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NORBO
Containment Data Report

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NORBO Instrumentation Summary

Instrumentation	Fielded on this Event	Data Return	Present in this Report
<u>Plug Emplacement</u>	yes	yes	no
<u>Radiation</u>	yes	yes	yes
<u>Pressure</u>			
Stemming	yes	yes	yes
Challenge	no	-	-
Cavity	no	-	-
Atmospheric	no	-	-
<u>Motion</u>			
Free Field	yes	yes	yes
Surface	yes	yes	yes
Plug	yes	yes	yes
Stemming	no	-	-
Surface Casing	no	-	-
Emplacement Pipe	no	-	-
<u>Hydroyield (a)</u>	yes	yes	no
<u>Collapse (b)</u>	yes	yes	yes
<u>Stress</u>	yes	yes	yes
<u>Strain (c)</u>	yes	no	-
<u>Other Measurements (d)</u>	yes	yes	yes

- (a) CORTEX or SLIFER in emplacement hole.
 (b) EXCOR or CLIPER in emplacement hole.
 (c) Emplacement pipe load.
 (d) Stress gauge development.

Event Personnel

Containment Physics

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1. Event Description

1.1 Site

The NORBO event was detonated in hole U8c of the Nevada Test Site as indicated in figure 1.1. The device had a depth-of-burial (DOB) of 271 m in the bedded tuffs of area 8, about 130 m above the Paleozoic formation and 280 m above the standing water level, as shown in figures 1.2 and 1.3⁽¹⁾. Stemming of the 2.44 m diameter emplacement hole followed the plan shown in figure 1.4. A log of the stemming operations was maintained by Holmes & Narver⁽²⁾.

Detonation time was 07:37 PST on March 7, 1980 and 53.5 minutes later a subsurface collapse or stemming fall to a depth between 75 and 24 m occurred.

A low level radiation arrival was detected in the emplacement hole below the top stemming plug after the subsurface collapse. This was attributed to activity contained within the prompt gas sample hose. No radiation arrival was detected above the top plug and the NORBO containment was considered successful.

1.2 Instrumentation

Figure 1.5 is a schematic layout of the instrumentation designed to monitor the emplacement procedures and stemming performance of the NORBO event.

The two stemming plugs were composed of coal-tar epoxy (LAE 59, denoted CTE). A soft layer of coal-tar and aggregate (LAE 59MY, denoted CTA) was poured on the top of the top plug to act as a gas seal.

Pressure and radiation were monitored in the coarse stemming at three locations in the coarse stemming between the device canister and the bottom plug and at three additional locations between the two plugs.

Vertical motion was monitored in both of the plugs in the emplacement hole, at two locations in the coarse stemming, and in the ground surface, 15.24 m from SGZ. An array of ten vertical motion stations was fielded in the satellite hole which was 22.52 m east of the emplacement hole. Vertical motion of the recording trailer was also obtained.

As part of a continuing effort to develop an in-situ dynamic stress transducer, three elevations of the satellite hole were instrumented with carbon foil stress transducers .

Data from each of the above instruments were transmitted to the recording trailer by an analog system and recorded on magnetic tape.

D-cable information was used both for quality assurance during the stemming operations and as an adjunct to the CLIPER collapse measurements.

Two CLIPER/CORRTEX sensors were fielded in the emplacement hole and one in the satellite hole to measure the hydrodynamic yield of the device and to monitor cavity collapse and chimney formation. In the emplacement hole, one CLIPER was fielded on the emplacement pipe and device canister and the second on the instrumentation pendant. Results of the yield measurements are reported elsewhere⁽³⁾.

A history of the fielding operations of the instrumentation is outlined in reference 4. Details of the instrumentation are given in reference 5.

1.3. Emplacement

A single strain station (83) was fielded near the top of the emplacement pipe to monitor the load during installation and stemming. This station was monitored randomly during these procedures and was recorded by hand during the device installation only. Emplacement was detailed by Holmes & Narver⁽²⁾.

The stemming plugs consisted of two "LAE 59" coal-tar epoxy (CTE) layers. The bottom was about 4.6 m thick while the top was about 4.9 m thick. The top plug was capped with about 2.9 m of soft coal-tar-aggregate "LAE 59MY" epoxy (CTA) to act as a gas sealant. Stemming between the plugs consisted of layers of fines and coarse gravel. The top of the hole (above the top plug) was filled with coarse stemming. See figure 1.4.

Figure 1.1 Map of the Nevada Test Site indicating the location of hole U8c.

Figure 1.2 North-South geologic cross sections through hole U8c.

Figure 1.3 East-West geologic cross sections through hole U8c.

Figure 1.4 As-built stemming plan for the event NORBO in Hole U8c.

Figure 1.5 As-built containment instrumentation plan for the emplacement hole (U8c) on the NDBB shaft

2. Stemming Performance

2.1 Radiation and Pressure

As seen in figure 1.5, pressure and radiation was monitored in the coarse stemming at a total of six stations. Three stations were placed in the loose stemming between the device canister and the bottom plug. An additional three stations were fielded in the loose stemming between the bottom and top plugs.

All stations above the bottom plug transmitted data until recording was terminated at about 6 hours after the detonation, signals from those below the bottom plug were lost prior to 4170 s, presumably due to subsurface collapse. Recorded pressure and radiation histories are shown in figures 2.1-2.6.

The pressure records from stations 34, 35, and 36 (above the bottom plug) suggest a stemming fall, initiated by the subsurface collapse, progressing to near the bottom of the top plug.

There is clear indication from station 31 (figure 2.1) that radiation penetrated the stemming column to a depth of 206 m, however, there is no evidence that it migrated another 70 m up the hole to station 33 at a depth of 136 m (figure 2.3). (The station 32 radiation channel is absent because of its loss during stemming.) Station 34 suffered a negative dose rate offset at both zero and subsurface collapse times, but indicated no radiation arrivals. The source chip in station 35 was dangerously high (about 0.5 R/Hr) and all but swamped any low-level radiation signals, however, it may be inferred that an increase of about 0.1 R/Hr occurred at collapse time. Station 36 (figure 2.6) clearly shows radiation arrivals occurring at and after subsurface collapse. It is strongly suspected that the source of radiation seen at station 36 (and probably station 35) after subsurface collapse was "shine" from the prompt gas sample hose and was not migrating gas from the explosion. This seems to be a collapse-related phenomenon and will be discussed in section 4, "Collapse Phenomena".

Standard Heath & Safety monitors detected no radiation arrivals above the ground surface and we conclude that pressure and radiation data are consistent with satisfactory containment.

Figure 2.1 Pressure and radiation measured in the coarse stemming at 206 m depth (Station 31). Signals from this station were lost at about 4167 s.

Figure 2.2 Pressure and radiation measured in the coarse stemming at 168m depth (Station 32). Signals from this station were lost at about 4167 s. The radiation channel was dead pre-shot and not recorded.

Figure 2.3 Pressure and radiation measured in the coarse stemming below the bottom plug at 136 m depth (Station 33). Signals from this station were lost at about 4167 s.

Figure 2.4 Pressure and radiation measured in the coarse stemming above the bottom plug at 119 m depth (Station 34).

Figure 2.5 Pressure and radiation measured in the coarse stemming at 85 m depth (Station 35).

Figure 2.6 Pressure and radiation measured in the coarse stemming below the top plug at 24 m depth (Station 36).

2.3 Motion

Explosion-induced histories of the containment related motion measured on the NORBO event are shown in figures 2.7-2.13. At station 22 (in the bottom plug, figure 2.8) only the velocimeter survived the initial shock wave, and that for less than 100 ms.

Station 23 accelerometer was driven to high band edge at the time that the associated velocimeter lost coherent signal (about 0.6 s, figure 2.9). Action of the calibration logic, applied at about +60 s, drove the acceleration signal back in band for the remaining time that it was recorded. However, the data from this channel are suspect after 0.6 s and should be used only for timing.

All other stations survived until subsurface collapse (at about 4170 s) or until recording was terminated. Characteristics of the associated motion and transducers are given in tables 2.1-2.3.

Stations 26A and 26B were mounted on the top of the surface casing for a study by the Mechanical Engineering department.

Table 2.1 Summary of Containment-Related Motion

Gauge	Slant Range (m)	Arrival Time (ms)	Acceleration Peak (g)	Velocity Peak (m/s)	Displacement Peak (cm)	Displacement Residual (cm)
21av	112	30(a)	7.2	0.95	18.6	-1
21uv		29(a)	-	0.93	17.9	4
22av(b)	147	-	-	-	-	-
22uv		36(c), 67	-	(d)	(d)	(d)
23av	186	48(a)	2.65(a)	0.36	9.1	(d)
23uv		53(c), 97	-	0.38	9.5	(d)
24av	250	62(c), 146	1.4	0.58	11.1	-4
24uv		64(c), 150	-	0.59	10.6	(d)
26avA	271	68(c), 140	2.08(a)	0.53	9.9	-6
26avB		68(c), 140	1.8(a)	0.53	10.3	3
61av	271	168	2.7, 13.3(e)	0.68	9.8	-6
61uv		165(a)	-	0.53	8.8	-2
71av	303(f)	215	1.4, 3.1(e)	0.59	6.0	-3
71uv		213	-	0.51	4.7	-3

(a) Poorly defined.

(b) Dead pre-shot.

(c) Pipe arrival.

(d) Signal lost before this value attained.

(e) Slap-down.

(f) Approximate: station in recording trailer.

Table 2.2 Containment-Related Accelerometer Characteristics

Gauge	Natural Frequency (Hz)	Damping Ratio	System Range (g's)
21av	1000	0.65	150
22av	730	0.55	75
23av	330	0.75	12
24av	340	0.55	20
26ava	410	0.75	20
26avb	510	0.65	50
61av	330	0.65	20
71av	230	0.75	10

Table 2.3 Containment-Related Velocimeter Characteristics

Gauge	Natural Frequency (Hz)	Time to 0.5 Amplitude (s)	Calibration Temperature (°F)	Operate Temperature (°F)	System Range (m/s)
21uv	3.60	7.2	73.1	63.9	7
22uv	3.91	9.8	72.5	(a)	6
23uv	3.44	8.15	72.7	59.4	2.4
24uv	3.64	8.0	73.4	88.5	4
61uv	3.50	11.8	73.0	56.0	10
71uv	3.75	13.09	74.75	64.7	1.2

(a) This item not recorded.

Figure 2.7

Explosion-induced vertical motion of the coarse stemming below the bottom plug at a depth of 159 m (station 21). Traces annotated with "a" are derived from the accelerometer.

Figure 2.8

Explosion-induced vertical motion of the bottom plug at a depth of 124 m (station 22). The acceleration channel was dead pre-shot and is not represented. The velocity channel was lost at about 90 ms.

Figure 2.9

Explosion-induced vertical motion of the coarse stemming between the bottom and top plugs at a depth of 85 m (station 23). Both channels seem to have been lost at about 0.6 s. Traces annotated with "a" are derived from the accelerometer.

Figure 2.10 Explosion-induced vertical motion of top plug at a depth of 35 m (station 24). Traces annotated with "a" are derived from the accelerometer.

Figure 2.11 Explosion-induced vertical motion of the surface casing (stations 26A and 26B). Where possible, the two gauge records are annotated by their suffix.

Figure 2.12 Explosion-induced vertical motion of the ground surface at a horizontal range of 15.24 m and a depth of 0.9 m (station 61).

Figure 2.13 Explosion-induced vertical motion of the recording trailer (station 23). Traces annotated with "a" are derived from the accelerometer.

3. Free field (satellite hole) measurements

Ten stations fielded in the satellite hole Ue8c 22.52 m east of the emplacement hole were instrumented to measure vertical acceleration and velocity as shown in figure 1.6. All stations were hung on a fiber glass pipe with a compass for orientation and a weight to keep the pipe straight. The hole was then grouted to the surface. Motion wave forms received from these stations are shown in figures 3.1-3.10.

Two of these stations (stations 44 and 47) were emplaced at the same slant ranges from the working point as were stations 21 and 23 in the loose stemming of the emplacement hole. Comparisons of the motion data at these two ranges are shown for the first 0.6 s in figures 3.11 and 3.12. Differences between the two wave forms in each figure can be attributed to the differences between mounting in loose stemming and grout.

A composite plot of the first 0.6 s of the acceleration histories from the top five stations is shown in figure 3.13. Of interest are the acceleration "noise" spikes seen at about 0.5 s in all of the records in the satellite hole but not in the emplacement hole. Furthermore, these spikes integrate to negligible interference in the velocity records as seen in figures 3.5 - 3.10.

As an explanation, the volumetric strain history has been estimated from the motion at each of the five stations and is displayed in figure 3.14. Assuming spherical symmetry, the volumetric strain, ϵ_v , is given by (See the appendix, equation 3);

$$\epsilon_v = \frac{D}{r} - \frac{U}{C}$$

where U is particle velocity, C is local sonic velocity (1696 m/s as given in reference 1 and supported by this work), D is particle displacement and r is position. It is postulated that when the medium goes into dilatation, the fiber glass pipe support is allowed to relieve its previously grouted-in weight-induced strain, sending local acceleration signals to the motion stations with little resulting displacement. From figure 3.14 it is seen that the signals in question occur near the time of maximum dilatation.

Table 3.1 Summary of Satellite Hole Motion

Gauge	Slant Range (m)	Arrival Time (ms)	Acceleration Peak (g)	Velocity Peak (m/s)	Displacement Peak (cm)
40av	54	(a)	-	-	-
40uv		30	-	14.7	163
41av	69	(a)	-	-	-
41uv		37	-	6.4	84
42ar	83	45	12.5	3.2	46
42at		46	-	3.0	40
43av	98	53	13.1	2.46	37
43uv		55	-	2.05	30
44av	112	61	10.0	0.89	16.7
44uv		63	-	0.85	15.1
45av	138	77	6.2	0.54	9.9
45uv		78	-	0.60	11.8
46av	162	91	4.0	0.42	11.2
46uv		91	-	0.41	9.3
47av	186	106	3.3	0.38	9.7
47uv		107	-	0.35	9.0
48av	211	120	2.3	0.31	8.9
48uv		121	-	0.28	8.3
49av	236	135	1.9	0.34	9.9
49uv		137	-	0.33	9.8

(a) Dead pre-shot.

Table 3.2 Satellite Hole Accelerometer Characteristics

Gauge	Natural Frequency (Hz)	Damping Ratio	System Range (g's)
40av	1600	0.65	2000
41av	1500	0.65	1200
42av	1400	0.65	500
43av	1200	0.75	200
44av	920	0.65	150
45av	720	0.55	50
46av	680	0.65	25
47av	340	0.60	12
48av	350	0.60	10
49av	300	0.65	10

Table 3.3 Satellite Hole Velocimeter Characteristics

Gauge	Natural Frequency (Hz)	Time to 0.5 Amplitude (s)	Calibration Temperature (°F)	Operate Temperature (°F)	System Range (m/s)
40uv	3.75	35.5	72.4	74.1	65
41uv	3.81	19.2	73.3	73.8	30
42uv	4.28	23.45	73.2	72.3	15
43uv	3.50	12.95	73.0	71.3	10
44uv	3.58	10.55	73.3	70.6	7
45uv	3.59	9.2	73.5	69.0	5
46uv	3.64	8.1	73.6	66.5	3
47uv	3.67	7.0	73.3	65.9	2.5
48uv	3.52	9.1	73.3	64.9	2
49uv	3.52	9.7	72.5	64.1	2

Figure 3.1 Vertical motion in the satellite hole at a slant range of 52.7 m (station 40 at a depth of 220.5 m). The accelerometer at this location gave an unreliable record and was not reduced to engineering units.

Figure 3.2 Vertical motion in the satellite hole at a slant range of 66.2 m (station 41 at a depth of 206.6 m). The accelerometer at this location gave an unreliable record and was not reduced to engineering units.

Figure 3.3 Vertical motion in the satellite hole at a slant range of 81.4 m (station 42 at a depth of 191.0 m).

Figure 3.4 Vertical motion in the satellite hole at a slant range of 96.2 m (station 43 at a depth of 176.0 m).

Figure 3.5 Vertical motion in the satellite hole at a slant range of 111.1 m (station 44 at a depth of 161.0 m).

Figure 3.6 Vertical motion in the satellite hole at a slant range of 137.0 m (station 45 at a depth of 134.8 m).

Figure 3.7 Vertical motion in the satellite hole at a slant range of 160.7 m (station 46 at a depth of 111.0 m).

Figure 3.8 Vertical motion in the satellite hole at a slant range of 185.6 m (station 47 at a depth of 86.0 m).

Figure 3.9 Vertical motion in the satellite hole at a slant range of 210.6 m (station 48 at a depth of 61.0 m).

Figure 3.10 Vertical motion in the satellite hole at a slant range of 235.5 m (station 49 at a depth of 36.0 m).

Figure 3.11 Comparison of first 0.6 seconds of station 21 motion with that obtained from station 44. Slant range for both was 112 m. Traces annotated with "s" are from the satellite hole (station 44). For further identification, the heavier trace is associated with the satellite hole.

Figure 3.12 Comparison of first 0.6 seconds of station 23 motion with that obtained from station 47. Slant range for both was 186 m. Traces annotated with "s" are from the satellite hole (station 47). For further identification, the heavier trace is associated with the satellite hole.

Figure 3.13 Composite of the first 0.6 s of acceleration from the top five stations in the satellite hole. The "noise" occurring between 0.4 and 0.5 s is clearly seen on each trace.

Figure 3.14 Volumetric strain computed from the motion of the top five stations in the satellite hole. The circled areas on each trace include the effects of the "noise" periods seen in the corresponding acceleration records (figure 1.13). Compression (decrease in strain) is in the upward direction relative to each base line.

4. Collapse phenomena

Data from all stations sensing collapse motion are shown in figures 4.1 through 4.12. Station 22, in the bottom plug, did not survive beyond the first 100 ms and is thus not shown. Both the acceleration and velocity channels of station 23 were lost at about 0.6 s and the action of the calibration system (applied at about 60 s) seemed to recover the acceleration signal. However, the validity of the data for this channel are in question and should be used only for timing. No collapse motion was detected at stations 24, 61, or 71.

The CLIPER cables in the emplacement and satellite holes (stations 92, 93 and 51, respectively) performed as expected, giving the lower positions of the cable ends as a function of time during the cavity collapse. These records are shown in figure 4.13 along with selected displacement wave forms measured both in the satellite hole and the emplacement hole. One pressure wave form from the station immediately below the top plug is also shown. Data obtained from the satellite hole are shown by heavy traces.

CLIPER data indicate that subsurface collapse terminated at a depth of about 75 m in the satellite hole while there were two collapse levels indicated in the emplacement hole. The deepest level was about 120 m (station 93), the depth of the bottom plug, and the second collapse level was just below the top plug. This was registered by station 92 and the D-cable, station 91. There is an apparent discrepancy of 3 to 5 seconds between the cable break data (CLIPER and D-cable) and the pressure and displacement wave forms.

Pressure records and the loss of motion signal from station 23 suggest that there was an emplacement stemming fall continuing to just below the top plug, at a depth of about 25 m. To gain further insight into the radiation detected in the emplacement hole after collapse, the pressure histories of the top four pressure stations are plotted in figure 4.14 for a period of 60 s covering the collapse. The signal from station 33 below the bottom plug was lost at about 4171 s while none of the data from stations at elevations above this were lost. The early portions of the collapse records from stations 35 and 36 are characteristic of rapid stemming fall, leaving an air gap in the vicinity of the sensors, station 36 for a longer period than station 35. Since no collapse motion was detected in the top plug (station 24), it is reasonable to assume that the top plug acted as a stemming platform. Later, upon reentry to the site, it was discovered that the top plug had fallen out of the surface casing and was displaced downward almost 25 m. (The interior of the surface conductor was inspected photographically and found to be coated with rust scale and mud cake with only a small area of bonding with the top plug remaining in evidence.)

As stated in section 2, it is suspected that the source of radiation seen at stations 35 and 36 was shine from the prompt gas sample hose. Station 35 had a very high background source chip which tended to mask the induced signal. However, to test the assumption that station 35 detected nearly the same external source as did station 36, the record from station 35 was low-pass filtered at 0.01 Hz and the background level of 0.5 R/Hr was subtracted. The resulting record is plotted in figure 4.15 along with that from station 36. Correlation of the two records is good, including the activity at about 12,000 s.

Gas sample activities halted a few minutes after the subsurface collapse and there was no further activity by the nuclear chemistry group, particularly around 12,000 s. This late perturbation in the radiation wave forms could have been caused by another shift in the stemming (not registered on the pressure transducers), further altering the radiation shielding effect of the stemming.

Figure 4.1 Vertical motion, during collapse, of the stemming below the bottom plug (station 21 at a depth of 159 m)

Figure 4.2 Vertical motion, during collapse, of the stemming between the bottom and top plugs (station 23 at a depth of 85 m). These data are used for timing and wave form only: the calibration is in question because the acceleration channel was driven out of band shortly after detonation and the velocity channel was lost at about 0.6 s.

Figure 4.3 Vertical motion, during collapse, of the satellite hole at a depth of 220.5 m (station 40).

Figure 4.4 Vertical motion, during collapse, of the satellite hole at a depth of 206 m (station 41).

Figure 4.5 Vertical motion, during collapse, of the satellite hole at a depth of 191 m (station 42).

Figure 4.6 Vertical motion, during collapse, of the satellite hole at a depth of 176 m (station 43).

Figure 4.7 Vertical motion, during collapse, of the satellite hole at a depth of 161 m (station 44).

Figure 4.8 Vertical motion, during collapse, of the satellite hole at a depth of 135 m (station 45).

Figure 4.9 Vertical motion, during collapse, of the satellite hole at a depth of 111 m (station 46).

Figure 4.10 Vertical motion, during collapse, of the satellite hole at a depth of 86 m (station 47).

Figure 4.11 Vertical motion, during collapse, of the satellite hole at a depth of 61 m (station 48).

Figure 4.12 Vertical motion, during collapse, of the satellite hole at a depth of 36 m (station 49).

Figure 4.13

Progression of the collapse as determined from the CLIPER records (stations 51, 92, and 93) and the D-cable (station 91). The upper limit of the subsurface collapse in the emplacement hole is indicated to be at a depth of about 25 m while in the satellite hole the depth of subsurface collapse is indicated to be about 75 m. The pressure record from the station just below the top the bottom plug and the displacement histories from the motion gauges in the stemming suggest that the stemming fall in the emplacement hole progressed upwards to the region of the top plug. Heavy traces are associated with the satellite hole. A discrepancy of several seconds between the CLIPER and D-cable data and the motion records is unexplained.

Figure 4.14 Composite plot of the pressure records from the top four stations. One minute covering the subsurface collapse is shown.

Figure 4.15 Overlay of the radiation records from stations 35 and 36. The record from station 35 (figure 2.5) was low-pass filtered at 0.01 Hz and 0.5 R/Hr was subtracted. The heavy trace is the record from station 36.

5. Stress measurements

As part of a continuing effort to develop a transducer to measure in-situ stress, three flat-pack, carbon foil element transducers were fielded in the satellite hole. Although at different elevations, each of the gauges was oriented such that the plane of the transducer was the expected plane of the wave front (to within 3°). Figures 5.1-5.3 show the output from each of transducers.

Each of the transducers was excited with a 30 ma constant-current source and the signal polarity was such that an increase in output signal indicated a decrease in resistance. The original foil resistance of each element is given in the corresponding figure caption. These data are shown only for completeness.

Figure 5.1

Output of carbon foil stress gauge at station 52 at a depth of 271.0 m (22.52 m from explosive source). The element had an original resistance of 320 Ω .

Figure 5.2 Output of carbon foil stress gauge at station 53 at a depth of 236.0 m (41.61 m from explosive source). The element had an original resistance of 313 Ω .

Figure 5.3

Output of carbon foil stress gauge at station 54 at a depth of 201.0 m (73.49 m from explosive source). The element had an original resistance of 326 Ω .

References

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APPENDIX Computation of strain from motion in a spherical field.

Under the assumptions that a spherical wave is traveling at large distances in a linearly elastic, isotropic, homogeneous medium, we may approximately derive the strain history from the motion history at a point.

The wave equation of the displacement potential, Φ , is given by^(a):

$$\frac{1}{C^2} \cdot \frac{\partial^2 \Phi}{\partial t^2} = \nabla^2 \Phi \quad \text{having a traveling wave solution of the form:}$$

$$\Phi(r, t) = \frac{f\left(t - \frac{r}{C}\right)}{r}.$$

The vector displacement is given by: $\vec{D} = \vec{\nabla} \Phi$.

In spherical symmetry, with all angular derivatives vanishing, these equations become:

$$\frac{1}{C^2} \cdot \frac{\partial^2 \Phi}{\partial t^2} = \frac{1}{r^2} \cdot \frac{\partial}{\partial r} \left(r^2 \frac{\partial \Phi}{\partial r} \right) \quad \text{and} \quad D = \frac{\partial \Phi}{\partial r}. \quad (1)$$

Strain along a transverse principal axis is given by^(a)

$$\epsilon_{\theta\theta} = \frac{D}{r} \quad (2a)$$

and along the radial principal axis

$$\epsilon_{rr} = \frac{\partial D}{\partial r} = \frac{\partial}{\partial r} \frac{\partial \Phi}{\partial r} = \frac{\partial}{\partial r} \frac{\partial}{\partial r} \left(\frac{f}{r} \right) = \frac{\partial}{\partial r} \left(\frac{1}{r} \frac{\partial f}{\partial r} - \frac{\Phi}{r} \right) \quad (2b)$$

But since we have a traveling wave, $\frac{\partial f}{\partial r} = -\frac{1}{C} \frac{\partial f}{\partial t}$, and replacing this in equation (2b) and performing the derivative we have:

$$\epsilon_{rr} = \frac{\partial}{\partial r} \left(-\frac{\Phi}{r} - \frac{1}{rC} \frac{\partial f}{\partial t} \right) = \frac{\Phi}{r^2} - \frac{1}{r} \frac{\partial \Phi}{\partial r} - \frac{1}{C} \frac{\partial}{\partial r} \frac{\partial \Phi}{\partial t} \quad (2c)$$

which reduces to^(b):

$$\epsilon_{rr} = \frac{\Phi}{r^2} - \left\{ \frac{\frac{\partial D}{\partial t}}{C} + \frac{D}{r} \right\}. \quad (2d)$$

Now, remembering that $\frac{\partial D}{\partial t}$ is the particle velocity, U , and neglecting the term $\frac{\Phi}{r^2}$, the volume strain is given by

$$\varepsilon_v = \varepsilon_{rr} + 2\varepsilon_{\theta\theta} = \frac{D}{r} - \frac{U}{C} \quad (3)$$

(a) Y. C. Fung; "Foundations of Solid Mechanics", Prentis-Hall, Inc., 1965, pp. 114 & 186.

(b) We are indebted to R. W. Terhune for initially showing us this relationship.

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