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RESULTS OF LONG TERM GROUND SURFACE MEASUREMENTS AT THE HOE CREEK III SITE

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RESULTS OF LONG TERM GROUND SURFACE MEASUREMENTS AT THE HOE CREEK III SITE

by

Harold C. Ganow 1/

ABSTRACT

Ground surface subsidence was first observed over the Hoe Creek III burn cavity 21 days after gasification ceased. It manifested itself as a small circular depression or sink and was followed five days later by the formation of a second collapse structure. Concurrently, a single large elliptically shaped depression, whose major axis parallels the experimental axis, slowly formed over the burn cavity. These features appear to represent two distinctly different deformation modes. The first mode includes discrete voids that propagate rapidly upward. The second mode is represented by the elliptically shaped classical subsidence depression that forms slowly by a strata bending. Seventeen isolation type survey monuments have been used to track both the horizontal (one dimensional) and vertical motion components intermittently over a 54 month span. The resulting data set is combined with ground surface sketches and post-burn core drilling results and provides an important case study against which numerical and centrifugation model results can be compared.

INTRODUCTION

Underground coal gasification (UCG) is a novel method for the extraction of an economically unmineable coal resource. Unmineability is often caused by site specific geologic conditions such as great overburden thickness, excessively weak roof or floor, and adverse hydrologic conditions in the rock overburden or in the coal itself. These conditions can also adversely affect the UCG process but not necessarily in the same manner, or to the extent of conventional mining. Both UCG and conventional mining create cavities underground. The overburden must now be supported by the remaining coal which causes increased stress in the ribs. However, the process and geometry of the excavation is carefully controlled in conventional mining while it is very poorly controlled during a gasification burn.

Two main environmental concerns associated with UCG are ground-water contamination and surface subsidence. Both are closely coupled by the formation of a collapse rubble chimney over the combustion cavity that penetrates superjacent aquifers (Stone et al., 1982). These environmental problems have been investigated through experiments associated with three UCG burns conducted at the Hoe Creek Site

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located in north-eastern Wyoming. This article reports the results of ground-surface motion measurements made in conjunction with the Hoe Creek III Experiment described by Hill (1981). This experiment resulted in ground surface subsidence which has been described by Ganow (1980). For completeness, a brief description of the site geology, Hoe Creek III, and the surface subsidence features is given below.

HOE CREEK SITE GEOLOGY

The Hoe Creek UCG Site is located near the east-central margin of the Powder River Basin. Here, the Eocene age Wasatch Formation contains two shallow subbituminous coals: the main Felix No. 2 (lower) and the Felix No. 1 rider coal which are 7.6 m (25 ft) and 3 m (10 ft) thick, respectively. They are separated by a 4.9 m (16 ft) thick crevasse splay sequence, and are overlaid by a stream channel sand and lacustrine sediment sequence (Fig. 1). The sedimentary rock units are comparatively weak and compressible although sporadic pods of extremely hard calcite cemented sandstone do occur (Ganow, 1979). The majority of the sand units are so weak that they can be easily crushed by hand. Depths to the top and bottom of the Felix Nos. 1 and 2 Coals are 39.7 m (130 ft) and 42.7 m (140 ft), and 47.9 m (157 ft) and 55.5 m (19=82 ft), respectively. In general, the coals are the strongest units present in the geologic section even though they are pervasively fractured by near vertical joints called cleats. Depth to groundwater is about 33.5 m (110 ft) at Hoe Creek III which places it about midway in the channel sand unit.

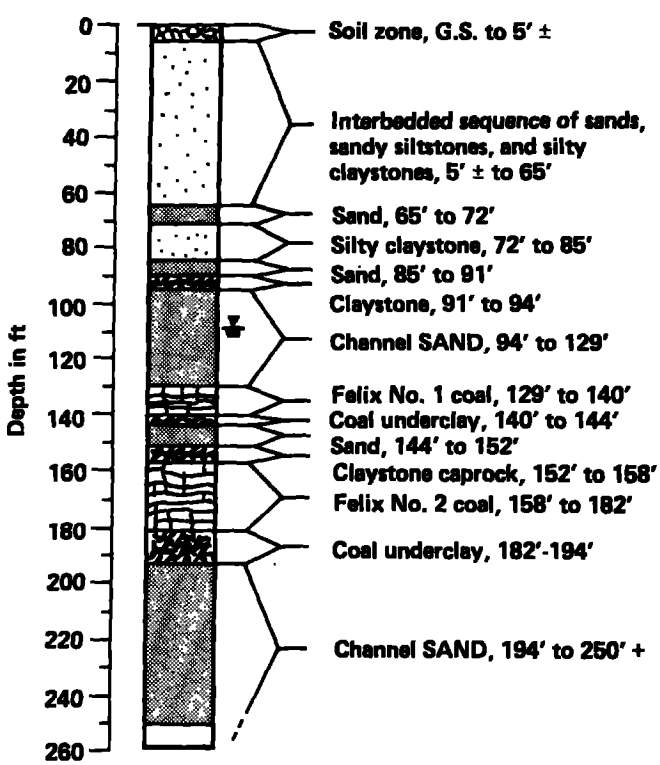


Figure 1. Hoe Creek III Simplified Geologic Section

HOE CREEK III EXPERIMENT

The experimental design and results of Hoe Creek III have been described in detail by Stephens, 1981. In summary, a small diameter directionally deviated borehole (DD-1) was drilled so as to provide a gas flow path near the base of the lower coal. Five vertical process wells (see Fig. 2) were then

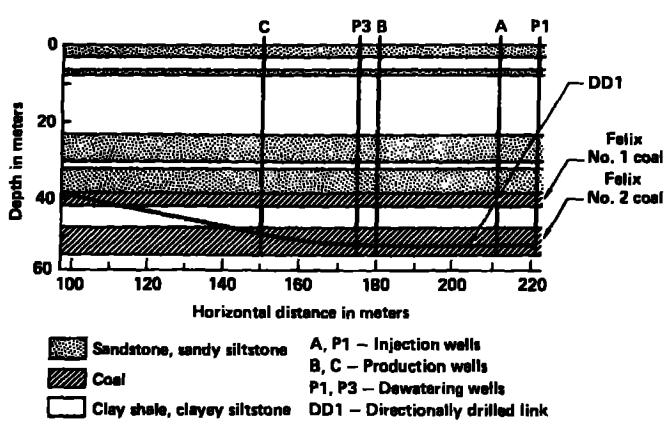


Figure 2. Hoe Creek III Process Wells, Geology, and Borehole DD-1.

drilled to intersect DD-1 or were linked to it by hydraulic jetting. Wells P-1 and A were used as injection points for mainly steam and oxygen while wells B and P-3 were used to produce the product gas. Well C was not used during the test. Important interwell spacings are as follows: Wells P-1 to A is 10 m (33 ft), A to B is 30 m (99 ft).

Ignition occurred in Well B on August 14, 1979. DD-1 was enlarged during three days of reverse combustion and was immediately followed by the forward-burn (cavity creation) phase which is Julian Day 1 of this report. Seven days after ignition, combustion reached the top of the Felix No. 2 coal and it is likely that limited roof collapse began very soon thereafter. By day 12 roof collapse had exposed the overlaying Felix No. 1 Coal and it too began to gasify. Forward combustion continued, using various combinations of injection and production wells, until October 10th (day 55). A total of 3945 tons of coal were consumed from both Felix Coals during the test (Stephens, 1981).

SURFACE SUBSIDENCE

About 23 days later (Julian day 78), a small 2 m (6 ft) diameter by 1 m (3 ft) deep depression suddenly appeared over the burn zone. It was located about 4 m (13 ft) from Well-A along the DD-1 symmetry axis toward B-well (Ganow, 1980). At first, a large

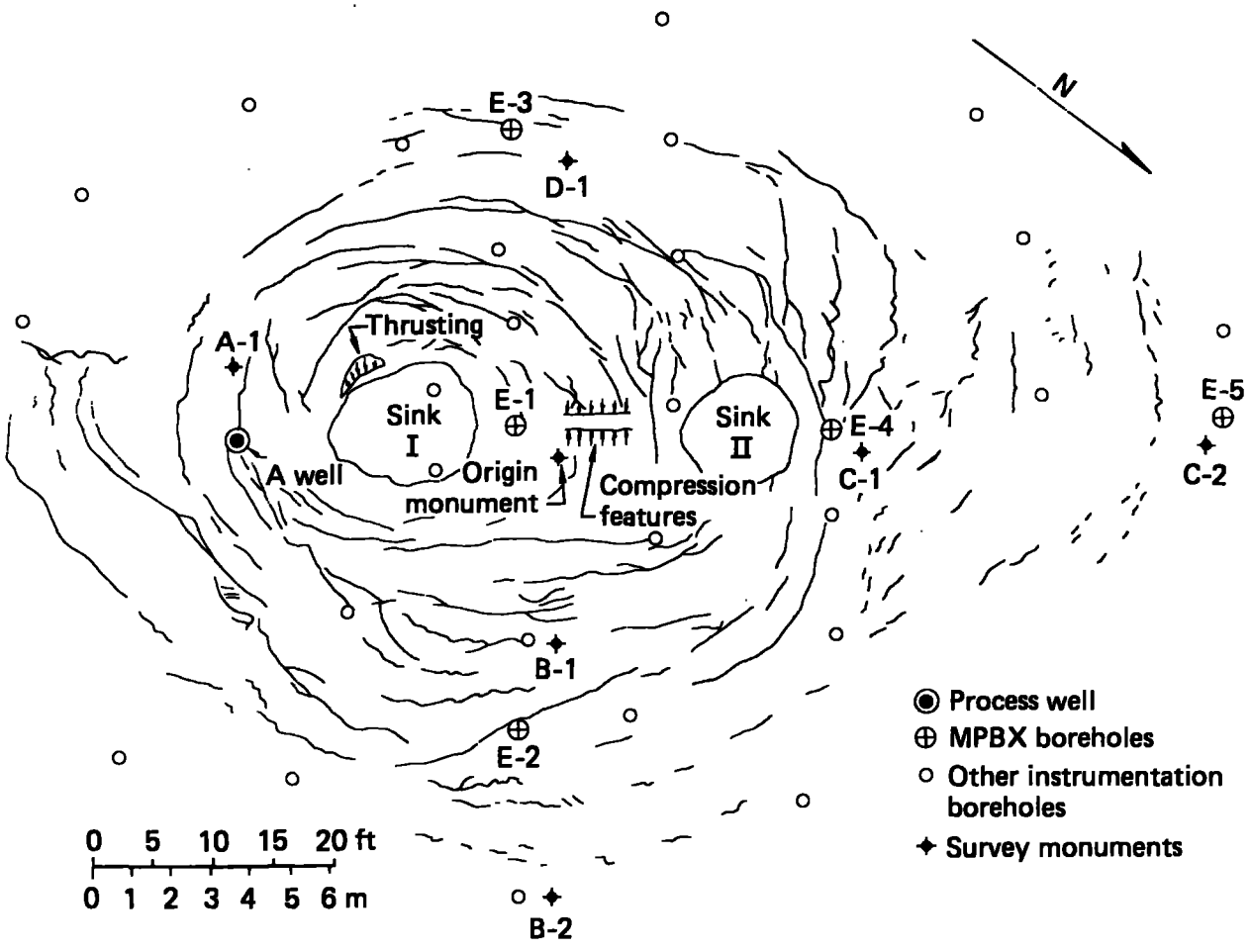


Figure 3. Hoe Creek III Subsidence Features on Julian Day 81.

amount of steam issued from the dimly visible soft broken material in its bottom. Several thin circumferential cracks were also noted and subsequently mapped around this feature which is designated Sink 1. For the next four days, the evolution of these and associated features, including a second suddenly formed sink, were carefully described and photographed. Figure 3 shows the final surface feature map just before they were obliterated by a major winter storm.

Several important points should be mentioned. First, both sinks, which represent the penetration of large single voids through the overburden, are located along the DD-1 symmetry axis. Second, the circumferential cracking is also roughly symmetrical to this axis, and is centered on what appears to be the region of maximum coal combustion thickness (see Fig. 4). Third, the appearance of small scale compression features such as thrust faults and buckles indicates the passage of a compressional "stress wave" through the overburden to the ground surface. This is a "progressive" form of "stoping" failure that continues until the combustion cavity is full of collapse rubble or the ground surface is intersected.

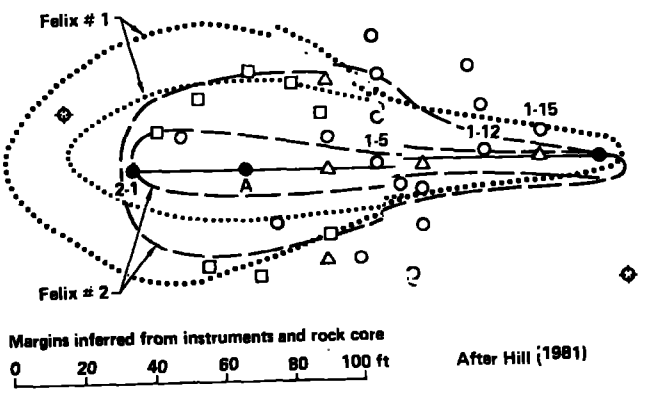


Figure 4. Hoe Creek III Burn Margins for Felix Nos. I and II Coals.

POST-BURN CORING RESULTS

Following the appearance of subsidence, 16 partially cored boreholes were drilled into the combustion region. Results from these boreholes have established the following important points. First, the presence of DD-1 strongly influenced the combustion zone position in both coals. It essentially forms a line of symmetry containing the process wells. Second, the combustion zone is wider at the top interfaces of the coals, and in the upper Felix No. 1 Coal, than in the No. 2 Coal where DD-1 had been located. Thus, the effectively unsupported overburden column is that portion within the outermost boundary shown in Figure 4. Because of thickness differences, it is likely that about equal amounts of coal were consumed from the two seams. Third, thermal alteration effects observed in rock core indicate that overburden collapse into the combustion cavity was well advanced before gasification ceased.

SURFACE MOTION EXPERIMENT

MONUMENT ARRAY DESIGN

The monument array plan view is shown in Figure 5. It consists of four lines containing 23 specially constructed isolation-type bench marks arranged in a simple crossing pattern aligned, as much as possible, parallel and transverse to the experimental (DD-1) axis. An origin (ORI) monument is located at the point of intersection and an elevation reference monument is located about 200 m (650 ft) to the west north-west. The A-line extends 70 m (227 ft) from ORI toward injection wells A and P-1, and beyond. C-line extends 93 m (304 ft) toward production wells B and P-3, and beyond. Lines B and D are oriented perpendicular to lines A and C, and extend 55 m (180 ft) and 77 m (153 ft) in opposite directions, respectively.

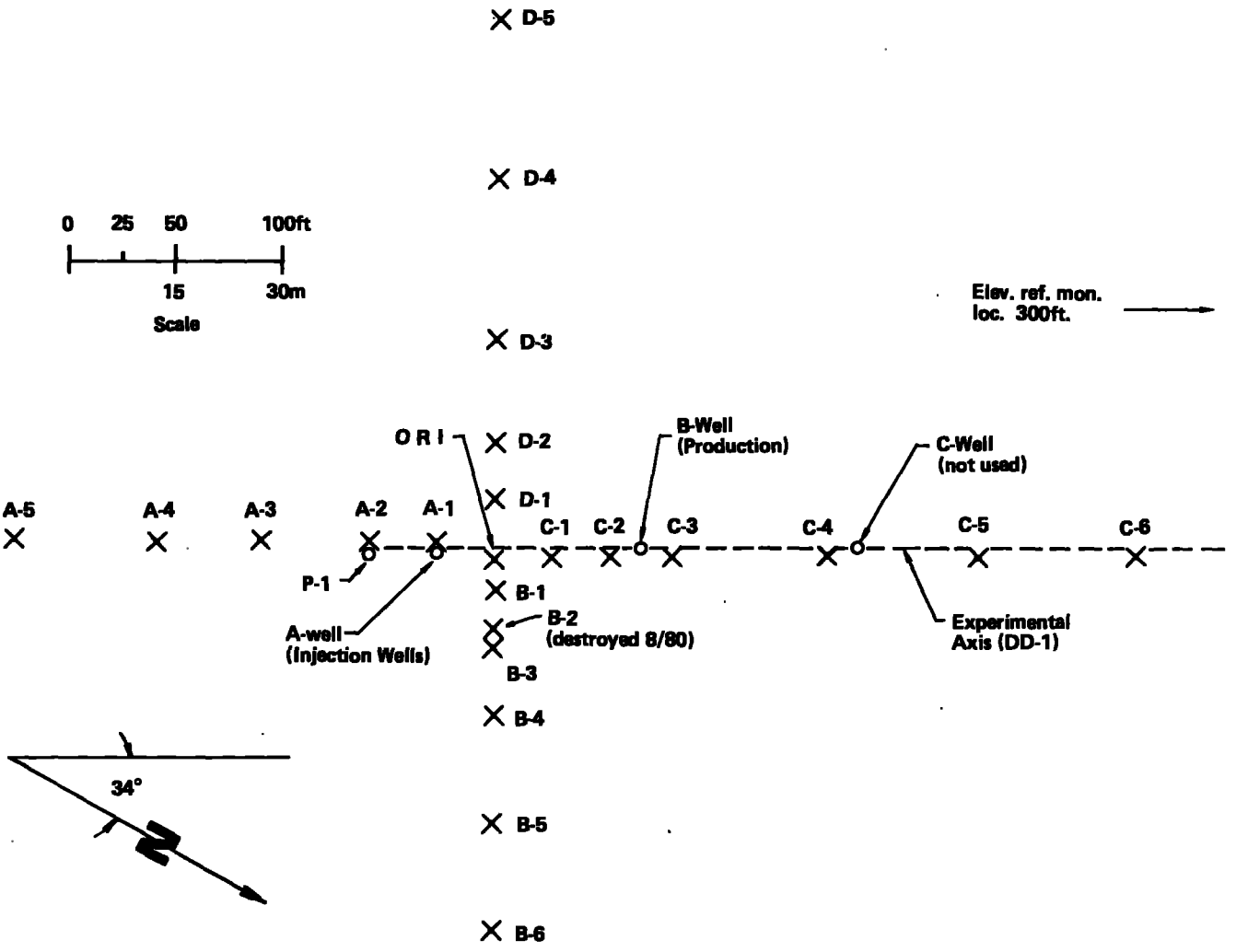


Figure 5. Plan View of Hoe Creek III Monument Array.

Together, the A - C and B - D lines, whose ends are located outside of the zone of motion, form a simple, one-dimensional, crossing pattern aligned parallel and perpendicular to the Hoe Creek III axis.

MONUMENT CONSTRUCTION

An "as built" section diagram of the isolation bench mark is shown in Figure 6. Previous experience has shown that the northeastern Wyoming soils contain abundant expansive clays and are extremely active. Standard 0.45 m (18 in.) long "brass cap" survey markers rise and fall with changing water content, and cannot be used for precision surveys. Therefore, the monument consists of a long 50 mm (2 in.) diameter iron pipe firmly anchored below the active shrink/swell zone. Isolation is provided by a 115 mm (4 1/2 in.) I.D. PVC tube held in place by a second stage of neat cement grout. Subsequent measurements indicate that the monuments performed very well.

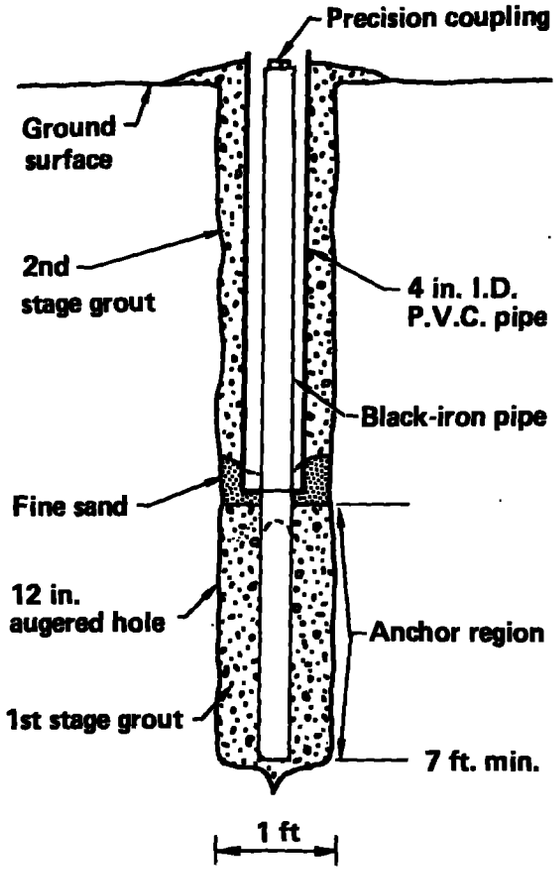


Figure 6. Isolation Monument Design

MEASUREMENT TECHNIQUES

Vertical Component

Elevation measurements were made using a standard Leitz self-leveling optical level and Philadelphia Rod marked in 3 mm (0.01 ft) divisions. An arbitrary Hoe Creek III datum of 30 m (100 ft) was assigned to the previously mentioned reference monument. Each survey consisted of a loop that began and ended at this monument. Sight path lengths were kept to less than 50 m (165 ft), elevations were estimated to 0.3 mm (0.001 ft), and closure errors averaged 1.11 mm (0.0037 ft) for the 13 surveys. Therefore, no data corrections have been needed.

Horizontal Component

Horizontal measurements were made using a SINCO Model 51855 Precision Tape Extensometer (TEX) shown in Figure 7. The unit consists of a 30 m (100 ft) long stainless steel tape in which small holes have been punched on 50 mm (2 in.) centers. A 50 mm (2 in.) range dial indicator gauge reading directly in 0.001 in., and a constant tension assembly consisting of a proving ring and dial indicator complete the package. To make these measurements, a special 0.3 m (1 ft) long adaptor pin was threaded into the precision coupling on top of two adjacent monuments (see Fig. 5). The TEX couplers were then placed on spherical seats and the unit was adjusted to the

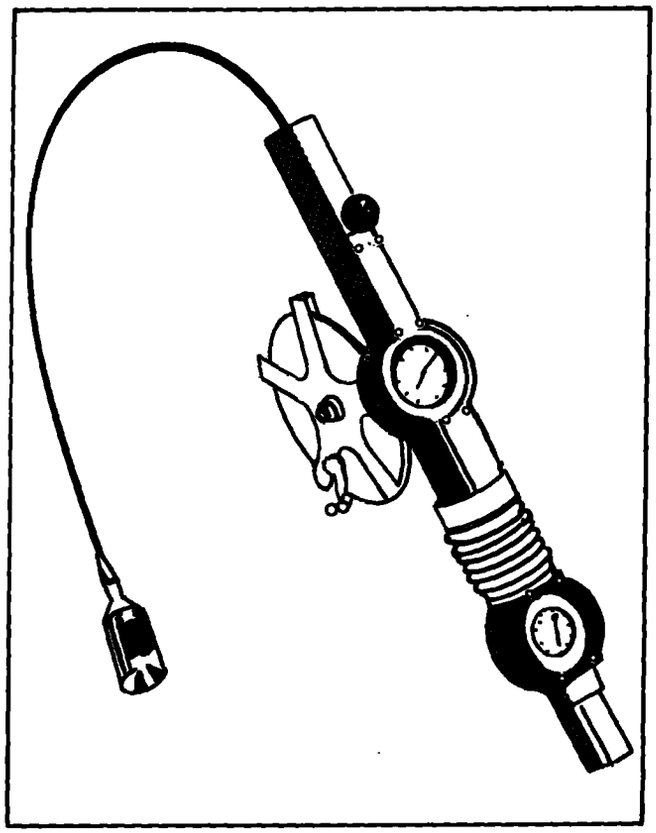


Figure 7. SINCO Precision Tape Extensometer Design.

275 kPa (40psi) tension with the tape hanging free. Three sets of measurements; including tape length and dial gauge, and tape temperature (measured with a Markson digital thermometer) in both the direct sun and shade (if any) were recorded for each span allowing for complete thermal expansion corrections. An INVAR metal tape is not made for the SINCO TEX unit. A complete survey consisted of 22 single span measurements. Instrument repeatability was about 0.08 mm (0.003 in.) while measurement repeatability is about 0.91 mm (0.036 in.). Data reduction and correction techniques are discussed below.

DATA REDUCTION

Vertical Component

Inspection of the elevation data clearly indicated them to be of such quality than no additional corrections needed to be made. The accuracy of each measurement is basically indicated by the closure error which was acceptably low in all cases. Thus, data reduction consists of the derivation of an initial composite data set for each monument from four surveys done before and during an early stage of the burn, subtraction of the post-burn measurement set of interest, and graphically displaying the resulting differential vs. position or log time.

Horizontal Component

The horizontal motion component data obtained from the TEX are inherently much more complex. First, unlike the elevations, each measurement in the A - C or B - D line pair is dependent on all other measurements in that line. Second, the TEX places a substantial lateral load on the monument shaft which caused it to deflect. The assumption that this deflection is repeatable between surveys appears to be acceptable based on examination of the data. Third, it is assumed that the temperature distribution along the tape can be adequately described by two measurements (sun and shade), the percentage of the tape in the sun, and the thermal expansion coefficients (alphas) for the materials involved. Last, the measured value is strongly influenced by the repeatability and drift characteristics of the tension load measurement assembly.

Data reduction consists of first making the necessary thermal corrections using codes written for the HP-41c calculator by the author. The initial data set values were derived from five surveys in the same manner previously described for the elevation data. The sum of the individual measurements for each line pair was then compared to the total initial line length value and small differences were partitioned between each measurement on a "percentage of total length" basis. This correction assumes that the total length error is systematic in nature, and is caused by changes in tape tension. The monotonic decrease in total line length (increasing tape tension), and the general appearance of the plotted data, support this contention. After corrections, the initial composite and subsequent data sets are each incrementally summed (beginning with monuments A-5 or B-6) and subtracted from each other. The result is an estimate of the horizontal motion component in the direction of the survey line. These data are then also graphed vs. positions or through log time like the elevation data.

Special Problems

During collection of the initial data surveys the TEX tape, which was weakened by the small indexing holes previously described, broke. The almost complete survey was quickly redone using the repaired but shortened tape, and an additive constant was derived that allows use of all pre-break data sets.

In August 1980, monument B-2 was accidentally destroyed during regrading associated with site restoration. This loss did not impact elevation measurements but strongly affected TEX measurements in the transverse B - D line. Fortunately, the TEX had sufficient remaining range to span the interval between B-1 and B-3 and, after deriving a new "initial distance" value, measurements were resumed.

MEASUREMENT RESULTS

The ground surface motion data is presented in the following sections. The elevation (vertical component) data are first presented for the A - C lines which are essentially parallel to the experimental axis, and then for the transverse B - D lines. Then, the horizontal motion data are presented, first for the A - C lines and then the B - D lines as before. Finally, the vertical and horizontal motions vs. time plots are presented for selected monuments.

VERTICAL DATA

A-C (axial) Lines

Figure 8A presents the elevation change data for the relatively early time data. The data shown are for Julian days 78 and 81 which are one and four days after the appearance of Sink I, respectively. The origin monument (ORI) is moving the most rapidly followed by A-1. Sink I is located slightly to one side of the line connecting ORI and A-1 (see Fig. 3). There is also a hint of motion on A-2, C-1, C-2, and C-3.

Figure 8B shows the full time span of data using a reduced y-axis scale. It is clear that the general displacement pattern had been established quite early and is centered over the region of maximum thickness of burned coal. C-1, located on the northern edge of Sink II, has not participated in large scale vertical motions. Maximum vertical motion on ORI is slightly less than 1 m (3 ft), although motions of 1 m and 3 m (3 and 10 ft) were observed in Sinks I and II, respectively.

B-D (transverse) Lines

Figures 9A and 9B display data in the same format as 8A and 8B. Early time data indicate that D-1 had subsided slightly more than B-1. This situation appears to reverse in the later data. The main impression is one of overall symmetry with the vertical motions having very sharply defined boundaries both parallel and transverse to DD-1.

HORIZONTAL DATA

A-C (axial) Lines

Figures 10A and 10B present the horizontal motion components parallel to DD-1. As should be expected, all A-line monuments are deflecting to the right wile all C-line monuments, including ORI, are deflecting to the left - all toward Sink I. The deformation shape has also quickly become established as with the elevation data. A-1 deflections are much larger than C-1 motions suggesting that the maximum unsupported span is near the P-1 well region. Also, the origin monument reverses direction between Julian days 81 and 114 indicating that the center of deformation moved from between A-1 and ORI to between ORI and C-1.

B-D (transverse) Lines

Figures 11A and 11B show the horizontal motions transverse to DD-1. B-line and ORI motions are to the right while the D-line monuments are moving to the left - again, all toward the cavity. Motion patterns are established early, and the neutral point appears to shift slightly toward the D-line side of the experiment).

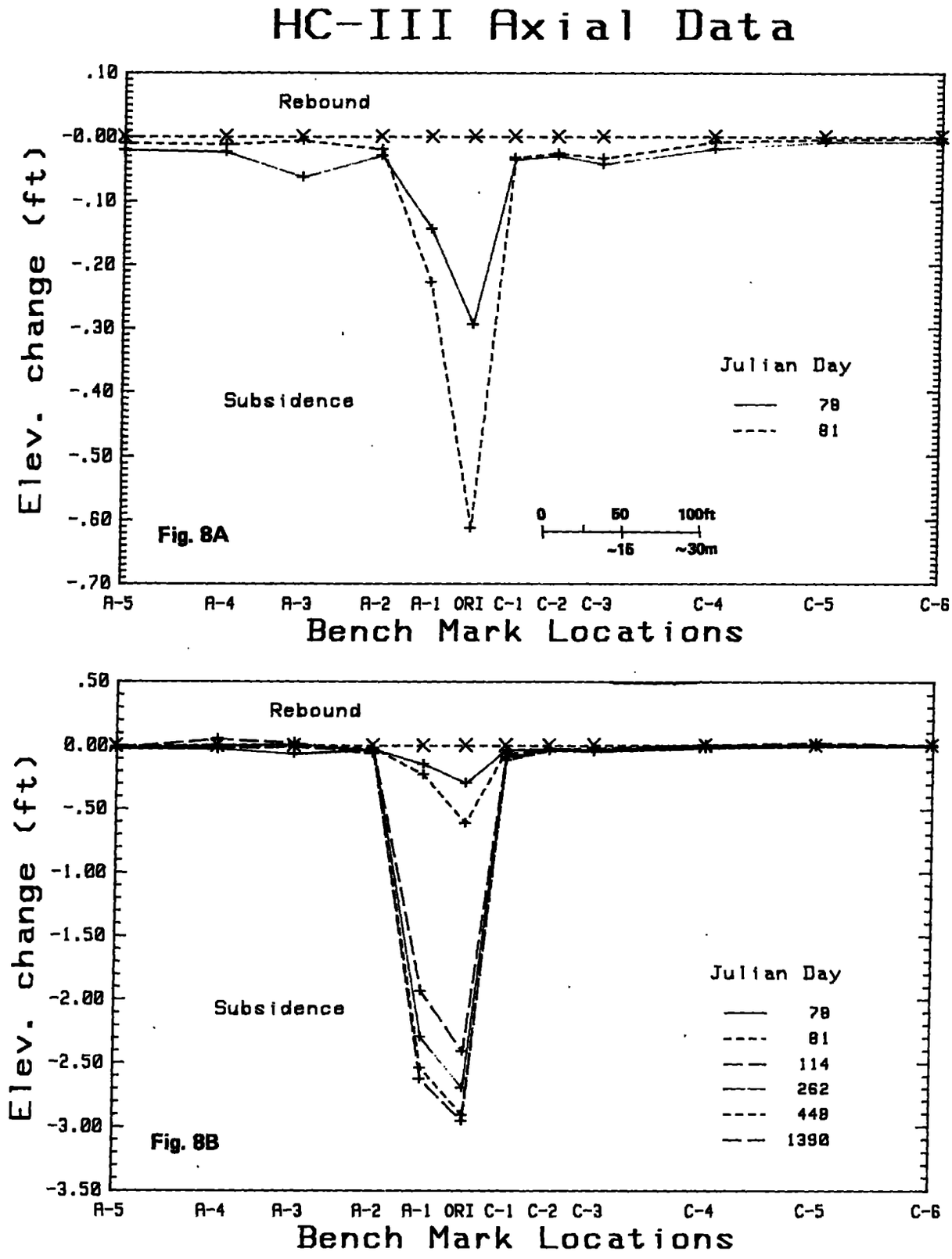


Figure 8. Vertical Motions Parallel to the Hoe Creek III Axis.

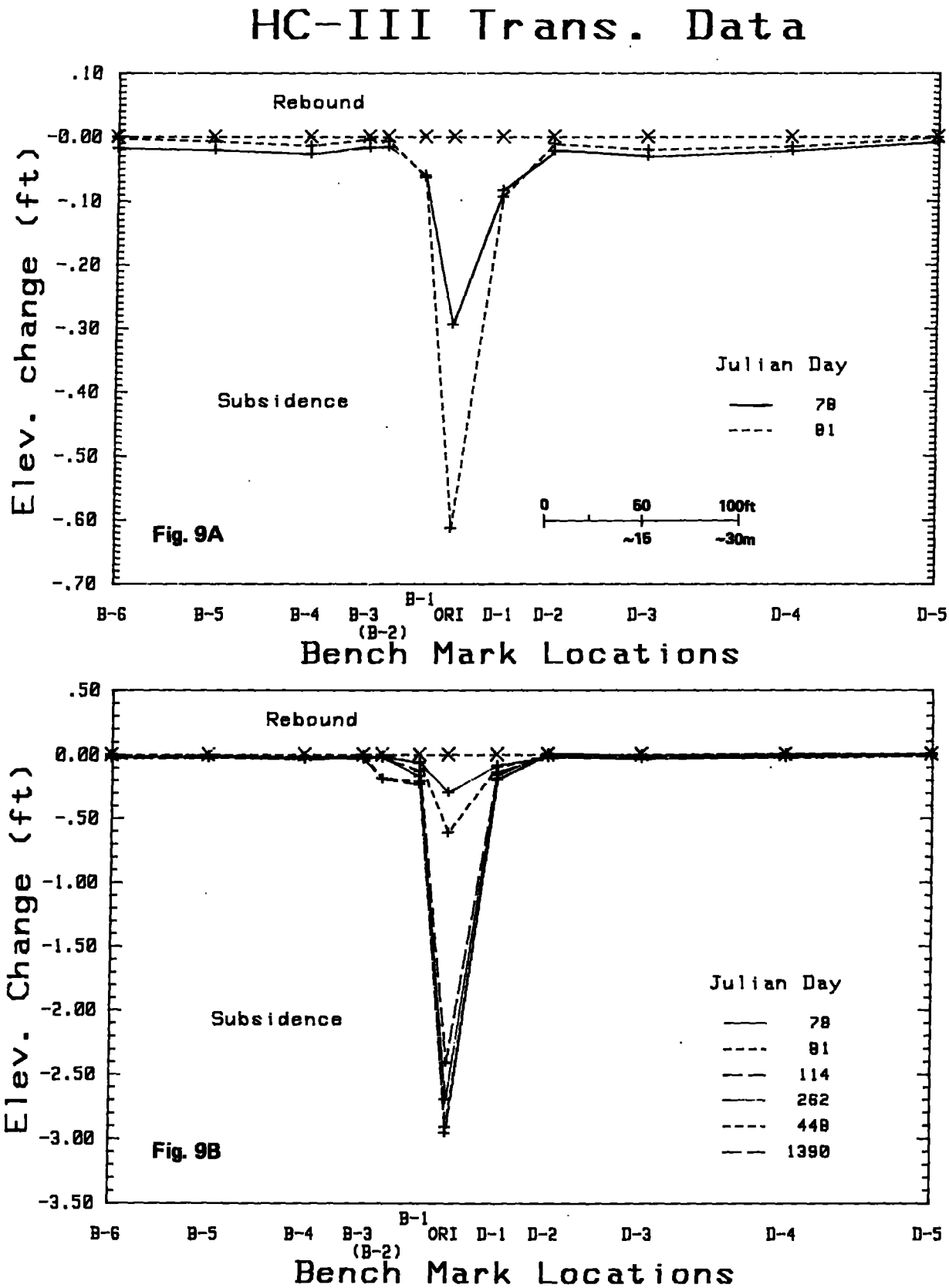


Figure 9. Vertical Motions Transverse to the Hoe Creek III Axis.

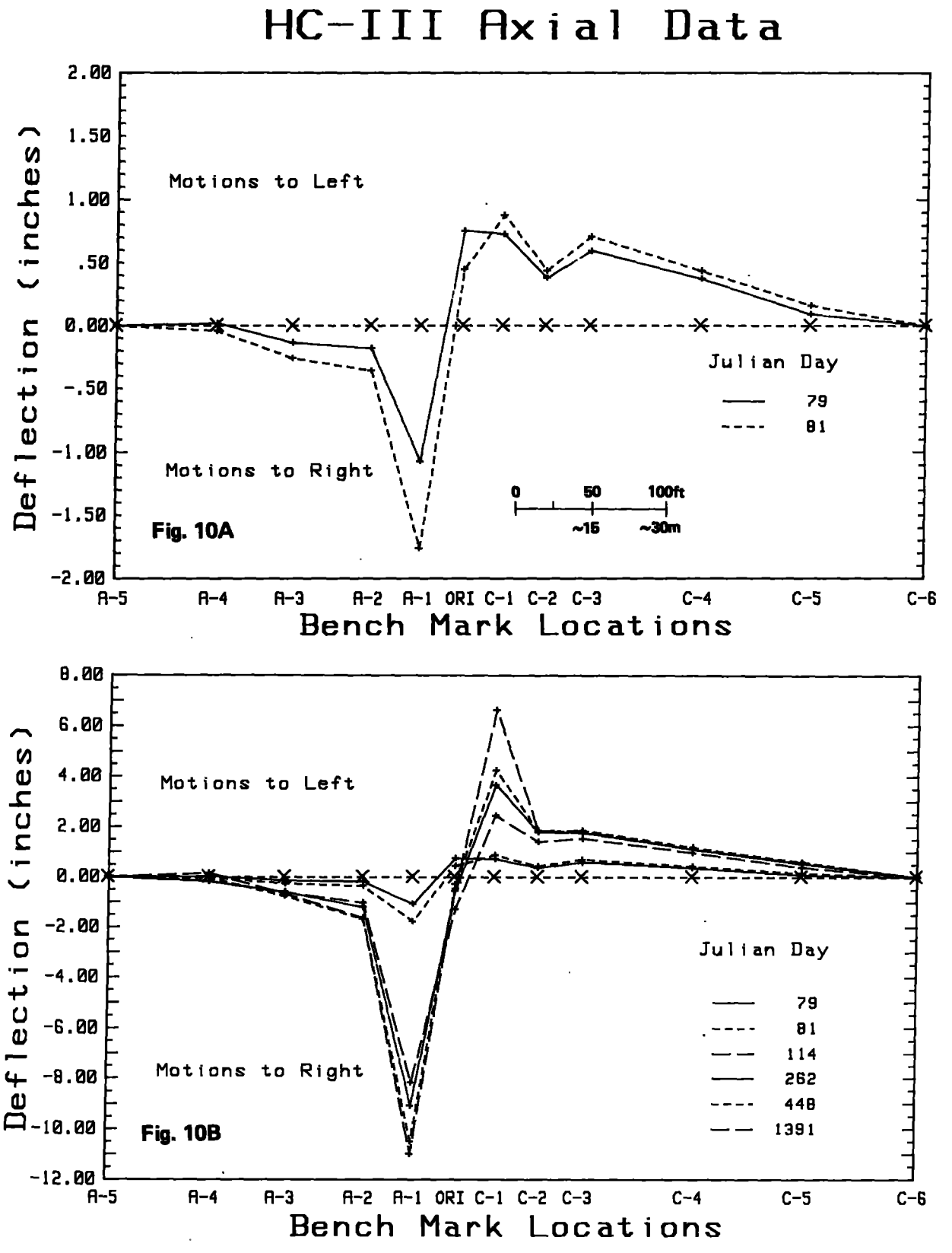


Figure 10. Horizontal Motions Parallel to the Hoe Creek III Axis.

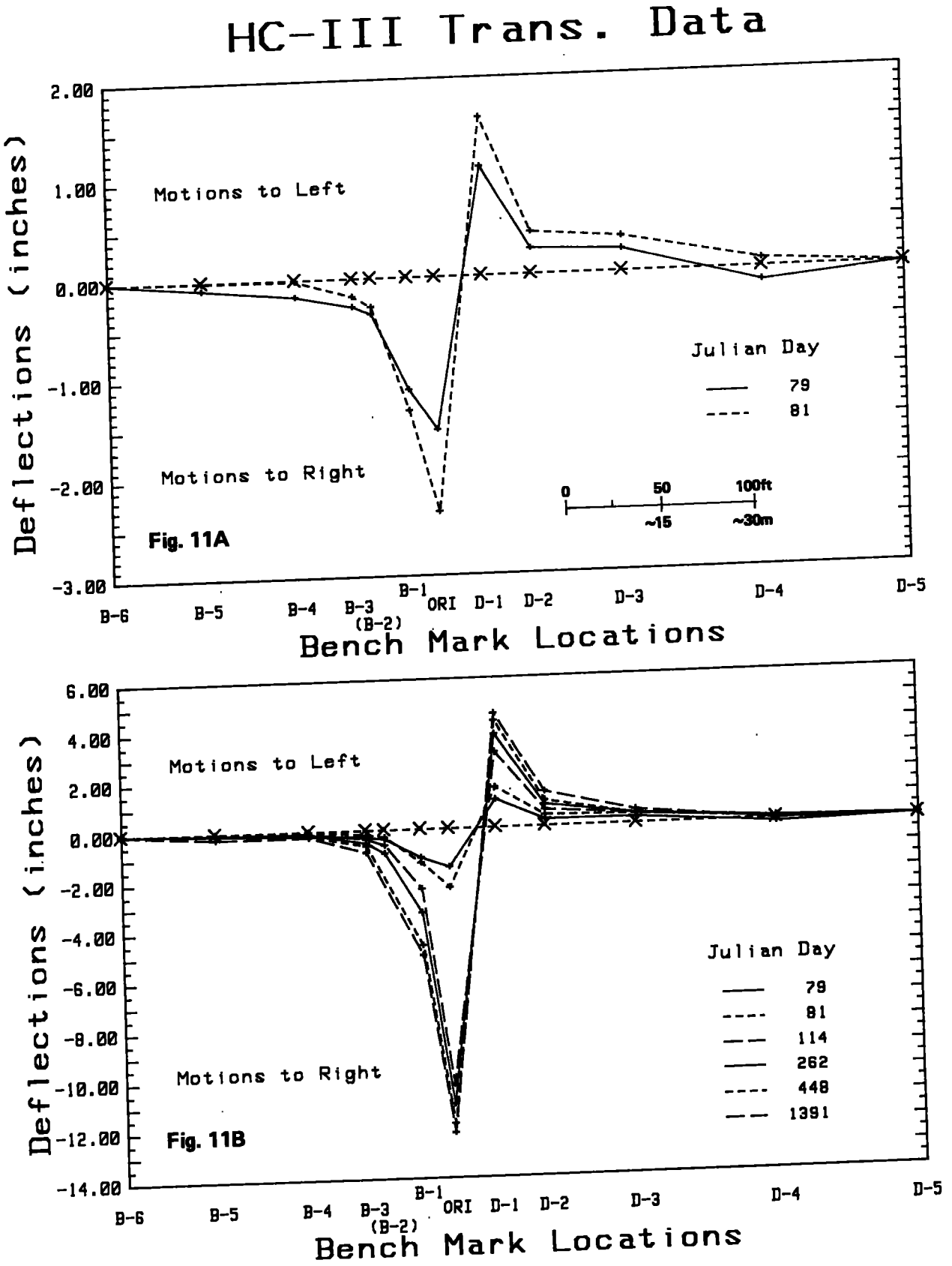


Figure 11. Horizontal Motions Transverse to the Hoe Creek III Axis.

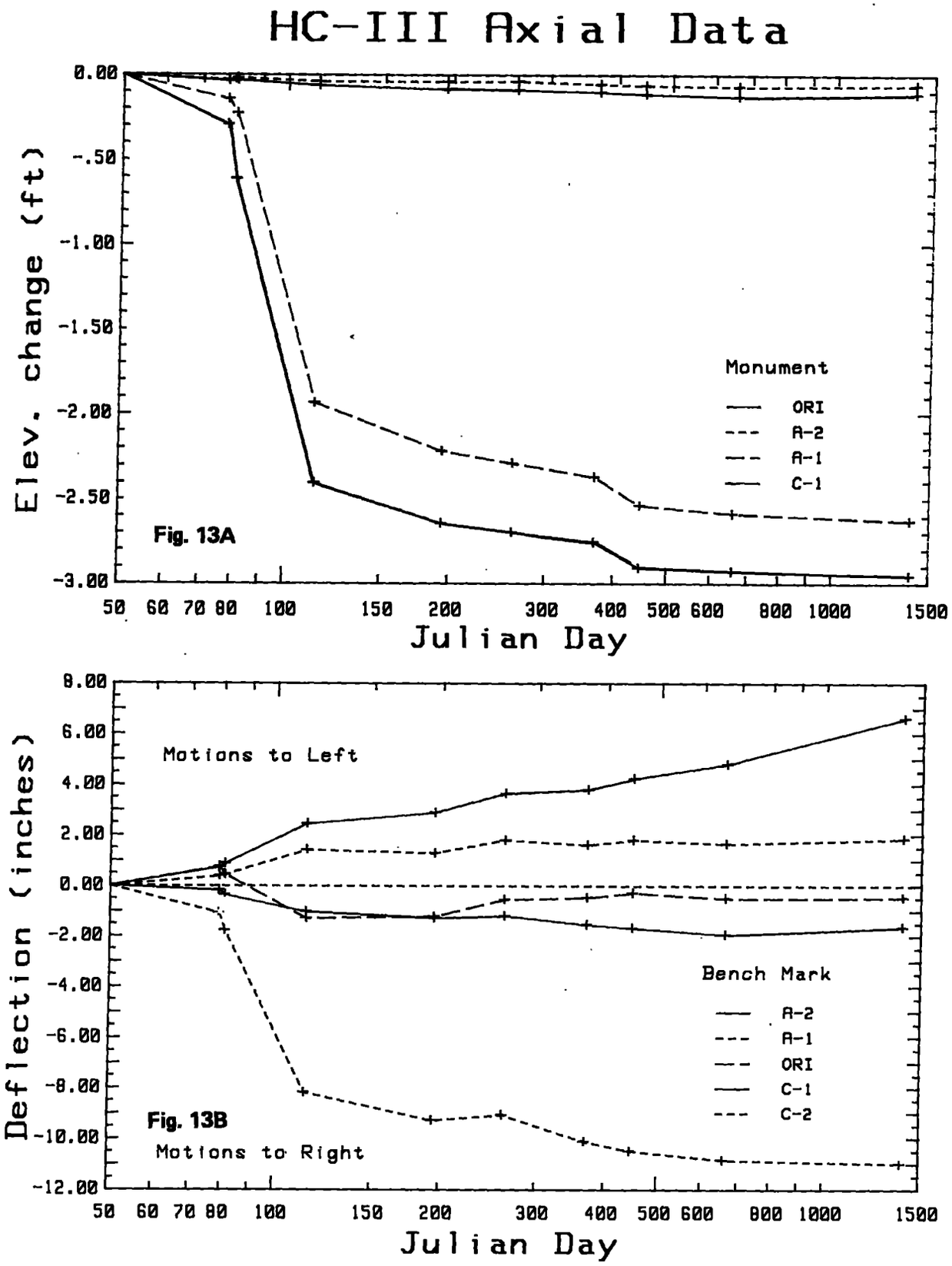
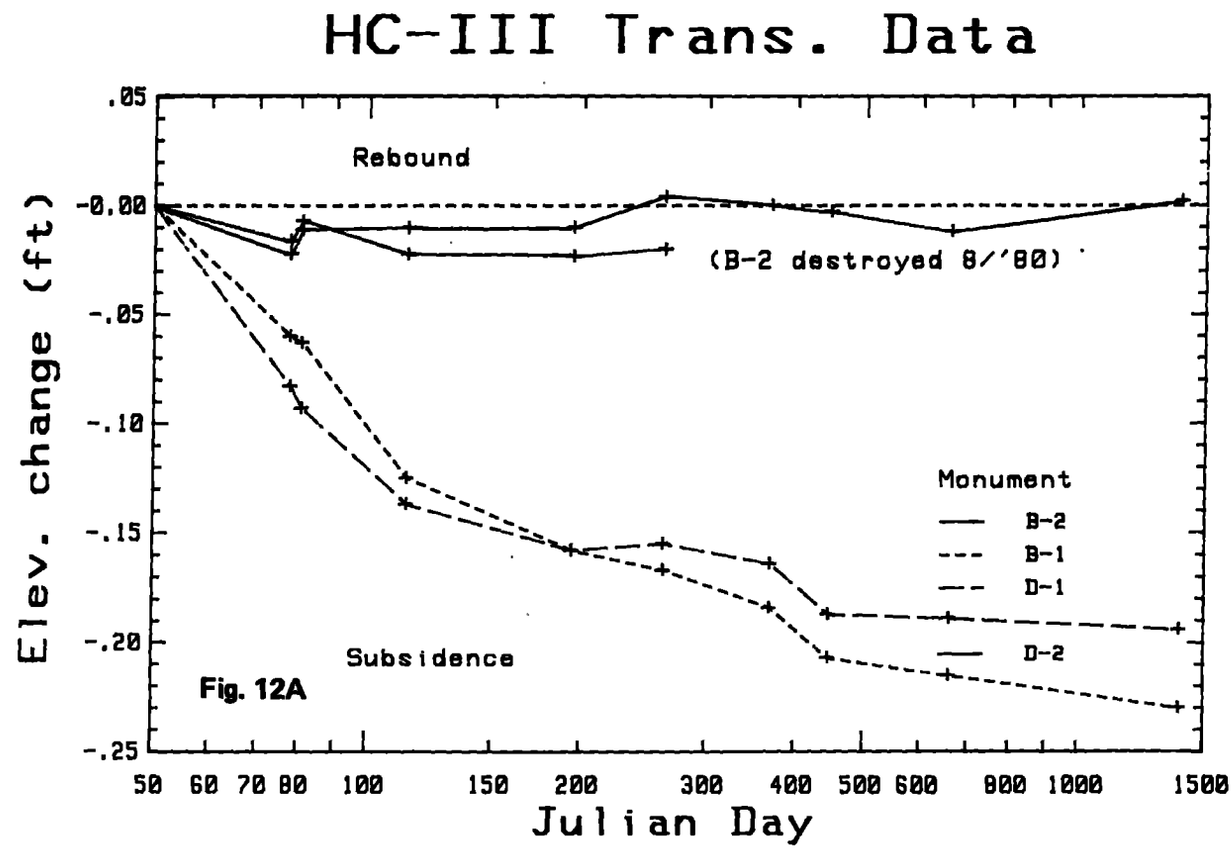


Figure 12. Axial Vertical (12A) and Horizontal (12B) Motions vs. Log Time.



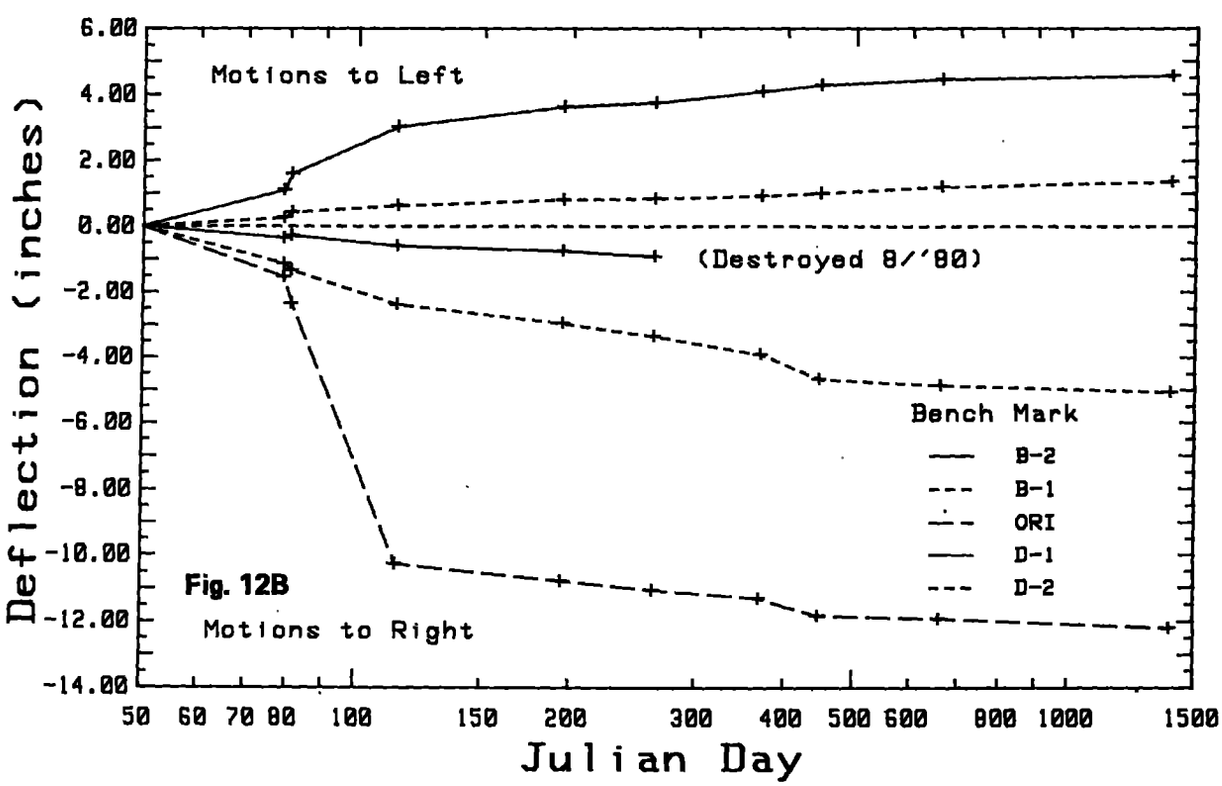


Figure 13. Transverse Vertical (13A) and Horizontal (13B) Motion vs. Log Time

DEFORMATIONS VS. TIME

A-C (axial) Lines

Figures 12A and 12B show vertical and horizontal motions vs. log time, respectively. Clearly, the majority of the vertical motion changes occurred between Julian days 81 and 114 when winter weather prevented their observation. In general, the curve shapes suggest that deformation has followed an exponential decay relationship with time, which would be expected from an increasingly slowly consolidating rubble column. Motion and rate changes also suggest that the process does not operate smoothly, but that adjustments continue to be made. The apparent rate change that occurred after Julian day 355 may have been caused by the post-burn coring activities which ended on that day.

B-D (transverse) Lines

Figures 13A and 13B are also vertical and horizontal motion vs. log time plots. Vertical motions (Fig. 13A) do not show the rapid early time changes apparent in the axial data (Fig. 12A) and monuments B-1 and D-1 show nearly identical subsidence. Symmetry of horizontal motion is also apparent between monuments B-1 - D-1 and B-2 - D-2 (Fig. 13B). Notice that the origin monument (ORI) appears to move rapidly to the northwest (Figs. 12B and 13B). It is likely that some of this motion is caused by monument shaft rotation rather than by pure vertical and horizontal translation.

CONCLUSIONS

The following conclusions are advanced concerning the origin and evolution of subsidence associated motion in conjunction with the Hoe Creek III Experiment.

1. The subsidence that occurred over the Hoe Creek III Experiment is simply the direct result of a successful UCG burn of up to 7.6 vertical m (25 ft) of coal under a comparatively shallow cover of weak rock.

2. Subsurface collapse was well underway during the burn, and the appearance of Sink I three weeks later was simply the culminations of a time dependent process.

3. Two types of subsidence occurred. The first was the suddenly formed sink which represents the eruption of large discrete voids. The second is the more classical subsidence depression that forms more slowly over the consolidating rubble column.

4. Properly constructed monuments arrayed in a simple crossing pattern can be used, along with simple direct measurement techniques, to measure both vertical and horizontal motions associated with the strata bending type of subsidence.

5. Vertical motions measured using an optical level ranged up to 1 m (3 ft). The vast majority of motion occurred on monuments near the injection end of the experiment, and was essentially symmetrically arrayed on either side of the DD-1 drilled link. The motion pattern became established early during the evolution of the feature, and rates have mainly decreased with time.

6. Horizontal motions measured using a precision tape extensometer ranged up to 0.3 m (1 ft). The larger motions occurred in the injection well region. Lateral motions along the B-D line suggest that the neutral point occurred between ORI and D-1 monuments. This may be caused by the slight westward slope to the ground surface. Here, too, the horizontal deformation pattern became established quite early. Rates have decreased with time with the possible exception

of C-1. An "incipient" Sink III briefly appeared in this region but was quickly obscured by plant growth. It is likely that voids exist and broken rock may still be moving down the narrow B-well end of the experiment.

7. It seems likely that the majority of motions have occurred and filling of the depression can take place. It would be advisable to avoid placing heavy trucks on the production well end of the experiment.

ACKNOWLEDGMENTS

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REFERENCES

Ganow, H. C., 1979, "In Situ Coal Gasification at the Hoe Creek, Wyoming Field Site - An Overview", Wyoming Geological Assoc. Earth Sci. Bull., V. 12, No. 3, p. 1-17.

Ganow, H. C., 1980, "Surface Subsidence Associated with the Third UCG Experiment at Hoe Creek", LLL In Situ Coal Gasification Project Quarterly Progress Report, October - December 1979, R. J. Cena and B. S. Strack, Eds., Lawrence Livermore Laboratory UCRL-50026-79-4, p. 7-12.

Hill, R. W., 1981, "Burn Cavity Growth During the Hoe Creek No. 3 Underground Coal Gasification Experiment", Proc. 7th Underground Coal Conversion Symp., Fallen Leaf Lake, CA, Sept. 8-11, p. 41-65.

Stephens, D. R., 1981, "The Hoe Creek Experiments: LLNL's Underground Coal Gasification Project in Wyoming", Lawrence Livermore National Laboratory UCRL-53211, 140 p.

Stone, R., Raber, E., and Winslow, A. M., 1982, "Effects of Aquifer Interconnection Resulting from Underground Coal Gasification", Lawrence Livermore National Laboratory UCRL-87722, 54 p.