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**SCHOONER SURFACE MOTION
AND VENTED-GAS TEMPERATURE MEASUREMENTS**

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SCHOONER SURFACE MOTION AND VENTED-GAS TEMPERATURE MEASUREMENTS

Abstract

Surface motion data as a function of time are presented for the Schooner nuclear cratering event. Data for the surface-motion time history up to the time of vent were obtained through the use of surface flares, high-speed photography, and film analysis with a digital computer. Graps are presented showing vertical displacement and vertical velocity of individual surface motion target flares versus time. Comparison of selected peak spall velocities obtained from the flares are made with selected peak spall

velocities obtained from nearby accelerometers. The peak spall velocity determined by the flare experiment was 55 m/sec, while that from the accelerometer was 67 m/sec. Also discussed are vented-gas temperatures as a function of time, determined by measurement of the density of the photographic images of the gas cloud on motion picture film. The hottest temperature recorded was 2590°C at ~2.1 sec after detonation time, or ~0.36 sec after the first vent.

Description of the Schooner Event

Project Schooner was a nuclear experiment in a layered tuffaceous medium executed as a part of the Plowshare Program for development of nuclear excavation. Schooner was detonated on December 8, 1968, at approximately 0800:00.149.6 (PST), 1600:00.149.6 (GMT), in Area 20, Nevada Test Site (NTS). The resulting yield was 31 ± 4 kt. The em-

placement hole was U20u at geodetic coordinates:

Longitude: W 116° 33' 57.1419"

Latitude: N 37° 20' 36.3187"

Surface ground zero (SGZ) was 5562.4 ft MSL; emplacement depth (to the working point) was 108.2 m (355 ft). The resultant crater was characterized by the following dimensions and volumes:

• Radius of apparent crater (R_a)	129.8 m	426 ft
• Maximum depth of apparent crater (D_a)	63.4 m	208 ft
• Average apparent crater lip crest height (H_{al})	13.4 m	44 ft
• Radius of apparent lip crest (R_{al})	147.2 m	483 ft
• Radius of outer boundary of continuous ejecta (R_{eb})	539 m	1768 ft
• Lip volume, apparent (V_{al})	2,099,000 m ³	
• Crater volume, apparent (V_a)	1,745,000 m ³	
	2,282,870 yd ³	

Objectives

Studies of the surface motion and the cavity-vent temperatures resulting from nuclear cratering experiments have been underway for some time. Surface displacement and velocity data are used to improve the understanding of the cratering physics, and to improve predictive techniques for future cratering events. Vent temperatures give information related to cavity thermodynamics, and are useful in fallout studies.

Two experiments were designed to obtain surface motion data for Schooner:

1. Surface motion flares were photographed so as to determine the surface

displacement and velocity over the mound up to the time of vent.

2. As a supplement to the flares, some accelerometers were placed in the ground zero (GZ) area to measure the surface accelerated motion.

Three cameras using infrared film were used to photograph the cavity vent. The temperature of the gas venting from the cavity was determined by measuring on infrared film the intensity of light emitted from the escaping incandescent gas and particle suspension, and then calibrating the film by making equivalent exposures with radiating objects of known temperatures.

Surface Motion Flares

Twenty-five surface targets were located through GZ in a direction $N55^{\circ}30'$ east and extending 440 ft northeast and southwest of Schooner GZ (Table 1). Targets 1-10 were to the left of GZ, looking north, and targets 11-22 were to the right.

Only 22 flares are listed in the table. The end targets 480 ft from GZ were too close to the film frame edge to read. The flare 40 ft to the left of GZ as viewed from the camera station was positioned on the film in such a manner that a zero-time strobe light or one of the fiducial lights was too close to it, and it was not possible to separate the two lights at the beginning of the film scan.

A view along the target array is pictured in Fig. 1. Each target was 5 ft high, and was bolted to a concrete pad with J bolts. The target and pad combina-

tion results in a low center of gravity, and provides coupling to the ground. The 5-ft height of the target tends to prevent spall of the surface material from obscuring the flare light during the mound rise.

Cakes of the solid rocket propellant, Pyrogen, were fastened on top of the targets. The Pyrogen when ignited gives a bright light, but with much less smoke than the standard magnesium flare.

The photo station was located 18,824 ft southeast of the flare array, and on a line of sight perpendicular to it. Two fiducial light sources were placed in front of the camera station. These fiducials were about one-third of the distance from the camera station to GZ.

The motion of the target flares was recorded by 35 mm and 16 mm high-speed cameras. The best results were obtained by the 35 mm cameras, and these results

Fig. 1. View of Schooner flare targets.

Table 1. Location of surface motion targets.

Target Number	General bearing from GZ	Distance from GZ		Target Number	General bearing from GZ	Distance from GZ	
		ft	m			ft	m
1	Southwest	440	134.15	12	Northeast	40	12.2
2	Southwest	400	122	13	Northeast	80	24.4
3	Southwest	360	109.8	14	Northeast	120	36.6
4	Southwest	320	97.6	15	Northeast	160	48.8
5	Southwest	280	85.4	16	Northeast	200	61
6	Southwest	240	73.2	17	Northeast	240	73.2
7	Southwest	200	61	18	Northeast	280	85.4
8	Southwest	160	48.8	19	Northeast	320	97.6
9	Southwest	120	36.6	20	Northeast	360	109.8
10	Southwest	80	24.4	21	Northeast	400	122
11	GZ			22	Northeast	440	134.15

will be presented in this report. The cameras were started by a signal from the control point, and timing marks occurring with a certain frequency were put on the film. A strobe lamp with a ~1 msec risetime was located near GZ, and was activated with a zero-time signal. This lamp recorded a zero-time reference on the film.

The 35 mm film was underexposed by several stops. This produces a high-contrast film with the flares recorded as bright images of light; the sky, mountains and terrain are blacked out. Thus, if the film is processed properly, only the pin-points of light representing the target array over GZ, and the fiducial targets, register on the film.

Eyeball Computer Program

The "eyeball" program for reading target data is designed for the Digital Equipment Corporation PDP-1 computer, equipped with a CRT recorder which performs the actual reading.¹ A film transport loaded with the developed 35 mm film is placed between the precision CRT and a photomultiplier tube and is focused on the precision CRT face, which projects the image of the CRT on the film plane.

The photomultiplier tube is directly behind the film so that light from the CRT passing through the developed film is detected by the photomultiplier in a light-tight environment. Then, starting from a point of known position on the CRT, the film is scanned until a perimeter point in an image is detected. The coverage X and Y CRT coordinates of the perimeter points are determined, and their

intersection is assumed to be the center of the image.

The CRT coordinates of each light spot in the frame of film are stored on magnetic tape. This tape is used as the input

for a 7094 computer code which performs a coordinate transformation, smooths the target displacement data, and computes velocity components of each target as a function of time.

Surface Motion Results

The flares on the 35 mm film were followed to +1.85 sec with the eyeball program. The first venting of the dome occurred at +1.75 sec. Most of the flares near GZ were obscured, or the light from them became too weak before vent time to be detected by the eyeball technique. This is due to spalling of the surface material which obscures the flare, or the motion of the flare backward away from the photo station.

Figures 2 through 23 illustrate the vertical surface displacement and vertical velocity of the flares in the array as a function of time. In those cases where the time history does not extend to 1.85 sec, the flare was lost to the eyeball computer for the reasons previously mentioned. The smoothing parameter for the displacement is 40, and for the velocity it is 80.

These smoothing parameters are needed because in determining the coordinate position of a point on a surface motion flare by means of the eyeball technique, there is scatter in the observations. Therefore, some statistical considerations are used to reduce the influence of the random errors and the reading errors. P is the ratio of the number of observations to the minimum number of observations required in the absence of noise. In this context, P times the data interval between

observations is the effective data interval. This is explained in greater detail in Ref. 1.

The target flare displacement and velocity reveal several things. For the flares that remained visible up to the time of vent, the maximum displacement along the mound occurs at T_r at 10, which is 80 ft to the left of GZ as viewed from the camera station. This displacement is ~83 m at 1.7 sec. The same target also gives a peak velocity of ~65 m/sec just before the time of vent. This is the only GZ area target which gives a complete history of the mound rise up to vent time, as it was not possible to follow other nearby targets for this length of time.

The GZ target remained visible long enough to record a peak spall velocity of ~55 m/sec at +200 msec.

The preshot calculation indicated a peak spall velocity of 37 m/sec. The discrepancy between this value and the 55 m/sec obtained from the GZ flare is due to a high porosity layer starting a few feet above the working point. This layer was ~45 ft thick with 28% water by weight.² A post-event calculation, taking this layer and the resulting vaporization of water into account, indicated a peak spall velocity of 48 m/sec.³

The gas acceleration phase of crater development is visible in the velocity time histories of Targets 10, 11 and 12 where it begins at 600-700 msec.

Figure 24 is a plot of the vertical component of displacement of the targets beginning at +0.200 sec. After 1.2 sec,

most of the target flares near the center of the mound were no longer visible.

First motion was seen at the GZ target, and occurs at $\sim +80$ msec. Figure 25 is an infrared photograph of the mound shortly before vent, and shows the good symmetry of the mound growth.

Fig. 2. Vertical displacement (a) and vertical velocity (b) of surface motion as a function of time for Target 1. Distance from GZ = 440 ft.

Fig. 3. (a) Vertical displacement and (b) vertical velocity of surface motion as a function of time for Target 2. Distance from GZ = 400 ft.

Fig. 4. (a) Vertical displacement and (b) vertical velocity of surface motion as a function of time for Target 3. Distance from GZ = 360 ft.

Fig. 5. (a) Vertical displacement and (b) vertical velocity of surface motion as a function of time for Target 4. Distance from GZ = 320 ft.

Fig. 6. (a) Vertical displacement and (b) vertical velocity of surface motion as a function of time for Target 5. Distance from GZ = 280 ft.

Fig. 7. (a) Vertical displacement and (b) vertical velocity of surface motion as a function of time for Target 6. Distance from GZ = 240 ft.

Fig. 8. (a) Vertical displacement and (b) vertical velocity of surface motion as a function of time for Target 7. Distance from GZ = 200 ft.

Fig. 9. (a) Vertical displacement and (b) vertical velocity of surface motion as a function of time for Target 8. Distance from GZ = 160 ft.

Fig. 10. (a) Vertical displacement and (b) vertical velocity of surface motion as a function of time for Target 9. Distance from GZ = 120 ft.

Fig. 11. (a) Vertical displacement and (b) vertical velocity of surface motion as a function of time for Target 10. Distance from GZ = 80 ft.

Fig. 12. (a) Vertical displacement and (b) vertical velocity of surface motion as a function of time for Target 11 at GZ.

Fig. 13. (a) Vertical displacement and (b) vertical velocity of surface motion as a function of time for Target 12. Distance from GZ = 40 ft.

Fig. 14. (a) Vertical displacement and (b) vertical velocity of surface motion as a function of time for Target 13. Distance from GZ = 80 ft.

Fig. 15. (a) Vertical displacement and (b) vertical velocity of surface motion as a function of time for Target 14. Distance from GZ = 120 ft.

Fig. 16. (a) Vertical displacement and (b) vertical velocity of surface motion as a function of time for Target 15. Distance from GZ = 160 ft.

Fig. 17. (a) Vertical displacement and (b) vertical velocity of surface motion as a function of time for Target 16. Distance from GZ = 200 ft.

Fig. 18. (a) Vertical displacement and (b) vertical velocity of surface motion as a function of time for Target 17. Distance from GZ = 240 ft.

Fig. 19. (a) Vertical displacement and (b) vertical velocity of surface motion as a function of time for Target 18. Distance from GZ = 280 ft.

Fig. 20. (a) Vertical displacement and (b) vertical velocity of surface motion as a function of time for Target 19. Distance from GZ = 320 ft.

Fig. 21. (a) Vertical displacement and (b) vertical velocity of surface motion as a function of time for Target 20. Distance from GZ = 360 ft.

Fig. 22. (a) Vertical displacement and (b) vertical velocity of surface motion as a function of time for Target 21. Distance from GZ = 400 ft.

Fig. 23. (a) Vertical displacement and (b) vertical velocity of surface motion as a function of time for Target 22. Distance from GZ = 440 ft.

Fig. 24. Vertical component of displacement of flare array at various times, in seconds.

Fig. 25. Infrared photograph of the Schooner mound shortly before vent.

Accelerometers

A number of accelerometers were fielded by W. Hurdlow (formerly of LLL) on the Schooner experiment. These were the Endevco Model 2255 type, and were similar to the array fielded on the Buggy experiment.⁴ Some of these accelerometers were in the same general location as the targets. Table 2 compares the velocities obtained from the flares with those from the accelerometers for comparable distances from GZ. There is good agreement between the flare velocity data and that from the accelerometers. Figures 26 through 30 show the vertical velocities as a function of time for the accelerometers listed in the table. The time at which peak spall velocity occurs is close to the 125 msec recorded on the GZ accelerometer which conserves high frequencies more effectively than does the photographic method used to obtain the target velocity. The electronic method for measuring surface phenomena has the advantage over the flare method of not having optical limitations. As the distance from GZ to the camera station increases, a point would eventually be reached where the flare images could no

Fig. 26. Vertical velocity from GZ area accelerometer.

longer be optically resolved, and the electronic method would have to be employed. The basic problem with the accelerometers appears to be that they can record the large accelerations early in the mound history, but their signal-to-noise ratio is such that the smaller accelerations associated with gas acceleration are lost in the noise.

Table 2. Comparison of selected surface target velocities with selected accelerometers.

Horizontal distance from GZ (flare) (m)	Horizontal distance from GZ (accelerometer) (m)	Peak spall velocity (target) (msec)	Peak spall velocity (accelerometer) (msec)
0	0	55	67
24.4	27.4	46	45
36.6	39.6	42.5	41
48.8	51.8	36	32
61	64	34	28

Fig. 27. Vertical velocity from accelerometer 27.4 m from GZ.

Fig. 28. Vertical velocity from accelerometer 39.6 m from GZ.

Fig. 29. Vertical velocity from accelerometer 51.8 m from GZ.

Fig. 30. Vertical velocity from accelerometer 64 m from GZ.

Sources of Error

The primary source of error in the surface motion experiment for Schooner is in the determination of the positions of the flares on each frame of film. An air blast wave, induced by the ground shock, was generated in the GZ area shortly after

zero time, and this caused refraction of the light from the flares making it difficult to determine their absolute position for some tens of milliseconds. Also, throughout the period of the surface motion some light shimmer is always present.

Vented-Gas Temperature Measurements*

THERMODYNAMICS OF THE CAVITY GAS

An observable effect of the thermodynamics of the cavity gas in a cratering event is the temperature at vent time. This temperature can be determined by measuring the amount of light emitted from the "gas" cloud by motion picture photography.

The Schooner emplacement medium was a layered tuffaceous material, mostly SiO_2 , with a probable water content of approximately 4 to 7 wt%. In the stratum a few feet above the shot point, the water content was approximately 28%.

In a cratering event, at explosion time the outgoing shock wave will be expected to vaporize all the nearby medium. Further from the explosion center, complete vaporization will not occur. The rock will appear in a two-phase state, while still farther out only the more volatile components of the medium, primarily H_2O , will undergo vaporization. At larger distances, the two-phase state of the water will be encountered, and

finally at large radii no vaporization will occur.

A further complication is that as the cavity expands and the pressure is reduced, some of the material components will pass from the unvaporized to the vaporized state. Along with this pressure drop, the vaporized components in the cavity wall will expand and will drive solid material into the cavity gas (decrepitation). This material will mix turbulently with the cavity gas and will tend to quench it.

The temperature of the cavity gas will drop both because of the adiabatic expansion of the gas and because of the addition of this colder solid and gaseous wall material. Eventually, the temperature will be lowered to the point where the refractory components, mainly SiO_2 , will begin to recondense spontaneously and form nuclei for condensation of more material. The ultimate size and composition of these grains, later to appear as fallout, will be determined by the temperature, density, and composition history of the cavity gas.

* Myron Heusinkveld wrote the majority of this part of the report.

Finally, at vent time an indication of the thermodynamic state of the vent gas is obtained by a measurement of the temperature. There is probably very little thermal contact between the hot gases and the shell of earth medium above the cavity at the time of break-through, so that the concept of a heat exchanger effect does not apply here.

In the usual cratering event, the gas is emitted at a pressure greater than atmospheric. This gas quickly expands until the pressure is equal to atmospheric pressure. The relative amount of energy lost during this final expansion by radiation of light is small so that after pressure equalization with the atmosphere occurs, the temperature measurements give the final thermodynamic point on the expansion adiabat specified by temperature and pressure.

PHOTOGRAPHIC DETERMINATION

Since the blackbody radiation emitted from an object follows the law $E = \sigma T^4$, a photographic determination of the radiant energy emitted should give a good indication of the surface temperature. A photographic emulsion system is sensitive to only a relatively narrow band of wavelengths, however, so that the photographic response is obtained by integrating the wavelength distribution weighted by the response curve of the detecting system.

The energy density is a maximum at a wavelength λ_m given by Wien's displacement law $\lambda_m = 0.2885/T$, in centimeters and degrees Kelvin. Consequently, for low gas temperature this maximum is in the far infrared, while the daylight background is peaked in the visible spectrum.

To obtain measurements at lower gas temperatures, infrared photographic film was used in the optical detecting system. With this film (Kodak 5210 type IR film) the lower temperature limit could be extended 200° below that possible with ordinary panchromatic film. Effects of atmospheric haze would also be minimized by the use of the infrared film.

The terms "gas temperature" and "blackbody temperature" are somewhat contradictory in that a gas will not ordinarily radiate as a blackbody. In this case, however, the measured temperatures are low enough that the SiO_2 component must have condensed into solid particles, and these particles will radiate as a blackbody. When the suspension cools below the point of radiating visible light it becomes a black opaque "smoke," indicating its condition as a suspension of solid particles. The emissivity of this suspension is probably quite high, so that only a small error in temperature determination is incurred by assuming an emissivity value of unity.

EXPERIMENTAL PROCEDURES

Three motion picture cameras were used to measure the gas temperature in the Schooner Event, as listed in Table 3. These cameras were located in a camera station ~19,000 ft from GZ. A W87 filter was used in each camera to eliminate sensitivity to the visible part of the spectrum.

For calibration, similar film exposures were made to radiating sources of known temperatures. A tungsten ribbon lamp and an argon furnace were used as the calibrating sources. Since the calibrating sources had to be near the cameras to

Table 3. Camera systems for Schooner vented-gas temperature measurements.

Camera No.	Nominal speed (frames/sec)	Actual speed (frames/sec)	Shutter sector (deg)	Exposure time (sec)	Aperture	Nominal focal length (mm)	Viewed area near GZ (ft)
Mitchell 20	24	~24	170	$\frac{1}{51}$	F 5.6	400	Horizontal ~1177 Vertical ~878
Mitchell 21	96	~96	15	$\frac{1}{2095}$	F11.0	600	Horizontal ~784 Vertical ~585
Mitchell 22	50	~30	15	$\frac{1}{2700}$	F16.0	400	Horizontal 1177 Vertical 878

obtain reasonable image sizes, a relay lens was used between the camera and the source to focus the image.

The field cameras were calibrated under conditions as similar as possible to those of the field exposures, i.e., film with the same batch number was used, W87 filters were used, lens apertures were the same, and shutter sectors and camera framing rates were the same as before. The upper temperature limit of the tungsten ribbon lamp was about 2300°C, and the argon oven was used to extend the calibration up to about 2900°C.

Calibration strips were attached to the beginning and end of each strip of shot film along with sensometric wedges from the Herdnfeld sensitometer to correct the temperature curve to the actual exposure of the field cameras. The shot film and all calibration film were developed in a Fulton negative processor using Acufine developer at a film travel of 8 ft/min at 63°F.

Since the timing marks on the calibration films indicated somewhat different actual framing rates than that on the shot films, corrections were made for the exposures. The D—log E curve produced from the Herdnfeld sensitometer wedges

was needed to correct the densities produced by the calibration run. The corrected densities from the calibration films were plotted as a function of temperature for the field cameras.

The densities of the images on the shot films were read with a Joyce-Loebl recording microdensitometer using a scanning aperture of 50 × 50 μ. The same aperture size was used in scanning the Herdnfeld wedge and laboratory temperature exposures.

The hottest part of the luminous image as indicated by the densest area in the film was recorded each time. The first frame on which the density was enough to give a recordable reading occurred at about 1.8 sec after detonation. The vent temperature time history for the Mitchell 21 camera is shown in Fig. 31. The hottest temperature recorded on this film is 2590°C at ~2.1 sec after detonation time, or ~0.36 sec after first vent. The field of view defined by the microdensitometer aperture corresponds to a square area at the gas vent ~1.57 ft on a side.

Also shown on Fig. 31 are the results from the Mitchell 20 and Mitchell 22 cameras. The maximum temperature recorded on the Mitchell 20 film was

Fig. 31. Schooner temperatures of vented gas as a function of time.

2350°C, which is 240° below the maximum temperature recorded with the Mitchell 21. For the Mitchell 20 film, the microdensitometer aperture defined a vent gas area of ~2.35 ft on a side, and for the Mitchell 22 film the corresponding dimension was also ~2.35 ft.

The temperature curve obtained with the Mitchell 22 curve does not show the peak at ~400 msec after vent time. The temperatures recorded are lower than those from the other two cameras. The maximum temperature observed was about 2060°C.

These temperatures as measured by the three cameras are not in good agreement. One possible source for this dis-

crepancy is the fact that the vent cloud was much larger than expected and was partly out of the field of view at an early time. It was possible that since no camera view contained the complete vent, each camera saw somewhat different parts of it, and thus different peak temperatures were recorded.

It is observed from Fig. 31 that the temperature at later time, where pressure has dropped to atmospheric, was ~1800°C.

The results from comparable temperature measurements on the Palanquin⁵ and the Cabriolet⁶ Events are given in Figs. 32 and 33, respectively. These results show that the vent gases from Palanquin were

Fig. 32. Apparent temperature of the vent gas from the Palanquin Event.

Fig. 33. Cabriolet temperatures of vented gas as a function of time.

the coolest, the Cabriolet gases were appreciably hotter, and the Schooner gases were still hotter.

Figure 34 shows a photograph of the Schooner vent as recorded on one of the infrared films.

Fig. 34. Infrared photograph of the Schooner vent.

Acknowledgments

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calibrations, and recorded the film densities on the microdensitometer. Myron Heusinkveld (LLL) began this type of vent temperature measurement on Project Palanquin. Thanks are due to him for his advice and assistance, and for his analysis and interpretation of the relation of the vent temperature to the cavity and cratering physics.

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