRII consisted of a 3/8 gm PETN charge detonated in a rubble filled chimney contained within a block of granite. The chimney's shape was idealized to a cylinder with a 3 to 1 aspect ratio. Velocity time history data were measured along the mid-plane of the charge in the granite. Several experiments were performed: a baseline tamped shot which consisted only of granite, a spherical chimney experiment, and large and small cylindrical chimney shots.

The goal of SAIC's portion of this study was to complement the data by providing insight into the 2-D nature of flow through numerical simulations. The data measured by SRII was used to validate the simulations and the material models. This report summarizes the work SAIC performed under contract SEA 90-477/1 (9-XT9-8512Z-1).

Material response models for granite and chimney rubble were required for the calculations used to perform simulations of the chimney experiments. One-dimensional simulations were run to refine these numerical models. First a granite model was constructed to match the tamped experimental results. Since the rubble acts to buffer the load on the granite, the granite EOS must correctly reproduce the response down to very low stress levels. A special effort, therefore, was made to match the low velocity regime. The model was in excellent agreement with the measured pulses out to a range of 5.0 cm, or peak velocity of 15 m/s. Beyond 5 cm the computed peaks are high. At the farthest range the computed peak is about 40% high. The arrival and rise times, however, agree more closely with the data at these ranges. The extra attenuation seen in the data could be caused by some small air void content not included in the model.

The chimney experiments were used to construct a model for the rubble. It was assumed that near the chimney wall, along the mid-plane, the flow is nearly spherical. 1-D calculations would, therefore, be sufficient to extract material response information. Excellent agreement was obtained out to a range of 3.5 cm. Again the computed response was high beyond this range. The source of this error is probably the granite EOS which has too little attenuation below peak velocities of 15 m/s.

In addition to refining the material models, the 1-D simulations were used to produce a strategy for zoning the 2-D simulations. Shocks in granite have a very sharp rise time and, therefore, require fine zones to accurately capture the wave shape. Given our computer budget, it was not possible to zone the 2-D problem sufficiently finely to fully resolve the rise and peak. The zoning scheme ultimately chosen produced a 20% reduction in peaks due to lack of resolution. Since the primary objective was to get a qualitative feel for the 2-D nature of the flow, this error was considered acceptable.

The 2-D calculations, like the experiments, showed that the flow along the mid-plane differs little from a 1-D solution. Some perturbation to this flow is caused by the cylindrical shape of the cavity. The cylindrical chimney causes a shoulder to appear on the velocity histories after the peak velocity is attained.

Off the mid-plane, the flow is quite complex. The shock propagates more rapidly in the granite than in the rubble, and the granite shock relieves into the chimney ahead of the shock in the chimney. When the chimney shock reaches this area, its stress is high enough to drive material out and up toward the mid-plane in the granite. This flow causes the shoulders seen in the velocity histories on axis. This shoulder is stronger in the computations than seen in the data, but otherwise the two are in good agreement.

The 2-D calculation for the small cylindrical chimney has a more rapid attenuation of peak velocity along the mid-plane than is seen in either the data or in the 2-D spherical chimney computation. The relief wave provided by the chimney material is stronger in this calculation than it is in the experiment. For the large chimney case, the computed and measured attenuation rates for peak velocity are very similar. In both calculation and experiment, however, rebound duration is increased by the presence of the chimney.

Peak stress contour plots show that the apparent center of the explosion is located at the chimney granite interface on the mid-plane. Peak velocity contours, on the other hand, have a double lobed structure. The first lobe is centered at the chimney-granite interface and is caused by the shock in the granite. The second lobe is generated by the upward moving material driven by the chimney shock which arrives after the granite shock.

One measure of the decoupling efficiency of the chimney is the energy transported into the far-field. The calculations find that most of the energy is deposited within the first 2.0 cm of the grid. There is, therefore, not much difference in energy transport between the large and small chimneys. Energy transport to the far-field was examined for the tamped, large and small chimney cases. Two radii, 6 and 10 cm, were chosen as the boundaries between the near and far-field. The 6 cm radius in the small chimney case was outside the

chimney, while 10 cm was chosen so as to be outside the large chimney. Roughly 1/10 of the energy transmitted beyond 6 cm in the fully tamped case is propagated beyond this range in the chimney situations.

A second measure of decoupling is the ratio of Fourier amplitudes of the chimney velocity histories to the tamped case. This provides information on the effect different size chimneys have on the spectrum of a velocity history. Since the chimneys act to spread out the wave forms in time, one expects most of the weight to be concentrated at the low end of the spectrum. This is exactly what is seen in the results. Both chimneys concentrate the power in the lowest frequencies. The larger chimney just moves the weight down in frequency relative to the small one.

This report begins with a section discussing the material models used for granite and rubble material. Comparisons of computed and measured velocity traces are also given in this section. The 2-D simulations are discussed in the next section. This report ends with a summary of conclusions and open questions.

SECTION 2

GRANITE AND RUBBLE MODELS

Response models for granite and rubble were required in order to perform numerical simulations of the chimney experiments. The granite used in the experiments was Sierra White granite, and the rubble was constructed out of sifted granitic sand. Static laboratory data are available for Sierra White Granite,⁽¹⁾ but ~~no~~ data were available for the constructed rubble. Dynamic data on Sierra White granite were available from past SRI experiments⁽²⁾.

*only
limited*

Static data were used to construct the initial granite model, and data developed in the tamped experiments⁽³⁾ were used in an attempt to validate this model. A 1-D simulation of the tamped experiment was run using this granite model. Comparison of the data with the results of this calculation is shown in Figures 1 and 2. The computed response clearly does not match the test data. The arrival time, peak velocity and positive phase duration are all incorrect. This model was abandoned and a new model was constructed to match the measured response.

Figure 1. Comparison of measured (dashed line) velocity history with a computation (solid line) using a granite model based on static data.

Models used in our codes to describe material response have two components, a volumetric and deviatoric part. The volumetric part of the granite model that best matched the SRI velocity data was parameterized using a Mie-Gruneisen form. The deviatoric response was modelled using a constant shear modulus and a yield strength that is a function of mean stress.

The Mie-Gruneisen EOS uses the Hugoniot as the reference curve for constructing the volumetric response. It assumes that the shock velocity can be represented as a quadratic function of particle velocity, i.e.,

Figure 2. Comparison of measured (dashed line) velocity history with a computation (solid) using a granite model based on static data.

$$u_s = A + Bu_p + Cu_p^2 , \quad (1)$$

where u_s is shock velocity and u_p is the particle velocity.

The energy dependent part of the pressure P_e is assumed to have a very simple form given by

$$P_e = \gamma \rho e . \quad (2)$$

It is further assumed that the combination $\rho \gamma$ is constant and equal to $\gamma_0 \rho_0$.

Given these assumptions and an ambient density, a p-v curve can be constructed. Table 1 summarizes the values for the parameters used to represent the volumetric response of granite.

Table 1. Volumetric Response Parameters for Granite.

A (Km/s)	B	C (s/Km)	ρ_0 (gm/cc)	γ_0
4.18	.05	30.	2.64	0.33

The deviatoric model is formulated with a constant shear modulus and yield strength which is a function of mean normal stress and possibly damage. A linear yield surface was chosen to represent the granite. In this model the virgin yield strength, Y_u , is given by the following function of mean stress, P ,

$$Y_u = Y_{uc} + Y_m P , \quad P \leq P_m , \quad (2a)$$

$$Y_u = Y_{uc} + Y_m P_m , \quad P \geq P_m , \quad (2b)$$

The parameter values used for granite are given in Table 2.

Table 2. Virgin Deviatoric Model Parameters for Granite.

Y_{uc} (MPa)	Y_m	P_m (MPa)	G (GPa)
500	2.0	600	13.1

A damage model was chosen for this granite in order to match the positive durations and decay from the the peak seen in the tamped experiment. This model is keyed on volumetric compression. A damage parameter, D , is defined by

$$D = \frac{v - v_1}{v_2 - v_1} , \quad (3)$$

where material compressed to volumes less than v_1 is completely damaged and material with volumes greater than v_2 is undamaged. The damaged yield strength, Y_d is taken to be linear in mean stress P and is given by

$$Y_d = Y_0 + mP \quad P \leq P_m , \quad (4a)$$

$$Y_d = Y_0 + mP_m \quad P \geq P_m , \quad (4b)$$

where P_m is the maximum pressure and m the slope. The pressure for damaged material is given by a linear interpolation between the damaged and undamaged surfaces with D as the interpolation parameter, i.e.,

$$Y = (1 - D) Y_u + D Y_d . \quad (5)$$

The damaged yield strength parameters are summarized in Table 3.

Table 3. Damaged Yield Strength Parameters for Granite.

v_1 (cc/gm)	v_2 (cc/gm)	Y_0 (MPa)	m	P_m (GPa)
.3735	.3759	250.	2	1.0

A comparison of the uniaxial strain response of this new model with the original model that was based on static data is shown in Figure 3. The deviatoric response is shown in the top figure and the volumetric response below it. Volumetrically, the new model, represented by a solid line, is stiffer and more linear than the original one over the range shown. This stiffer response was chosen to bring the arrival time into closer agreement with experiment. The shear modulus of the new model is about a factor of two less than the old one. This was done to improve the agreement of peak velocity. The failure envelopes of the two models are similar. Given the low shear modulus of the new model, however, it did not yield during this test.

Comparison of the results of a calculation using the new model with the data from a tamped experiment is shown in Figures 4 and 5. The model is in excellent agreement out to a range of 5 cm, or a peak velocity of 15 m/s. Beyond that range the computed peaks are 10-30% high, but arrival times and duration are in good agreement.

No air void content was included in the model. The granite has about 0.8% air void content, and this amount could account for the difference in velocity attenuation. The current model response was considered sufficiently accurate for the purposes of the subsequent computations, and no further changes were made.

Figure 3. Comparison of final granite model (solid line) with the model based on static data (dashed).

Figure 4. Comparison of measured (dashed) and computed (solid) velocity histories for the tamped granite case.

Figure 5. Comparison of measured (dashed) and computed (solid) velocity histories for the tamped granite case.

Less data was available for the response of the rubble material. SRII⁽⁴⁾ measured compaction up to a stress of about 2.0 Kbar for unconsolidated rubble. A model for consolidated rubble based loosely on this data was constructed. Large and small chimney prediction calculations were then run using this model⁽⁵⁾.

The agreement between these calculations and experiment was not good. The measured wave speed through the chimney was much slower than expected, and the attenuation rate was faster. A series of 1-D simulations of the small chimney experiment were run to derive a more representative chimney material model. The final chimney model was also validated with data from the spherical chimney experiment.

The volumetric response of the rubble was represented using a P- α model. This model consists of a solid base curve and a crush response. The crush response determines the way in which the air void content is irreversibly compacted. A Tillotsen model was used for the solid response.

In the Tillotsen model, pressure is a function of energy, e , initial volume, v_0 , and specific volume, v . The major contribution to the pressure is given by,

$$P = A\mu + B\mu^2, \quad (6)$$

with μ given by,

$$\mu = \frac{v_0}{v} - 1. \quad (7)$$

The crush curve is parameterized by the total compaction, c , the crush pressure, P_c , the elastic pressure, P_e and initial modulus, K_0 . In addition to these parameters, a series of points are used to determine the compaction as a function of pressure. The values for the parameters used to describe the rubble's volumetric response are given in Table 4.

Table 4. Volumetric Response Parameters for Rubble.

A (GPa)	B (GPa)	v_0 (gm/cc)	c	P_c (MPa)	P_e (MPa)	K_0 (MPa)
1.2	0.0	0.3788	0.1	500.	40.	350.

The virgin deviatoric response for rubble was parameterized the same way as granite was. No damaged yield surface, however, was constructed. The shear modulus and yield surface parameters are given in Table 5.

Table 5. Deviatoric Model Parameters for Rubble.

Y_{uc} (MPa)	Y_m	P_m (GPa)	G (GPa)
10.0	1.33	1.0	1.0

Plots of the volumetric and deviatoric response of the final chimney model are shown in Figure 6. The new model was softened in order to match the measured wave speed. The air void content was assumed to be 10%. It was assumed that the yield strength at low pressures is much less than granite and that it gains strength with pressure more slowly.

Comparison of 1-D calculations using this model with the small cylindrical chimney data is shown in Figures 7 and 8. The agreement is excellent at 2.0 cm and gets worse with increasing range. The disagreement is caused in part by the granite equation of state. As pointed out above, the granite EOS begins to deviate from the measured response at peak velocities in the 15 m/s range.

The computed duration of outward motion is shorter than measured at all ranges. In the tamped case, a damaged yield surface was introduced to obtain the measured positive phase duration. In the chimney situation, the granite is never subjected to stresses high enough to damage it, so the broad pulses seen experimentally must be caused by some other feature of the granite or rubble response.

Two-dimensional effects do contribute to the wave broadening at the farther ranges, but they are not sufficient to account for the differences shown in Figures 7 and 8. This was demonstrated in a spherical chimney experiment that was performed by SRII. The cylindrical chimney case had a slightly broader positive phase than the spherical case, but it was not as large as the differences shown in these figures.

A one-dimensional simulation of the large chimney experiment was also run in order to validate the granite and rubble equations of state in a lower stress regime. Comparison of the computed and measured velocity histories are shown in Figures 9 and 10. Peak velocities and arrival time are in good agreement, but the rises are different. The computed pulse has a two wave structure, whereas the measured pulse has just a smooth and gentle rise. As in the small chimney case, the computed duration of the positive phase is shorter than measured.

The two wave structure is caused by the shape of the deviatoric response of the rubble at low stress. The fact that the computed peak velocities stayed close to the measured ones out to 9.5 cm is evidence that the granite model is relatively accurate in this low stress regime.

Comparison of calculations for the the tamped, small and large chimney situations with experiment pointed out the strengths and weaknesses of the

Figure 6. Volumetric and deviatoric model response of the chimney material.

Figure 7. Comparison of measured (dashed) and computed (solid) velocity histories for the small chimney case.

Figure 8. Comparison of measured (dashed) and computed (solid) velocity histories for the small chimney case.

Figure 9. Comparison of 1-D large chimney computation (solid) with the data (dashed).

granite model. Roughly speaking, there are three regimes in the granite response. The high stress regime, characterized by stresses above 200 MPa or particle velocities above 15 m/s, an intermediate regime with stresses between 200 and 70 MPa or peak particle velocities between 15 and 5 m/s, and the low stress regime below 70 MPa. The small chimney experiment probed the second and third regimes and the large chimney experiment just the third one. The granite model works best in the high pressure regime and is relatively good at the lowest stress levels. It is worst in the intermediate regime where the attenuation of the signal was less than measured, and the pulse width was too narrow.

Figure 10. Comparison of 1-D large chimney computation (solid) with the data (dashed).

These deficiencies were not as evident in the tamped experiment as in the chimney experiments. The damaged yield strength model which is activated at ranges close to the detonation point by the strong shock, broadened the pulse width at the farthest ranges in the tamped calculation. The comparison of data with calculation in the tamped case, therefore, only pointed out a problem in the attenuation rate beyond 5 cm.

This too low attenuation rate was also seen in the small chimney case. In the large chimney case, however, the computed and measured attenuation of peak velocity were in good agreement. We conclude that some hysteresis in the volumetric response for granite is needed to produce the attenuation rate measured in the tamped

and small chimney experiments. The results of the large chimney experiment imply that most of this hysteresis should be in the intermediate stress regime.

In the chimney situations, where the granite was not subjected to strong shock loading, the damage model could produce no broadening, and therefore, the resulting computed pulses were too narrow. Thus, this type of shock damaged response is not the source of the broad pulses seen in the experiments. We did not succeed in finding a model that reproduced this aspect of the measured response.

These experiments inherently shed less light on the rubble behavior since no velocity histories were measured in the chimney. A slight modification of the low stress behavior of rubble would be required to eliminate the precursor produced by the calculation.

The overall agreement between the computed and measured response was judged to be good enough to proceed without further modification to the material models. Since the primary goal of the calculations is to provide insight into the two-dimensional nature of the flow, 20-30% agreement between computation and data was considered sufficient.

SECTION 3

CHIMNEY SIMULATIONS

This section discusses the 2-D simulations of large and small chimney experiments. The strategy used to model the experiments is described first. This is followed by a general discussion of the flow in each of the chimney cases. Next the data are compared to results from the computations for the chimney experiments. The section ends with a summary and conclusions.

The granite response makes it difficult to run two-dimensional simulations of the chimney cases. The problem is caused by the sharp rise time of the granite shock. In order to accurately capture the rise and the peak, very fine cells are required. So many zones are needed, that a full 2-D grid would have too many cells to run efficiently. Several 1-D calculations were run to develop a zoning scheme that would not introduce too much error, and that could be run at an acceptable cost. The bulk of these studies involved the small chimney case. It is the most difficult case because the chimney spreads the pulse, and the smaller the chimney the less spreading. The final grid was a compromise that had more cells than was desirable, but still introduced more error in the stress and velocity fields than would have been ideal. Comparisons with 1-D simulations for a spherical chimney case make it possible to quantify this error.

A plot of the best grid for the small chimney calculation is shown in Figure 11. The interface between the granite and the chimney is marked by a heavy line. Only one-half of the experiment is modelled, with the mid-plane taken to be a plane of symmetry in the calculation. This reduced the number of cells required by a factor of two. As the shock propagates through the chimney it is attenuated rapidly (compared to granite) and is spread out, requiring less resolution. We, therefore, chose to allow the cells to increase more rapidly in the y direction, i.e., along the axis of the chimney, than along the x axis. Even with these choices, the mesh contained more than 10,000 cells and covered only the first 7 cm of the granite cylinder.

A two dimensional STAR computation of a spherical chimney using the above grid was run to 20 μ s. The grid was identical to the cylindrical chimney case, just the distribution of materials in the mesh was changed. Chimney material was used to fill an approximately spherical region whose radius equalled the radius of the cylindrical chimney. This run served two purposes. The first was to verify that STAR behaves the same way the 1-D code does for similar zoning. The second was to provide a basis of comparison with the 2-D cylindrical chimney simulation in order to extract the size of 2-D effects. A 1-D run is not sufficient for this purpose because the zoning varies as a function of angle relative to the x axis in the 2-D mesh.

Figure 11. Grid used for 2-D simulations of small chimney calculations. Material interfaces are marked by the heavy lines.

Line plots of the radial stress and velocity components versus range along the x and y axis for the 2-D calculation are compared with 1-D simulations in Figure 12. These are snapshots at a particular time with the 1-D results shown as solid lines. Two 1-D simulations are considered, a fine zoned and a coarse zoned one. The coarsely zoned one was chosen to match the overall zone sizes of the 2-D run. The coarse 1-D run matches the 2-D quite well, however, the coarse zoning spreads and drops the peak by about 20% relative to the finely zoned computation. This was considered the maximum tolerable error.

To maximize resolution at the shock front, the chimney simulation was divided into a number of steps. The first step was run in 1-D and consisted of the initial phase of the shock running out in the chimney to the nearest interface. The explosive detonation can be modelled most accurately this way. This solution was then overlaid into the 2-D mesh and run further in time. Several meshes were used in the course of the 2-D simulation. As the shock neared the edge of one mesh, the solution was overlaid into the larger grid. The number of cells in each grid was limited to approximately 10,000, and the resolution was concentrated at the shock front. The larger meshes, therefore, had coarser zoning behind the shock front. Three overlays were required to complete the small chimney simulation, while the large chimney required two overlays. The sizes of the chimney and granite block, as well as the overlay times for all the 2-D computations, are summarized in Tables 6 and 7. These dimensions are close, but not identical to the actual experimental configuration.

Table 6. Size of grid and chimney used in chimney calculations.

Final Dimensions (cm)	Small Chimney	Large Chimney
Radius of Chimney	1.56	3.175
Radius of Granite	12.38	12.40
Radius of Water	14.00	14.40
Axis of Chimney	4.68	9.525
Axis of Granite	12.38	12.40
Axis of Water	14.8	14.80

The nature of the flow in both chimney cases is determined by the wave speeds in the granite and chimney, as well as the attenuation rate characteristic of these two media. The difference in wave speed for these two materials is so large that a very complex flow field is generated.

Figure 12. Comparison of radial velocity and stress components for 1-D (solid) and 2-D along the x (short dashed) and y (long dashed) axis. These are snapshots taken at 20 μ s.

Table 7. Calculational procedure used in chimney calculations.

	Overlay time μ -seconds	Purpose
Small Chimney	7.5	Overlay from 1-D Calculation Radius of Granite = 7 cm Axis of Granite = 7 cm
	20.0	Expand Grid Radius of Granite = 10 cm Axis of Granite = 10 cm
	25.0	Expand Grid Radius of granite = 12.38 cm Axis of Granite = 12.38 cm Radius of Water added = 14.00 cm Axis of Water added = 14.80 cm
Large Chimney	17.5	Overlay from 1-D Calculation Radius of granite = 12.4 cm Axis of granite = 12.4 cm
	35.0	Expand Grid Radius Water added = 14.40 cm Axis of Water added = 14.80 cm

The outward phase of flow can be divided into two stages. In the first stage the shock propagates out in the chimney and hits the rubble granite interface at the mid-plane. This generates a shock in the granite and a reflected compression wave in the chimney. In the second phase two shocks are propagating through the medium, a fast one in the granite and a slow one in the chimney. As the shock in the granite runs out ahead of the one in the chimney, the granite releases into the chimney and its stress drops more quickly than it would have in the absence of the chimney. Then the chimney shock arrives. If the chimney signal is large enough, it will drive a second shock into the relieved granite. The flow associated with this second shock will not be radially outward, but will be dictated by the state of stress in the granite at the time of its arrival. These two phases can be seen clearly in the pressure contour plots for the small chimney calculation shown in Figures 13-16.

The shock has just arrived at the interface at 15 μ s, Figure 13. The compressive reflection can be seen just inside the rubble on the mid-plane at $x = 1.45$ cm. The shock is out 1.7 cm in the chimney.

Figure 13. Pressure contour plot at 15 μ s for the small chimney calculation.

Figure 14. Pressure contour plot at 20 μ s for the small chimney calculation.

Figure 15. Pressure contour plot at 25 μ s for the small chimney calculation.

Figure 16. Pressure contour plot at 30 μ s for the small chimney calculation.

By 20 μ s, Figure 14, the shock in the granite is out 5 cm, while the one in the chimney is only out to a radius of 2.1 cm. The compressive reflection has moved in to 1.1 cm along the mid-plane. Note the low at the chimney boundary in the granite at $y = -2$ cm, where the granite is releasing into the chimney just ahead of the chimney shock. There is also a small high pressure region visible at $y = -1.4$ cm along the chimney granite interface where the chimney shock hits the granite.

The relief wave has moved down to $y = -3$ cm by 25 μ s, shown in Figure 15. The granite shock has moved out to 7.25 cm, while the chimney shock is back at $y = -2$ cm. Note how the peak pressure contour in the granite extends to just above the 45° line, rather than being completely circular. The presence of the chimney material drops the stress for larger angles.

The peak pressure finally does achieve a nearly circular shape at 30 μ s, shown in Figure 16, when the shock has reached 10 cm in the granite. The granite relief wave has continued down the interface another 2 cm. The peak stress at this time is between 10 and 15 MPa. In the fully tamped case, the peak stress at the 10 cm range is 75 MPa, a factor of 5 higher.

The velocity vectors plot given in Figure 17, at 25 μ s, shows the effects of these different shocks on the flow. The chimney material has been blanked out to make it easy to show the details of the flow in the granite. The granite at the mid-plane is rebounding into the chimney, while the chimney shock in the $y = -2$ to -2.5 cm location is forcing material out and up toward the mid-plane.

This same type of development can be seen even more dramatically in the large chimney calculation. The larger chimney allows more separation between the chimney and granite shocks. Pressure contour plots illustrating the state of stress in the chimney and granite at five times are shown in Figures 18-22.

The shock hits the granite rubble interface at around 20 μ s. Since the granite shock travels at roughly 5 Km/s, it will have moved out of the granite along the mid-plane about 16 μ s later, or at a time of 36 μ s. The first contour plot shown in Figure 18 is a snapshot taken at 45 μ s. No granite shock is readily visible at this time. The chimney shock, though, is out only to a radius of 4.5 cm. A small region of high pressure is visible near where this shock would hit the material boundary. A low pressure region is also visible at about $y = -5$ cm on the interface.

The high and the low pressure associated with the granite relief ahead of the chimney shock are much more apparent at 55 μ s shown in Figure 19. At this time the chimney shock is at 5 cm, and at $y = -4.25$ cm there is a high pressure area on the material boundary. The low associated with granite relief ahead of the rubble shock can be seen at $y = -6.5$ cm.

Figure 17. Velocity vector plot at 25 μ s for the small chimney calculation.

Figure 18. Pressure contour plot at 45 μ s for the large chimney calculation.

Figure 19. Pressure contour plot at 55 μ s for the large chimney calculation.

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Figure 21. Pressure contour plot at 70 μ s for the large chimney calculation.

Figure 22. Pressure contour plot at 80 μ s for the large chimney calculation.

These two extremes continue to propagate down the interface as shown in subsequent contour plots. By 80 μ s, shown in Figure 22, the chimney shock is barely visible. The shock in the granite has run down and around the underside of the chimney and has begun to load the chimney from below.

The chimney shock slows down as the stress level drops. In a 1-D calculation containing only chimney material, the shock reaches a range of 7.5 cm at 90 μ s. The peak stress is just 9 MPa. The overburden is 7 MPa, so a live stress of just 2 MPa is being propagated at that range.

Velocity vector plots at three interesting times are shown in Figures 23-25. At 45 μ s, shown in Figure 23, the up and out flow generated by the chimney shock is just beginning. By 55 μ s, shown in Figure 24, this flow is fully developed, and the granite above it is rebounding. In addition, a small region of the chimney ahead of the shock is completely inactive.

At 65 μ s, shown in Figure 25, a large inward moving flow develops at the chimney boundary near $y = -4.0$ cm. This flow is caused by the high at the material interface, seen in Figures 18 and 19. This high, generated by the stagnation of the chimney shock at the granite interface, persists until after the chimney shock moves forward. Eventually the stress drops in the chimney and the high in the granite drives material into the chimney.

Maximum pressure and speed contour plots for the small chimney calculation are shown in Figures 26 and 27, and for the large chimney case in Figures 28 and 29. The maximum pressure contours have a nearly circular shape with a center at the chimney granite interface on the mid-plane, $y = 0.0$. In the small chimney case the contours are pulled up near the chimney as expected. In the large chimney case the contour levels 5 and below are drawn down the chimney. This additional high pressure areas is the reflection of the high caused by the stagnation of the chimney shock in the granite at $y = -5.0$ cm discussed above.

The maximum speed plots have a different character. The contours in the small chimney case have a double lobe shape. The first lobe corresponds to the outgoing shock in the granite and is centered at the granite chimney interface. The second lobe is caused by late arriving chimney shock that drives material up and out toward the mid-plane. In the large chimney case, the two lobed structure is less pronounced. The initial granite shock quickly peters out, and the chimney shock drives material out as it runs down the length of the chimney. This produces the elongated contours shown in Figure 28.

Figure 23. Velocity vector plot at 45 μ s for the large chimney calculation.

Figure 24. Velocity vector plot at 55 μ s for the large chimney calculation.

Figure 25. Velocity vector plot at 65 μ s for the large chimney calculation.

Figure 26. Peak pressure contour plot at 50 μ s for the small chimney calculation.

Figure 27. Peak speed contour plot at 50 μ s for the small chimney calculation.

Figure 28. Peak pressure contour plot at 90 μ s for the large chimney calculation.

Figure 29. Peak speed contour plot at 90 μ s for the large chimney calculation.

The flow near the mid-plane is closest to what would be generated by a spherically symmetric solution. Comparison of computed velocity histories from two 2-D simulations are shown in Figures 30 and 31. The solid line represents the results from a spherical chimney and the dashed from the small cylindrical chimney. The calculations used identical zoning so the differences are caused by the asymmetry of the cylindrical chimney. Three differences are apparent from these comparisons. In the cylindrical calculation, the peaks attenuate more rapidly, and the positive and negative phase of the velocity lasts longer.

The rapid attenuation of peak velocity seen in the cylindrical chimney case is caused by a relief wave moving out from the chimney. As discussed above and shown in Figure 16, the source of the granite shock is at the interface between chimney and granite and on the mid-plane. As long as the chimney shock is in that vicinity, energy is transmitted out into the granite. As the chimney shock propagates down the chimney, the stress drops and the granite can relieve into the chimney. The relief wave can catch the shock since it is propagating at a wave speed compatible with the compressed material. The data from the spherical and cylindrical chimney experiments, however, do not show a difference in the attenuation rate of peak velocity.⁽³⁾

The longer duration of the outward motion is caused by the arrival of the upward directed flow generated by the chimney shock. This was shown in Figure 17. The arrival of this pulse is signalled by a shoulder on the velocity history and is seen clearly at all time histories beyond 3.5 cm. The time of arrival of this shoulder increases as the range increases. The longer rebound phase is also not surprising. The elongated chimney presents less resistance to the inward moving granite.

Comparison of the cylindrical chimney velocity data with the 2-D simulation is shown in Figures 32 and 33. The data is higher and attenuates more slowly than the computation. Both the data and calculation show a shoulder in the velocity history. This shoulder is much less pronounced in the data and leads to a shorter duration for the positive velocity phase. The computed and measured minimum velocity and shape of the rebound phase beyond the minimum are quite similar.

As was seen in the discussion of the flow for the large chimney, many features were similar to the small chimney case. The difference between a cylindrical and spherical large chimney is also qualitatively similar to the small chimney case. A 2-D large spherical chimney calculation was not run. Instead the comparison is made to a 1-D simulation of a large chimney. This comparison is shown in Figures 34 and 35. The 1-D simulation is represented by a dashed line and the 2-D by a solid one.

Figure 30. Comparison of computed 2-D small spherical chimney velocity histories (solid line) with computed 2-D cylindrical chimney results (dashed line).

Figure 31. Comparison of computed 2-D small spherical chimney velocity histories (solid line) with computed 2-D cylindrical chimney results (dashed line).

Figure 32. Comparison of computed 2-D small cylindrical chimney velocity histories (solid line) with measured results (dashed line).

Figure 33. Comparison of computed 2-D small cylindrical chimney velocity histories (solid line) with measured results (dashed line).

Figure 34. Comparison of computed 1-D large spherical chimney velocity histories (solid line) with computed 2-D cylindrical chimney results (dashed line).

Figure 35. Comparison of computed 1-D large spherical chimney velocity histories (solid line) with computed 2-D cylindrical chimney results (dashed line).

Large zones in the 2-D simulation spread the pulse relative to the 1-D case. The lack of resolution also produces lower peaks. Overall though, the peak velocity attenuation rate is similar, in contrast to the small chimney case. The strong upward and outward flow begins later in the large chimney case and hence is not visible in the velocity histories on the mid-plane until the 8.0 cm range. Beyond this range, the duration positive phase is longer in the cylindrical chimney situation.

Comparisons of the measured and computed velocity histories for the large chimney case are shown in Figures 36 and 37. The data traces were truncated when the reflected signal arrived. The computational record ends at 90 μ s when the calculation was stopped. The reflections from the water and steel interfaces is quite weak in the calculation and no attempt was made to find them. The agreement in peak velocity is quite good. The differences between simulation and experiment is similar to what was seen in Section 2, in the comparison of 1-D results and experiment.

The computed pulse at the 8.0 and 9.0 cm range stations is broader than measured. The broadening is caused by the wave generated by chimney shock just as in the small chimney case. The computed broadening is stronger than measured in the large chimney, just as it was for the small one.

Comparison of computed and measured water pressure histories for the small and large chimney cases are shown in Figure 38. The gauges were located along the axis in the center of the water layer.

Figure 36. Comparison of computed 2-D large cylindrical chimney velocity histories (solid line) with measured results (dashed line).

Figure 37. Comparison of computed 2-D large cylindrical chimney velocity histories (solid line) with measured results (dashed line).

The arrival time of the computed pulse is too early in the large chimney case, but its amplitude is fairly close. This is a reflection of the agreement in peak velocity seen in the large chimney computations. A shoulder develops in both the data and the computation after the peak in the pressure arrives. The computed shoulder is more pronounced than the one in the data, just as it was in the velocity comparisons.

For the small chimney, the arrival time is in good agreement, but the peak is down by about a factor of two. This is consistent with the velocity comparisons, where the computational peak velocity dropped more rapidly than the data.

The calculations generally are in good agreement with data. We feel confident that the simulations are capturing the important aspects of the flow. The calculations for both chimney geometries overestimate the strength of the wave produced by the chimney shock as it moves down through the rubble. Slight changes to the wave speed or attenuation rate of the chimney material would have a major impact on this.

The peak velocity attenuation of the cylindrical small chimney calculation is more of a mystery. This is especially true in light of the large cylindrical chimney results which showed the same attenuation rate as the spherical case. One possible explanation is that, since the stress levels are much higher in the small chimney case, the wave speed of the release wave can be noticeably higher than the shock speed. At low stresses, such as those seen in the large chimney, the two speeds are closer together and the relief wave cannot catch up.

The main purpose of these calculations was to examine how effective the chimney is in disguising the true yield of the explosive. Two different approaches were taken to address this issue. One approach examined how the chimney affected energy transmission into the far-field. The second approach looked at the Fourier transforms of the velocity time histories to see how their spectrum is changed by the presence of a chimney.

Since far-field detectors are ultimately sensitive to the energy transported to them, the energy transport in the 2-D calculation was examined. A boundary location was chosen, and the energy inside was summed up. The total energy in the grid is also kept, so by subtraction the energy outside the boundary can be deduced. This energy edit is performed at several times during the run. Since the material never comes to rest during the computation, energy is constantly

Figure 38. Comparison of computed (solid line) water pressure history at the mid-plane with the data (dashed line).

moving back and forth through the grid. At late times, however, it is possible to make estimates of the ultimate energy transmitted beyond a certain radius to within 10-20%.

Energy transport for the tamped, small and large chimney calculations is summarized in Tables 8 - 10. Since only half the problem is modelled in 2-D, the energy balance is done for half the explosive yield. The times at which the balance is performed is given in the first column. The times for each computation, each chosen so that the shock was well outside the boundary of interest, is different for physical situation. The energy contained in the chimney material is included in Tables 9 and 10 for reference. This does not include the energy remaining in the explosive.

The total energy in the grid is also given and is different in the two 2-D computations. The process of overlaying the 1-D solution into 2-D is the source of this difference. In the 1-D calculation, the explosive is part of the mesh and is contained in a number of cells. In 2-D the explosive is replaced by a cavity and a pressure boundary condition computed using the appropriate JWL EOS for the explosive. Appropriate average density and energy for the cavity must, therefore, be deduced from the 1-D results. The average is done so that the cavity pressure in 2-D is as close as possible to the pressure at the explosive-material interface in 1-D. This leads to changes in the cavity energy, and thereby to the total energy. Half the total yield of the PETN is 1.0×10^{10} ergs. In the small chimney calculation, the energy was 2% high, and for the large chimney run 6% low.

In the tamped case, given in Table 6 and taken from a 1-D computation, roughly 3.5×10^8 ergs out of 1.0×10^{10} ergs is transported beyond 6 cm. Of the 3.5×10^8 , 2.5×10^8 ergs is transmitted beyond 10 cm. Comparing the energy transported beyond 6 cm, roughly seven times more energy is transmitted in the tamped case than in the small chimney case. Ten times more energy is transmitted in the tamped case than in the large chimney case. In the case of the 10 cm boundary, the tamped case transmits 10 times more energy than the small chimney case and 20 times more than the large chimney case. Clearly the chimneys lead to a marked reduction in energy transmitted to the far-field.

The chimney also acts to spread the wave form as can be seen in the velocity time histories shown in Figures 34 and 35. One way to quantify the effect of the chimney on the wave shape is to compare the Fourier transform of the velocity histories. Ratios of the Fourier transform of the small and large chimney mid-plane velocity to the tamped case were constructed. These ratios are shown in Figures 39 and 40. Values greater than 1 imply that the chimney velocity has a higher strength at that frequency than the tamped case.

The small chimney ratio, shown in Figure 39, is the ratio of the 3.0 cm range velocities. The computation is represented by the solid line and the data by a dashed one. Both show that the small chimney signal is richer at low

Table 8. Energy transmitted beyond 6 and 10 cm radius in fully tamped case.

Time μ -seconds	ENERGY 1e8 ergs	Fully Tamped > 6 cm	Fully Tamped >10 cm
15	Internal	2.1	
	Kinetic	1.4	
	Total	3.5	
22	Internal	2.4	1.5
	Kinetic	1.4	1.0
	Total	3.8	2.5

Table 9. Energy transmitted beyond 6 and 10 cm radius, and contained within the chimney for the small chimney case.

Time μ -sec	ENERGY 1e8 ergs	Small Chimney Total energy = 1.02e10 ergs		
		Chim	> 6 cm	> 10 cm
45	Internal	57.6	.268	.224
	Kinetic	.395	.161	.042
	Total	58.0	.429	.266
50	Internal	57.8	.264	.183
	Kinetic	.322	.198	.078
	Total	58.12	.462	.261
60	Internal	57.3	.394	.183
	Kinetic	.370	.245	.176
	Total	57.67	.639	.359

Table 10. Energy transmitted beyond 6 and 10 cm radius, and contained within the chimney for the large chimney case.

Time μ -sec	ENERGY 1e8 ergs	Large Chimney Total energy = 9.43e9 ergs		
		Chim	> 6 cm	>10 cm
70	Internal	52.7	.414	.281
	Kinetic	.304	.111	.045
	Total	53.0	.525	.326
80	Internal	52.9	.328	.185
	Kinetic	.301	.168	.082
	Total	53.2	.496	.267
90	Internal	53.0	.227	.020
	Kinetic	.504	.188	.086
	Total	53.5	.415	.106

Comparison of Measured and Computed Ratio of Velocity Transforms
Range = 3.0 cm

Figure 39. Ratio of Fourier transform of small cylindrical chimney velocity at 3.0 cm range to the tamped case. Comparison of computed (solid) and measured (dashed) results.

Figure 40. Ratio of Fourier transform of computed large cylindrical chimney velocity at 3.0 cm range to the computed tamped case.

frequencies and weaker at the high frequencies as is expected. The computed trace drops more rapidly with frequency than the data, but is in reasonable overall agreement.

The large chimney result is shown in Figure 40. The 4.0 cm velocity histories were used to construct this ratio. No data was available. Again the peak is shifted to low frequencies, even lower than the small chimney case. Again this is expected from looking at the velocity histories since the duration of the large chimney pulse is much longer than the tamped case at the same range.

In conclusion, the 2-D simulations of the large and small chimney experiments agreed fairly well with the data. The area of worst agreement was in calculation of the small cylindrical chimney. The computed velocity attenuation did not reproduce the measured results. We believe that this, as well as the other deficiencies, are caused in part by the inadequacy of the rubble model at low stress.

This degree of agreement was sufficient to lend confidence to the simulations. The simulations showed that the presence of a chimney leads to a very complex flow field. About a factor of ten less energy was transmitted to the far-field in the presence of the chimney compared to the fully tamped case. The chimney also spreads the pulse in time, and this leads to a modification of the Fourier spectrum of the velocity pulse. The chimney signals have much more weight in the low end of the spectrum and less in the high end than the tamped case.

Comparisons of the measured and computed results for three cases: tamped, small and large chimney, seem to imply that the granite has some hysteresis in the 75 to 25 MPa pressure range that is not included in the model. Such hysteresis could be included using a $P-\alpha$ model, and there is physical property data to support an air void content of roughly 0.8%. In the absence of any data regarding the shape of loading curve, it was decided that the difference between experiment and calculation was not large enough to justify further tuning of this aspect of the granite response.

The chimney rubble presents a more difficult problem. All the data were taken in the granite and, therefore, provide only an indirect test of the rubble model. Based on the small chimney results, it appears as if the chimney shock drives the granite more strongly than measured. A rubble model with a slower wave speed and more attenuation would correct this problem.

The large chimney case also pointed out problems with the low pressure rubble model. The computed velocity histories have a two peaked structure while the data show only a very gentle rise to a single peak. Peak arrival times and velocities, however, were in good agreement. The differences imply that the slope of the $P-v$ curve, or the yield strength, at low pressures is different than modelled.

SECTION 5

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