30/4-7-86 JES (1)

I - 25659

DA # 1641-1

(12)

UCID--20667

DE86 008789

RESEARCH ON GAS TRANSPORT IN CHIMNEYS
A Progress Report

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March 18, 1986

Lawrence
Livermore
National
Laboratory

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Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

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RESEARCH ON GAS TRANSPORT IN CHIMNEYS-- A Progress Report

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ABSTRACT

The results of the AGRINI and TIERRA experiments have led us to study three general topics: collapse phenomenology, CO_2 content measurement, and gas transport in chimneys. Our results so far are fragmentary, but we have been able to come to some tentative conclusions: 1) A layer of strong material between depths of 24 and 32 m, and perhaps some relatively strong material deeper, may have caused the AGRINI crater shape. This layer was absent at the nearby LABAN and CROWDIE events. We were unable to locate the layer with a surface penetrometer or surface seismic methods, but it may be possible to measure strength vs depth in situ by examining the penetration depth of a projectile. 2) We can probably improve our knowledge of the in situ CO_2 content by calibrating a commercial carbon/oxygen logging system for MTS conditions. 3) It is possible to measure the response of the gas in a chimney to changes in atmospheric pressure. There can be significantly different gas transport in chimneys with the same pressure response, depending on the porosity and the distribution of the porosity. It is possible to perform an inexpensive experiment to study the gas transport in an existing chimney.

INTRODUCTION

AGRINI was a low-yield event detonated at a depth of 320 m in hole U2ev on March 31, 1984. A very deep (approx 70-m), narrow, bottle-shaped crater was formed about 1.75 h after detonation (Hudson et al; 1985). Figure 1 shows a schematic of the crater.

Radioactive gas was detected by a gas-sampling system immediately after collapse (Smith, 1985). The bottom of the sampling hose is thought to have been at a depth of between 170 and 220 m. Prompt sampling hoses have usually broken fairly high in the hole upon collapse. Gas is ordinarily

pumped from these hoses after subsidence, but a significant amount of radioactivity has rarely been observed in the gas. It has never before been observed as soon after collapse and as high in the chimney as it was at AGRINI. The gas was 73% CO₂, 7% hydrogen, and 20% air, at a pressure of 12.2 psia. The uncertainty in pressure is thought to be about 1 psia. Analyses indicate that the gas was not in communication with the cavity throughout the 20-day sampling time.

About 9 h after detonation, unexpected radioactivity was detected at the surface, apparently coming from the crater. During the following 26 h, about 1700 Ci (predominantly isotopes of xenon) were determined to be released (Oswald, 1984). There is considerable uncertainty in these times. Atmospheric pressure at the surface was comparable to that observed downhole. In fact, surface pressure (Fig. 2, Soule, 1984) was greater than (but within the uncertainty of) reported subsurface pressure. Consequently, there is no evidence that high gas pressure drove the activity to the surface.

Hudson et al. (1985) have shown that the emplacement hole and its stemming did not contribute to the release. Radiation levels above the deep soft plug at 225 m remained at background through the termination of recording at collapse. In addition, there was no negative pressure that would indicate loss of stemming before collapse. Therefore, we may conclude that if we are to seek an explanation of the release, we must look somewhere other than the emplacement hole.

Besides the release, there are two obvious differences between the AGRINI observations and those on "normal," satisfactorily contained events. Never before has there been such a deep collapse crater. And never before has radioactive gas been observed so high in the chimney so soon after collapse.

Since gas was observed with a hose whose opening was at a depth between 170 and 220 m, and the crater was almost 70 m deep, the gas had to travel a maximum of 100 to 150 m to escape. It seems logical to look to this combination of circumstances for an explanation of the AGRINI release. It is unlikely that we will ever be able to predict a similar situation, but by

Investigating the individual elements of the combination, we may be able to understand the transport of gas through a chimney.

So our investigation should center on three questions:

1. What caused the unique crater shape?
2. Why did the gas get as high as 170 m deep in the chimney so soon after collapse?
3. How did the gas get from about 170 m deep in the chimney to the surface?

These questions led us to study three general topics:

1. Collapse phenomenology:

There is evidence that some of the alluvium above AGRINI was unusually strong. We should study collapse phenomenology to learn whether this strong alluvium could have caused the unusual crater shape.

2. CO₂ content measurement:

The observed CO₂ content at AGRINI was within experience. We measure CO₂ content from cuttings, usually taken at ten foot intervals. There is good evidence that although each measurement may be quite accurate, the cuttings may not represent a good average of the CO₂ content of the medium. More representative measurements of CO₂ content might have shown that in fact the CO₂ at AGRINI was higher than reported, and therefore could have been a significant factor in transport of activity to the surface.

3. Gas transport in chimneys:

It is possible that the shallow gas in the AGRINI chimney was caused by unusual gas transport during collapse. We need to better understand gas transport during collapse. It is also quite possible that transport after collapse was more rapid than usual. The chimney rubble may have been more permeable than in ordinary Yucca Flat chimneys, or there may have been blocks of rubble, whose edges provided easier transport paths than usual. We need to investigate gas transport properties of chimneys.

In particular, we are studying the differences between AGRINI and two nearby "normal," successfully contained events with similar reported CO_2 content, yield, and scaled depth of burial: CROWDIE in U2fe, 450 m from U2ev, which had a fairly normal crater, 81 m in diameter and 13 m deep; and LABAN in U2ff, 3 km from U2ev, which had a steep-sided "cookie-cutter" crater, 42 m in diameter and 38 m deep. This should help us understand which characteristics of AGRINI were normal and which were anomalous. The remainder of this report will describe the studies we have started, and their results to date.

COLLAPSE PHENOMENOLOGY

Hudson et al. (1985) point out that the medium property most relevant to crater shape is probably shear strength. To determine the strength of the near-surface alluvium at AGRINI, a shallow exploratory hole, UE2ev, was drilled with an auger 113 m SW of U2ev, to a depth of 36 m. An examination of samples from the hole indicated a partially to well-indurated calcite-cemented sandy conglomerate zone extending from 24 to 32 m in depth.

A two-dimensional Lagrangian TENSOR calculation of AGRINI (Hudson et al. 1985) was carried out using the observed near-surface properties, and its results were compared with those of an identical calculation using "normal" near-surface alluvium properties. In the normal calculation, the shear strength of the alluvium between depths of 0 and 50 m was zero at zero mean stress and 0.52 MPa at 0.35 MPa mean stress, and increased to a maximum of 1.1 MPa. The tensile strength was zero. In the AGRINI calculation, two materials were used above 50 m. In the indurated zone between 24 and 32 m, shear strength increased from 0.5 MPa at zero mean stress to 11 MPa at 10 MPa mean stress, and then increased to a maximum of 34 MPa. Tensile strength was 0.36 MPa. In the rest of the region above 50 m, shear strength increased from zero at zero mean stress to 10 MPa at 10 MPa mean stress, and then to a maximum of 21 MPa. Tensile strength was zero in this region. Both sets of properties represent the lower bound of measured strength data.

In the normal calculation, there was shear failure to the surface during the outgoing wave, and tensile failure upon spall. In the AGRINI calculation, there was no shear failure above 50 m, the high-shear-strength

region, and no tensile failure between 32 and 50 m, the high-tensile-strength region. The calculated and measured free-surface velocities compared well. These results suggest that if the actual strengths are similar to those used in the calculation, then the near-surface material was strong enough to sustain little damage from the stress wave. Consequently, the AGRINI crater shape was at least partly due to the relatively high-strength, near-surface alluvium.

Since it appeared that the near-surface strong layer might be important to crater shape, we drilled similar exploratory holes near LABAN and CROWDIE (Wagoner, 1985). At LABAN (U2ff) there were rare beds of calcite-cemented sediment. At CROWDIE (U2fe) there were several thin zones of calcite-cemented sediment. There was no evidence of material with greater strength at the straight-sided LABAN crater site than at the normal CROWDIE crater site. In fact, if anything there was more calcite-cemented material at CROWDIE than at LABAN. Consequently we could not associate the presence or absence of cemented layers with crater shape at these sites.

Because the strong layer seems to be of considerable importance, it would be very useful to be able to locate such a layer from the surface before drilling an exploratory hole. Two methods for locating the layer were tried. Reflection seismology was attempted at AGRINI (Hauk, 1986). The shallow depth required very close station spacing, and consequently the surface wave was so strong that reflections from the strong layer could not be observed. Therefore the layer could not be located. It may, however, be possible to improve the technique with further attempts.

A truck-mounted penetrometer (Blouin and Noel, 1985) was tried at one site in Area 3 and eight sites in northern Yucca Flat. The force on the tip of the penetrometer cone and the force along the side of the cone are measured as functions of depth. A schematic of the tip is shown in Fig. 3. The penetrometer is forced into the ground by a steel rod until the truck, weighing about 18,000 kg, begins to lift off the ground, or until the rod buckles (not desirable). Plots of tip stress vs depth for several Yucca Flat sites are shown in Fig. 4. In Area 3 the penetrator was able to penetrate more than 28 m before the truck began to lift. There was only one northern Yucca Flat site, U2ff, at which the penetrator advanced more than

18 m before the truck began to lift. At several sites penetration was less than 10 m. At U2ev, maximum penetration was about 15 m, which is above the indurated layer. Furthermore, we were unable to find any characteristic differences between the U2ev site and other sites in Northern Yucca Flat at the shallow depths that could be studied.

The AGRINI calculation used a much thicker strong layer than that observed in the field, and Thigpen (1984) points out that a thick strong layer is required for an arch to form above a subsurface chimney. Consequently, it would be highly desirable to be able to measure shear strength, or even unconfined compressive strength, vs depth in place.

Two methods were tried for such a measurement. The first used of the force on the tip of the truck-mounted penetrator and was not successful (Hearst and McKinnis, 1985). The other used penetration of a projectile, and appears quite promising. Figure 5 shows depth of penetration of a flat-nosed 80-g projectile at a velocity of 530 m/s vs unconfined compressive strength in tuff. We are now developing a more sophisticated system for testing improved versions of this method at the surface; if the method continues to appear successful we will adapt it for downhole use.

Eventually it will be necessary to make a more complete calculational model of collapse phenomena. A beginning has been made. Thigpen and Rambo (1985) have used a finite-element method to show that creep is a possible mechanism for cavity collapse. This method may eventually lead to a more detailed understanding of collapse. We are also beginning work to simulate cavity and chimney collapse with a centrifuge; experiments will probably not take place before FY 87.

CARBON DIOXIDE CONTENT

Table 1 shows the weight fraction of CO_2 , obtained from three different sources, for the working point (WP) regions of our three events. The first column is CO_2 as given for the WP interval in the Site Characteristics Summary. For AGRINI this value was obtained from cuttings; for LABAN and CROWDIE it was obtained from sidewall samples. In all three cases, the average was a numerical average of all of the sample data in the

WP interval. The second column is the same average of a second set of samples: for AGRINI new splits of the cuttings, for LABAN and CROWDIE, samples from the cuttings. The third column comes from postshot gas analysis, assuming that the measured total mass of CO_2 was evolved from 1200 tonnes of rock per kiloton of yield.

The agreement between the first two columns is within their standard deviations, and so is satisfactory. But consider Fig. 6, a plot of CO_2 derived from both sidewall samples and cuttings from U2ff. The region used in Table 1 is indicated by arrows; there is good agreement between sidewall sample and cutting data in that region. Had the WP been 30 m higher, however, it would have been in a region of great disagreement between sidewall sample and cutting data. If we had been evaluating that region today, since we no longer take sidewall samples, we would have used the results from cuttings: 0.035 ± 0.18 . Had sidewall samples been used instead, the result would have been 0.06 ± 0.031 —an unacceptable value of CO_2 ! (Furthermore, in this region there are individual CO_2 values as high as 0.1.) Had the WP been another 15 m higher, the result from cuttings would have been 0.041 ± 0.012 , and that from sidewall samples would have been 0.011 ± 0.008 . In that case the old method would have indicated satisfactory CO_2 content, whereas the current method would have shown it to be marginal. Disagreements this large between averages of sidewall samples and cutting values of CO_2 are common at U2fe and U2ff.

The CO_2 values from gas sampling fall within the standard deviations of the sample data in two of the three events; the result is very different for LABAN. The choice of rock mass, 1200 tonnes per kiloton, represents an

Table 1. Measured weight fraction of CO_2

Event	CO_2 from Site. Char. Summ.	Second value of CO_2 from samples	CO_2 from gas sampling
AGRINI	0.025 ± 0.017	0.022 ± 0.014	0.023
LABAN	0.033 ± 0.007	0.040 ± 0.006	0.016
CROWDIE	0.004 ± 0.003	0.009 ± 0.008	0.007

average obtained from gas sampling on five recent events (Smith, 1986.) Had we used a different value, the event for which agreement was bad would have changed, but the fact of disagreement would not.

The combination of significant disagreement between individual CO_2 values at many horizons, as exemplified in Fig. 6, disagreement between average values, and disagreement between values from rock sampling and gas sampling leads us to believe that a more reliable, or more representative, measurement of CO_2 content is very desirable. Recent evidence (Axeirod, 1986) even questions the reliability of the laboratory CO_2 measurements on individual samples. We are working on two methods of measuring CO_2 content vs depth.

The carbon/oxygen log is a standard commercial method for measuring carbon in rock (Hearst and Nelson, 1985, p. 274.) It contains a neutron generator and a gamma-ray detector. Its primary output, the carbon/oxygen (C/O) ratio is the ratio of the gamma ray count rates in two windows, one bracketing the energy of gamma rays resulting from inelastic neutron scattering from carbon, the other the energy of gamma rays produced by inelastic neutron scattering from oxygen. Several corrections are applied to the count rates from each window before the C/O ratio is formed. As is usual with commercial logging equipment, the system available to us is designed for small-diameter water-filled holes, whereas we ordinarily use large-diameter air-filled holes.

We have begun a program to calibrate a commercial logging system for NTS situations. We have found that the C/O ratio is sensitive not only to the carbon content of the rock, but also to the water content and the gap between the instrument and the wall of the hole. Preliminary results indicate that both of these effects are fairly linear, and it is likely that we will be able to correct for them. Figure 7 shows a plot of the C/O ratio vs weight fraction CO_2 in a test facility with no gap and with a 6.3-cm gap. As the figure shows, if the gap is known, CO_2 can be measured to better than 0.02.

We are working with Los Alamos National Laboratory to make a detailed study of the effect of water content, gap, and the chemical composition of

the rock on the measured C/O ratio. We are also trying to decide on the best way to modify the equipment to minimize the effect of the gap, and to measure the gap so that we can make a good correction. We are in the process of building a new test facility, and it should be completed during FY 86.

For several years we have been working with a professor at the University of Washington to use infrared reflection spectroscopy to measure CO₂ content in samples on-line. This would permit us to obtain and measure the CO₂ content of many samples automatically in the field, and thus obtain more representative results. The project has not been proceeding rapidly, and the C/O log appears more promising; it is unlikely that we will continue the project beyond FY 86.

GAS TRANSPORT IN CHIMNEYS

Our interest in gas transport is caused not only by the results of AGRINI, but also by those of TIERRA and KAPELLI. In the case of the latter events, leaks occurred over long periods, several to many days after execution. We are considering several questions:

How is gas transported during collapse? How did it get so high in the AGRINI chimney so soon after collapse? How is gas transported after collapse? How do chimney properties affect transport? How do medium properties affect transport? How can we measure the relevant properties?

It is believed that the dominant method of gas transport during collapse is the displacement of gas by rubble. There is, however, no direct observation of this displacement, nor is there likely to be. We are planning small-scale laboratory experiments at S-CUBED to give us some qualitative understanding of the displacement phenomenon, but at present we have no results.

It appears that the AGRINI leak occurred during an episode of atmospheric low pressure (Hudson et al. 1985). Figure 2 shows the situation. The uncertainty in the subsurface pressure does not permit us to state whether the subsurface pressure was in fact greater than atmospheric

pressure. There is evidence (Raschke, 1985) that the TIERRA leak rate was correlated with low pressure. Consequently, we are studying the effect of changes in atmospheric pressure on the transmission of gas through chimneys.

In a homogeneous isotropic medium, the hydraulic diffusivity α can be determined by comparing the pressure history at the surface to that at some depth in the medium (Hanson, 1984, 1986), such that

$$\alpha = kP_s/\mu\phi, \quad dP/dt = \alpha (\partial^2 P/\partial z^2),$$

where α is the diffusivity, P_s is the mean pressure, k is the permeability, μ is the viscosity of the gas, and ϕ is the medium porosity. Figure 8 (Nilson and Peterson, 1986) shows the effect for an idealized case.

The postshot gas sampling hole has been used as a source of the subsurface pressure measurements for several NTS chimneys. Figure 9 shows the pressure measured at U2ev compared with that measured at the surface. To determine the diffusivity, one performs a series of one-dimensional forward calculations, using the surface pressure history and varying the diffusivity, until one obtains the best match to the subsurface pressure history. Figure 10 shows the final calculated subsurface pressure history compared with the measured history.

Results so far have not been consistent with observed leaks, as is shown in Table 2.

Table 2, Measured chimney diffusivities.

Hole	Diffusivity (m ² /hr)
U2ev	2288.
U2ff	188.
U2fe	9370.
U19ac	3599.

These results may be caused by problems with the postshot hole. The signal at U2ff appears to indicate that the postshot hole is blocked. In the case of U2fe, the casing of the postshot hole is very short, and there may either be fractures to the surface, far from the chimney, or a leak around the casing. More data are needed before we can understand the situation.

It is possible to make similar analyses assuming layered media and treating the chimney as a medium different from its surroundings, but the results of the analyses are not greatly different from those using a one-dimensional analysis. We are continuing to develop analytical methods and improve our measurements.

The interpretation of the experiment in terms of diffusivity applies only for homogenous isotropic media. In fact, however, we are not interested in transmission of pressure, but rather in the transmission of radioactive gas. S-CUBED is studying the effect of "atmospheric pumping" on gas transmission in various media. Nilson and Peterson (1986) have compared two situations--crude approximations to TIERRA--in which an experiment like that described above would give the same result.

In the first situation, a void of about the same volume as the TIERRA cavity was connected to the surface through a 200-m column of overburden material having a permeability of 350 D and a porosity of 0.1. This corresponds to a diffusivity of about $60,000 \text{ m}^2/\text{hr}$ (a value measured at U19ac preshot.) A sinusoidal pressure wave with a period of 100 h and a peak-to-peak amplitude of $1/30 \text{ atm}$ was imposed at the surface. As the surface pressure decreased, the cavity gas rose in the chimney, but because of the large pore volume in the chimney, the gas was stored in the pores and never reached the surface. At the end of a half cycle, the surface pressure increased, and the gas returned to the cavity.

In the second situation, the chimney was replaced by a zero-porosity medium in which the path to the surface consisted of a fracture network. Each fracture had an aperture of 1.7 mm, and the fractures were separated by 1-m-thick blocks, so the effective porosity was 0.017. The pressure response was identical to the first situation, but there was far less pore volume in the chimney. Consequently, as the surface pressure decreased, the

gas rose rapidly and reached the surface before the end of the first half cycle.

These two situations represent extreme cases, pure porous permeable medium and pure fractures. In real chimneys there is likely to be a combination. S-CUBED has performed a series of laboratory experiments indicating that in fact a combination of situations will result in an intermediate type of transmission of gas. Gas travels part of the way to the surface in the fractures during the first cycle, and then some is stored in the porous medium adjacent to the fractures. Then on the next cycle some of this stored gas continues towards the surface. This ratcheting mechanism continues until gas reaches the surface. The experiments are continuing.

We plan to investigate gas transmission in the field by injecting a very small amount of SF_6 into postshot gas sampling holes and measuring the concentration at the surface as a function of time. Concentrations of 10^{-12} can be measured routinely. We will simultaneously compare surface and subsurface pressure. Thus, we will attempt to link pressure response and gas transport.

CONCLUSIONS

Our results so far are fragmentary:

1. The strong layer, coupled with relatively strong material deeper, may have caused the observed AGRINI crater shape.
2. The strong layer is essentially absent at LABAN and CROWDIE.
3. The strong layer at AGRINI could not be found by surface penetration or seismic reflection.
4. We have shown that it may be possible to measure strength vs depth by means of penetration of a projectile.
5. Calculations show that creep behavior is important in collapse initiation.
6. The commercial carbon/oxygen log appears to be good enough that, with corrections, it can improve our measurements of CO_2 in place.
7. It is possible to measure the response of the gas in a chimney to changes in atmospheric pressure.

8. There can be significantly different gas transport in chimneys with the same pressure response, depending on the porosity and the distribution of the porosity.

9. It is possible to do an inexpensive experiment to study the gas transport in an existing chimney.

ACKNOWLEDGEMENTS

This report could not have been written without the active cooperation of Billy Hudson, Cliff Olsen, John Rambo, Chuck Smith, and Jeff Hagoner of LLNL; Bob Milson of S-CUBED; and Jon Hanson of Hanson Associates.

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Figure 1. Schematic of the AGRINI crater, including the indurated zone.

Figure 2 Release and atmospheric pressure histories.

Figure 3. Schematic view of ARA high-capacity cone penetrometer.

Alb NTS ARA Mar 12, 1985
Yucca Alluvium, Area 3 Sand Pile

Figure 4a. Tip resistance vs depth in Area 3 sandpile.

A2b NTS ARA Mar 15, 1985
U2ev (Gravelly Sand and Boulders)

Figure 4b. Tip resistance vs depth at U2ev

A4a NTS ARA Mar 16, 1985
U2ff (Yucca Valley Alluvium)

Figure 4c. Tip resistance vs depth at U2ff.

Fig. 5. Depth of projectile penetration vs unconfined compressional strength.

Figure 6. CO₂ content from Hunt sidewall samples and cuttings at U2ff,

Figure 7. Results of preliminary calibration of a commercial Carbon/Oxygen log.

Figure 8. Idealization of response of pressure at the bottom of a column with various values of diffusivity to changes in pressure at the top.

Figure 9. Surface (solid) and downhole (dashed) pressures recorded at the postshot gas-sampling hole U2ev-PS-1a.

Figure 10 Measured (solid) and predicted (dashed) downhole pressure for U2ev. Infinite half-space, 1-D (vertical average) model.