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ROCK DEFORMATIONS RESULTING FROM PROJECT SALT VAULT

W. C. McClain

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W. C. McClain

NOVEMBER 1973

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ROCK DEFORMATIONS RESULTING FROM PROJECT SALT VAULT

W. C. McClain

ABSTRACT

Following the completion of the Project Salt Vault experiment on the disposal of radioactive waste in an underground salt mine, a final report was prepared. That report presented the results and analysis of the extensive rock deformation measurement network. Since that time, deformation measurements have continued so that the results from a total time approaching 10 years is now available. Analysis of this extended data base, including re-examination of experimental period, is presented in this document. This analysis confirmed many aspects of the earlier one and served to considerably broaden the general understanding of the long-term consequences of the application of heat in an underground salt formation.

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1. INTRODUCTION

During the period from November 1965 to October 1967, an experiment called Project Salt Vault was carried out in the disused Carey Salt Company mine at Lyons, Kansas. The principal objective of this experiment was to demonstrate both the feasibility and safety of the disposal of solidified high-level radioactive wastes in underground salt mines and the techniques and equipment which might be used in an actual disposal facility. In this experiment, spent fuel assemblies from the Engineering Test Reactor at Idaho Falls were used to provide sources of intense radioactivity which were supplemented with electrical heaters to simulate the decay heat which would be generated by real wastes. Section 2 of this report provides a brief description of the Project Salt Vault experiment.

Additional objectives of this experiment included the collection of data on the properties and behavior of in-situ salt for use in the design of an actual waste repository. For this purpose, a rock mechanics instrumentation network involving over 800 individual gage stations of several different types was installed in and around the experimental area.

The results obtained from these instruments, and their analyses and interpretation, were presented in considerable detail in the final report of the Project Salt Vault experiment.[1] Those results and analyses are also briefly summarized in Section 3 of this report.

Since the preparation of the final report on the experiment, the measurements on the network of rock deformation instruments has continued, but at a much reduced reading frequency. The purpose of this document is to present some of the more interesting of these later results along with a reinterpretation of the earlier ones.

2. PROJECT SALT VAULT

The Project Salt Vault experimental area consisted of five rooms newly mined at a level approximately 15 ft above the existing mine floor, which is about 1000 ft deep (see Fig. 1, which also shows the locations of the rock deformation instrumentation in the existing mine area). This increase in elevation was necessary to assure that the holes in the floor into which the radioactive materials were deposited would be in the purest available salt strata. The main part of the experiment was carried out in the two end rooms of the experimental area (see Fig. 2, which also shows some of the instrumentation in the experimental area). The first room contained the main radioactive array of seven specially lined 12-ft deep holes in the floor, laid out in a circular pattern on 5-ft centers. Each of these holes contained auxiliary electrical heaters and two ETR fuel assemblies sealed in a 7-ft-long canister. The end room contained an electrical array which was identical with the main array in every way except for the absence of radioactivity. This array provided a control for the main array, and any unexplainable differences in the behavior of the salt of these two rooms could be ascribed to the effects of radiation. The two center rooms of the experimental area contained a part of the experiment which was designed especially and exclusively to obtain additional information on the deformational properties of the salt at elevated temperatures. A row of electrical heaters was installed

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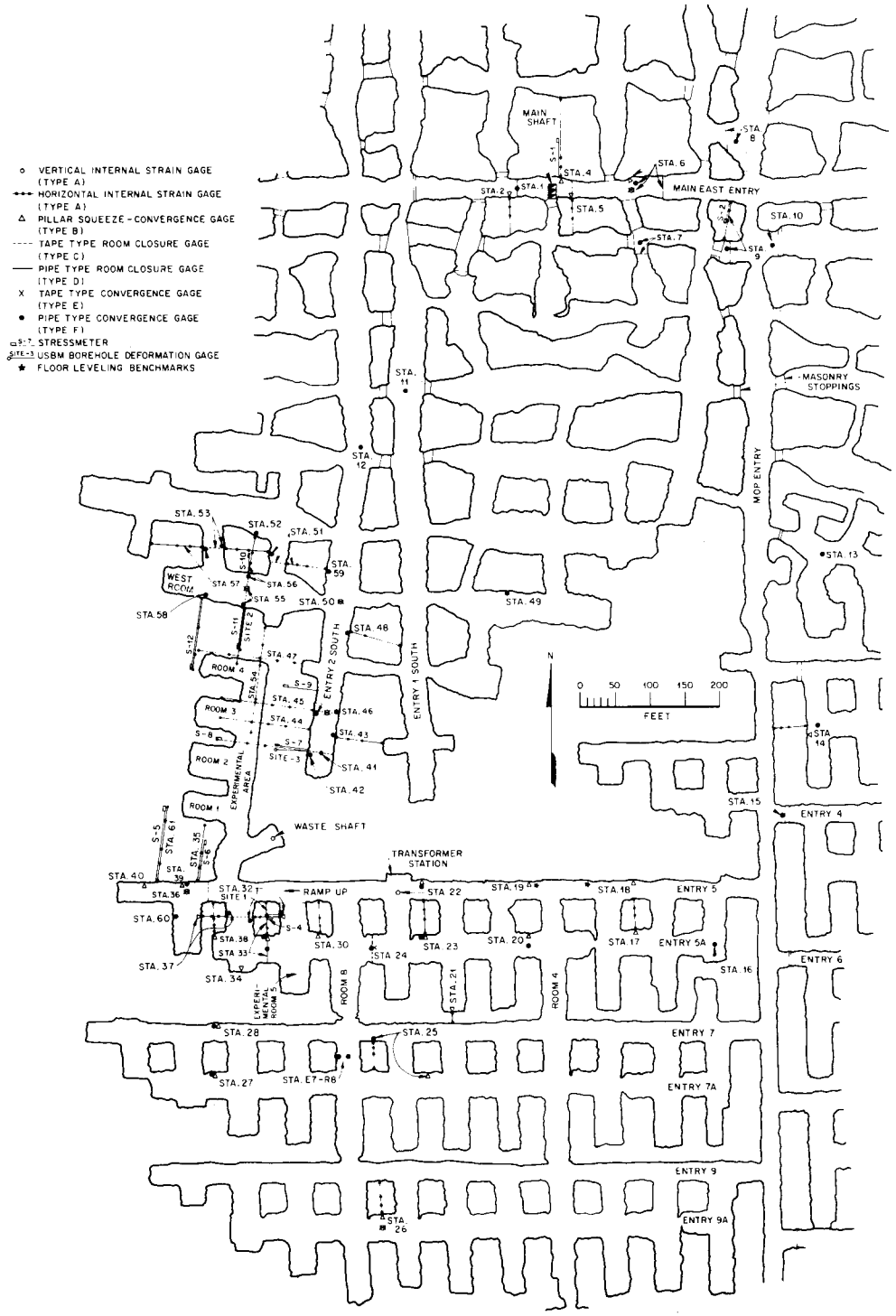


Fig. 1. Plan of a Portion of the Existing Lyons Mine Showing Project Salt Vault Experimental Area and Gage Locations

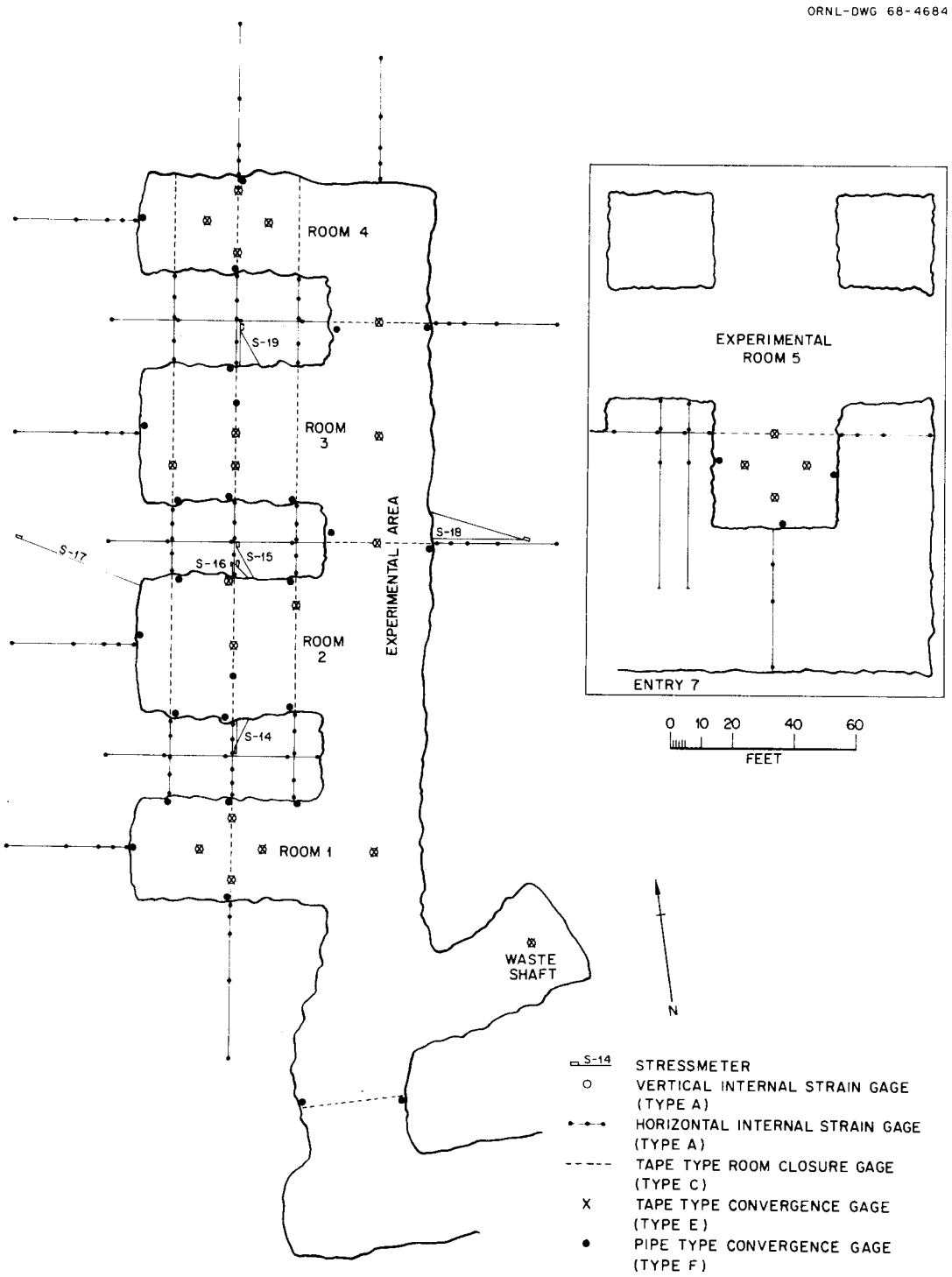


Fig. 2. Plan of Project Salt Vault Experimental Area Showing Principal Rock Mechanics Gages and Their Identification

in the floor along both sides of the intervening pillar, which was narrower than the other support pillars. These heaters simulated the heat flowing into the base of the pillar from a room filled with waste. In addition to this experimental area, one room of the existing mine was incorporated into the experiment (see Fig. 1, experimental room 5). This room contained the floor radioactive array which was identical to the main radioactive array. The array holes in this room were drilled into salt, which contained appreciable quantities of interbedded shale and therefore significant moisture. This part of the experiment was undertaken to investigate the possibilities of using old, mined-out areas for disposal rather than mines specifically designed and excavated for the purpose.

The various operations involved in the handling of the radioactive materials (Fig. 3) began in a hot cell at Idaho where two reactor fuel assemblies were placed in each canister. Seven of these canisters were then loaded into a shielded shipping cask which was transported to the Kansas mine by truck, along with its self-contained cooling system. At the mine, the cask was removed from the truck and placed in a vertical position over the 20-in.-diameter shaft leading to the experimental area. The canisters were then lowered, one at a time, into the underground transporter at the mine level. This transporter, which is similar to the equipment which might be used in an actual disposal operation was used to carry the canister to the experimental room and deposit it into an awaiting hole.

In order to increase the radiation dose delivered to the salt and to gain additional experience with the handling equipment and techniques, the fuel assembly canisters were exchanged for fresh ones every six months. Each set of canisters was placed first in the main radioactive array for six months then moved to the floor radioactive array for six months before being removed from the mine and returned to the National Reactor Test Station. Over the 19-month course of the experiment, three different sets of seven canisters each were handled three separate times. Each of these canisters contained approximately 200,000 curies of activity when first received at the mine. All handling operations

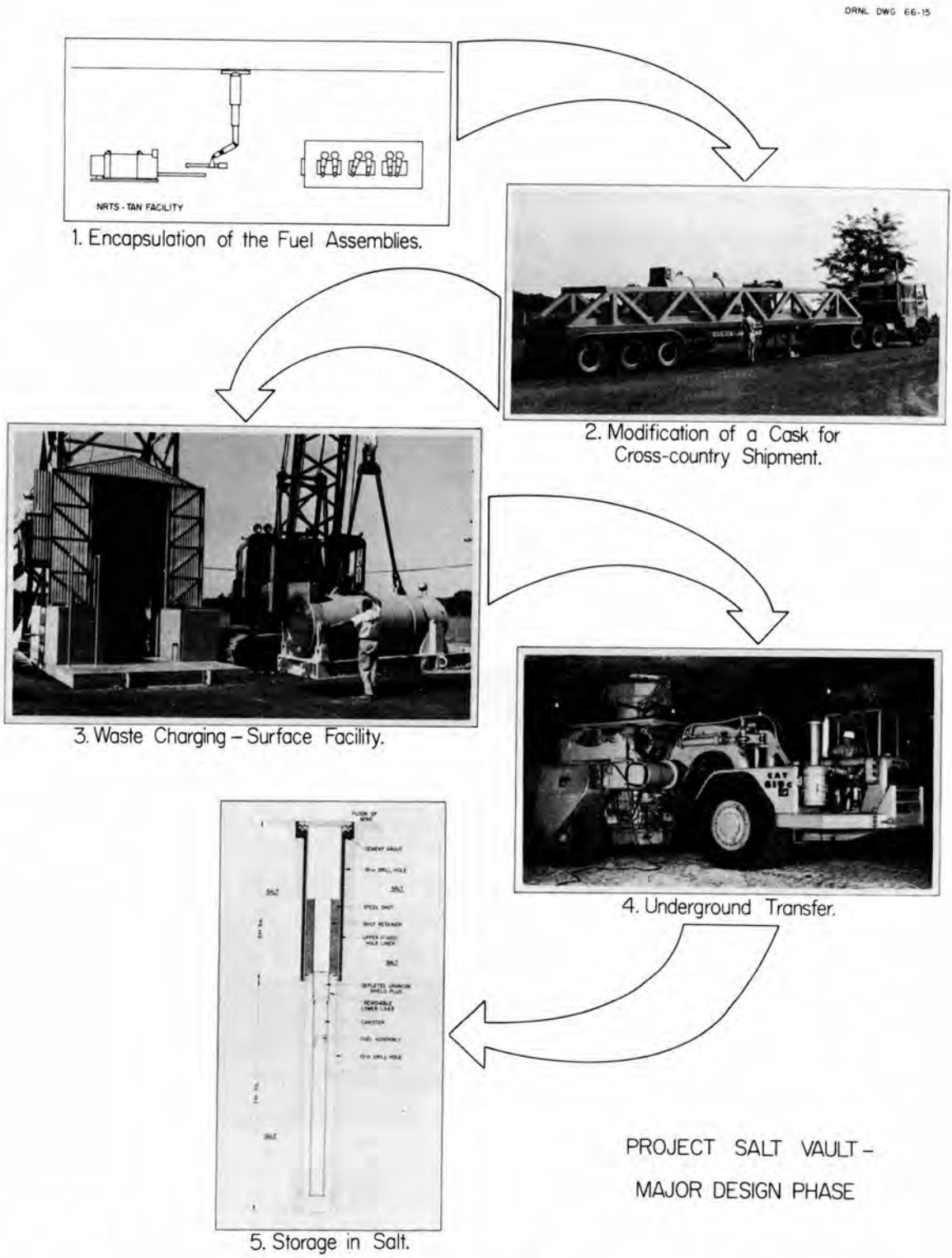


Fig. 3. Summary of Fuel-Element Canister Handling Operations in Project Salt Vault

were performed by remote control without the aid of hot cells. Hot cells would be required in a disposal facility. The experiment was completed without any accidental exposure of mine personnel or releases of activity to the off-gas system. The experiment successfully achieved the objective of demonstrating the feasibility of salt mine disposal and the operation of the handling equipment.

3. SUMMARY OF ROCK DEFORMATION RESULTS

In order to understand and properly interpret the rock deformation results, it is necessary to consider both the temporal relationships of the various excavation and experimental activities and to appreciate the temperature distributions achieved by the various episodes of heating. The chronology of the preparation and experimental phases is summarized on Table 1. Notice that the two 7-hole main arrays were operated at a constant power input of 1.5 kW each (10.5 kW per array) for about the first year and at the final five months. The eleven heaters on each side of the center pillar were operated at a constant power of 1.5 kW each (33 kW total) for approximately a year but beginning one year after the start of the array experiments. The maximum temperatures achieved by this program are shown on Fig. 4. As can be seen, an approximately spherical volume of salt in the center of the floor of the array rooms was heated to appreciable temperatures while a much more extensive volume of salt under and in the center pillar was heated to a lesser but still significant extent.

The various types of rock deformation gages used included:

1. Internal strain gages consisting of wires anchored at various distances along boreholes by expanding-shell roof-bolt anchors and a portable extensometer attached at the mouth of the hole.
2. Vertical convergence gages and horizontal closure gages using a similar instrument with steel tapes stretched across the openings.

Table 1. Chronology of Project Salt Vault Experimental Activities

Date	Standard Day	Event
October 30, 1964	425	Excavation of Experimental Area Room 1 (mean)
December 19, 1964	475	Excavation of Experimental Area Room 2 (mean)
February 2, 1965	520	Excavation of Experimental Area Room 3 (mean)
February 22, 1965	540	Excavation of Experimental Area Room 4 (mean)
November 15, 1965	806	Started Array Experiments Rooms 1 and 4 - 10.5 kW/Room
June 22, 1966	1025	Started Single "Modified" Pillar Heater, Room 2 - 2.8 kW
November 14, 1966	1170	Started All Pillar Heaters Rooms 2 and 3 - 33 kW Total
January 23, 1967	1240	Array Heat Input Increased 40% to 14.7 kW/Room, Rooms 1 and 4
June 14, 1967	1382	Array Experiments Rooms 1 and 4 Terminated - Power Off
October 9, 1967	1499	Pillar Heater Experiments, Rooms 2 and 3 Terminated - Power Off

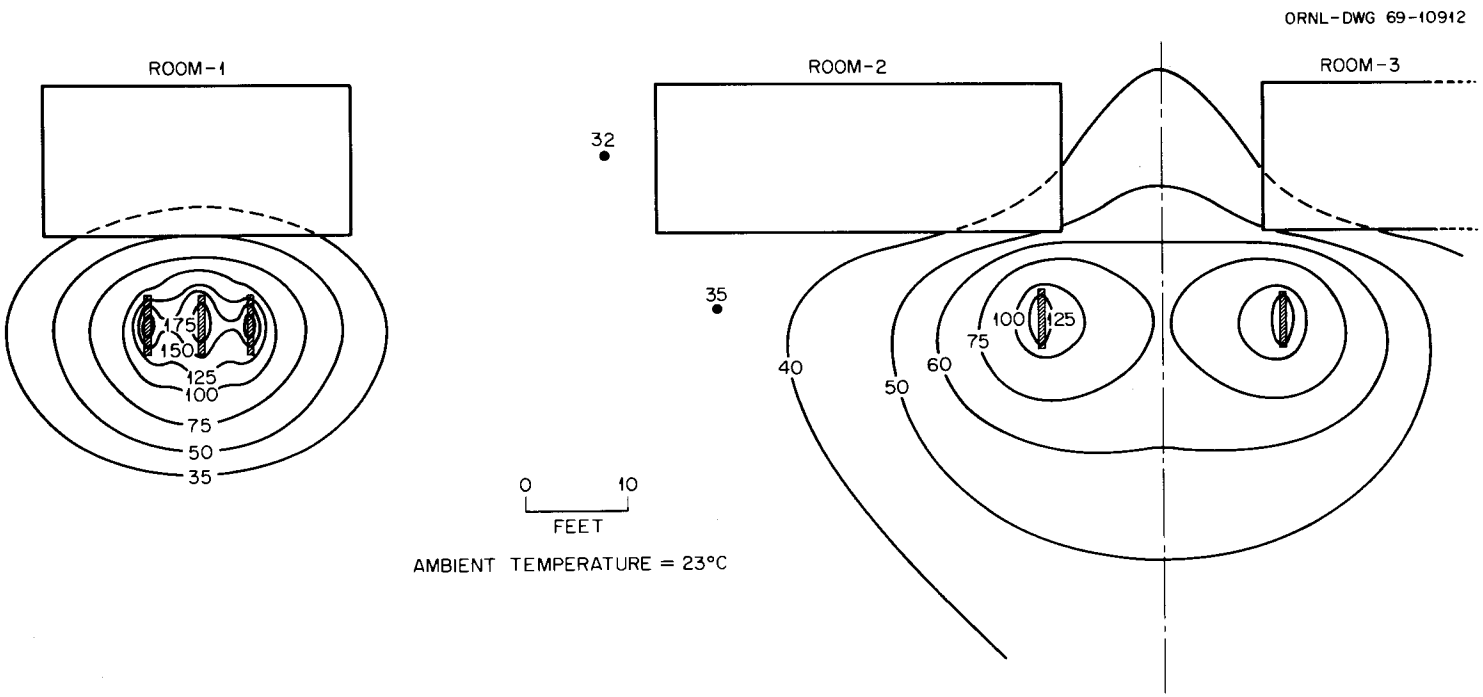


Fig. 4. Temperature Contours (at Maximum Values) in Longitudinal Section Through Center of Experimental Area (Room 4 not Shown but was Essentially Identical with Room 1)

3. Vertical convergence gages and horizontal closure gages fabricated from 1/2-in. pipe, anchored by roof bolts and read with a standard dial gage inserted between abutting ends of the pipe.
4. Diametral borehole deformation gages of three different types: low, intermediate, and high modulus.
5. Floor leveling networks consisting of roundhead stainless steel rivets driven into the floor and read using precision techniques by a self-leveling engineer's level from a base point outside the disturbed area.
6. Borehole leveling stations where the elevations of illuminated targets mounted at the back of horizontal holes drilled into the pillars were determined.
7. Special remote-reading roof sag indicators, simplified roof bolt load cells, and roof bed slip gages.

Some of these gages were installed from the existing portions of the mine around and under the experimental area before it was excavated (Fig. 1). The instrumentation network in the experimental area (Fig. 2) was installed as quickly as possible following excavation so as to permit an evaluation of the deformations, stress redistributions and other consequences of the excavation process itself.

The experimental area was bounded on three sides by a continuous pillar of 75 to 100-ft thickness separating it from the existing excavations and on the fourth side by solid salt. As would have been expected from the modest overall size of the experimental area, the deformations indicated that a significant portion of load formerly supported by the excavated area was transferred to these abutments rather than to the three rib pillars within the experimental area.

Although it was not possible to estimate the absolute value of the average loads on those pillars, it was possible to draw some qualitative conclusions concerning their relative condition. The differences in these relative initial conditions are important factors in interpreting the deformations resulting from the subsequent application of heat and derive principally from the two factors of

geometry and age. First, it is fairly obvious that the average stress on the central pillar would be greater than the other two rib pillars because of its central location, smaller width and larger adjacent rooms. Second, the area around room 1, including the pillar between rooms 1 and 2, would be subject to a somewhat higher average stress than the area around room 4, including the pillar between rooms 3 and 4. This is because the connecting corridor does not pass beyond room 4 and because of the influence of the shaft room (see Fig. 2). In addition to these gross geometrical relationships and lesser second-order geometrical effects growing out of the wall irregularities and departures from the nominal widths of the rooms and pillars (see Fig. 2), there is a major difference between rooms 1 and 4, resulting from their different ages. When an opening is created in stressed materials, a stress concentration zone is created near the walls of the opening. If the opening is in salt, potash, or other materials having highly time-dependent deformational properties, the plastic deformation or creep of that highly stressed zone causes the stressed zone to broaden and the peak stresses to decrease. This decrease in peak stresses in turn causes the initially high rate of plastic deformation to be decreased gradually over a period of time. The response of the material around the opening to subsequent disturbances (in this case the heating) will depend upon its position along this transient at that time. In the experimental area, room 1 was approximately 12 months old at the time of heating, whereas room 4 was only about 8 months. Therefore, other things being equal, the response to the heating in room 1 would be expected to be somewhat less than in room 4, since it had achieved a slightly more stable condition. In actual fact, other things were not equal and the age effect served to counterbalance the geometrical effects. The effect of these differences will be seen in the initial (before heat application) portions of the convergence curves presented in the next section.

The deformation of the experimental area produced by the heating experiments was, in many aspects, quite dramatic. Considering first the array rooms 1 and 4, it was seen that the floor area around the array holes was immediately uplifted when the heaters were turned on but that this uplift soon slowed to a nearly constant rate. The same behavior was found when the heat input was increased by 40%. The recovery of this floor uplift after the heaters were turned off indicated that the mechanisms involved were more complicated than simply thermal expansion of the salt around the heaters. The recovery of the floor uplift amounted to only a fraction of the total floor uplift--about 16% in room 1 and about 11% in room 4. The salt at the center of the rooms around the arrays was confined in the horizontal directions by the stresses resulting from the pillar loading but was free to expand vertically up into the rooms. When the salt was heated, elastic thermal expansion in the vertical direction resulted in an uplift of the floor. This component of the total floor uplift should be recoverable upon cooling. Direct thermal expansion in the horizontal directions was not possible because of the constraining stress. Therefore, there is an appreciable thermal stress induced in the horizontal direction. The salt in the floor will creep upward (the only direction available to it) under the influence of this horizontal thermal stress, thus providing a second and apparently sizeable component of the floor uplift which would not be recoverable. The difference in the amount of recoverable floor uplift between the two rooms was probably primarily a function of their different ages. Room 1, having had a longer period in which to relieve the horizontal stresses resulting from pillar loading, would be expected to have a smaller component of nonrecoverable floor uplift. In general, and in spite of the slight differences discussed above, the floor uplift in the two rooms would appear to be almost identical in both magnitude, shape, rate and response to the heating.

The vertical convergence measurements taken at the walls of the experimental rooms were perhaps the most useful of the various deformation results. These data in particular will be examined in detail in the

next section. These gages were constructed in such a way as to include a component of floor uplift. However, when this component was estimated and deducted from the total convergence, it was obvious that the entire height of the pillars had experienced an accelerated vertical deformation in response to the heating at the center of the rooms. The total convergence during the heating period can be interpreted as the sum of components due to: (1) the overburden and mining stresses, (2) the uplift of floor, which at this distance from the heat sources is almost entirely due to horizontal thermal stresses, and (3) an increase in the vertical loading of the pillar due to thermal stresses. This picture of the deformations was further complicated by the variation of salt creep properties as a function of temperature at a later date. However, this effect did not become significant in the array rooms. Further insight into the relative magnitudes of these three effects was obtained by examining the convergence curves during the cooling period. At those gages where the effects of heating were greatest, the recoverable components were large enough to compensate for the continuing (viz., mining and overburden stress-induced deformation) components and to produce a period of essentially zero convergence.

Horizontal borehole strain gages were installed in three sides of the two experimental array rooms. The acceleration of the horizontal deformation in response to the heating was clearly seen at all gage locations. This effect extended completely through the narrow pillars and could be detected at the walls of rooms 2 and 3. The deformations around room 4 were approximately equivalent to those in room 1. The deformations of the pillars adjacent to rooms 1 and 4 were examined in much more detail. This examination indicated that there is no gross difference between the deformational behavior of the two experimental rooms or their adjacent pillars which could be ascribed to the effects of radiation.

The vertical deformation of the floor and roof in the vicinity of the heater arrays was measured on the vertical borehole strain gages. Since these stations were tied into the leveling network, it was possible to calculate displacement of each of the wire anchors relative to what should be an absolute base line.

The movement of points on and near the floor was, of course, identical to the floor uplift results. However, the deformation of points deeper in the floor, down to a depth of 25 ft, also showed an uplift of the same type, which diminished with increasing depth. The immediate response to the initial heating of the anchors at a distance of 25 ft below the floor (i.e., 13 ft below the heater zone) and the magnitude of that movement, amounting to several tenths of an inch, was somewhat surprising even though the mechanism of that movement was the same as was discussed with respect to the floor uplifts. The results obtained for the deformation of the roof over the arrays were perhaps the most interesting of all the rock mechanics data. First, it was seen that the points 25 ft above the ceiling of the rooms had lowered appreciably during the approximately three-year period examined in detail. A small part of this movement, which amounted to about 3/4 in., may be due to local deformation of the roof strata toward the rooms, but at this height above the room ceilings, local effects can hardly account for more than a small fraction of the total. The inference is that the pillars supporting the experimental area had squeezed enough to allow the entire overlying rock mass, including the ground surface, to subside (but not by the whole amount). The effects of heating could still be seen at the 25-ft level as a very slight acceleration in the rate of lowering. However, there was no evidence of recovery when the power to the heaters was turned off. This is not inconsistent with the previous discussion, since the accelerated deformation of the pillars due to thermal stress loading would be expected to be reflected throughout the roof strata.

The various deformations occurring around the array rooms 1 and 4 and their adjacent pillars were combined in Fig. 5 to show the movements which took place in the vertical north-south plane through the array centers during the heating period. The significant features of these deformations are:

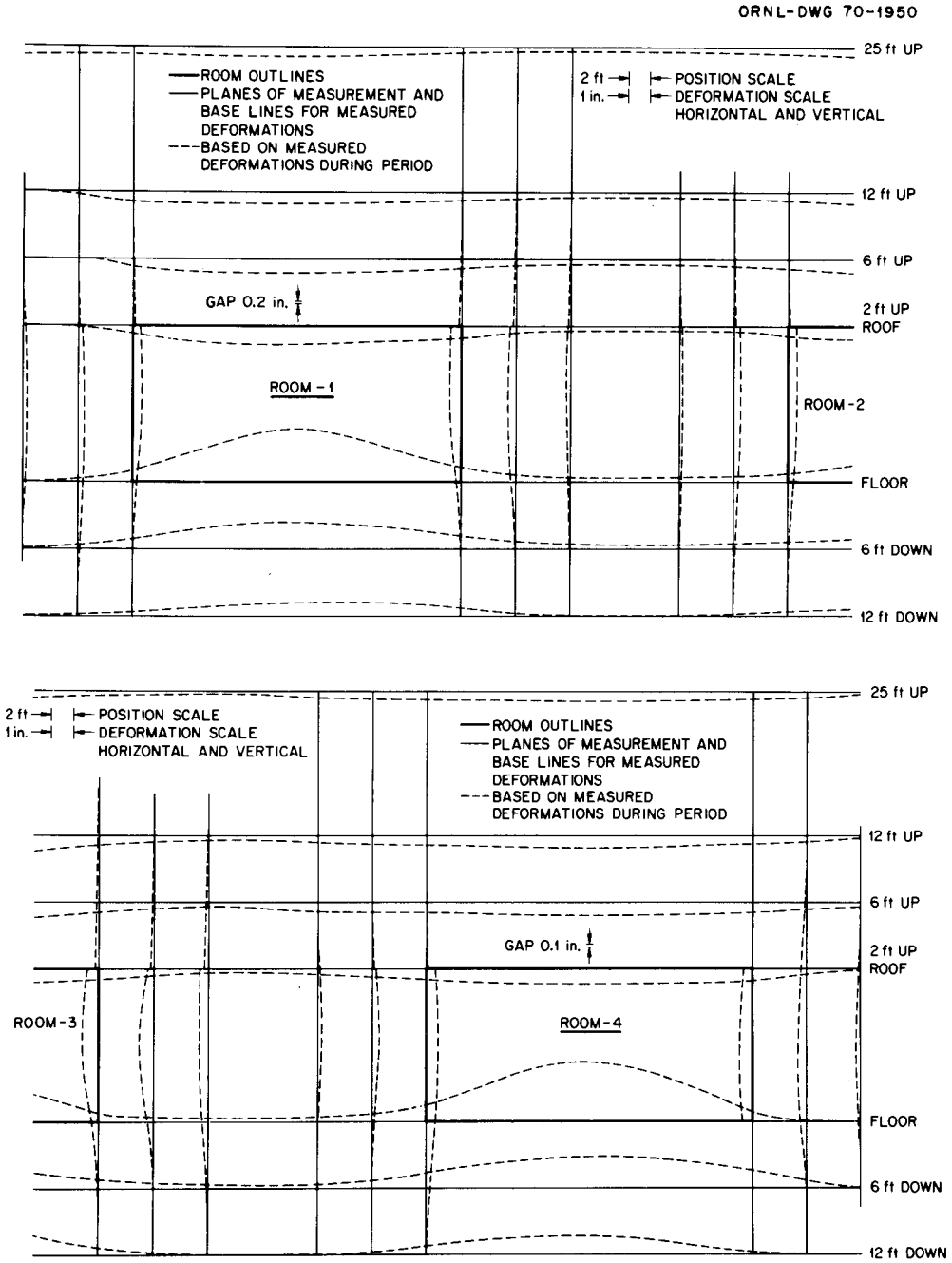


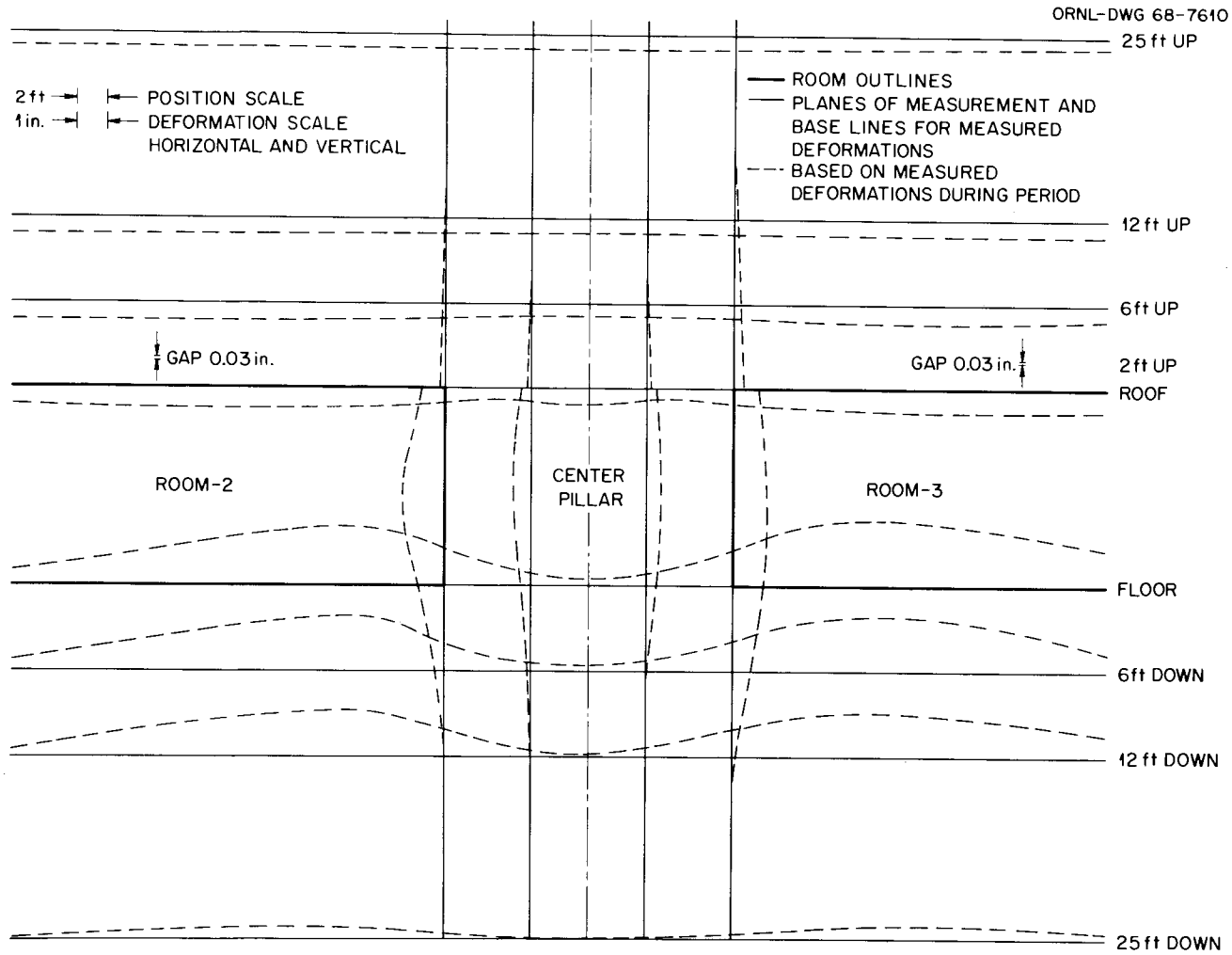
Fig. 5. Summary of Deformations Around Rooms 1 and 4 During Heating

1. The total deformations were primarily the result of creep of the salt under the influence of overburden and thermal stresses.
2. Deformation resulting from the alteration of the physical properties of the salt (especially creep rate) due to an elevated temperature, for the most part, was not seen around the array rooms because of the location of the heat sources. Significant portions of structural load-bearing salt were not heated fast enough or high enough to produce an observable effect.
3. The effects of the transference of stresses resulting from the thermal expansion of the salt in the floor around the array heaters were unexpectedly widespread. Accelerated deformation rates resulting from the increased stresses were observed at points 25 ft into the floor and roof and on the walls of the pillars in the adjacent rooms.
4. The deformations were so similar between rooms 1 and 4 that it can be concluded that there were no significant structural effects produced in the salt by the intense radiation fields. The similarity between the two rooms was even better than expected because of the counteracting effects of slight differences in age and geometry.

In general the measured rock deformations around the heated pillar were similar to those around the array rooms but considerably larger, since more heat was being supplied, and they included a significant component resulting from the change in the deformational properties of the salt with increased temperature.

Based on the detailed analysis and interpretation of the deformations summarized in Fig. 6, the following conclusions can be drawn:

1. Even in this heated pillar experiment where a large volume of salt was heated appreciably, the deformations resulting from the influence of thermal stresses and their transferal to remote points were clearly much larger and more dominant than the deformations resulting from increased creep properties of salt at elevated temperatures. However, the heating of the



Summary of Deformations in and Around Center Pillar (Vertical Section) Between 1170-1500 Standard Days.

Fig. 6. Summary of Deformations Around Center Pillar During Heating

pillar took place over a much shorter time than would be the case in a typical waste disposal operation, and the situation might be somewhat different where the rate of temperature rise is considerably slower.

2. The effect of the local geological situation, especially the presence and locations of thin shale partings capable of providing a lubricated surface, on the deformations was much larger than initially anticipated. This influence will somewhat limit the applicability of the analysis to different geological environments. However, the fortuitous circumstances of having a shale parting at the roof and the pillar bottom keyed into the floor in this experimental installation coupled with the laboratory pillar-model tests,[1] will allow some limits to be placed on the variations to be expected from different geological configurations.

4. LONG TERM DEFORMATIONS OF EXPERIMENTAL AREA

The rock deformation measurements have been continued since the completion of the heating experiments and also far beyond the period included in the interpretations presented in the previous section. These long term results were recently examined and certain selected portions will be presented in this section.

First, a re-examination of the floor uplift data indicated that although recovery continued for several hundred days beyond the period covered in the earlier analysis (see reference 1, Figs. 11.58a and b), the rate of that continued recovery was very small and the total amount insignificant compared with that which occurred earlier. Therefore, the conclusions in this regard remain unchanged: The recovery of the floor uplift due to thermal contraction on cooling amounts to only a fraction of the uplift which occurred during heating - specifically about 16% in room 1 and about 11% in room 4.

The vertical deformations in the roof above the experimental rooms was also re-examined. In this case, it had been concluded earlier that the roof bolting program had reduced the roof bed sag rate to zero and that the roof over the entire experimental area was behaving as a single unit. The examination of the subsequent data confirmed this conclusion.

These two points taken together mean that further examination of the vertical deformations in the roof and floor would not be fruitful: Since the floor uplift measurements indicated that the movement of the floor was very small, the deformations of the material at greater depth below the floor would be nil, at least at the sensitivity and accuracy of the very infrequent readings now being obtained; and since the roof was behaving as a single unit, those deformations can be best examined by interpretation of the pillar convergence data. The vertical convergence in room 1, room 4 and around the central heated pillar, plotted as a function of time, is shown on Figs. 7, 8 and 9 respectively. These figures are replots of the convergence data given in the Project Salt Vault final report[1] on Figs. 11.60a, 11.60b and 11.81 respectively but extended to include the additional data. For the convergence in rooms 1 and 4, the plots show: (1) the normal rapid convergence following excavation of the room, which decreases in rate with increasing time, (2) the accelerated convergence rates resulting from the array heaters and the subsequent increase in power input (note also that the response of the pillar <u>immediately</u> follows the initiation or increase of heating), (3) the abruptly decreased convergence rate when the power to the heaters is turned off, and (4) the continuing convergence, at a much decreased rate following the stabilization of the disturbance created by the heating experiments. Notice also that both the convergence rates and the total amount of convergence in rooms 1 and 4 due to the heating are very nearly identical, especially after adjustment for their different ages. The vertical convergence around the heated pillar (Fig. 9) shows a similar behavior except that the total amount of convergence (and the convergence rate) is much greater because of the smaller dimensions of the pillar and the closer proximity of

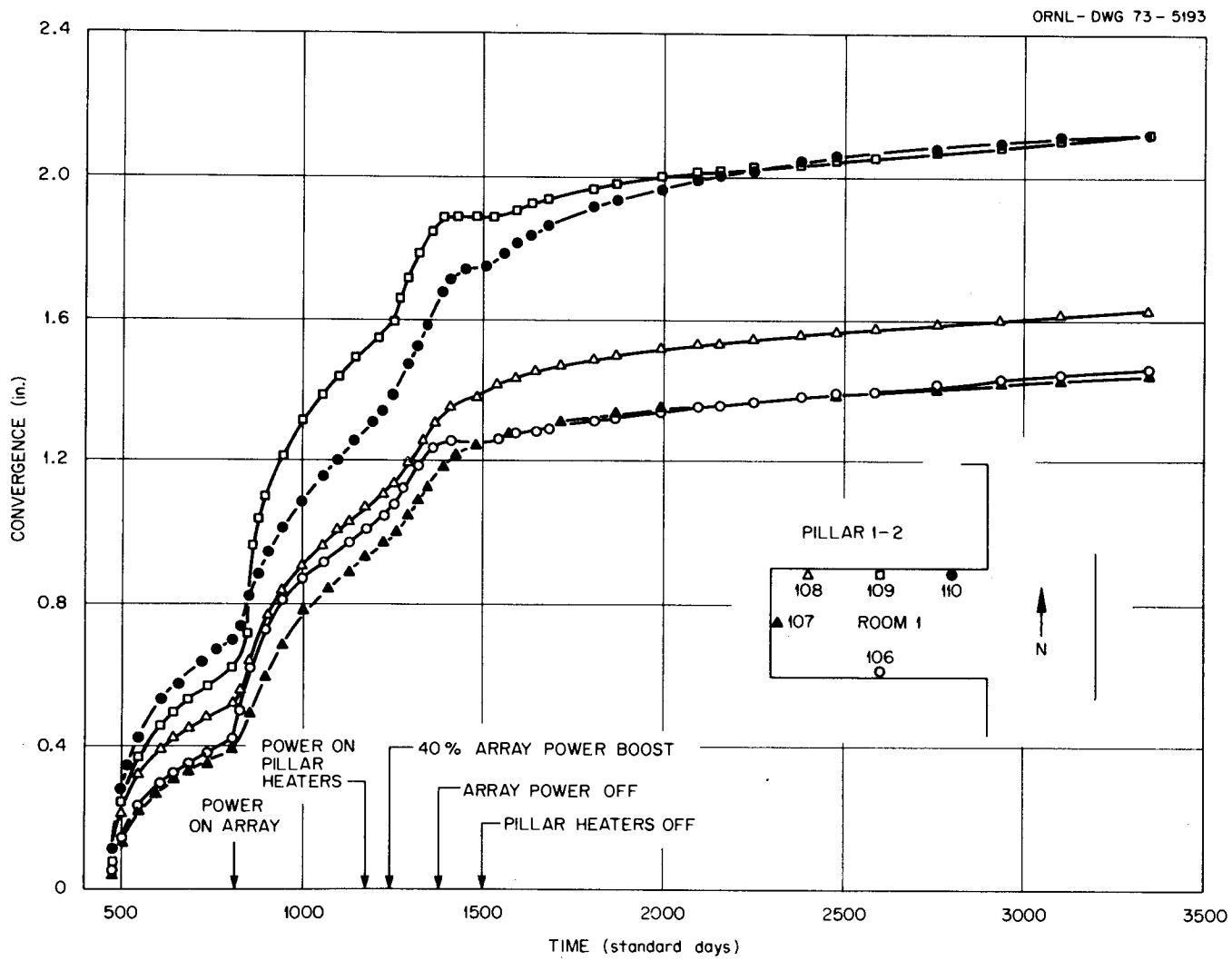


Fig. 7. Vertical Convergence as a Function of Time - Room 1

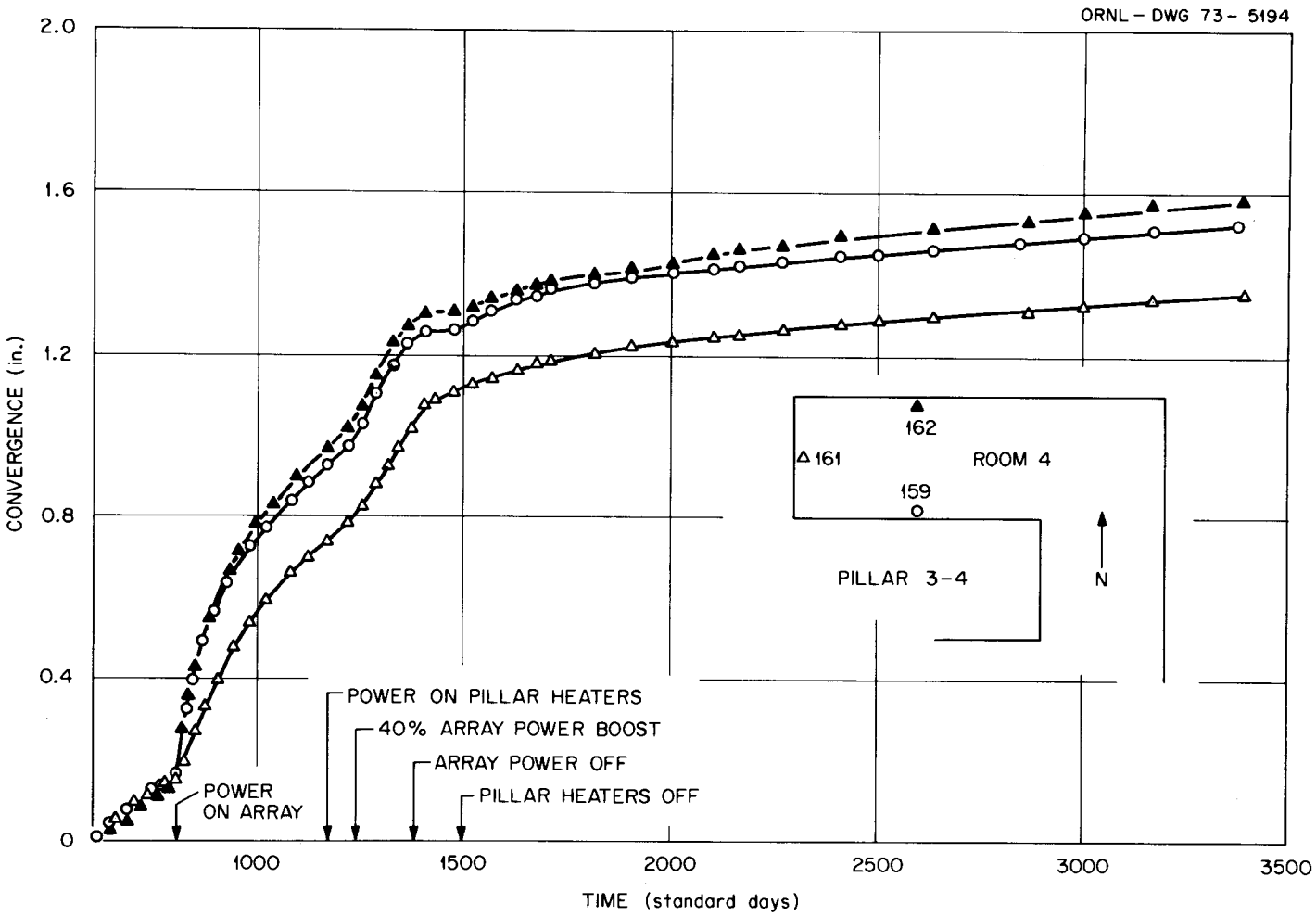


Fig. 8. Vertical Convergence as a Function of Time - Room 4

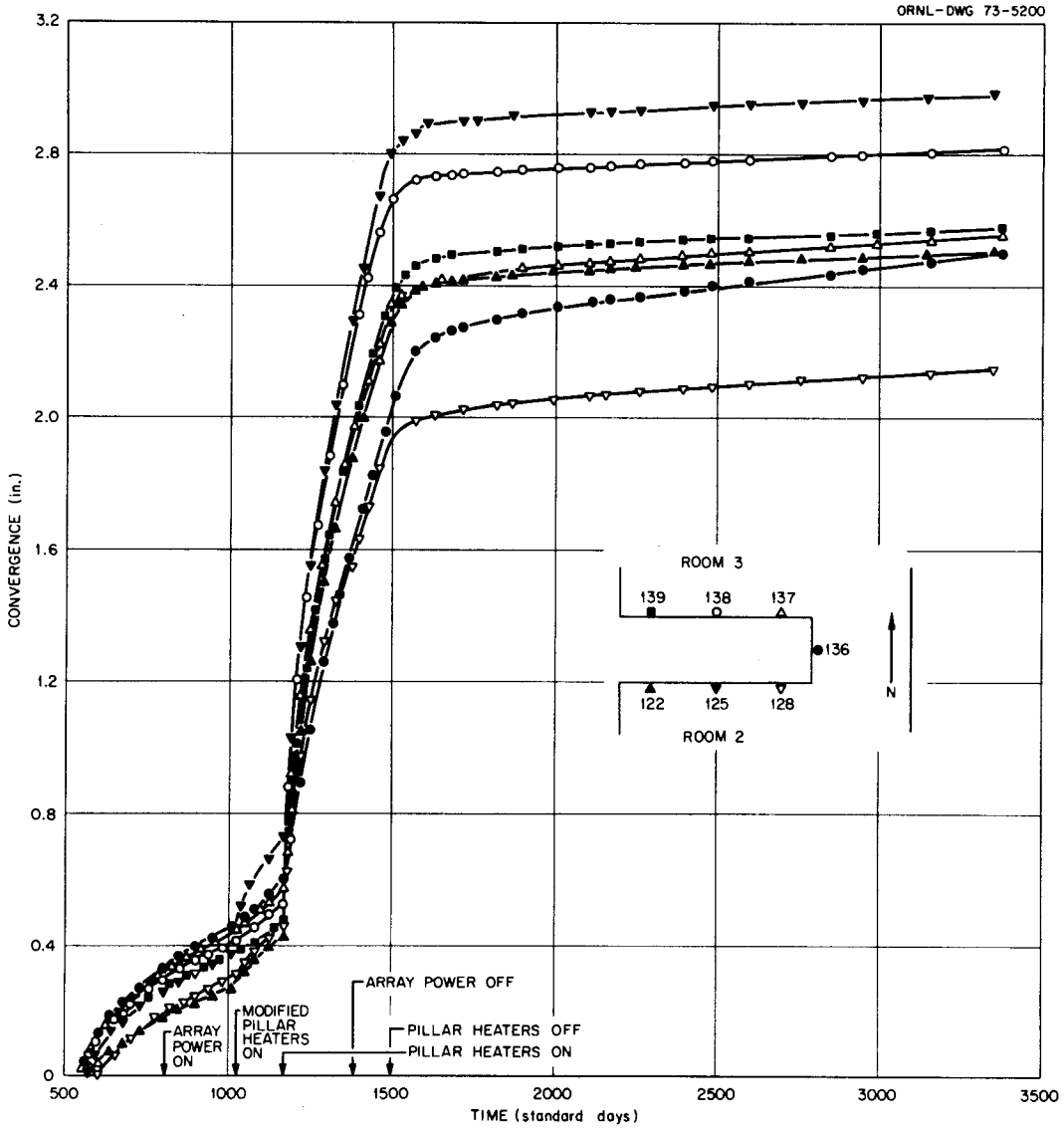


Fig. 9. Vertical Convergence as a Function of Time Around Heated Pillar

the heaters. Notice that the total amount of convergence is greatest at the middle section of pillar (gages 125 and 138) because this region was the most severely affected by the heating. However, the present rates of convergence are such that eventually the normal situation will be established where the greatest convergence will be at the open end of the pillar (gages 128, 136 and 137) with the least convergence at the solid abutment end of the pillar (gages 122 and 139).

In the Project Salt Vault final report,[1] the details of the horizontal deformations of the pillars separating the four experimental rooms were examined in such a way that the strain profiles were emphasized (see reference 1, Figs. 11.62, 11.63, 11.64, 11.82, 11.84 and 11.85). For the present analysis, it is more convenient and instructive to omit the intermediate points within the pillar and consider the total deformation of the pillar, from edge to edge, as measured horizontally through the pillar. The total horizontal deformation at various points on Pillar 1-2 and Pillar 3-4 are shown in Figs. 10 and 11 as a function of time. Note that the shape of these curves is very similar to the shape of the convergence curves around rooms 1 and 4 except that the influences of the heating are less sharply defined. This would be excepted because the horizontal pillar deformations represent the average behavior of the entire pillar, including the more confined central portions, whereas the vertical convergences are measured at the edges of the pillars, which are the least confined portions.

The total horizontal deformation at various points through the central heated pillar are shown on Fig. 12 as a function of time. In this case, the total horizontal deformation curves are very nearly identical to the vertical convergence curves, including a sharply defined response to the heating. This sharper response to the heating is a consequence of the combined factors of pillar size and heater locations.

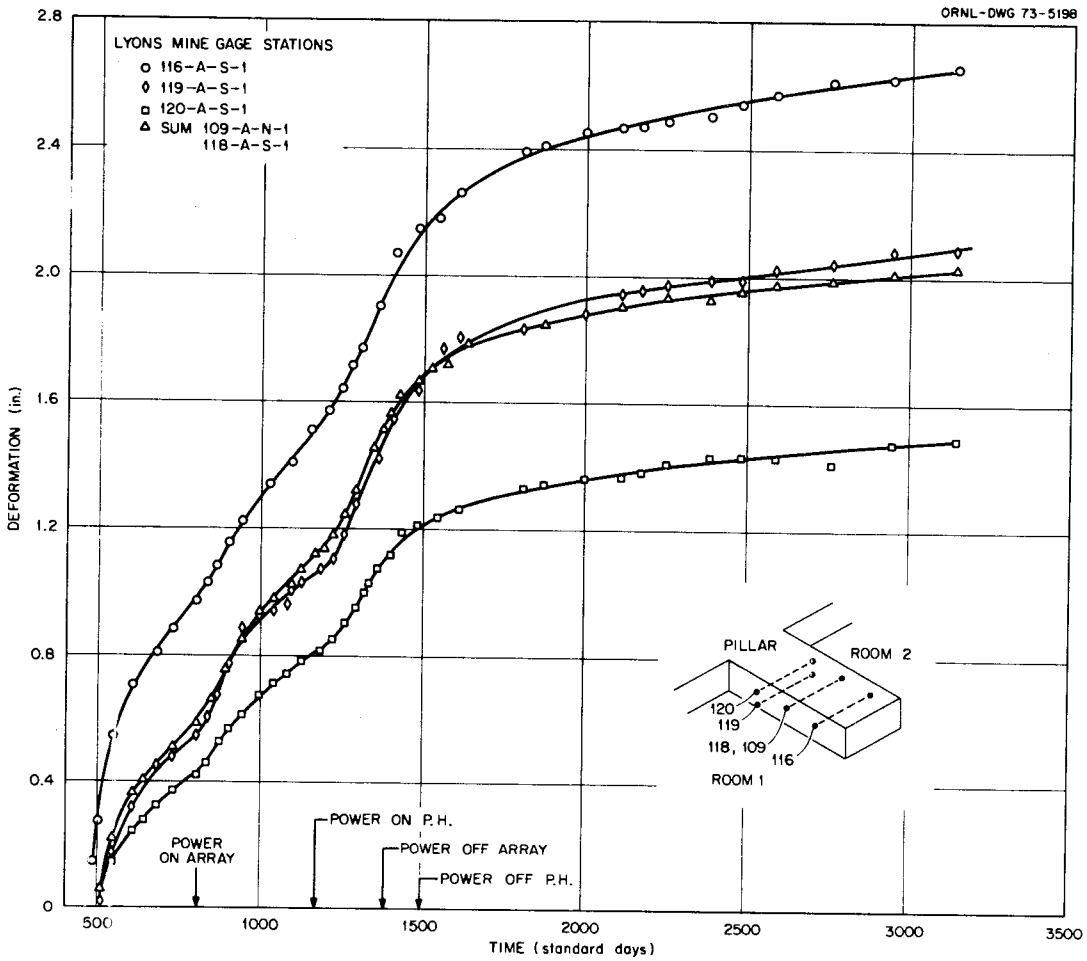


Fig. 10. Total Horizontal Deformation as a Function of Time - Pillar 1-2

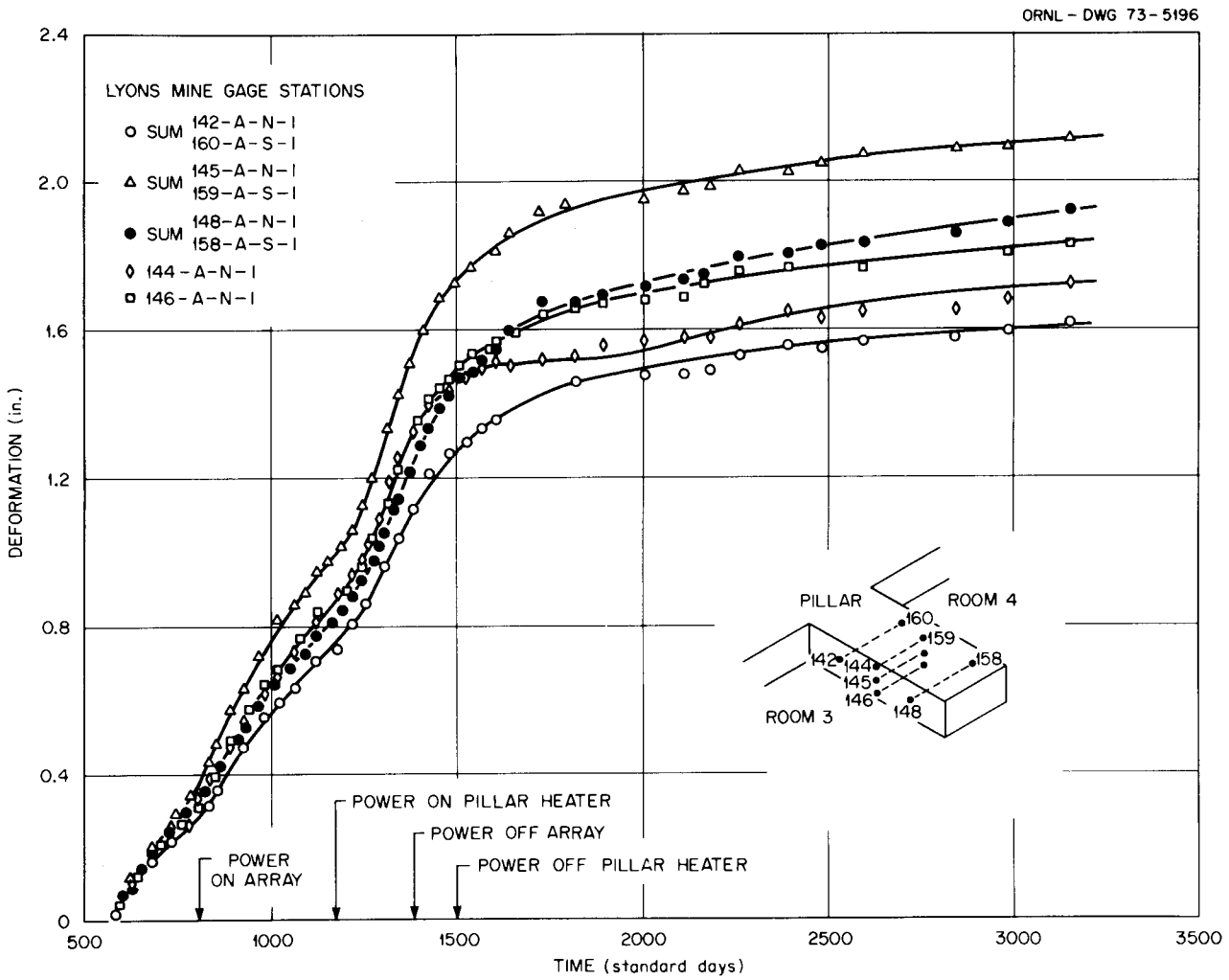


Fig. 11. Total Horizontal Deformation as a Function of Time - Pillar 3-4

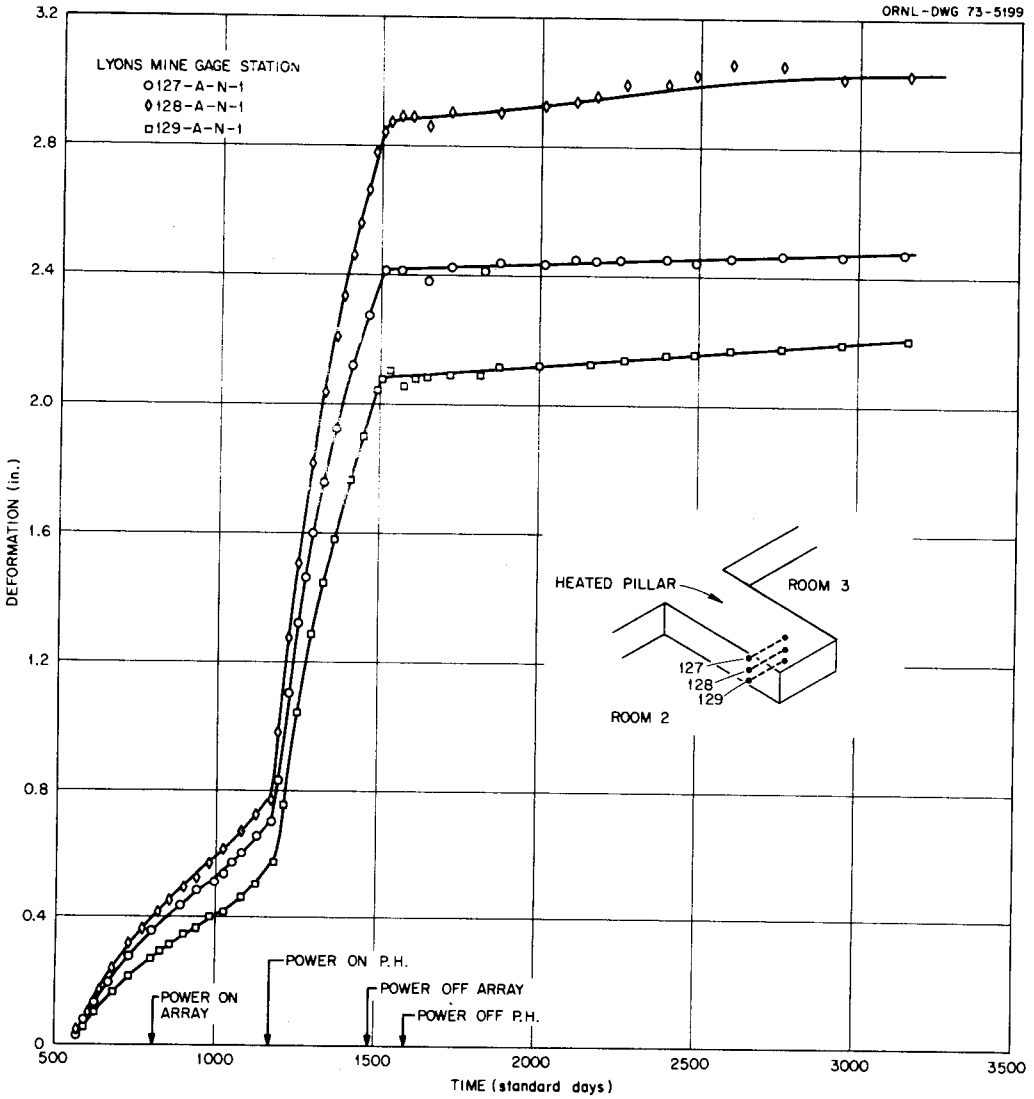


Fig. 12a. Total Horizontal Deformation of Heated Pillar, as a Function of Time

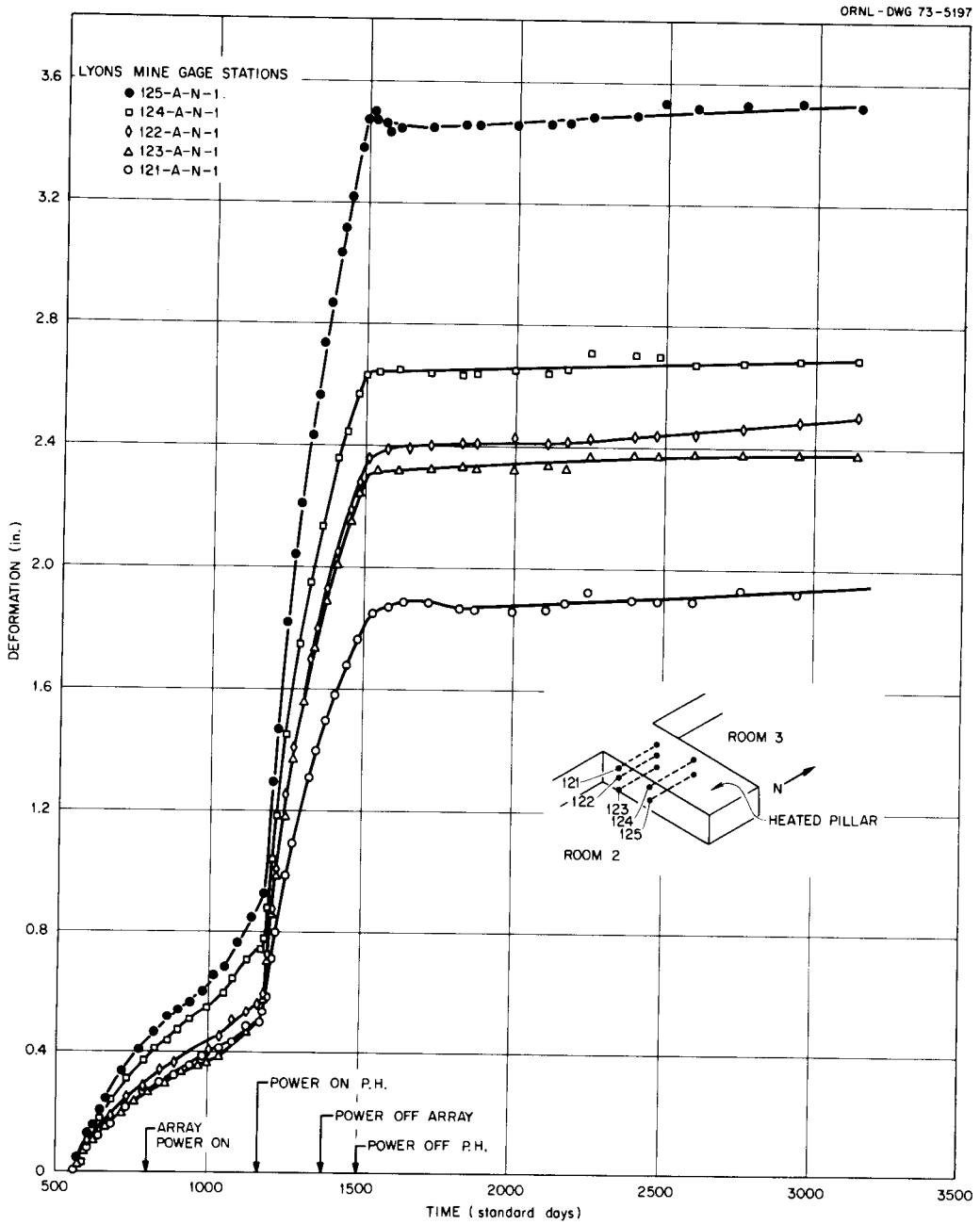


Fig. 12b. Total Horizontal Deformation of Heated Pillar as a Function of Time

5. ANALYSIS OF DEFORMATION RATES

The availability of deformation data over an extended period of time makes possible an analysis based on strain rates. The advantages of using the variations in the deformation rate or strain rate for analyzing nonelastic (especially plastic flow) behavior of in-situ rocks such as salt and potash have been previously pointed out.[2] For the Project Salt Vault experimental area, a plot of the strain rate as a function of age of the opening or pillar is the most convenient way to examine these variations in the rate of deformation. The vertical and horizontal deformations shown on the preceding several figures have been reduced to this form, and the minor differences between the several gages in a room or pillar were averaged to produce the curves shown in Figs. 13, 14 and 15.

Previous work (reference 1, Fig. 4.11) has shown that the deformation of salt pillars (both laboratory models and actual underground mine support pillars) can be described by the expression

$$\dot{\varepsilon} = A\, T^{\alpha}\, \sigma^{\beta}\, t^{\gamma} \qquad (1)$$

where

$\dot{\varepsilon}$ = strain rate (for rib-pillars, either vertical or horizontal)

T = absolute temperature

σ = mean pillar stress

t = time

A, α, β, γ = constants (usually β is approximately 3 and γ is in the range -0.6 to -0.7)

For the ordinary mining situation, the mean pillar stress can be assumed to be nearly constant (after further excavation in the area has been completed) and the pillar deformation rates would then plot as straight lines on figures of this type. This was assumed to be the initial straight line portion of curves shown in Figs. 13, 14 and 15.

The remaining portions of the vertical convergence rate curves for rooms 1 and 4 shown in Fig. 13 can be interpreted as follows:

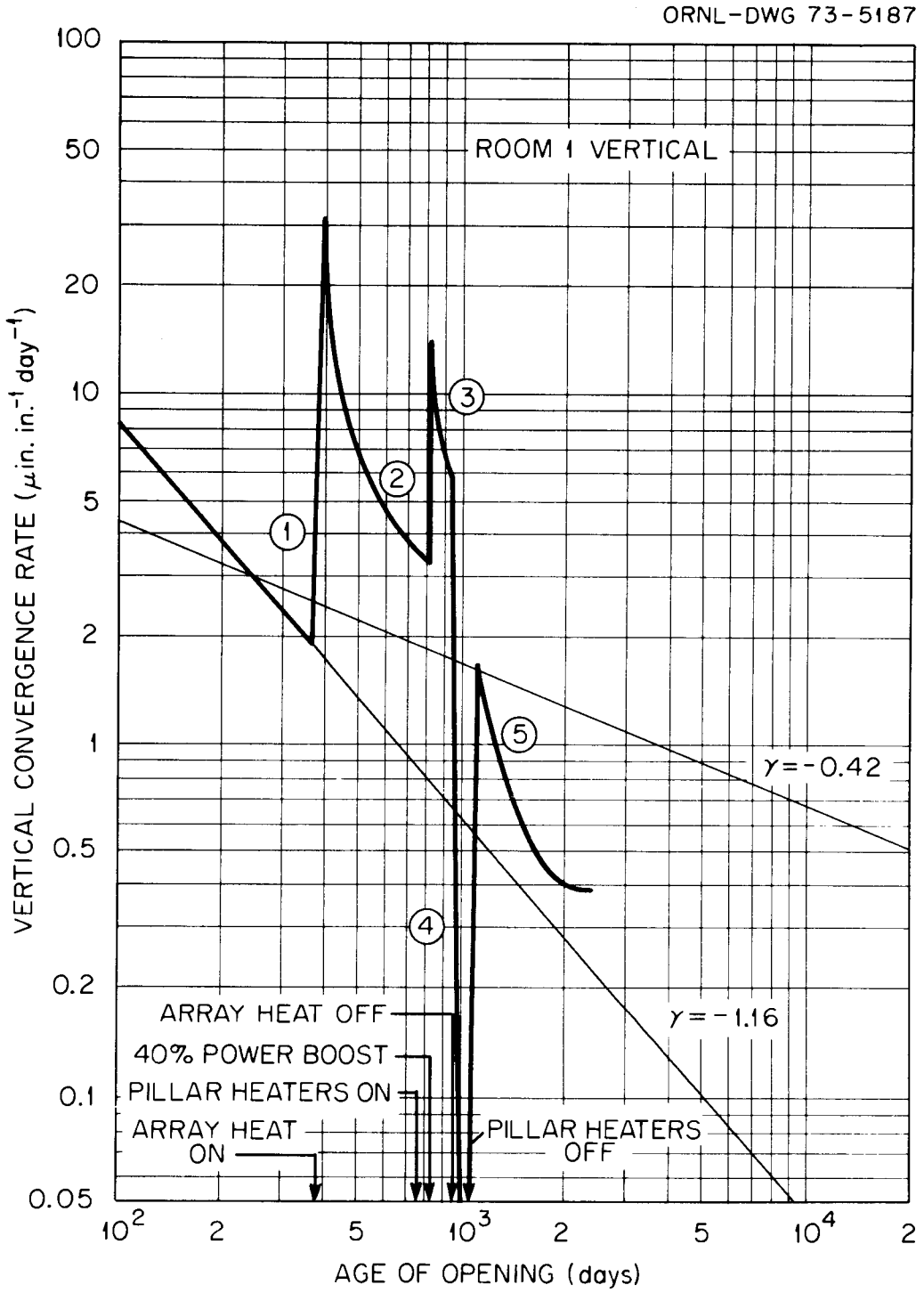


Fig. 13a. Vertical Convergence Rate as a Function of Age of the Opening - Room 1

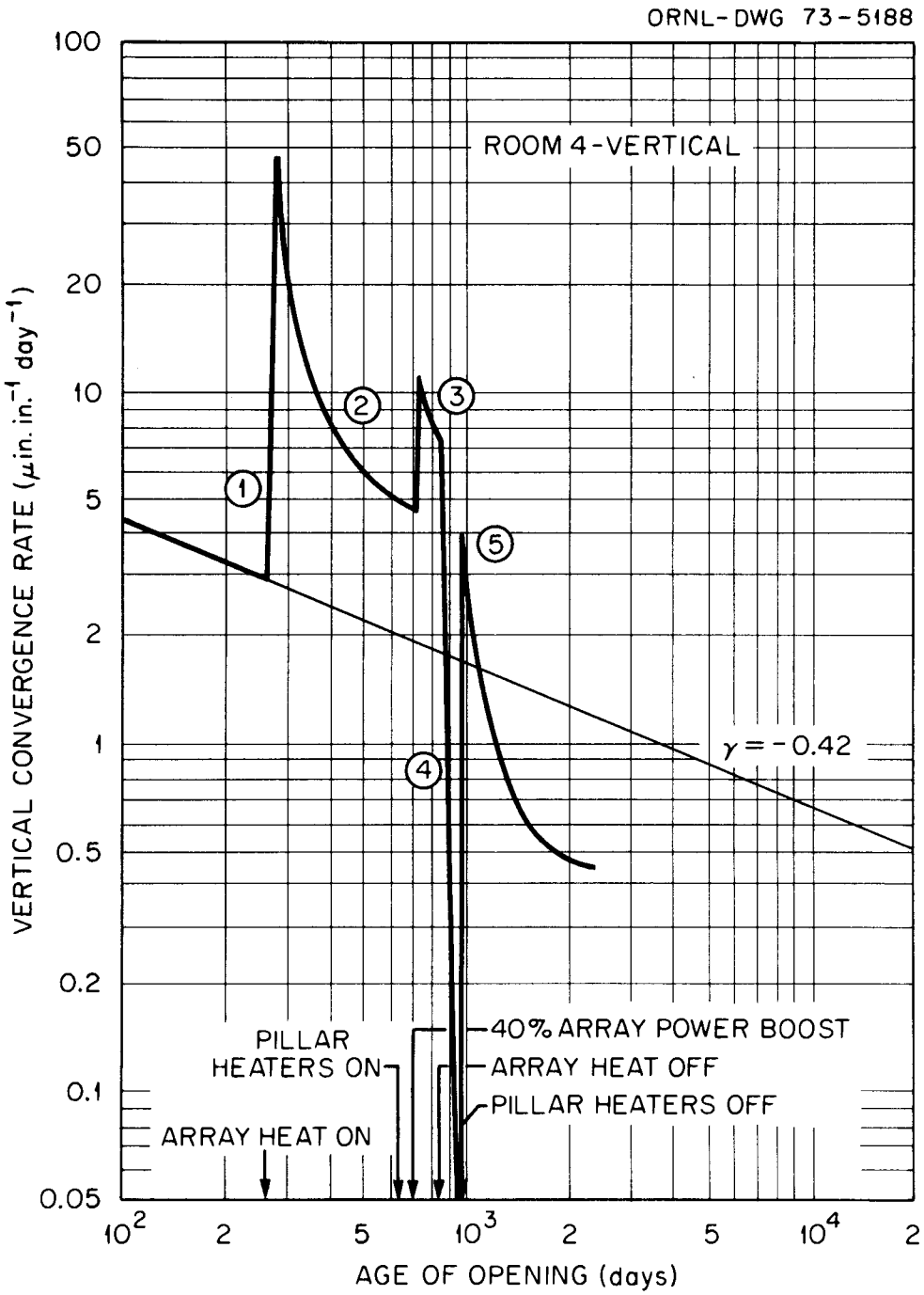


Fig. 13b. Vertical Convergence Rate as a Function of Age of the Opening - Room 4

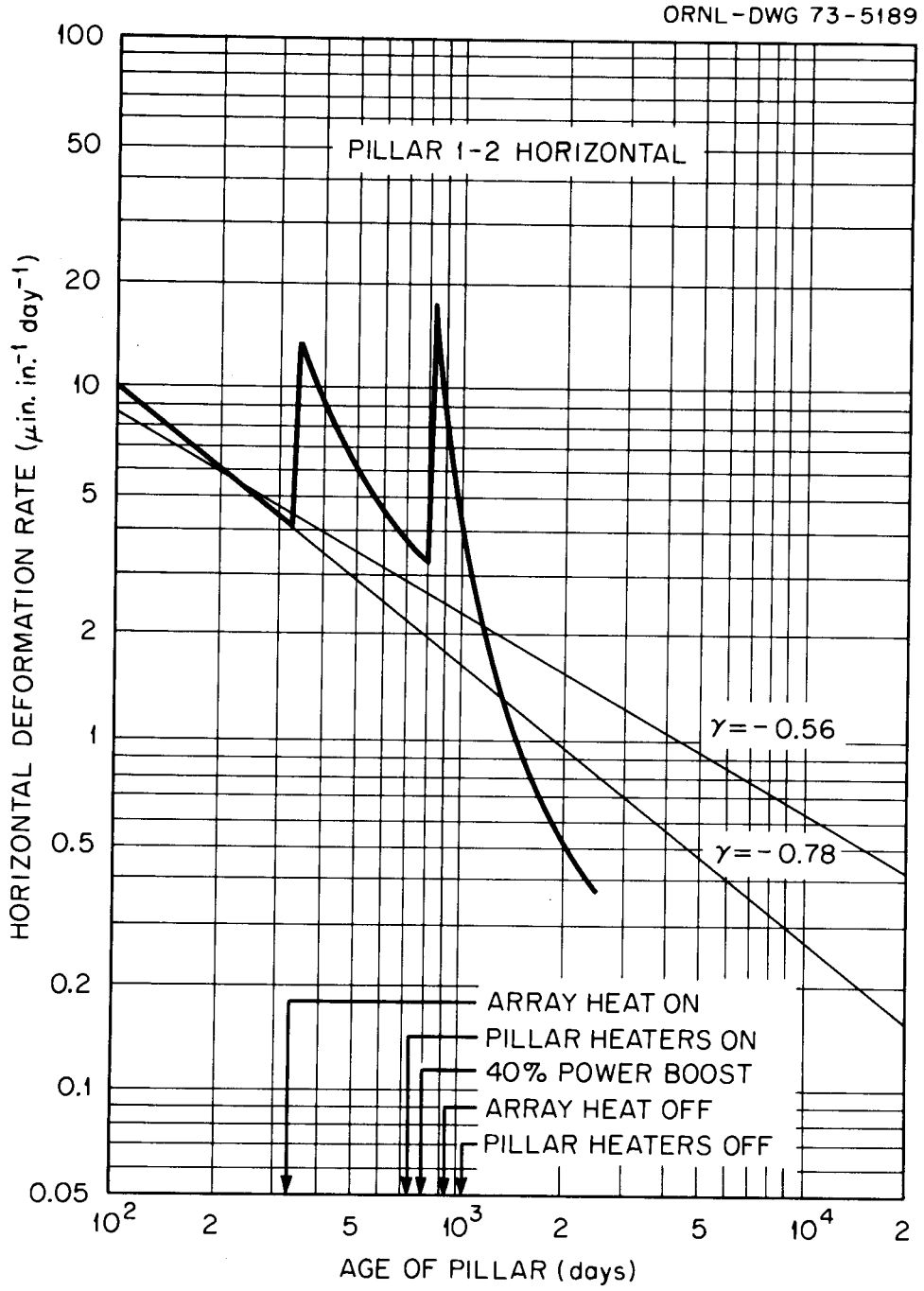


Fig. 14a. Horizontal Deformation Rate as a Function of Age of Pillar - Pillar 1-2

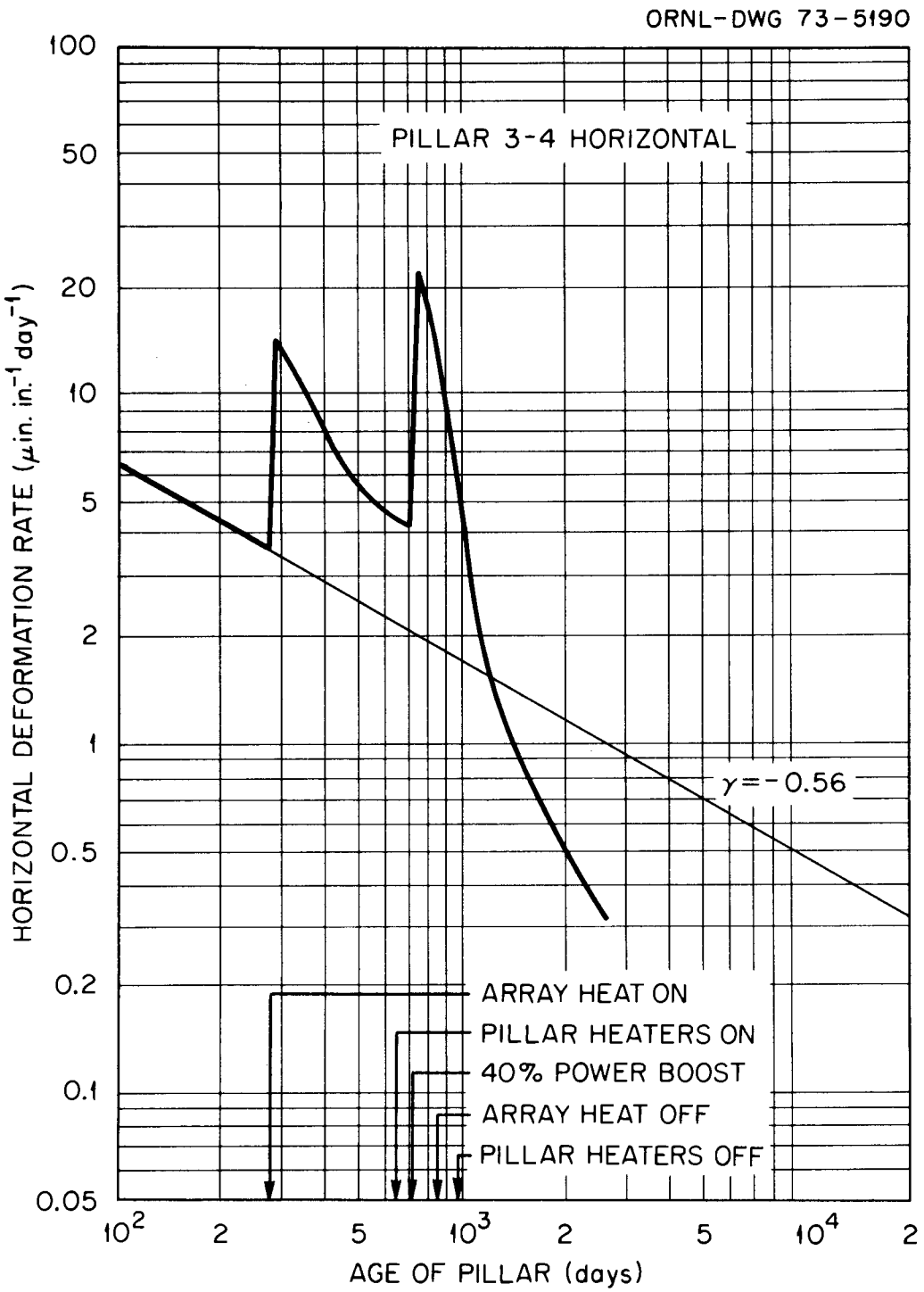


Fig. 14b. Horizontal Deformation Rate as a Function of Age of Pillar - Pillar 3-4

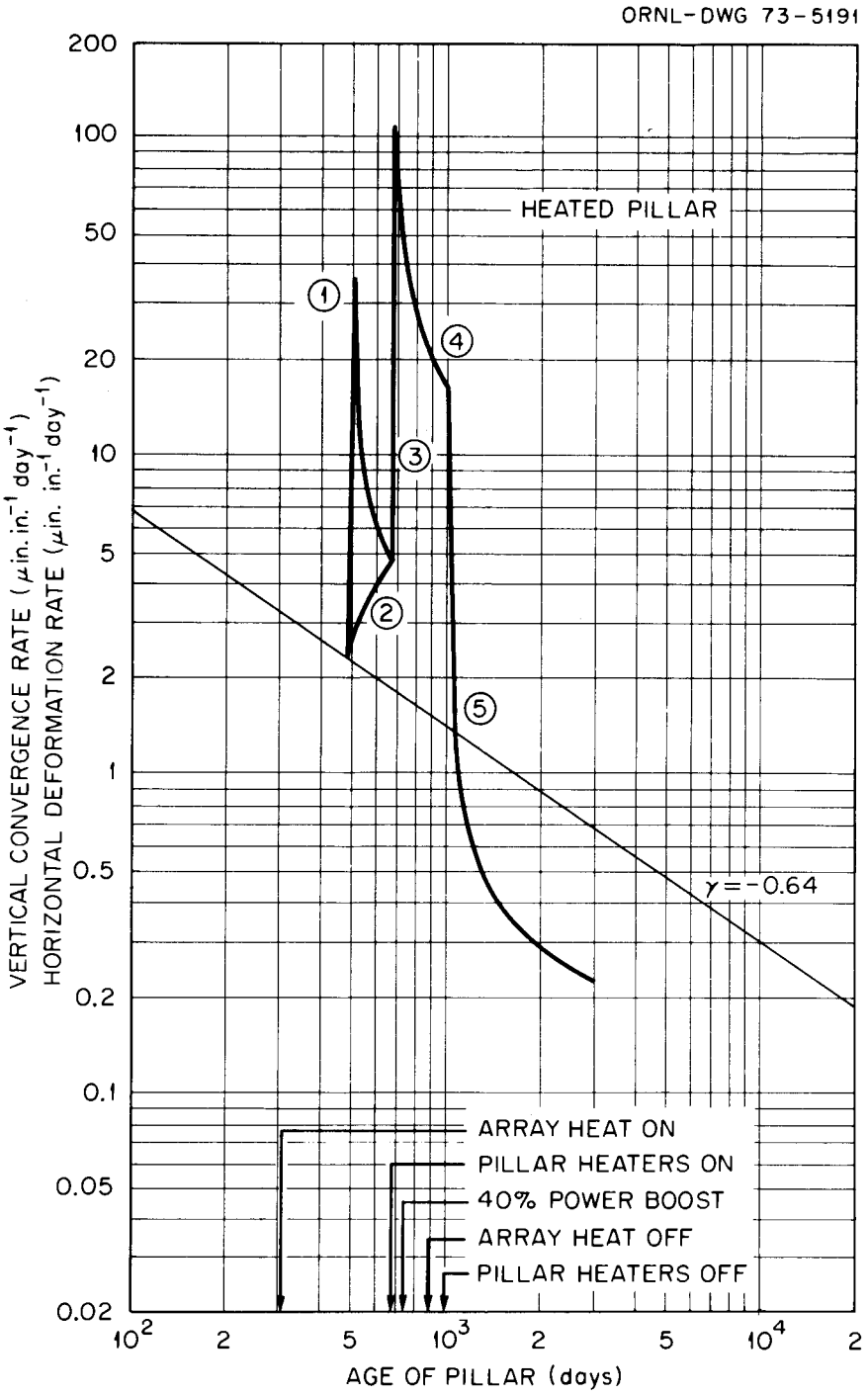


Fig. 15. Vertical and Horizontal Deformation Rate as a Function of Age of Pillar - Heated Pillar

1. When the array heaters in the floor of the room were turned on, there was an immediate thermal stress imposed on the pillars which was reflected as the discontinuous increase in convergence rate (note 1 in Fig. 13);
2. After passing a maximum, the convergence rate declines according to some complicated function because neither the (thermal) stress nor the temperature was constant during this period. Note however that these declining convergence rates (note 2 in Fig. 13), appear to be asymptotically approaching a line parallel to the earlier portion;
3. When the power input to the array heaters was increased by 40%, there was again a discontinuous increase in the convergence rate followed by a rapid decline as a function of time (see note 3 in Fig. 13);
4. When the array heaters were turned off, the thermal contraction of the salt on cooling was equivalent to the superimposition of a negative or tensile stress field on the existing compressive stress distribution. This unloaded the pillars and produced a drastic and discontinuous decrease in the convergence rate (see note 4 in Fig. 13). In some cases, the convergence rate reached zero and even slightly negative values for a short time during this period;
5. The next convergence rate spike (see note 5 in Fig. 13) was not detected in the results presented in the Project Salt Vault final report because of the insufficient data available at that time. It is, however, most interesting and can be interpreted as follows: When the pillar heaters at the central pillar were turned off, that pillar was suddenly unloaded (due to the thermal contraction) in the same way as described in item 4 above. This unloading of the pillar would have been much more abrupt and of greater magnitude than the unloading around the array rooms because of the greater heat input and higher temperatures. When that central pillar was unloaded, the load had to go somewhere

and at least a portion of it went to the pillars surrounding rooms 1 and 4, thereby producing the observed discontinuous increase in convergence rate. This rate then decreased as a function of time but again in a complicated way, because of the varying stress as equilibrium is approached.

This interaction of the central heated pillar with array rooms 1 and 4 is of particular interest because it suggests that the two experiments were not as independent of each other as suggested by the earlier analysis.[1] It is probable that an earlier interaction occurred at the time the pillar heater experiment was started but that its expression in the behavior of rooms 1 and 4 was masked by the high deformation rates and stress variations then occurring as a consequence of the array heating experiments. The prospect of separating any other interactions between the array rooms and the heated pillar does not appear to be promising.

The horizontal deformation rates at pillars 1-2 and 3-4 (Fig. 14) are similar to the vertical deformation rate curves, as would be expected, but show several significant differences:

1. The peak deformation rates occurred when the array heaters were turned on, but the changes in rates were much broader and less sharply defined. As discussed earlier, this effect resulted from the fact that the horizontal deformations are averaged over the entire width of the pillar, including the interior, more confined portions;
2. The peak strain rate produced by the 40% power increase was greater than the strain rate due to the initial heating. For the vertical deformation rate, the opposite was the case (see Fig. 13). This difference was probably real and implies that the stress and temperature conditions at that time were such that a much broader portion of the pillar was more sensitive to the 40% power increase, whereas the conditions at initial heating caused the pillar effects to be concentrated at the pillar edge;

3. The drastic decrease in the deformation rate when the array heaters were turned off (note 4 in Fig. 13) and the subsequent increase in rate when the heated pillar was unloaded (note 5 in Fig. 13), were not reflected in the horizontal deformation rates. This difference also was probably a consequence of averaging the total horizontal deformation across the entire width of the pillar.

Both the vertical and the horizontal deformation rates measured in and around the heated pillar are given in Fig. 15. In this case, the narrower pillar and the concentration of heat sources around it (rather than at the center of the rooms) increased and sharpened the horizontal deformations to the point where they were essentially identical with the vertical deformations. Furthermore, the arrangement of the gages was such that the gage lengths for both the vertical and the horizontal instruments were very nearly the same, making it possible to plot both results on the same scale as strain rate. The interpretation of the curve in Fig. 15 follows:

1. The initial spike in the deformation rate (see note 1, Fig. 15) was due to the operation of a single "modified" pillar heater and occurred <u>only</u> at the gages adjacent to that heater. All other gages around the pillar responded to this single heater at the much reduced rate shown by note 2, Fig. 15;
2. When the entire array of pillar heaters was turned on, the deformation rates experienced a drastic and discontinuous increase (see note 3, Fig. 15). This increase was entirely a consequence of the thermal stress and not due to elevated temperatures because it occurred too rapidly;
3. As was the case in rooms 1 and 4, the increased deformation rate rapidly decreased as a function of time from its peak value (see note 4, Fig. 15). In this case, however, the increasing temperatures of the pillar would have served to keep the deformation rates higher than was the case in rooms 1 and 4;
4. When the pillar heaters were turned off, the deformation rate rapidly and discontinuously decreased (see note 5, Fig. 15).

As was seen earlier, this decrease was the result of the recovery of the thermal expansion which forced the pillar to "shed" a significant portion of its load onto nearby areas. The deformation rate has continued to decrease but at a slower rate and now appears to be approaching a constant rate of about 0.2 μin./in./day.

If the heating experiments had not been carried out, presumably this pillar would have continued to deform as it was before the heaters were turned on; that is, along with the continuation of the initial straight line portion described by equation 1 where the value of γ is -0.64 (see Fig. 15). The present deformation rate is considerably below that projected straight line which can be interpreted as meaning that the pillar stress remains abnormally low. Since the pillar deformation was abnormally high during the heating experiments as a direct consequence of the externally introduced thermal stress and elevated temperatures, this result is to be expected. The implication, however, is that the center pillar is still not carrying its "fair share" of the overburden load. Extrapolation of the lower portion of the curve in Fig. 15 is impossible but it seems reasonable to assume that the deformation rate will not increase with time but will approach a constant value or will continue to decline. In either case, it appears that the actual deformation curve will not return to its normal undisturbed value within a period of at least 20,000 days. In other words, in this particular case, the 18-month-long heating period of the experiments introduced a structural anomaly which, although very small, will not be completely eliminated for a period of about 50 years.

If an attempt is made to apply this type of analysis to the results from the array rooms 1 and 4, problems are immediately encountered. The initial behavior of room 1 and pillar 1-2 as defined by the slope of the preheating deformation rate vs. time curve seems to be abnormal. Specifically, the deformation rates decrease too rapidly as a function of time, especially when compared with the results from other portions of the experimental area. In room 1, the values of the exponent γ for the vertical and horizontal deformations

were -1.16 and -0.78 respectively. The equivalent values for room 4 were -0.42 and -0.56, and at the heated pillars both values were about -0.64. Closer examination of the initial portions of the deformation curves (Figs. 7 and 13a) indicated that they depart appreciably from a power function of the form

$$\varepsilon = A\ t^{(1\ +\ \gamma)} \tag{2}$$

where

ε = strain

t = time

A, γ = constants.

This departure from a true power function produces the unusually low values of γ when the deformation rates are calculated incrementally. The reason for this abnormal behavior in room 1 is not known. It could be related to the geometry of the experimental area or to the previous strain history of the area, which subsequently became room 1 resulting from the previous excavation of the existing mine. However, based on our previous experience, any effects from these factors should be reflected in the amount of the deformation rate, that is, the value of the coefficient A in equation (1) and not in the value of the exponent γ. A more reasonable candidate explanation for the abnormal behavior in room 1 would be the transient stresses resulting from the continuation of the excavation of rooms 2, 3 and 4 in the experimental area. Since room 1 was the first part of the experimental area to be mined, it would have had the longest history of subsequent stress alteration resulting from the excavation of the rest of the experimental area. By the same token, mining operations ceased after excavation of room 4 so it would have had no subsequent alteration of the stress field. The only difficulty with this explanation is that it seems the later mining adjacent to room 1 should have added load to the surrounding pillars, thereby serving to maintain an abnormally high deformation rate rather than causing a too rapid decline in the rate of deformation.

If it is assumed that the initial values of γ for the deformations around room 1 were too small, for whatever reason, and that the behavior would have been very similar to that for room 4 had it been allowed to proceed undisturbed by the heating experiments, the problem is overcome. In this case, the deformations around room 1 would be represented by the lines identified as $\gamma = -0.42$ and $\gamma = -0.56$ on Figs. 11a and 12a respectively. Now it can be seen that the discussion of the present status of the heated pillar also applies to pillars 1-2 and 3-4; that is, the accelerated deformation during the heating experiments induced by the thermal stresses and elevated temperatures produced a situation where these pillars are presently carrying less of the overburden load than they should. Furthermore, many tens of years will be required before the stress distributions and deformation rates return to equilibrium.

6. LONG TERM DEFORMATION IN EXISTING MINE

The measured vertical convergence as a function of time at selected points in the existing mine workings around the experimental area are shown on Figs. 16 and 17 (see Fig. 1 for gage locations). These plots are simply extensions of those appearing in the Project Salt Vault final report[1] as Figs. 11.92 and 11.93. The average convergence rates during selected intervals at these stations and at several other locations are given in Table 2.

Examination of Figs. 16 and 17 indicates that the behavior of large portions of the existing mine workings was influenced by the various experimental activities and that that influence gradually decreased with increasing distance from the experimental area. The variations of the convergence rates seen in Figs. 16 and 17 (and Table 2) can be interpreted as follows:

1. The principal activity in the experimental area prior to standard day 800 was its excavation. Since these mining operations were removing material which had formerly been supporting the weight of the overlying material plus an

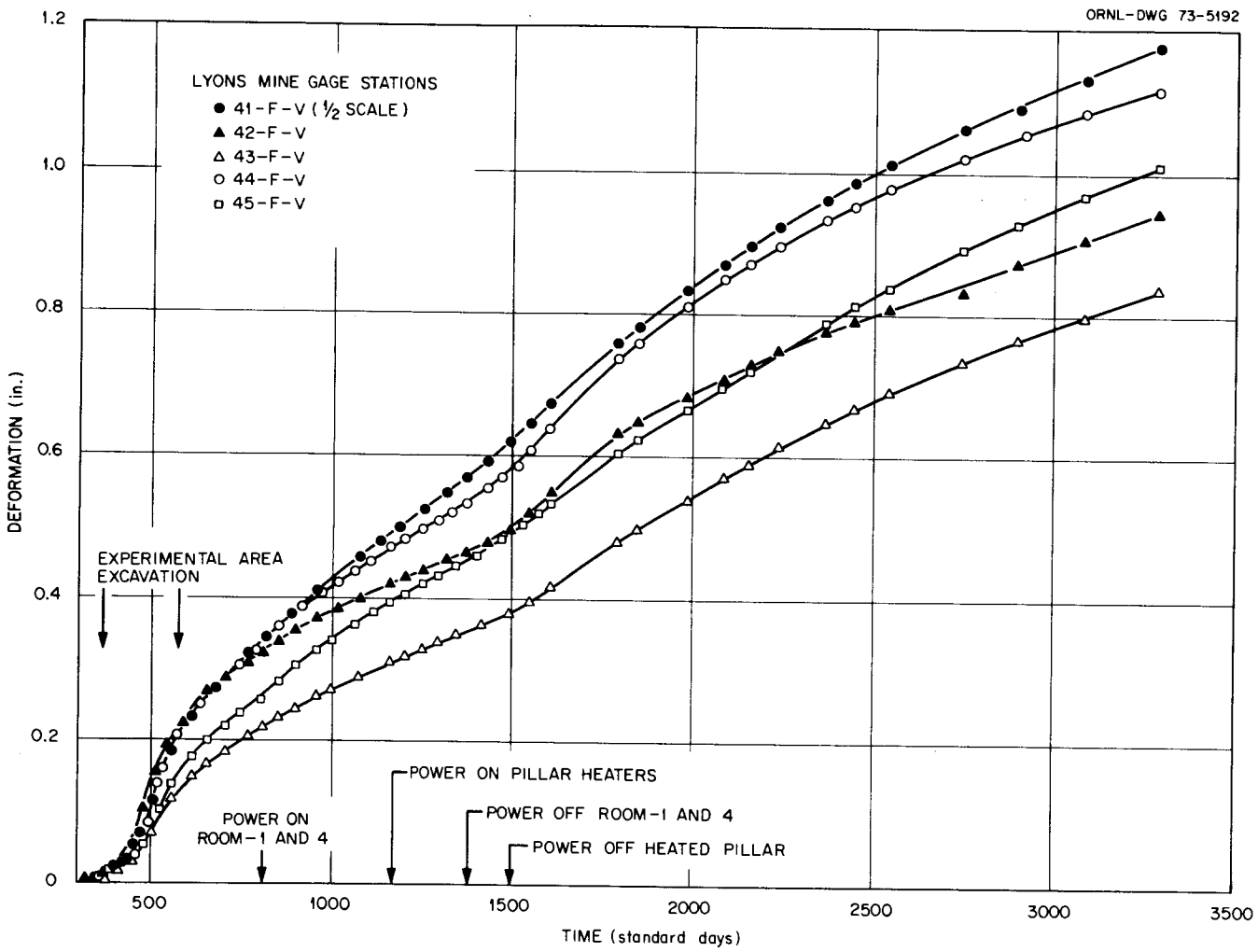


Fig. 16. Vertical Convergence as a Function of Time - Existing Mine Area

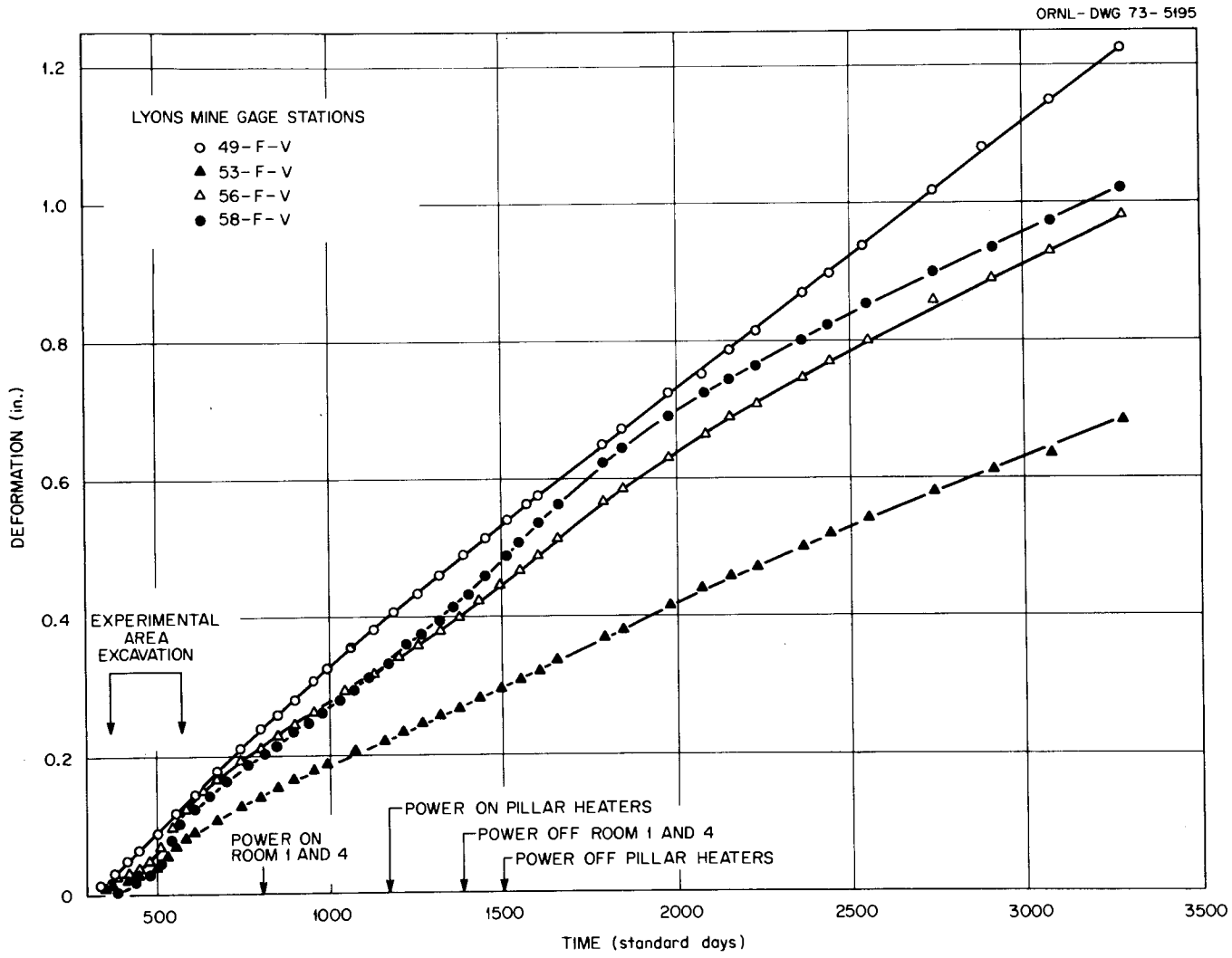


Fig. 17. Vertical Convergence as a Function of Time - Existing Mine Area

Table 2. Convergence Rates in Existing Mine Area

Gage	Vertical Convergence Rates (10^{-3} in./day) Standard Days				
	<800	800 to 1500	1500 to 1900	1900 to 2500	2500 to 3200
1-F-V	0.75	0.80	0.72	--	--
6-F-V	1.22	1.00	0.94	0.96	--
11-F-V	0.50	0.50	0.41	0.52	--
12-F-V	0.41	0.38	0.35	0.31	--
14-F-V	0.66	0.60	0.58	0.61	--
15-F-V	0.34	0.32	0.31	0.36	0.51
16-F-V	0.44	0.41	0.43	--	--
20-F-V	0.23	0.20	0.20	0.24	0.24
22-F-V	0.36	0.19	0.17	0.19	0.17
23-F-V	0.30	0.17	0.18	0.22	0.20
41-F-V	1.41	1.81	0.94	0.33	0.22
42-F-V	0.42	0.25	0.46	0.22	0.18
43-F-V	0.36	0.24	0.34	0.28	0.20
45-F-V	0.52	0.35	0.53	0.30	0.20
46-F-V	0.45	0.33	0.38	0.30	0.24
48-F-V	0.32	0.26	0.29	0.26	0.24
49-F-V	0.49	0.42	0.40	0.38	0.39
51-F-V	0.30	0.23	0.27	0.27	0.23
53-F-V	0.28	0.22	0.25	0.22	0.20
56-F-V	0.39	0.34	0.40	0.30	0.25
57-F-V	0.23	0.19	0.22	0.22	0.18
58-F-V	0.38	0.40	0.48	0.28	0.24
59-F-V	0.34	0.22	0.35	0.27	0.18

"abutment load," that load was redistributed as an increased stress to other areas, including the pillars in the existing mine. This increased pillar stress produced the increased convergence rates for the period prior to standard day 800;

2. The thermal stresses induced in the experimental area pillars during the various heating phases (standard day 800-1500) served to overload those pillars. Since that overload must come from some place, some of the load previously borne by the pillars of the existing mine area was transferred back toward the experimental area. The resulting decreased pillar stress produced a lower than normal convergence rate during this period;
3. From standard day 1500 to about day 1900, the experimental area was cooling and as was seen above, the pillars of the experimental area were drastically unloaded during this period. Some of that load was transmitted back onto the pillars of the existing mine, again producing a higher than normal convergence rate;
4. Since the experimental area pillars have remained in an unloaded condition following standard day 1900, the average stress on the pillars of the existing mine adjacent to the experimental area remains higher than normal and consequently the convergence rate remains higher than it would have been if the heating experiments had not been carried out. However, the continued creep deformation of the entire mine as a function of time means that it is gradually catching up with the experimental area which is deforming at a much slower rate because of its low stress. Part of this catching up is the return of load from the surrounding areas to the experimental area pillars. Therefore, although the convergence rates in the existing mine remain abnormally high, they are decreasing more rapidly with time than ordinarily would have been the case because their average stress is slowly decreasing.

7. CONCLUSIONS

The analysis of the rock deformations associated with the Project Salt Vault demonstration experiment presented in this report was made possible by the gage reading program which continued long after the termination of the experiments. In some cases, these later data only served to confirm earlier conclusions, but in many cases they provided an increased understanding of the rock deformation behavior. This was particularly true of those data subjected to a deformation rate analysis. In this case, it was concluded that the interaction of the various parts of the experiment and different portions of the experimental area was probably much greater than suggested by the earlier analysis. A second interesting conclusion was the very long term persistence of the structural anomaly introduced by heating for a fairly short term.

A further conclusion which could be drawn from the analysis is that continued monitoring of the rock deformations in and around the Project Salt Vault experimental area would produce very little additional useful data. Accordingly, this gage reading program has now been discontinued.

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