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16. Abstract (Limit: 200 words)

This report presents the results of a survey on blasting effects on ground water supplies in Appalachia. Literature was searched and cases of alleged water well damage were investigated. Occurrence of ground water in Appalachia is primarily in low yield, fractured, water table aquifers. Four test sites were chosen based on geographic and geologic diversity and wells were drilled at each site. Base line data on water quality, static water level, and drawdown characteristics were obtained before surface mining commenced. Blast-induced ground vibrations were measured at the surface at levels up to 5.44 inches per second maximum resultant particle velocity. Measurements made at the bottom of the wells indicated that vibrations were considerably attenuated at depths of 140 to 160 feet. No direct evidence of change in water quality or well performance was produced by blast vibrations, but removal of downslope support by excavation does cause lateral stress relief which permits the water-bearing fractures to become more open. This additional storage capacity causes the static water level to drop and for well-bore permeability to improve. Static water level recovers if sufficient recharge is available and well performance is improved.

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FOREWARD

This report was prepared by Philip R. Berger and Associates under U.S.B.M. Contract No. J0285029. The contract was initiated under the Minerals Environmental Technology Program. It was administered under the technical direction of Twin Cities Research Center with Mr. John Kopp acting as Technical Project Officer. Mr. B. G. Horton was the contract administrator for the Bureau of Mines. This report is a summary of the work recently completed as a part of this contract during the period September 29, 1978 to September 29, 1980. This report was submitted by the authors on November 28, 1980.

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EXECUTIVE SUMMARY

Prior to any field effort or investigation of damaged wells, a search was made of the literature. Little was found pertaining directly to effects of blasting on wells or ground water aquifers, but there is a considerable amount of peripheral literature dealing with earthquakes, nuclear tests, and the effects of mining on groundwater.

State agencies and coal companies in Appalachia were contacted to develop a list of reportedly blast damaged wells. Of 36 wells so reported, 24 were investigated in the field but there was no clear evidence that the problem was blast related. In most cases, it was evident that other factors were responsible for the changes in well behavior.

Groundwater in Appalachia may occur in glacial deposits, valley alluvium, and sandstone aquifers, but for the most part the water is found in fracture systems which act as low-yield, water table aquifers. Some of these fractures are tectonic in origin but most are the result of lateral stress relief associated with natural topographic development. These low-yield, water table, fracture systems have received little attention. One of the objectives of this report is to provide case history data which will aid in understanding the occurrence of ground water in these aquifers and how it differs from the more commonly described groundwater concepts.

The general quality of water encountered at the test sites in this project fell within the U. S. Public Health Service Standards except for iron and manganese. At times, the turbidity was also excessive but the cause of the turbidity was not clear and couldn't definitely be related to blasting on the basis of time occurrence. The most objectional aspect of the high iron and manganese concentrations is that the growth of iron bacteria is promoted. These can cause red slimes which if disturbed will give the water a reddish color. Sulfate concentrations which have been shown to be the best indicators of mine acid pollution, were all in the acceptable ranges of 14 to 240 mg/l and did not change significantly as mining progressed at the test sites.

Drilled wells are the most common sources of groundwater in Appalachia. These are generally between 100 to 150 feet in depth with the hole uncased except for the uppermost 20 feet. Water yield is commonly less than one gallon per minute and most drillers estimates are exaggerated. If pumped at a rate within the capability of the sedimentary rocks to yield water, the well will be drawn down abruptly for 20 to 30 minutes and then reach near-equilibrium. Wells in Appalachia are commonly poorly designed and are pumped at too fast a rate. Many reported problems can be solved with improved design. Adequate submergence of the pump intake is very important.

Tests were conducted at four sites which were chosen on the basis of geographic and geologic diversity. At three of the sites water quality, static water level, and drawdown characteristics were determined in advance of any mining, and at the fourth, wells were drilled and tested in an interval between blasts. At all sites, wells were located approximately 1,000 feet from the first blast and were situated so as to be in the path of mining or within 50 feet of ultimate pit limits. Drawdown tests were performed during the first blast and monthly thereafter. Ground vibrations from all blasts were monitored, and water levels were monitored continously. Water samples were taken before and after blasts at frequencies which increased as mining approached the wells.

Maximum ground vibration levels at the surface at the four sites were 2.2, 5.44, 2.14, and .84 inches per second resultant particle velocity. Based on observable change in well conditions immediately after a blast, there was no direct evidence of any significant change as a result of blasting. At three sites, when mining approached within a distance of approximately 300 feet, a fairly abrupt drop in static water level occurred followed by a significant improvement in well performance as indicated by specific capacity. At the fourth site, there was no change.

The timing of these changes indicate they were not the direct result of blasting and the observed ground vibration levels substantiate that a level of 2.0 inches per second peak particle velocity (normally 80 to 85% of maximum resultant particle velocity) is not sufficient to cause damage to wells or typical Appalachian groundwater aquifers.

The time of the changes, the length of time involved, and the location of active mining at the time of occurrence indicate that the lowering of static water levels results from increased storage space in the aquifers as the result of fractures becoming more open because of lateral stress relief. This is followed by improved well performance because permeability is improved by the same mechanism. If sufficient recharge from rainfall is available, the static water level recovers. In the interim, wells with inadequate pump submergence will experience a loss of water. If mining is being conducted 300 feet away, blasting is assumed by neighbors to be the cause instead of the true mechanism.

With the concept of lateral stress relief resulting from downslope excavation, certain precautionary steps may be taken. These are described and low-cost methods for obtaining the necessary information are described.

Additional research to quantify the effects of lateral stress relief would be of value to the surface mining and construction industries.

SURVEY OF BLASTING EFFECTS ON GROUND WATER SUPPLIES IN APPALACHIA

by

Donelson A. Robertson, James A. Gould, Jeffrey A. Straw and Michael A. Dayton

INTRODUCTION

Surface mining of coal is one of the most important economic activities in Appalachia. It provides direct economic benefits to the residents of those areas where it is mined as well as providing an important source of energy for the nation's use. Nevertheless, there are significant environmental impacts and some of these are poorly understood. One of these is the effect of blasting on underground supplies of water. This report describes work that was performed over a period of twenty-four months to determine what these effects are.

Ground water supplies are a vital concern to residents in rural areas who depend on water wells to meet their daily needs. Most have a poor understanding of how ground water occurs and even less understanding of the potential for damage resulting from the nearby use of explosives. Consequently, there is considerable apprehension when surface mining activities move into an area and blasting is performed to remove the strata overlying the coal.

The situation is aggravated by the fact that for the most part, yields from wells in the coal bearing strata in Appalachia are low in comparison with other areas of similar population density such as Illinois. Many rural residents in Appalachia have wells which are not capable of producing one gallon per minute over a period of several hours. Having lived with a frugal water budget for years, it is only natural that such people would view any potential threat to their supply with alarm.

Surface mine operators also are concerned because of their liability if they do damage a nearby well and because of the public relations problem created by the neighbor's fears whether they are well-founded or not. These problems can require considerable management time and attention. Frequently, State and Federal regulatory agencies become involved which further increases the cost. Determination of cause and effect is usually inconclusive because there have been no definitive studies of the effect of surface mine blasting on ground water supplies such as those found in the coal-bearing strata of Appalachia.

Many operators have provided new wells for complainants although the responsibility for change in quantity or quality of water, if indeed there was a change, was debatable. In most cases, it appears this was done as a matter of expediency and may be an acceptable solution to some managements when one isolated well is involved. It can become unacceptable when there are other neighbors who may be encouraged to seek a new well for whatever reason.

Because of the lack previously of reliable information, such issues have generated emotional situations of significant proportions which have the potential of being resolved in a manner which may be to the detriment of all concerned parties.

The results of this study should be of value to landowners, coal operators, and government regulators in understanding what blasting can or cannot do to water wells, and what effects are probably associated with other causes.

Before any field testing was undertaken, a literature search was made to determine if there was any previous work which addressed the problem of the effect of blasting on water wells. Many items of peripheral interest were located but nothing bearing directly on the problem was found. Special Publication 67 of Montana Bureau of Mines and Geology, "A Study of the Influence of Seismic Shotholes on Ground Water and Aquifers in Eastern Montana", provides the most pertinent data but the smaller magnitude of the blasts, the absence of repetition of the blasts, variations in the characteristics of ground water occurrence, and different surface geometry inhibits the application of the conclusions in this study to the situation in Appalachia.

There is a considerable amount of literature dealing with the extent of fracturing caused by nuclear devices and conventional explosives in boreholes. The findings of Derlich (30), Siskind (87,88), Atchison (5), D'Andrea (26), and Hearst (42), all indicate that the fracture zone is limited to a small radius around the blasthole. Different rock types and different explosives introduced some variation but in general, the fracture zone was limited to a radius of 20 to 40 blasthole diameters.

Literature dealing with the effect of earthquakes, earth tides, nuclear blasts and other transient phenomena was also searched. Nazarian (71) comments that a survey of published reports describing the conditions of numerous water wells during and after three major earthquakes indicate very little damage to the wells. Almost all wells reported to be permanently damaged were in regions of permanent displacement of the surrounding earth, primarily landsliding. For 350 wells in areas where severe damage to structures occurred, he found 57 cases of well damage broken down as follows:

Well destroyed:

Earth displacement---------------7
Casing collapse------------------1

Well inoperable but reparable:

Deformation of casing------------3
Submersible pump cable break-----1

Damaged wells but operable:

Misalignment of pump column-----10
Reduction in well capacity------13
Displacement of pump base-------22

In addition, there were many instances reported of sanding or mudding of wells, and electric power failure. The intensity of the earthquakes in Nazarian's study were VIII, IX and X on the modified Mercalli scale.

There are a number of papers (2, 11, 20, 23, 36, 39, 43, 44, 45, 57, 59, 60, 63, 64, 65, 68, 74, 76, 77, 78, 79, 84, 90, 94, 95, 96, 104) dealing with quality and quantity changes of ground water in association with surface mining. Nearly all of this literature is concerned with the interception of aquifers by the open pit, the effect on ground water levels of pumping water from the pit, and/or pollution by mine waters.

In addition to the literature search, inquiry was made to surface mine regulatory agencies in each state in Appalachia where coal is mined, and to many coal companies, insurance companies, trade associations, and explosive suppliers. These inquiries asked for data on water wells where a complaint of blast damage had been received. In all, 36 wells were reported as damaged by blasting. Field visits were made to 24 of the sites and additional information was obtained from either direct well measurement, discussion with the owner, or individuals handling the complaints for the coal company.

In many cases, it was apparent that the damage claimed was caused by something other than blasting. In other cases it was clear that there had been a general lowering of the water table, possibly as the result of unplugged flowing test holes, drainage at the high wall, or a two-to-three fold increase in the number of residences utilizing a limited supply, combined with seasonal changes.

In nearly every case, there was a lack of good bench mark data. Many residents have only a vague idea of the depth of their wells. Fewer know the depth of the casing. None of the residents interviewed knew the source of the water in their well. About fifty percent had a vague idea of the static water level in the well when it was initially completed. Only one well had been tested in any quantitative way. That test was inadequate and made the owner think he had a much better well than was actually the case.

Consequently, it was very difficult to confirm or deny that blast damage had occurred but among the 36 examples, some of the well histories suggested two scenarios in which blasting might cause damage. The first is that the ground vibrations might be sufficient at times to cause loose material such as drill cuttings to slough off the uncased borehole and cause the water to become temporarily turbid, or if enough material was involved, to bury pump components at the bottom of the well. The second concerns those wells that obtain their water from flooded and abandoned deep mine workings. Ground vibrations might be sufficient at times to cause roof falls which could stir up sediment in the water or disturb an existing potable water/mine acid stratification. Of course, sloughing of the well bore and mine roof falls can occur in the absence of blasting so these scenarios are not exclusive.

In the field testing phase of this project, effort was directed to finding what quantitative and qualitative changes, if any, took place in the well and the water it produced as levels of blast-induced ground vibrations became stronger and excavation moved closer. The results indicate a predictable pattern of rock behavior as mining approaches water wells. Recognition of the pattern and its relationship to such things as water well design and rate of pumping provide a rational basis for determining what has happened to a well and the most efficacious remedial procedure.

NATURE OF GROUND WATER OCCURRENCE IN APPALACHIA

In some coal-producing areas of northern Appalachia, ground water may be obtained from glacial deposits. In other areas, alluvial valley fill materials may be important sources for water wells but the vast majority of rural, domestic water wells in the coal regions of Appalachia obtain their water from the sedimentary rocks of the Pennsylvanian and Permian Systems. Wells with large yields have been developed in these rocks for industrial and municipal purposes, but the focus of the report is on the common domestic well which is usually much shallower and has a location determined largely by convenience of access and nearness to the residential dwelling it serves. On small one-to-five-acre tracts, which are common along main roads, there isn't much latitude in the search for ground water. Consequently, the larger yields that are commonly reported in the ground water publications of the State and Federal geological surveys are not commonly obtained in Appalachian domestic wells. Even the low yields which are reported by drillers are usually based only on a visual estimate as water is blown from the hole. Experience gained from this project where driller's estimates could be compared with later drawdown tests indicates that the estimates are commonly 300% too high.

There is considerable variation in the water bearing properties of the Pennsylvanian and Permian rocks, depending principally on rock type and topographic location with respect to local drainage. Over such a large area as Appalachia and with strata as variable as they are, one can only make broad generalizations but these are helpful in understanding why domestic well water is of such concern. Except for the sandstone and conglomerate beds in the Pottsville Group in some areas where water occurs in the pore spaces between the sand grains, most of the water in the coal bearing strata of Appalachia occurs in nearly vertical fractures, joints and along bedding planes. Observation of road cuts in the wintertime provides a good visualization of the distribution of these localizing features and the degree of interconnection, because ice masses accentuate the water bearing areas. In many cases, the observations do not fit the common textbook generalizations. For example, sandstones with shale at the top and bottom are generally considered to be confined aquifers but in Appalachia it is common to see water percolating downward through fractures in shale and then flowing laterally out into the cut when its downward movement is impeded by a relatively impermeable sandstone. This is because the shale with its lower tensile strength has more vertical fractures at such sites than the sandstone. This is not to say that Pennsylvanian and Permian sandstone aquifers younger than those of Pottsville age do not exist in Appalachia, but from the observations made in connection with this project vertical fractures are more important. They establish a vertical network which present the characteristics of a water table aquifer; water levels responding to rainfall in less than 24 hours; water levels not responding to changes in atmospheric pressure; and, on drawdown tests, the pump rate decreasing as the drawdown increases even though the power supply remains constant. This latter characteristic occurs because the saturated thickness is decreasing.

Much additional work needs to be done to provide guidelines for estimating the frequency of joints and fractures in strata of different lithology. Some of these joints are undoubtedly tectonic in origin and exhibit a regional pattern. But there is also a local system of vertical features, whether they be called joints or fractures, which are the result of lateral stress relief associated with the natural topographic development.

> According to Ferguson(38), "This pattern developed when the lateral supporting rock was removed by erosion from either side of the valley by river downcutting causing a series of stress relief fractures. These stress relief fractures show a general parallelism to the valley walls and the pattern of fractures is limited in vertical extent to individual beds. They also become less frequent with depth and they do not occur beyond the destressed zone in the valley wall. This mode of occurrence has been verified in tunnels, by angle directional drilling, and in the excavation of numerous abutments. . . . . . .
>
> . . . . . . .In thousands of observations throughout the area it has been noted that each rock type develops its own frequency and pattern of fracture. All are high angle to vertical fractures and their frequency and pattern depends on:
>
> 1. Thickness of bed
> 2. Competency of bed
> 3. Competency of adjacent beds
> 4. Position in valley wall
>
> In cyclicly deposited rocks, the fractures that developed in one rock type generally stop at the bedding plan contact with a differing strenth rock. These patterns are easily recognized. They consist of a dominant linear fracture parallel to the valley wall and a set of fractures sub-perpendicular to it. These sub-perpendicular fractures are the result of the dominant blocks inability to move outward away from the wall indefinitely without breaking at some point along its long axis. The resultant fracturing is at some angle to the perpendicular face."

Coal is perhaps the most brittle material in the Pennsylvanian and Permian strata of Appalachia and it also probably has the lowest tensile strength. Consequently, it has extensive vertical fractures although the permeability of these systems may be very low. Nevertheless, ground water occurrence in Appalachia is most frequently associated with coal seams. This may be because the high frequency of fracturing assures some intersection of the fracture system by the well bore or it may be because the coal seams are frequently underlain by underclays which are more likely to deform plastically and be relatively fracture-free. This relationship can also be observed in many roadcuts where water can be seen flowing out of a coal seam and flowing downward over the underclay, frequently resulting in colorful iron-rich deposits called yellowboy.

In either event, the coal seam frequently acts as the conduit through which water in overlying fractures can move downward and into the well. In this case, the water first appears as the coal is drilled but the level may rise well above the coal because of the head in the total system. From the effect one may mistakenly conclude that the coal seam is a confined aquifer.

Of course the well-bore may intercept the fracture system in some other bed with similar result, but from reviewing many Appalachian well records, water is most commonly encountered when the coal is drilled.

The effect of altitude above the local drainage is fairly straightforward. Wells in the valleys which penetrate a fractured section below the drainage level, are generally better wells than those near the tops of hills. This is because the water table is a subdued replica of the topography and the ground water is migrating toward the streams. Consequently, wells on hills will have less water-saturated thickness than valley wells if the wells are the same depth.

Although the wells drilled in conjunction with this project generally exhibited the characteristics of water-table wells in a fractured system there was a surprising lack of accordance of initial static water levels in wells in some cases. Frequently at distances from 10 to 35 feet, water levels varied by 30 to 50 feet. Obviously, the wells must be connected to different systems or sub-systems which are separated by local differences in permeability of the fractures or non-connection. In conducting drawdown tests, the response in observation wells did not decrease inversely with the surface distance. In fact, wells at 35 to 65 feet commonly responded with more drawdown than observation wells only 10 feet away. In many wells, there was no response. It is possible that the fracture route distance to a well 35 feet away on the surface might be shorter than the fracture route distance to a well only 10 feet away on the surface.

While most textbooks dealing with ground water discuss the occurrence of water in fractures, the treatment is usually brief and oriented more toward the high yield situations. Low yield, water-table, fracture systems have apparently received little attention because they generally cannot serve as industrial or municipal sources, but only as small, domestic supplies.

Regulatory agencies tend to follow the lead of academe. Accordingly, ground water data requirements in connection with surface mining permits in Appalachia are sometimes at odds with the nature of these low yield, water-table, fracture systems. For example, the stratigraphic section encountered by a well may be much less important than its topographic relationship to the excavation. One of the objectives of this report is to provide case history data which will be of benefit to regulators, home-owners, and operators in understanding the occurrence of ground water in these low yield, water-table, fracture systems, and how it differs from the more commonly described ground water concepts.

GENERAL CHARACTER & QUALITY OF GROUND WATER IN APPALACHIA

The various publications of the State and Federal geological surveys provide a wealth of information on the general chemical character of ground water in Appalachia.

A summary of all this information is beyond the scope of the project and only the broadest generalizations will be made here.

From analyses made in connection with this project and a general impression from the literature, ground water in Appalachia has a high iron concentration which commonly exceeds the U. S. Public Health Service maximum standard of 0.3 mg/l. Nevertheless, the iron concentration is not high enough in itself to account for the very rusty colored water which is sometimes encountered. Analyses of very reddish water may show an iron content no higher, and possibly less, than clear water with only a slight iron taste.

At two of the test sites which will be described later, the water from the well was very reddish when first pumped after being dormant for two or three weeks. It required about 50 minutes of pumping before any significant clearing occurred. If this occurred in a domestic well, perhaps after a family had been on vacation, the reddish water would be pumped into the storage tank that is usually present, and it might be several weeks before the water cleared.

It seems likely that water standing in the well is more oxygenated than water in the formations. This would permit any ferrous iron to be oxidized and produce a reddish color. Ferric iron is less soluble, however, and one would expect it to precipitate. But the material is very fine and there may be just enough agitation to keep it in suspension. Some of this effect may also be the result of iron bacteria. This is suggested by the fact other test wells which have a higher iron concentration produce no fine reddish particulate matter even after dormant periods of nearly two months. Also, some other wells not included in this project which have exhibited a reddish color but only moderate iron concentrations, have been tested and the presence of iron bacteria was confirmed.

Project testing indicates that manganese exceeds the standard level of 0.05 mg/l in nearly every sample, and usually by a substantial amount.

Turbidity in the test wells also commonly exceeded the standard limit of 5 units, considering only pre-blast samples. This is a common occurrence in other non-project wells that have been tested by P. R. B. & A.

Acid mine drainage is a problem in Appalachia but there were no indications of a problem of this sort at any of the test sites. High sulfate concentration is probably the best indicator of this problem (Hilgar, 44). Sulfate levels encountered at all test sites were in the range of 14 to 240 mg/l, all below the recommended level of 250 mg/l.

Much has been said by others about the acid rain problem. Random tests confirmed that rainfall in the Pittsburgh area does commonly have a pH ranging from 4.5 to 5.0. Because of the fast response of the test wells to rainfall recharge, one would expect the ground water to reflect this situation.

There was considerable fluctuation at each site withmost pH values between 6 and 8, but the overall range did extend as low as 5 and as high as 8.7. Neutralization of the acid rain in ground water appears to be fairly rapid.

Color, alkalinity, odor, total suspended solids, and total dissolved solids all fell within acceptable ranges at the test sites.

TYPICAL DOMESTIC WELLS AND HOUSEHOLD SYSTEMS

Hand-dug wells are common in Appalachia. These are usually situated in the valleys where the water source is from pore space in alluvium or on the hillside along a spring line. In the latter case, the well is more of a catchment basin than a well. It is unusual to hear of alleged blast damage to a hand-dug well and in these situations the complaint is generally that the water level has dropped gradually. Development of this condition is more likely related to factors other than blasting.

Drilled wells are much more common and they may be drilled with either rotary or cable tools. Most drillers use rotary drills with air circulation. Locally, in areas where yields are particularly low, cable tools are popular because there is less chance of sealing off the fractures in the bore-hole. Also, in these areas, larger diameter holes are usually drilled in contrast to the 6" ± diameter holes that are commonly encountered with rotary drilled holes, because the larger holes are likely to yield more water. With either type of drill, the amount of casing is usually limited to that necessary to case off the soil and weathered rock that might slough into the hole, leaving a maximum of open hole. In general, about 20 feet of casing is used and the holes are drilled to a depth of 100 to 400 feet, with the average being about 100 to 150 feet.

Apart from the fact that the well must be deep enough to encounter a source of water, it is important that the well be deep enough to permit a drawdown (distance from static water level to pumping level) that will meet the intended needs. A characteristic of wells in these low yield, fractured, water-table systems is that the drawdown for the first 10 to 20 minutes is quite rapid, followed by a near-equilibrium situation. The distance between the static water level and the pump must be sufficient to permit the water level at near-equilibrium (pumping level or dynamic water level) to be well above the pump. This is called submergence and requires consideration of not only the depth of the pump but of the capacity of the pump at the depth at which it is to be set. If the pump is over-sized at the depth at which it is set, the drawdown will continue to be rapid. When this happens, the length of time the well can be pumped will be limited to 10 to 20 minutes unless the flow is restricted at the surface by a valve arrangement. Such rapid drawdowns cause abrupt pressure changes at the bottom of the well and the water movement in the well is more likely to cause sloughing than if the drawdown was smaller and occurred at a slower rate. Consequently, if the pumping rate is significantly in excess of the rate that water is flowing into the well the water may remain turbid and frequent "sanding up" of the pump might be expected. Under these conditions, if the static water level drops to a lower level for some reason, the condition is aggravated because the pump will have to draw the level down more frequently to supply the same quantity of water.

It is instructive to consider this situation in some detail in terms of the relative demand placed on the water-bearing strata because many water well problems in Appalachia could probably be solved by making the water well design more compatible with the ground water sources. In order to do this, it is necessary to define the term <u>specific capacity</u>.

Many different quantities are used in ground-water hydrology but in these low yield, fractured, water table systems we have found <u>specific capacity</u> to be very useful. Specific capacity is the pumping rate in gallons per minute per foot of drawdown. Because the drawdown changes as the well is pumped, a time after pumping is started should be specified. Because of this, specific capacity may be a more useful concept in Appalachia than it is elsewhere because there is commonly little change in the drawdown after an hour or so unless one is dealing with a very marginal well.

To get more comparable specific capacities, an adjustment in the raw drawdown data is required. This is because in water table situations the saturated thickness available to the well is constantly decreasing as the well is being drawn down. This adjusted quantity is called the adjusted drawdown, s', and in the work of this project it has been calculated using an equation derived by Jacob (47):

$$s' = s - \frac{s^2}{2m}$$

where:

s' = drawdown that would occur in an equivalent nonleaky artesian aquifer, in ft.

s = observed drawdown under water table conditions, in ft.

m = initial saturated thickness of aquifer, in ft.

When specific capacity is referred to in this report, it means the pumping rate in gpm divided by this adjusted drawdown.

Consider the four following well situations:

	Well A	Well A'	Well B	Well B'
Depth of well	100'	100'	150'	150'
Static water level	40'	40'	40'	40'
Depth to pump	90'	90'	140'	140'
Pumping rate, Q	10 gpm	5 gpm	10 gpm	5 gpm
Initial saturated thickness, m	60'	60'	110'	110'
Maximum available drawdown, s *	45'	45'	95'	95'
Maximum adjusted drawdown, s'	28'	28'	54'	54'
Required specific capacity, $\frac{Q}{s'}$	0.357gpm/ft	.179gpm/ft	.185gpm/ft	.093gpm/ft

* Unadjusted. Assuming a final water level 5 feet above the pump.

Using the specific capacity as an index of the capability of the surrounding strata to yield water to these wells, it is clear that Well B' requires a yield only about 25% as good as that required by Well A. In other words, by drilling the well 50 feet deeper and reducing the pump rate to 5 gpm, the demand is within the capability of many, if not most low yield, fractured, water table systems in Appalachia. Well A, however, could not be pumped for more than 20 to 30 minutes unless it was situated in water-bearing strata significantly better than the average found on hillsides in Appalachia.

It should be clear that the well most likely to become a problem around a surface mining site (assuming fairly uniform conditions) is the one with the least distance between the static water level and the pump, particularly if it is equipped with an oversize pump that is allowed to run at full capacity.

Domestic well pumps in Appalachia are predominantly one of three types; submersible, jet, or a hand-operated piston pump. The latter is generally close to the house and water is drawn by hand as needed. There is rarely, if ever, any complementary storage facility.

Jet pumps operate by having water pumped down the well in one line (pressure line) by a centrifugal pump at the surface. Below the static water level, the pumped water discharges through a nozzle into a Venturi tube. The pressure drop at the nozzle is sufficient to draw additional water into the Venturi from whence it is forced up a second pipe (suction pipe) to the surface. At that point, some of the water is recycled back down the pressure line and the remainder goes to a pressurized storage tank, in most cases. Pumping cycles are determined by the pressure in the tank. When water is used and the pressure falls below a pre-set level, the pump starts and continues until the pressure in the tank has built up to a pre-set cut-off level. A foot-valve, or check-valve, on the water intake line near the Venturi maintains water columns in both the pressure and the suction lines. In iron-rich Appalachian water, many people find it is necessary to replace the foot valve about every two or three years.

Submersible pumps seem to be the most popular and are more efficient than jet pumps. Submersible pumps have an electric motor at the lower end of the pump which drives a series of impellers that force the water up the single discharge line. Water intake is between the impellers and the electric motor. A check valve above the impellers prevents the discharge line from draining and causing an interruption of flow when the pump is started. Generally, the discharge line runs into a storage tank and the pump cycles are usually controlled by pre-set pressure settings in the same manner as the jet pump. With large storage tanks at atmospheric pressure, pump cycles may be controlled by time switches and float devices.

Submersible pumps are available in a wide range of sizes, capacities, and impeller stages. Most of those in domestic use in Appalachia are ½ to 1 H.P. units with 110-volt or 220-volt motors. Wiring may be two-wire or three-wire. The wires are generally taped to the discharge line which is usually tied to the pump with the other end tied at the surface in some manner such that it can't go back down the well. The discharge lines may come straight out the top of the casing, through a split well-seal cap, in which case the well-head installation is usually in a pit about two to three feet deep. A breather pipe is installed in a small, threaded hole in the well seal, and after suitable protective covering and insulation, the well head is buried or enclosed in a structure. Alternatively, pitless connections are becoming more popular in which the discharge line passes through the side of the casing about four feet below the surface of the ground. At that point it connects with an underground line running to a storage tank in the house. Electric lines are also buried in the trench. The casing extends vertically above ground level for about one foot, and a fabricated casing cap is placed over the open end. The nylon safety line is brought over the top of the casing, passes through a small, semi-circular bulge on the side of the cap, and then is usually tied to the discharge line where it protrudes through the casing. It is easy to measure the static water level in wells with pitless adapters because one has only to remove the well cap and lower a probe. The main difficulty is to avoid getting the probe caught in one of the places where the electric wiring is taped to the discharge line. Where a pit is used, measurement of the static water level can be a full days job. The sod must be saved and set to one side, the underlying soil removed, and the protective covering (usually a piece of plywood) lifted up over the breather pipe. The breather pipe is then removed and a standard probe will usually fit down through the breather-tube hole in the split well-seal. If one planned to do a number of such measurements, it would be worthwhile to make a special probe which would pass through the breather tube.

Jet pump nozzles and intakes are usually placed only a few feet below the static water level in order to minimize the discharge head. This is largely because of the inherent inefficiency of this method of pumping. As the discharge head increases, additional stages have to be added to the centrifugal pump to supply the necessary pressure. Because of the relatively small submergence, a lowering of the static water level may cause the intake to be above the water in the well.

Submersible pumps on the other hand are generally set about ten feet above the bottom of the well. The part of the well below the pump is referred to as the well sump and it serves as a place for sloughing material to fall without interferring with the operation of the pump. Ten feet is probably sufficient for most areas, but there are localities where claystones, redbeds, and expansive shales can cause sloughing to be severe. In such cases other well designs and clean-out histories should be investigated to determine a more adequate-sized well sump. In assessing the possibility of blast damage, it is essential to understand that sloughing of material from the well sidewalls is a common and normal occurrence. Periodic sampling and testing for turbidity in the absence of blasting should provide some measure of the natural potential of sloughing material to do damage. Measuring the accumulation of material in the well sump is difficult because it is hard to get the measuring device past the pump with certainty.

To help overcome the sloughing problem, plastic liners are being used more frequently. This is a 4", 4½" or 5" plastic pipe with a 3/16" wall which comes in sections that can be coupled with a plastic coupling and plastic cement. One quarter inch holes are drilled down the length of the pipe at intervals of one foot and in three rows which are roughly equispaced circumferentially. Many drillers recommend the use of liners in all wells which exceed 100 feet in depth. It is probably good insurance. If material sloughs into the hole, it may wedge the pump against the sidewall. The pump may be ruined in getting it out of the hole and of course, the clean-up operation is also expensive in comparison to the cost of the liner. ($1 to $2/ft)

The importance of having the pump submerged a sufficient depth to permit the well to approach approximate equilibrium has been discussed, but related to this is the value of the storage capacity of a well; that is, the water in the well above the pump intake. In a 6" diameter well, each foot of water above the pump represents about 1.5 gallons. If there is 60 feet of water above the pump, the well can provide 90 gallons of water without any inflow from the surrounding strata. If this amount is added to the water in a storage tank, say, 200 gallons, then there is a total of 290 gallons available at any given time that the well has recovered to a level 60 feet above the pump. If one started using water from such a system at the rate of 10 gallons per minute, and if the pumping rate was also 10 gallons per minute, the well could be pumped for about nine minutes (because the pumping rate will change as the water is drawn down) before it would run out of water. If ground water is entering the well at an average rate of 2 gpm while the well is being pumped, then the well might be pumped for a total of 11 or 12 minutes before the pump would pull air into the intake about 80% of the time.

Fortunately, most households do not use water at the rate of 10gpm unless there is a lot of livestock so the above scenario doesn't happen often. A common rule-of-thumb for estimating daily requirements is 100 gallons per person per day. In the above example, the well storage and the tank storage would probably supply the needs for a family of three for one day. To maintain this condition, ground water has to flow into the well at the average rate of only 0.21 gpm (290 gallons/24 hours x 60 minutes). Situations approximating these conditions are common in Appalachia but they are poorly understood by much of the public. In the above situation it is common to hear the well-owner claim that he has a 10 gpm well because he saw such a flow come out of the discharge line for several minutes when the pump was installed and tested.

The importance of this background discussion is that an understanding of individual water well design and its role in providing an adequate supply is essential in evaluating whether a well has been damaged by blasting or some other cause, or whether the well design is no longer adequate for the demands being placed on the well.

CHARACTERISTIC COMPLAINTS

Perhaps the most common complaint and, also, the most serious, is that there has been a total loss of water. This is frequently stated as, "They cracked my well and let the water run out. I had it one day and it was gone the next." Around an active strip mine, there may well have been a blast sometime in the interim, but did the blasting cause the damage? That, of course, is the answer sought by this study, and in the subsequent chapters the results of the field testing will provide an answer to this question.

Another common complaint is that the well has partially caved in and the pump won't work. A similar mechanism of failure but to a lesser degree is indicated by complaints that the water became muddy or turbid. Generally, this latter condition is temporary and by the time it is investigated the water from the well has become clear.

Reddish iron discoloration of the water is also frequently a source of trouble and the discoloration may be accompanied by a sulfur odor. As mentioned previously, when such water is tested for iron it frequently contains no more iron in solution than many other "clear", odor-free wells. Many wells which are far removed from any blasting or excavation have this problem and periodic clean-out is required to keep the wells operating. There is a strong suggestion that this problem has a bacterial origin rather than a chemical or physical one. The reddish water differs from acid mine drainage in that it generally has sulfate levels below 250 mg/l and the pH is generally above 6.0. Because the bacteria are intolerant of changed conditions, particularly temperature, getting valid samples to a laboratory for analysis is a relatively expensive proposition. Some testing for iron bacteria had been done but not in relation to this project. Where the complaint was that the water was iron red and had a sulfur odor, iron bacteria but no sulfur bacteria were found. When this condition exists, a red slime forms on all well parts, and all sampling bottles and measuring devices that are lowered into the well have a pronounced red stain when they are removed.

Lower productivity or intermittent productivity is sometimes heard as a complaint. This may be a harbinger of complete loss of water and differs from that complaint only in degree. If all the mechanical and electrical parts of the pump system are working properly, the complaint obviously relates to a lower static water level. Again the question is, did blasting cause the lowering?

These complaints may be associated with any distance up to several miles but a random sample of 35 complaints indicates that 26, or 74% were at distances less than 1300 feet, and 10 complaints, or 29%, were at distances of less than 300 feet. Not too much should be deduced from these percentages because they represent unverified blast damage claims and they may only indicate that the residents who were closer to blasting were more conscious of the blasting and consequently felt that it was more likely to cause damage. The main point from these data utilized in the study was that the field effort was concentrated on blasts less than 1000 feet distant.

TECHNICAL APPROACH TO THE PROBLEM

The most essential need was to have water well data before any mining or blasting occurred to compare with data obtained as mining and blasting approached the wells. This pre-mining data should include a lithologic log of the strata penetrated by the wells with notation as to where water was encountered. This would be supplemented by gamma ray/density/caliper logs at each site in order to have an impartial record of the "before" condition of the wells.

In general, the plan was to have a shallow well which would penetrate the section overlying the coal and obtain its water from the coal being mined or from the overlying strata. As to well design, the driller was instructed to drill the well, equip it with casing, and discharge line in the same manner as he would any other water well in the same neighborhood. The pump capacity was specified for reasons explained later. This turned out to mean that the shallow well had approximately 20 feet of either steel or plastic casing, was drilled with a 6" diameter air rotary bit, was uncased in the lower section, and had a submersible pump set ten feet off bottom. This well would have two or three similar observation wells.

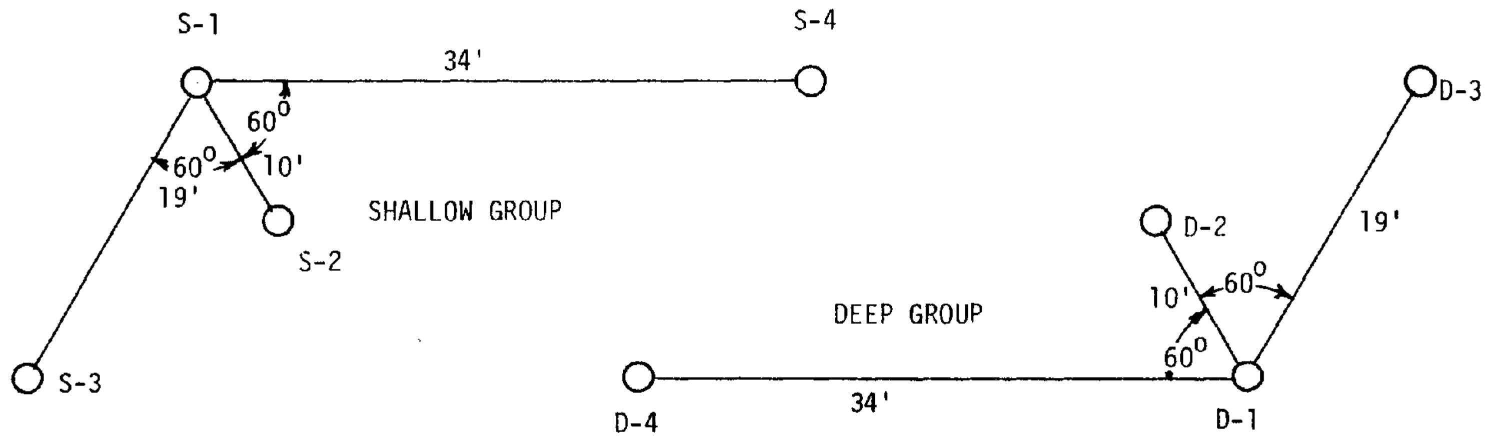
In addition to the shallow well set, another well would penetrate the coal to be mined and would obtain its water from strata below that depth. Completion would be similar to the shallow well except that a plastic liner would be used to seal off any water entering from the coal to be mined or above. This was to be done by using a perforated liner in the lower part of the well, below a packer, and an unperforated liner above. Cement was placed in the annulus between the casing and the liner to assure a good seal above the packer. Two or three observation wells would be drilled near this well, and completed in a similar manner except for the pump.

These shallow and deep well sets would permit a separate evaluation of the effects of blasting on water being obtained from the mined coal or above, and for wells obtaining water from sources below the coal being mined. The shallow well group dictated that at least that set had to be on the highwall side of the pit. For convenience of project testing and to minimize the inconvenience to the coal operator, the deep well group was planned to be adjacent to the shallow wells. In this manner, we could also test whether the two systems might be interconnected.

As to specific location of the wells, the original plan was to space the observation wells at 25,50, and 75 feet from the pumped well and use a pump rate up to 20gpm. Conversation with U. S. Geological Survey geologists in Ohio indicated that we probably wouldn't see any change in the observation wells at those distances, and that we should be prepared to use a pumping rate of 0.5gpm. Consequently the observation well distances were decreased to 10, 19 and 34 feet and it was planned to install pumps with a capacity of less than 10gpm. These distances were selected because they are an equivalent linear distance apart on logarithmic graph paper and it was thought that this would be helpful in constructing distance/drawdown curves. A basic pattern of placing the observation wells in an array so that they would be on 60° arcs from the pumped well was used to determine the degree of anisotropy in the cone of depression, if any. The planned layout of the well groups is shown in Figure 1.

FIGURE 1

GENERAL TEST WELL LAYOUT



SCALE: 1" : 10'

After the drilling of the wells, they were to be tested briefly to see what pumping rate they might be able to sustain. This was to be followed in a few days with a ten-hour drawdown test at the indicated rate to determine the pre-mining productive capability of the wells. Electric power for the pumps was to be supplied by a portable gasoline generator. Pump rate would be determined by measuring the flow through a standard municipal 5/8" water meter and the pump rate would be controlled with a gate valve. Water depth would be measured in all wells with electric probes which have markings every five feet, and the interval between can be read with a measuring stick or tape.

It was decided to maintain all records and make all measurements in English units because these would be more readily understood and compared by many of the people who might be interested in the results of the project, such as well owners in Appalachia and coal operators who use English units in their measurements rather than metric.

It was planned to pump both shallow and deep wells at the same time unless they showed indications of interconnection.

Water samples were to be taken at the time of this initial drawdown test from each well group and analyzed for various common parameters.

Continuously recording float gages would be placed on one of the shallow observation wells and one of the deep observation wells at each site. These would monitor changes in the static water level that might occur over the period of the field testing.

Depths of the wells would also be recorded initially and checked periodically.

When the first blast was scheduled to be detonated, another 10-hour drawdown test would be conducted so as to be in progress when the blast occurred. Water samples would be taken before the blast and after the blast and analyzed for change.

Blast-induced ground vibrations would be measured at the surface besides one of the observation wells for all blasts and frequent virbration measurements would be made at the bottom of this observation well to determine the amount of attenuation with depth, until such time as the blasting was too close for such measurements to be feasible. If on-site analog recording was not done for every blast, the vibrations would be measured by an unmanned continuous monitor.

Subsequently, the wells would be tested by drawdown once a month to determine if any change had occurred. Water samples would be taken at these times in addition to samples taken before and after any blast where on-site recording was done. Water samples taken during drawdown tests would be obtained from the pumped water flow. Water samples collected before and after blasts were of necessity collected by lowering a sample bottle into either the pumped well or one of the observation wells. Static water level of all wells was to be measured before and after each blast when on-site recording was performed.

These observations would continue for a period of one year. By estimating the rate of advance of the mining, the wells would be situated so that mining would pass through the well site in about one year, or approach it within 50 feet.

The concept of the drawdown tests was not so much to determine the true theoretical values of the coefficients of transmissibility, storage, and vertical permeability, as it was to simply determine whether a change in the productive capability of the well had occurred as the result of blasting. The former would require a complete understanding of the porosity and permeability distribution of the fractures, joints, and bedding planes, while the latter probably would involve only the observed slope of the drawdown curve, Δ s, and the amount of drawdown under fairly uniform pumping rates. Of course, determination of the true values of the above coefficients might be obtained from the data and used as quantitative determinants of change, but this was not critical to the success of the program.

SELECTION OF TEST SITES

Possible test sites were sought by contacting several coal operators in West Virginia, Maryland, Pennsylvania, and Ohio, and inquiring as to new coal strip operations that might commence in early 1979.

Because of the need to transport a portable generator and other pieces of test equipment from site to site, and the need to make frequent visits to each site to measure blast vibrations and collect water samples, we limited our inquiry to the above states in order to keep the round trip travel to less than 400 miles.

We were particularly interested in operations which would commence in late March or early April because this would permit the drilling and initial testing of the wells before mining began.

Eleven new sites were offered by five different operators. The test program called for four different sites so a selection was in order. Some of these sites were rejected because the start-up date was so immediate that it didn't permit sufficient time to drill and test the wells. Others involved such small tracts that the wells could not be situated 1000± feet from the initial blast. Another problem at some sites was that some previous stripping by other operators had taken place nearby and the integrity of the site might be questionable.

In selecting the four sites from among the remaining candidates, it was desired to have geographical representation as broad as possible within the radius described. A variety of geologic situations was also sought in order to evaluate the effects of blasting on strata which were predominately shale, sandstone or sandstone and shale mixed. Other factors which entered into the selection were:

1. The likelihood of encountering water.

2. A balance of different but typical topographic situations.

3. Accessibility for the drill and test vehicles.

4. The ease of coordinating our activities with those of the operator.

A total of five sites was initially recommended to the Bureau of Mines and four were selected as test sites from among these. Later, one of these sites was abandoned with Bureau approval because the first hole drilled failed to encounter water although it was in the most favorable location based on the coal operator's test drilling. Another site was substituted and although mining activity had already started, drawdown testing at other sites had indicated by this time that blasting activity was sufficiently distant that it would have created no pre-existing condition. Furthermore, the relationship of the strata penetrated by the test wells to the coal being mined was such that one would not expect that mining up to that time would have had any non-blasting effect on the wells such as intercepting an aquifer, or lowering the static water level by pumping. This is because the test wells were started below the crop line of the coal, and there was no pumping in the pit.

The location of the final four test sites is shown on the map in Figure 2. The test sites were called, Brotherton, Pennsylvania Site; Rose Point, Pennsylvania Site; Tenmile, West Virginia Site; and St. Clairsville, Ohio Site.

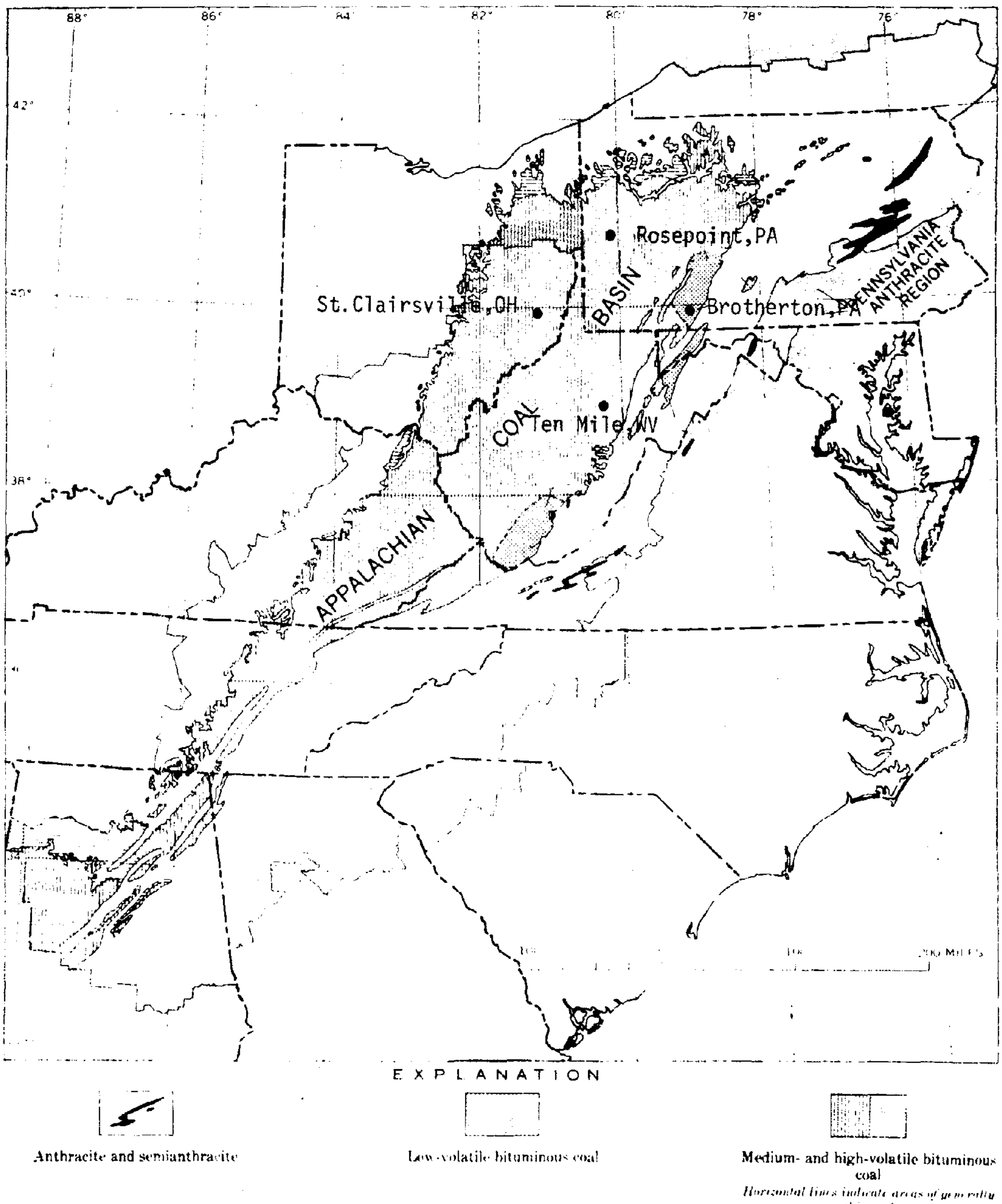


FIGURE 2
INDEX MAP OF TEST SITE LOCATIONS

From USGS Prof. Paper 580

BROTHERTON, PENNSYLVANIA TEST SITE

This site is located about six miles east-southeast of Somerset, Pennsylvania. The Allegheny Group of the Pennsylvanian System occurs at the surface and the coals being mined are the Lower Freeport and the Upper Kittanning seams. Dip of the strata is to the southeast at 105' per mile, or 2%. Topography at the site is illustrated on Figure 3 which also shows the relationship of the test well site to the area being mined as of June, 1980. Eventually mining will proceed through the well site and destroy the wells. A cross-section showing the relationships between the seams being mined, the test wells and the pit is included as Figure 4.

The specific test location was picked because it was about 40 feet higher in elevation than where mining was to commence. Because the initial mining would be a box-cut method starting at the base of a relatively gentle slope, it would be necessary to pump a significant amount of water from the pit. This would provide an opportunity to evaluate the relative significance of blasting effects and pumping effects on the water-bearing strata. Initial plans called for the first blast to be at a distance of about 1400 feet but this was modified later and the first blast was actually at a distance of 500 feet.

Eight test wells were drilled in March, 1979, in accordance with the test pattern and well numbering system previously described. Initial depth of the test wells is as follows:

Shallow Well Group		Deep Well Group	
S-1	109 feet	D-1	169 feet
S-2	108 feet	D-2	169 feet
S-3	108 feet	D-3	149 feet
S-4	109 feet	D-4	149 feet

Approximately 20 feet of steel casing was used at the top of each well, and after logging was completed, plastic liners were placed in the deep wells. Liners were unperforated above the packer and perforated below. Depth to packers was 115 feet for all except Well D-4 which had the packer placed at 100 feet. The depth of the shallow wells was selected to provide for penetration of the lowest coal to be mined with about 10 feet of additional drilling to provide a sump below the pump. The depth of the deep wells was approximately 50 feet deeper than the shallow wells depending on the occurrence of water below a depth of 100 feet.

In addition to the drilling time and lithologic logs made at the time of drilling, gamma ray, caliper and density logs were run on Wells D-1 and S-1. Caliper logs were run on all others. Figure 5 is a composite of all of these logs.

Water entry varied in nearly every well, but if some time is allowed for the water to accumulate and be blown to the surface, the entry depths are generally clustered near the base of the coal seams that were penetrated.

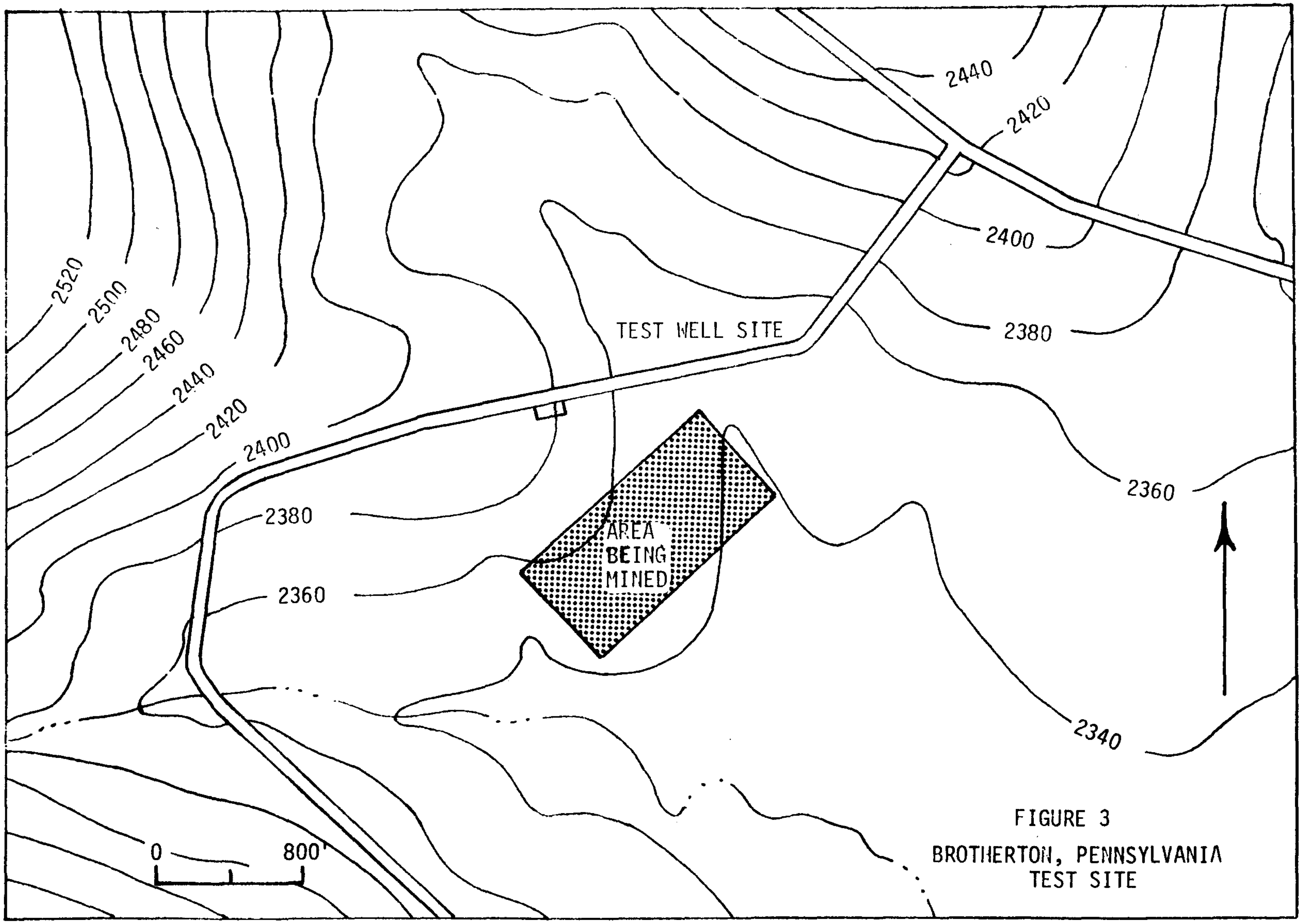


FIGURE 3
BROTHERTON, PENNSYLVANIA
TEST SITE

FIGURE 4

BROTHERTON SITE

CROSS SECTION

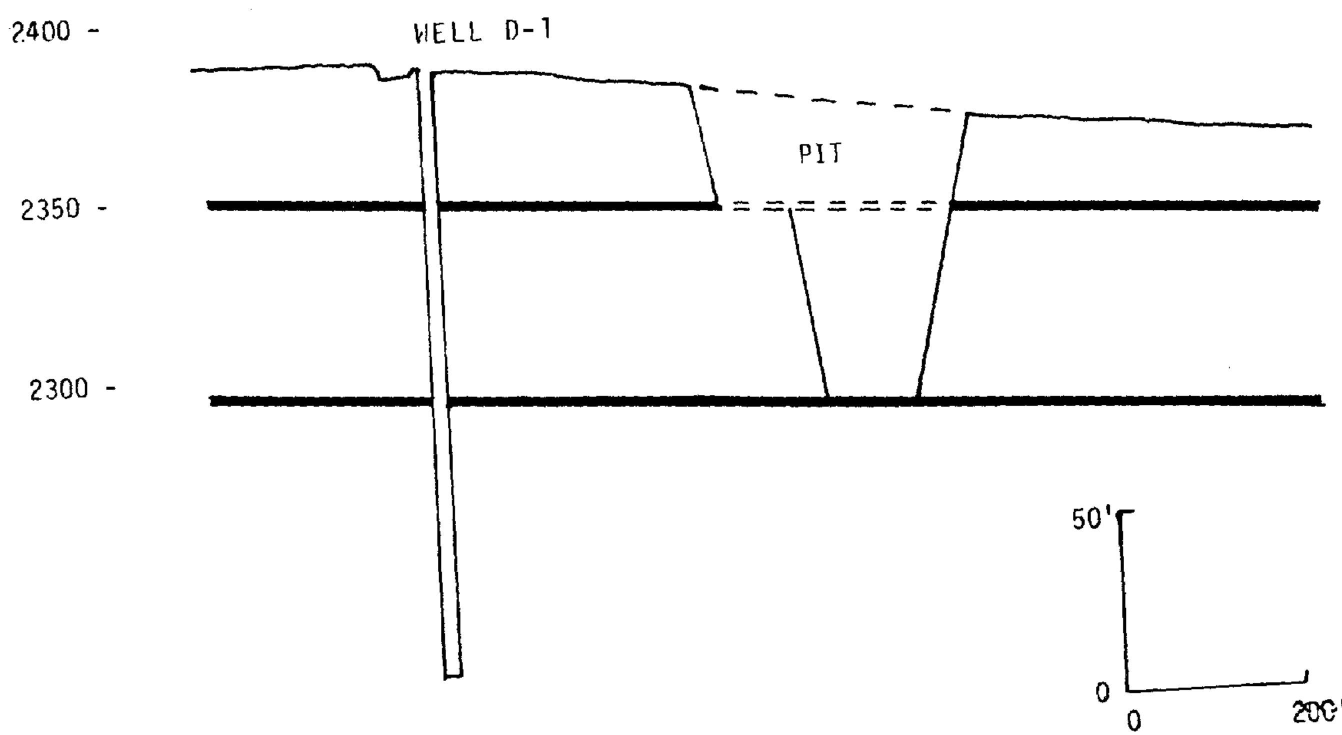


FIGURE 5. BROTHERTON TEST SITE COMPOSITE WELL LOG

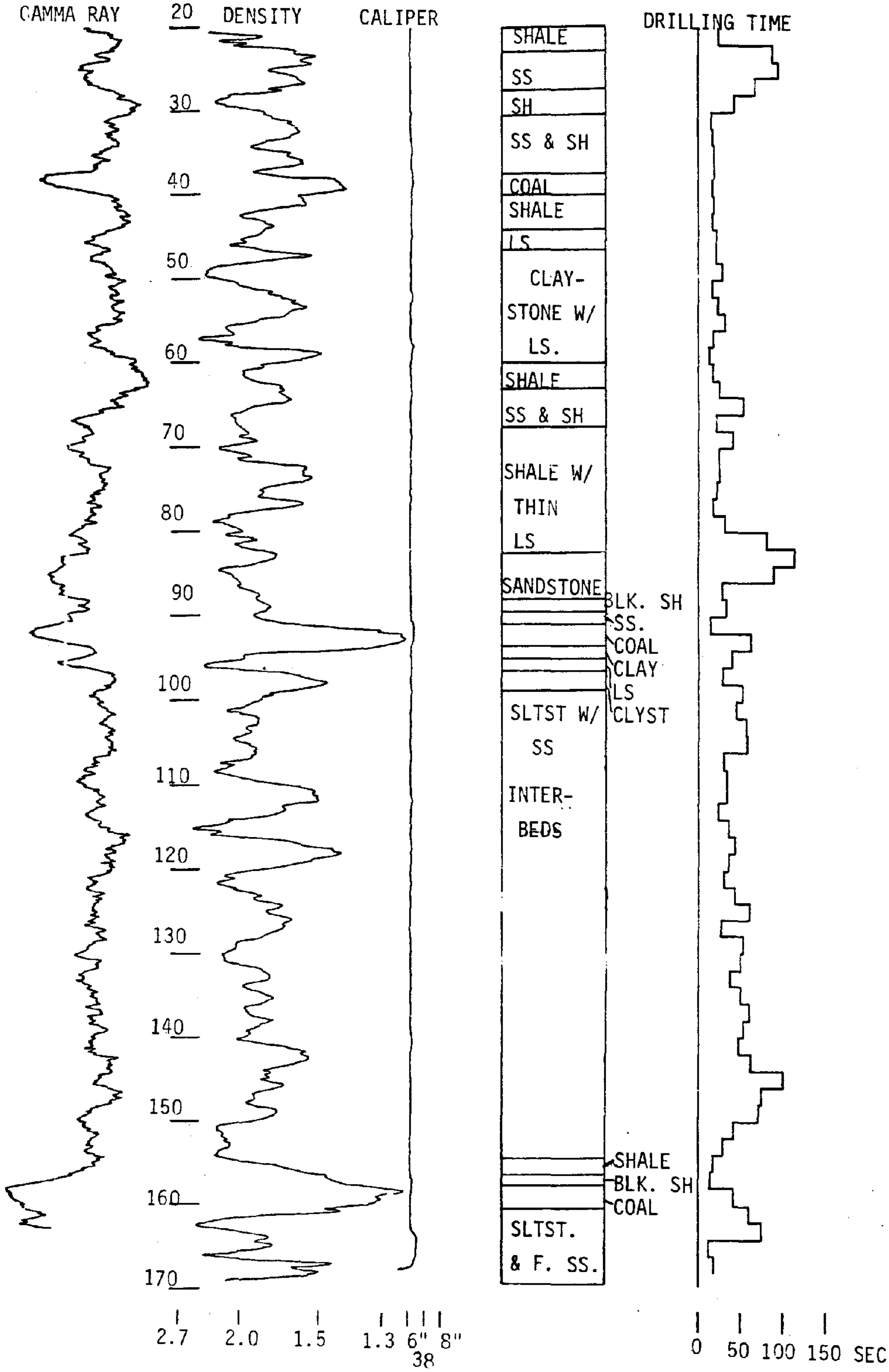


Figure 6 illustrates the various depths of these water entry zones and the static water levels that were observed shortly after the wells were drilled.

The first drawdown tests were conducted on Wells D-1 and S-1 in April, 1979. Because the start-up of mining was delayed primarily because of market conditions, another pre-mining drawdown test was conducted for Well S-1 on July 26, 1979. There were two minor blasts in 10' holes with charge weights of 26 pounds per delay detonated on August 3, 1979. Notice of these was received too late to have a drawdown test going when the blast occurred. Additional blasting was scheduled for August 7 and preparations were made to conduct a test at that time. When electric power was relayed from the portable alternator to the pumps it was discovered that it was insufficient for either well to start pumping. At the time, we didn't know whether the problem was with the pump or with the alternator although the ammeter indicated the problem was with the pumps. With a spare pump and 1" vinyl discharge line, a pump was placed in Well D-3 and observations were made in this well during the blast because previous tests had indicated good interconnection between S-1 and S-3. As a result of this effort, it was determined that the alternator was the problem because the power supply started fluctuating and couldn't be controlled. Although the test was running when the blast was detonated, the results were generally inconclusive because the fluctuations masked any small change. Drawdown curves in observation wells were not affected as much by the pump variations. These curves indicated no significant change in the drawdown slope as a result of blasting but the data after the blast are sparse. The blast occurred 157 minutes into the test, and the alternator motor failed completely after 186 minutes.

The problem with the alternator was excessive buildup of carbon on the head and a sticking valve. These were repaired.

On September 11, 1979, a drawdown test was commenced in S-1 and near-equilibrium was attained after 30 minutes. At 109 minutes into this test, the pump on Well D-1 was started because initial testing had indicated the two systems were not interconnected. Well S-1 responded 47 minutes later with the water level rising 4.63 feet. Response in Observations Wells S-2 and S-3 was more immediate and water levels in both of these wells dropped almost one foot. Well S-4 was not significantly affected although there was a very slight change in the drawdown slope. As a result of these observations, it was decided to test the deep and shallow wells at different times.

On September 26, 1979, a drawdown test of Well S-1 was conducted while a blast was detonated 291 minutes into the test. Figure 7 is a time-drawdown curve of this test and shows the effect of the blast. There was virtually no immediate effect on the well, if any. Because the changes are in tenths of a foot, the following data gives a more precise measure of the change.

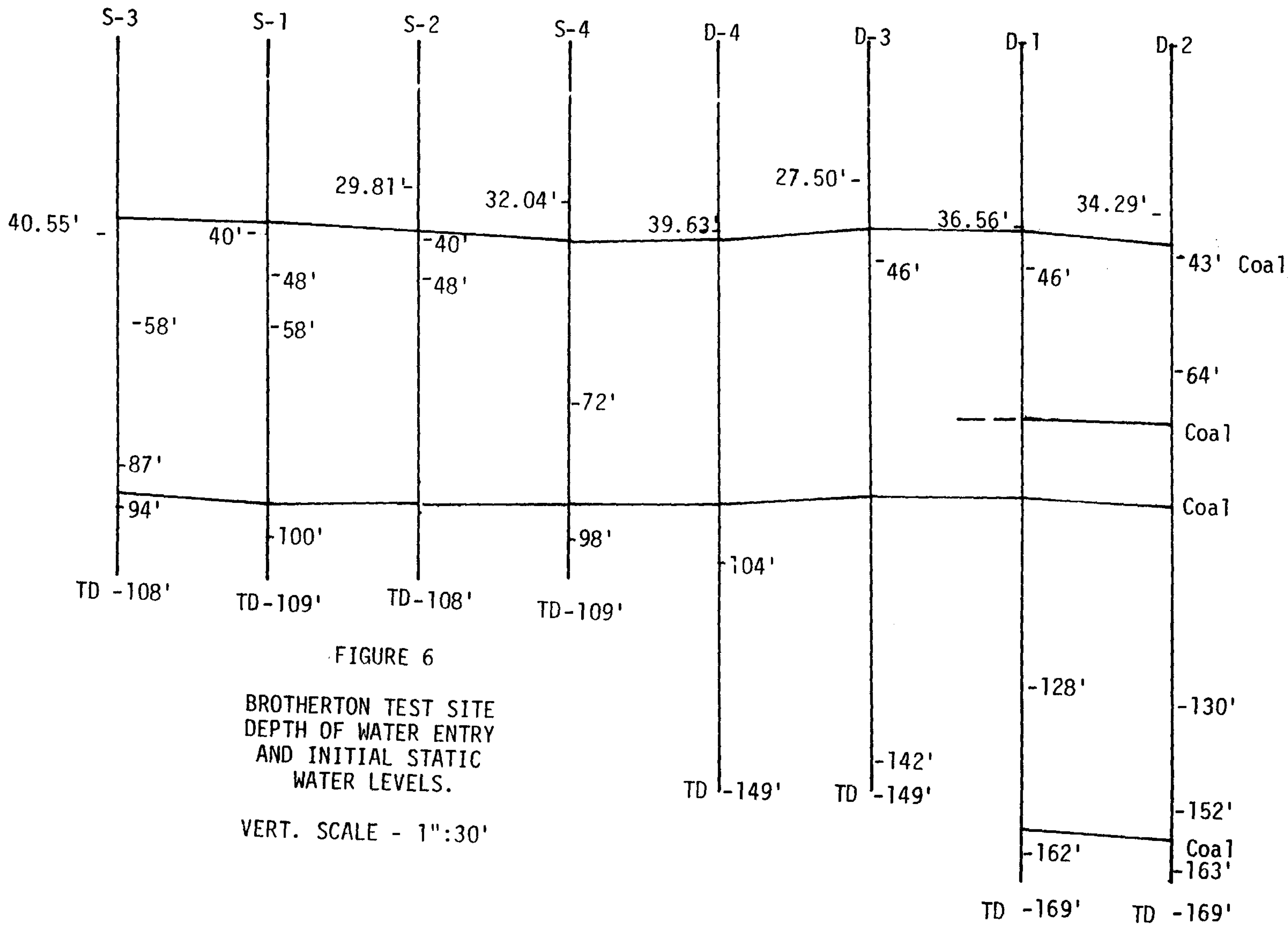


FIGURE 6

BROTHERTON TEST SITE
DEPTH OF WATER ENTRY
AND INITIAL STATIC
WATER LEVELS.

VERT. SCALE - 1":30'

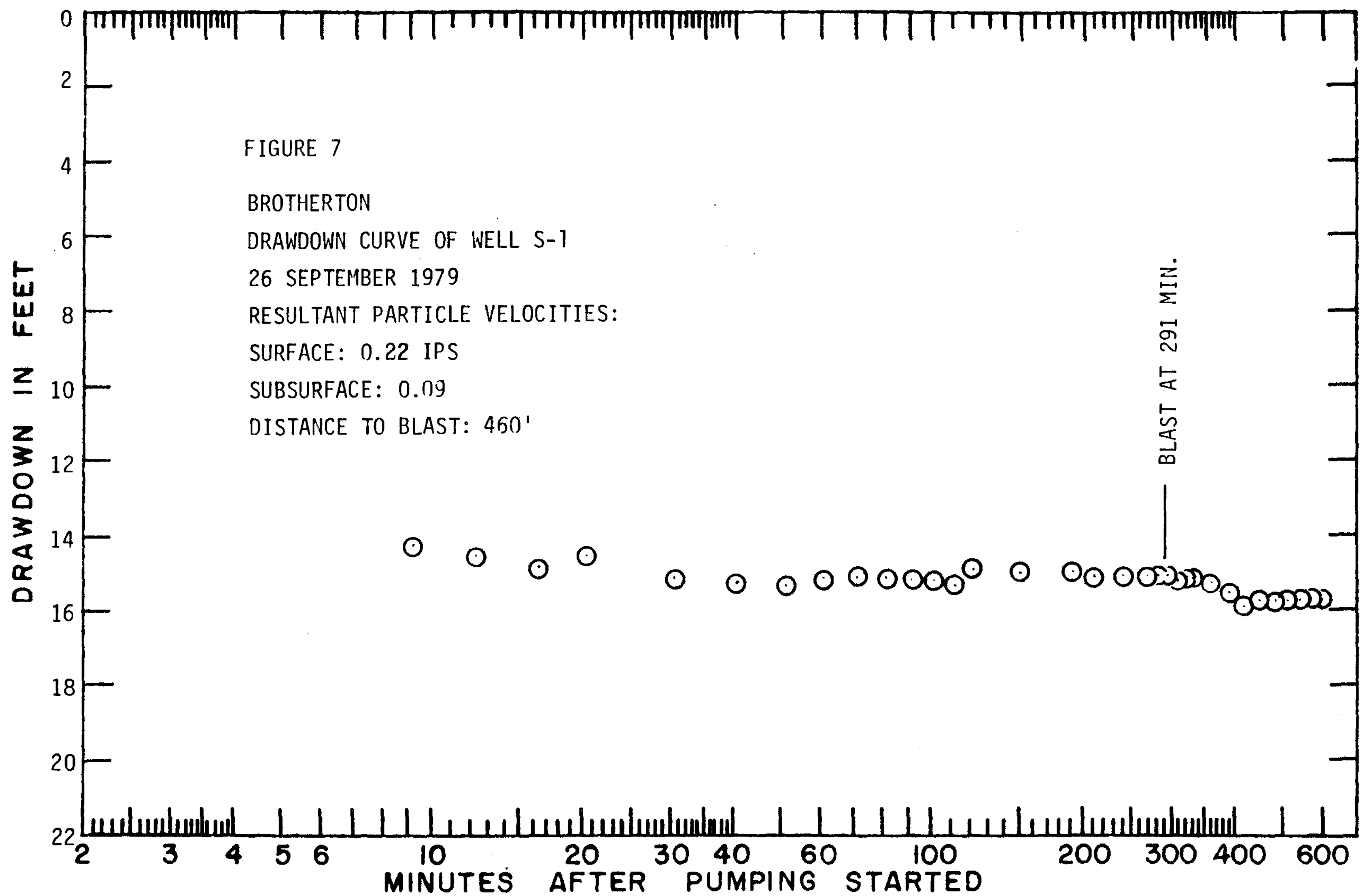


FIGURE 7
BROTHERTON
DRAWDOWN CURVE OF WELL S-1
26 SEPTEMBER 1979
RESULTANT PARTICLE VELOCITIES:
SURFACE: 0.22 IPS
SUBSURFACE: 0.09
DISTANCE TO BLAST: 460'
BLAST AT 291 MIN.
DRAWDOWN IN FEET
0
2
4
6
8
10
12
14
16
18
20
22
2
3
4
5
6
10
20
30
40
60
100
200
300
400
600
MINUTES AFTER PUMPING STARTED

	Depth to Water	Net Change
5 minutes before blast	67.94 feet	0 feet
Immediately after blast	67.93 "	+0.01 "
19 minutes after blast	68.15 "	-0.21 "
29 " " "	68.11 "	-0.17 "
39 " " "	68.10 "	-0.16 "
69 " " "	68.30 "	-0.36 "
99 " " "	68.74 "	-0.80 "

Although the well was near equilibrium when the blast was detonated, minor fluctuations are common and some of the slight variation indicated above may be normal to the drawdown conditions. Resultant particle velocity from this blast was 0.22 inches per second at the surface and 0.09 inches per second at the bottom of Well D-3. Distance to the blast was 460 feet.

On April 24, 1980, another test was conducted when a blast was detonated. Figure 8 is a time-drawdown curve for Well D-1 which was being pumped at a rate of 4.25 gallons per minute at the time. In this case, the effect during the two hours following the blast is more noticeable but still limited to a variation of about 1.6 feet. In this blast, the resultant particle velocity at ground surface was 1.80 inches per second, and 0.66 inches per second at the bottom of Well D-3.

Resultant particle velocity is used in reporting these results because with the downhole geophone the orientation of the horizontal components could not be determined. For comparative purposes, the surface measurements are also in terms of the resultant.

The geophone for the surface measurements was buried about 7 to 8 inches in the ground with the soil tamped firmly around it. The downhole geophone was held firmly in place at the bottom of the well by pouring a measured quantity of sand into the hole which was sufficient to fill the annulus between the geophone and the liner. Drill cuttings between the liner and the sidewall of the hole maintained good coupling with the ground.

Initially, analysis of the drawdown data was directed toward determining the coefficients of transmissivity and storage using the nonequilibrium method of Theis and the simplified straight line methods developed by Jacobs. The thought was that transmissivity would probably provide the best index of change.

Difficulty was encountered when the plot of drawdown versus $\frac{r^2}{t}$ on log-log paper was virtually flat because the wells frequently approach equilibrium and the possible match points indicated a value of "u" in the range of 10^{-8} to 10^{-9}. In this region, the precision of picking a fairly precise matchpoint is impossible. Consequently, if different persons pick the matchpoints, and the

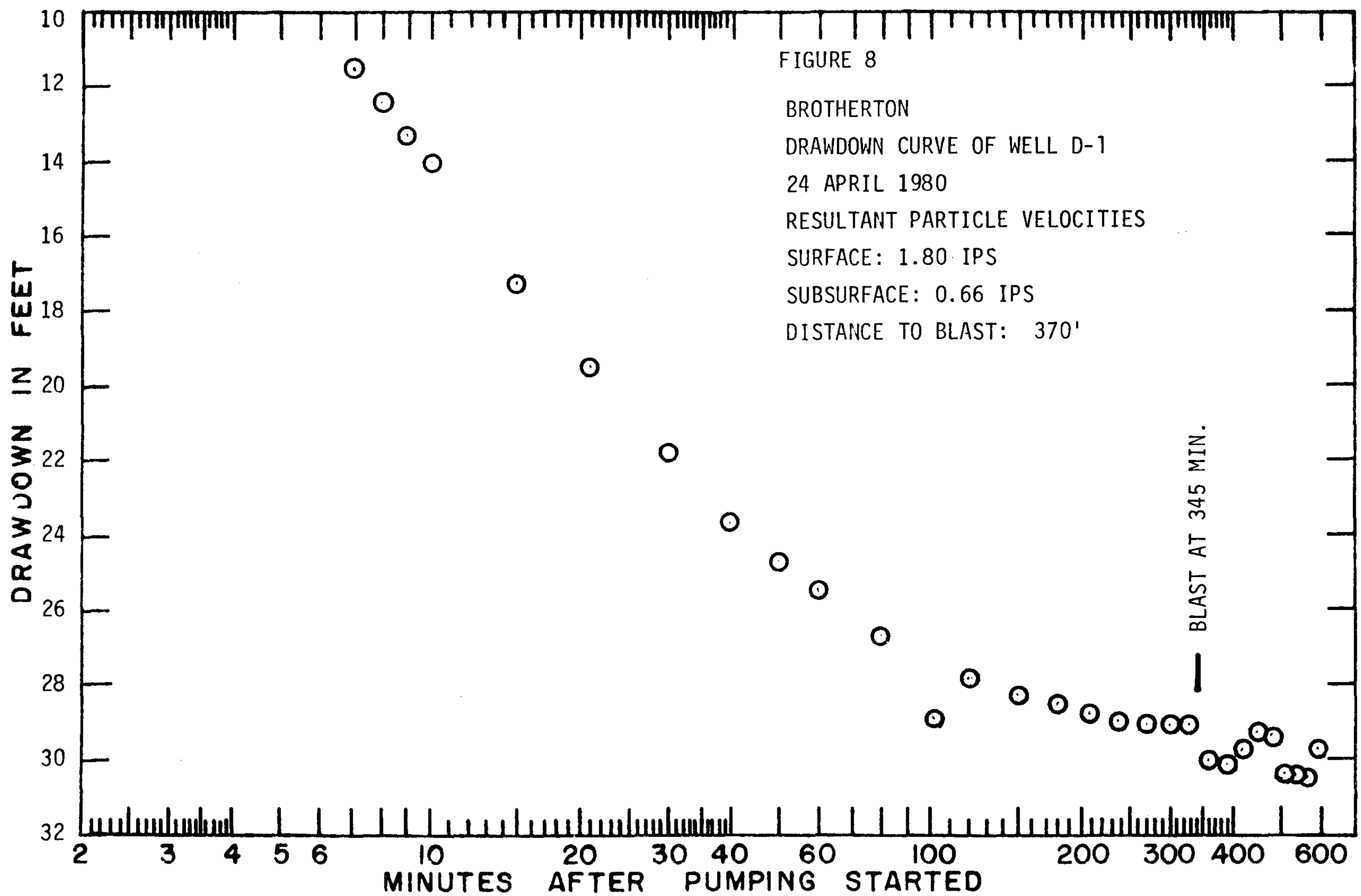


FIGURE 8
BROTHERTON
DRAWDOWN CURVE OF WELL D-1
24 APRIL 1980
RESULTANT PARTICLE VELOCITIES
SURFACE: 1.80 IPS
SUBSURFACE: 0.66 IPS
DISTANCE TO BLAST: 370'
BLAST AT 345 MIN.
DRAWDOWN IN FEET
10
12
14
16
18
20
22
24
26
28
30
32
2
3
4
5
6
10
20
30
40
60
100
200
300
400
600
MINUTES AFTER PUMPING STARTED

values of "u" and W(u) are substituted into the appropriate formulas, the resulting values for the coefficient of transmissivity can easily vary by a magnitude or more.

Utilizing the Jacob straight-line method and determining the value for Δs, the slope of time-drawdown curve or the increase in drawdown across one log cycle, by linear regression analysis, and then substituting this into the formula below, did not significantly decrease the large variation in values.

$$T = \frac{264\ Q}{\Delta s}$$

where:

T = Coefficient of transmissivity, in gallons per day per foot

Q = Pumping rate in gallons per minute

Δs = Slope of the time-drawdown curve, feet per log cycle

Not only was the variation large, but the concepts embodied in transmissivity and slope of the drawdown curve require some knowledge of ground-water hydrology and may not be very meaningful to a layperson. Consequently, a simpler index of possible change was sought. Because the wells frequently attained near-equilibrium, and the drawdown after, say, 100 minutes, was fairly constant, it appeared that specific capacity might be more understandable and more meaningful for the purposes of this project. The specific capacity of a well is:

$$\text{Specific capacity, in gallons per minute per foot of drawdown} = \frac{Q}{s}$$

where:

Q = Pumping rate in gallons per minute

s = Drawdown in feet

The adjusted drawdown s' is utilized in this report because of the water-table aquifer.

Normally a time is specified when using the specific capacity but if near-equilibrium conditions exist, or if the slope is very small in relation to the total drawdown, then the departure from an ideal value is slight.

A total of 18 drawdown tests were run at Brotherton. Table 1 summarizes the test data for Well S-1 and the one test of Well S-3. Table 2 summarizes

TABLE 1

BROTHERTON: TEST SUMMARY WELL S-1

Depth of Well: 109 feet

Depth to Pump: 98 feet

DATE	PUMP RATE, Q	DRAWDOWN, S	$\frac{Q}{S}$	ADJUSTED DRAWDOWN, S'	$\frac{Q}{S'}$	STATIC WATER LEVEL AT TEST START	LENGTH OF TEST
4/25/79	7.78 gpm	13.59 ft.	.572 gpm/ft.	12.41 ft.	.627 gpm/ft.	37.50 ft.	600 min.
7/26/79	7.50 "	20.15 "	.372 "	17.37 "	.432 "	34.85 "	600 min.
8/ 7/79*	2.90 "	13 + "	.223 "	11.77 "	.246 "	39.04 "	186 min.
9/11/79	7.23 "	27.90 "	.259 "	22.18 "	.326 "	39.78 "	600 min.
9/26/79	7.76 "	27.40 "	.283 "	21.71 "	.357 "	41.66 "	600 min.
11/19/79	7.52 "	32.63 "	.230 "	24.04 "	.313 "	46.11 "	600 min.
1/17/80	7.53 "	40.22 "	.187 "	27.58 "	.273 "	44.10 "	600 min.
3/20/80	7.53 "	16.45 "	.458 "	13.69 "	.550 "	58.60 "	600 min.
5/26/80	2.52 "	3.20 "	.787 "	2.86 "	.881 "	92.68 "	300 min.

* Pump in S-3

TABLE 2

BROTHERTON: TEST SUMMARY WELL D-1

Depth of Well: 169 feet

Depth to Pump: 159 feet

DATE	PUMP RATE, Q	DRAWDOWN, S	$\frac{Q}{S}$	ADJUSTED DRAWDOWN, S'	$\frac{Q}{S'}$	STATIC WATER LEVEL AT TEST START	LENGTH OF TEST
4/18/79	4.01 gpm	30.59 ft.	.131 gpm/ft.	27.27 ft.	.147 gpm/ft.	27.70 ft.	500 min.
9/11/79	4.58 "	21.99 "	.208 "	20.01 "	.229 "	47.01 "	600 min.
10/16/79	4.23 "	20.02 "	.211 "	18.36 "	.230 "	47.73 "	600 min.
12/27/79	4.44 "	29.54 "	.150 "	25.50 "	.174 "	56.25 "	510 min.
2/26/80	4.48 "	31.66 "	.142 "	27.06 "	.166 "	59.76 "	300 min.
4/24/80	4.25 "	36.75 "	.116 "	29.86 "	.142 "	70.80 "	600 min.
5/26/80	4.30 "	29.65 "	.145 "	24.16 "	.178 "	88.90 "	210 min.
7/ 9/80	4.13 "	30.94 "	.133 "	21.85 "	.189 "	96.31 "	420 min.
9/26/80	4.29 "	31.27 "	.137 "	21.92 "	.196 "	96.73 "	540 min.

NO SIGNIFICANT CHANGE AS OF 26 SEPTEMBER 1980 the test data for Well D-1. Utilizing the single value specific capacity, it can been seen that with the exception of the initial test, Well S-1 had values around .350±0.1 gallons per minute per foot until the test of March 20, 1980, when the results indicate that the specific capacity began to improve. A composite of all of those parts of the time-drawdown curves after the initial steep-sloped storage effect disappears is illustrated Figure 9. With the pumping rate held as constant as possible, this composite shows that the slopes remained fairly constant throughout the test period but curves plot at positions of increasing drawdown until the March 20 test when near-equilibrium was reached near the initial April 25, 1979 test. Considering that the saturated thickness was much less because the static water level when the March, 1980 test commenced was 21.1 feet lower, the improvement indicated by the specific capacity appears to be valid. Consequently, for Well S-1, one must conclude that the permeability in the well has improved over the eleven-month period and that the improvement occurred after the test of January 17, 1980. Although the specific capacity continued to improve as indicated by the results of the test of May 26, 1980, one can hardly say that the total performance of the well had improved because by that time the static water level had fallen to a point only 5.32 feet above the pump intake. In this situation the well could not be pumped at a rate in excess of 2.52 gpm because any greater rate would pull the water down to the intake. By June 15, 1980, the static water level was below the pump intake and for all practical purposes the well is now dry.

This is a good illustration of one of the problems discussed in the Chapter on Typical Well and Household Systems. Well S-1 penetrated only a few feet below the lowest coal being mined. Originally it had water entry from depths near both coal seams. With approximately 500,000 gallons of water per day being pumped from the pit, the static water level moved gradually lower and when the pit approached to within 300 feet of the well, the static water level dropped to a point where the pump could not sustain wide open flow for even two or three minutes.

If mining were to approach no closer, pumping of the pit were to cease, and area reclaimed, it is reasonable to expect that the static water level would rise. The well would not only recover to its former capability, but because of the improved permeability indicated by the higher specific capacity, it would be a better well.

An explanation for the improved permeability will be deferred until the end of the chapter after other results are examined. Table 2 is a summary of drawdown test results for Well D-1. Values for specific capacity of this well have remained fairly constant although the static water level has dropped more than 70 feet. Figure 10 shows the composite of all the time-drawdown curves, again excluding the early casing storage effect for clarity. In this case, the initial test on April 18, 1979 appears with a relatively large drawdown. All subsequent curves have approximately the same slope, but all but one have less drawdown at equal values of time. Only the test on April 24, 1980 appears in a lower position. Another interesting feature is that although the slopes are small, they do not approach the near-equilibrium condition that is common in Well S-1, only 60 feet away. Also, as of June, 1980, Well D-1 is still a functioning well and S-1 is not.

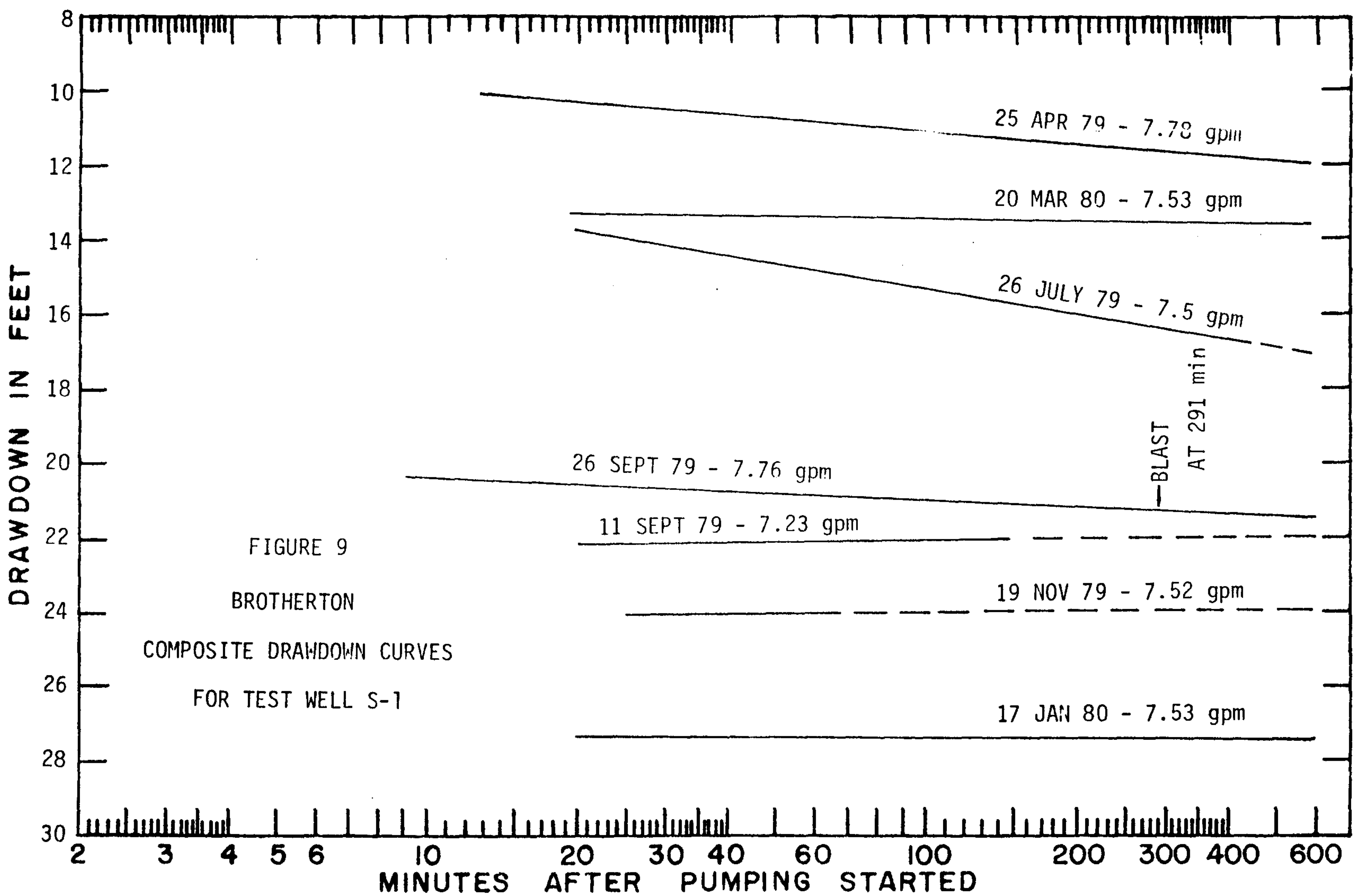


FIGURE 9

BROTHERTON

COMPOSITE DRAWDOWN CURVES

FOR TEST WELL S-1

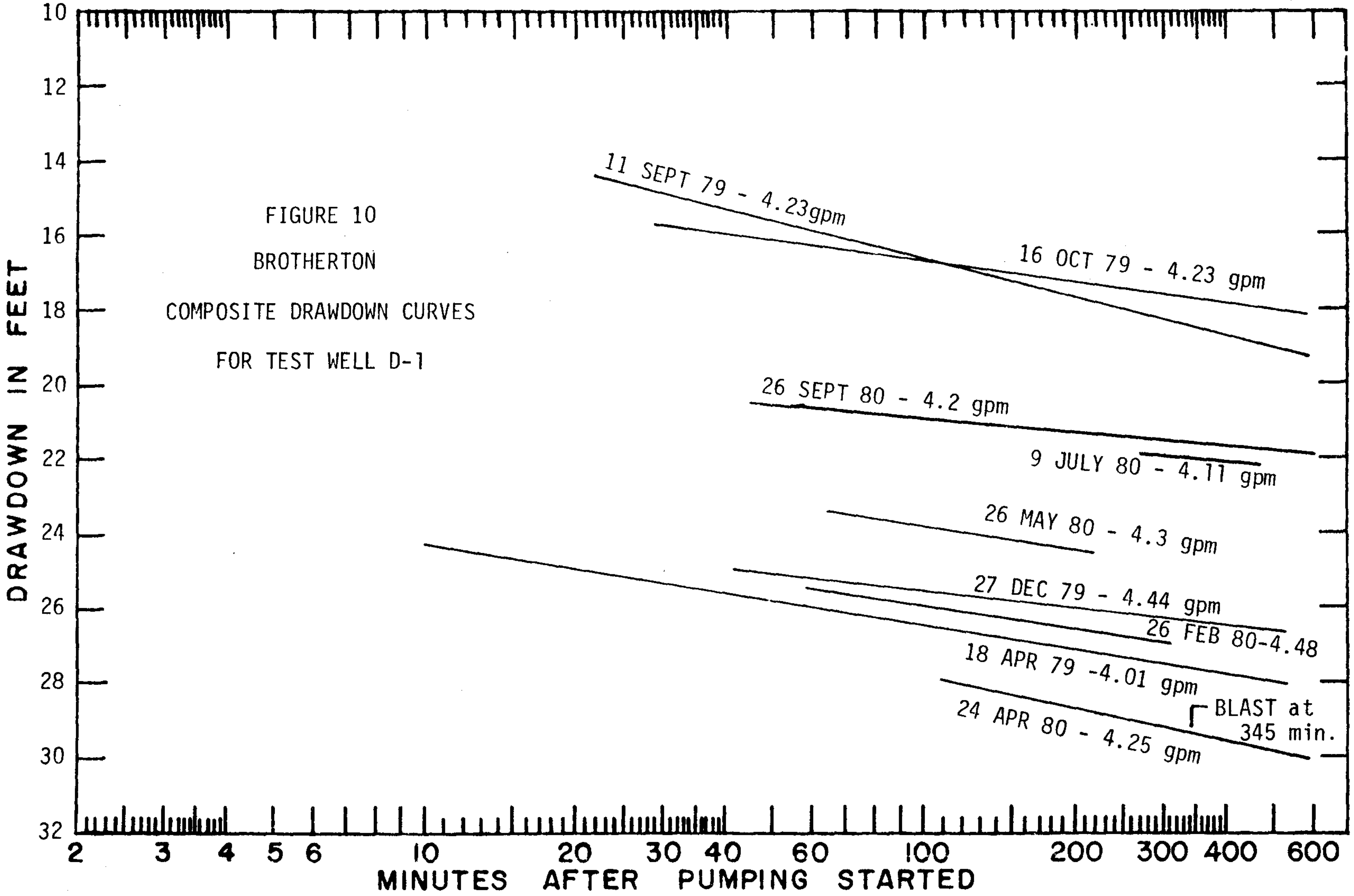


FIGURE 10
BROTHERTON
COMPOSITE DRAWDOWN CURVES
FOR TEST WELL D-1

Table 3 is a listing of all blasts at the Brotherton site with pertinent details. Vibration levels at the surface ranged from 0.04 to 2.20 inches per second resultant particle velocity. Except for the first two blasts, vibrations at the surface were measured for all blasts either with continuous recording monitors that remained at the site from August 7, 1979 until the end of the test period, or by on-site recording with three-component waveform seismographs. The 13 blasts where no vibration data are reported occurred because of malfunction of the remote instrument such as the battery freezing, or the paper chart looping around the drive roller. Figures 11 and 12 show the approximate location of these blasts to test well site.

Vibration levels at the bottom of Well D-3 were measured for 26 blasts in order to determine the degree of attentuation with depth. Analysis of these data indicate that the degree of attentuation is dependent upon the confinement of the blast. Table 4 shows a segregation of these data according to whether the blasts were in the upper seam where the confinement was at a minimum, and in the lower seam where the confinement was relatively great. In both cases, the vibrations at the bottom of the well are less than on the surface, but the confined blasts produced vibrations which average only 68% of the surface level, and the poorly confined blasts produced vibration levels which average only 34% of those on the surface. Typical waveform recordings of surface and subsurface vibrations are presented in Figure 13.

Figure 14 summarizes all of the data on a time scale in order to show the relationship of events. Static water levels from the continuous recorders in Wells S-4 and D-2 are shown in graphic form at the top. By connecting the troughs over the first six months a long-term downtrend is evident, probably resulting from the pumping in the pit. The gradients are 6.25 feet/100 days for the shallow well, and 5 feet per 100 days for the deep well. If this trend had continued after January, 1980, the suggestion is that Well S-1 would still be productive. A relatively abrupt decline in both wells starts near the end of January, 1980, with recovery to more normal levels in March and early April. Toward the end of April, another sharp drop occurs and it is particularly severe in Well S-4.

Blast-induced ground vibrations are shown with a bar graph below the static water level curves, and rainfall is similarly depicted nearer the bottom of the figure. Below the rainfall graph, the specific capacities derived from the drawdown test data are shown. It can be seen that an improvement of the specific capacity of S-1 occurs on the first test after the drop in late January. The second improvement in specific capacity of S-1 occurs on the first test after the drop in late April. This suggests a relationship between the sharp drop in water level and the improvement in specific capacity.

Why did the relatively sharp drops in static water level occur? Figure 14 indicates that blast vibration levels were higher at times roughly corresponding with these events, but then blasting levels are also relatively higher during the end of March and the early part of April when water levels were recovering and reaching levels that hadn't been observed since November or December, 1979. Abundant rainfall during this period accounts for the significant recovery. To get an answer to the problem, it is necessary to look at the relationships in more detail.

TABLE 3

BROTHERTON

SHOT NO.	TIME	DATE	DISTANCE	LBS/DELAY	RESULTANT AT SURFACE	RESULTANT IN D-3
1	9:50 a	8/03/79	500 ft.	26	---	---
2	2:00 p	8/03/79	500 ft.	26	---	---
3*	2:52 p	8/07/79	500 ft.	26	0.25 inch/second	0.16 inch/second
4	8:42 a	8/09/79	480 ft.	51	0.30 inch/second	---
5*	2:30 p	8/09/79	480 ft.	76	0.20 inch/second	0/08 inch/second
6	11:40 a	8/10/79	470 ft.	75	0.16 inch/second	---
7	1:10 p	8/10/79	470 ft.	46	0.16 inch/second	---
8	8:50 a	8/14/79	455 ft.	66	0.06 inch/second	---
9	9:40 a	8/16/79	450 ft.	76	0.06 inch/second	---
10	2:22 p	8/16/79	450 ft.	67	0.42 inch/second	---
11	2:10 p	8/17/79	445 ft.	76	0.07 inch/second	---
12	9:40 a	8/20/79	445 ft.	76	0.20 inch/second	---
13	3:15 p	8/20/79	445 ft.	76	0.10 inch/second	---
14	1:10 p	8/21/79	445 ft.	76	0.17 inch/second	---
15	11:58 a	8/22/79	450 ft	83	0.28 inch/second	---
16	11:30 a	8/23/79	450 ft.	78	0.14 inch/second	---
17	8:55 a	8/24/79	450 ft.	81	0.19 inch/second	---
18	10:20 a	8/27/79	455 ft.	81	0.16 inch/second	---
19*	3:02 p	9/26/79	460 ft.	81	0.22 inch/second	0.09 inch/second
20	1:55 p	9/27/79	465 ft.	81	0.21 inch/second	---
21	3:11 p	9/27/79	465 ft.	81	0.10 inch/second	---
22	1:08 p	9/28/79	480 ft.	82	0.21 inch/second	---

SHOT NO.	TIME	DATE	DISTANCE	LBS/DELAY	RESULTANT AT SURFACE	RESULTANT IN D-3
23	11:55 a	10/01/79	490 ft.	56	0.13 inch/second	---
24	8:45 a	10/02/79	495 ft.	63	0.11 inch/second	---
25	9:45 a	10/03/79	500 ft.	56	0.14 inch/second	---
26	1:45 p	10/04/79	510 ft.	58	0.11 inch/second	---
27	10:00 a	10/04/79	520 ft.	59	0.15 inch/second	---
28	2:10 p	10/05/79	530 ft.	65	0.14 inch/second	---
29	2:35 p	10/05/79	530 ft.	81	0.13 inch/second	---
30	11:50 a	10/08/79	570 ft.	106	0.25 inch/second	---
31	1:50 p	10/08/79	580 ft.	81	0.12 inch/second	---
30A	2:15 p	10/17/79	570 ft.	81	0.21 inch/second	---
31A	8:30 a	10/18/79	580 ft.	81	0.25 inch/second	---
32	1:45 p	10/18/79	580 ft.	81	0.11 inch/second	---
33*	2:50 p	10/1979	585 ft.	56	0.23 inch/second	0.06 inch/second
33A	1:10 p	10/23/79	595 ft.	56	0.20 inch/second	0.04 inch/second
34	3:10 p	10/23/79	600 ft.	56	---	---
35*	3:05 p	10/25/79	620 ft.	51	0.12 inch/second	0.05 inch/second
36*	3:40 p	10/25/79	630 ft.	51	0.12 inch/second	0.02 inch/second
37	1:10 p	10/26/79	550 ft.	51	0.06 inch/second	---
38	1:55 p	10/26/79	550 ft.	27	0.04 inch/second	---
39	1:05 p	10/29/79	535 ft.	26	---	---
40	3:05 p	10/29/79	535 ft.	26	---	---
41	1:00 p	10/30/79	525 ft.	26	---	---
42	3:00 p	10/30/79	525 ft.	26	---	---
43	3:10 p	11/05/79	525 ft.	71	---	---
44	11:27 a	11/06/79	520 ft.	182	---	---

SHOT NO.	TIME	DATE	DISTANCE	LBS/DELAY	RESULTANT AT SURFACE	RESULTANT IN D-3
45	12:00 noon	11/07/79	520 ft.	172	---	---
46	11:10 a	11/08/79	520 ft.	179	0.30 inch/second	---
47	9:08 a	11/09/79	520 ft.	168	0.24 inch/second	---
48*	3:43 p	11/09/79	520 ft.	185	0.27 inch/second	0.09 inch/second
49	10:56 a	11/13/79	525 ft.	169	0.22 inch/second	---
50	9:40 a	11/14/79	525 ft.	161	0.18 inch/second	---
51	9:45 a	11/15/79	530 ft.	120	0.10 inch/second	---
52*	10:08 a	11/16/79	530 ft.	87	0.33 inch/second	0.08 inch/second
53*	1:57 P	11/16/79	530 ft.	98	0.16 inch/second	0.05 inch/second
54	1:40 p	11/27/79	545 ft.	81	0.09 inch/second	---
55	9:13 a	11/28/79	550 ft.	81	0.07 inch/second	---
56	4:20 p	11/28/79	550 ft.	83	0.10 inch/second	---
57	1:00 p	12/11/79	565 ft.	61	---	---
58	9:50 a	12/12/79	575 ft.	128	---	---
59	2:25 p	12/12/79	585 ft.	156	---	---
60	1:30 p	12/13/79	590ft.	150	0.24 inch/second	---
61	1:40 p	12/14/79	600 ft.	183	0.27 inch/second	---
62	1:55 p	12/17/79	610 ft.	196	0.15 inch/second	---
63	1:47 p	12/18/79	620 ft.	191	0.11 inch/second	---
64	11:55 a	12/19/79	630 ft.	199	0.21 inch/second	---
65	10:30 a	12/20/79	640 ft.	131	0.10 inch/second	---
66	3:00 p	12/20/79	650 ft.	118	0.07 inch/second	---
67	2:05 p	12/21/79	665 ft.	132	0.10 inch/second	---
68	2:30 p	12/26/79	680 ft.	209	0.10 inch/second	---
1	12:50 p	1/24/80	420 ft.	118	0.31 inch/second	---
2	1:00 p	1/28/80	400 ft.	170	0.41 inch/second	---

SHOT NO.	TIME	DATE	DISTANCE	LBS/DELAY	RESULTANT AT SURFACE	RESULTANT IN D-3
3	11:55 a	1/29/80	385 ft.	170	0.87 inch/second	---
4*	1:00 p	1/30/80	380 ft.	170	0.61 inch/second	0.23 inch/second
5	11:05 a	1/31/80	360 ft.	157	0.74 inch/second	---
6	2:05 p	2/01/80	360 ft.	144	---	---
7*	12:06 p	2/04/80	360 ft.	131	0.79 inch/second	0.24 inch/second
8*	10:42 a	2/05/80	370 ft.	79	0.43 inch/second	0.11 inch/second
9	10:00 a	2/06/80	380 ft.	66	0.25 inch/second	---
10*	8:45 a	2/07/80	380 ft.	66	0.32 inch/second	0.12 inch/second
11	8:30 a	2/08/80	400 ft.	79	0.16 inch/second	---
12	10:10 a	2/08/80	420 ft.	92	0.87 inch/second	---
13	9:10 a	2/11/80	440 ft.	66	0.10 inch/second	---
14	11:30 a	2/11/80	460 ft.	79	0.08 inch/second	---
15	11:30 a	2/12/80	490 ft.	66	0.07 inch/second	---
16*	2:05 p	3/21/80	460 ft.	351	0.81 inch/second	0.51 inch/second
17	2:30 p	3/25/80	450 ft.	293	0.37 inch/second	---
18*	2:40 p	3/26/80	435 ft.	219	0.40 inch/second	0.27 inch/second
19*	11:30 a	3/28/80	430 ft.	259	0.58 inch/second	0.27 inch/second
20*	2:50 p	3/31/80	430 ft.	255	0.86 inch/second	---
21*	10:10 a	4/01/80	420 ft.	256	0.59 inch/second	0.33 inch/second
22*	3:00 p	4/01/80	400 ft.	244	0.58 inch/second	---
23*	1:20 p	4/02/80	380 ft.	258	0.43 inch/second	0.41 inch/second
24*	3:45 p	4/03/80	370 ft.	295	0.41 inch/second	---
25	12:08 p	4/17/80	365 ft.	490	---	---
26*	2:15 p	4/18/80	365 ft.	447	0.83 inch/second	0.65 inch/second
27*	3:30 p	4/22/80	360 ft.	485	1.04 inch/second	0.80 inch/second

SHOT NO.	TIME	DATE	DISTANCE	LBS/DELAY	RESULTANT AT SURFACE	RESULTANT IN D-3
28*	2:30 p	4/23/80	365 ft.	481	0.99 inch/second	0.91 inch/second
29*	2:07 p	4/24/80	370 ft.	460	1.07 inch/second	0.86 inch/second
30*	2:18 p	4/25/80	375 ft.	484	1.80 inch/second	0.66 inch/second
31*	3:05 p	4/28/80	380 ft.	474	1.35 inch/second	0.68 inch/second
32*		4/29/80	390 ft.		0.95 inch/second	0.65 inch/second
33*	12:07 p	5/ 1/80	400 ft.	812	0.72 inch/second	0.47 inch/second
34	2:15 p	5/ 2/80	420 ft.	508	0.72 inch/second	---
35*	11:30 a	5/ 9/80	430 ft.	510	0.68 inch/second	0.25 inch/second
36	2:15 p	5/12/80	450 ft.	519	0.52 inch/second	---
37*	1:20 p	5/19/80	180 ft.	53	0.26 inch/second	0.08 inch/second
38	2:35 P	5/20/80	170 ft.	64	0.42 inch/second	---
39*	1:55 p	5/21/80	165 ft.	67	0.46 inch/second	0.20 inch/second
40	2:30 p	5/22/80	270 ft.	501	---	---
41	2:40 p	5/23/80	280 ft.	513	---	---
42	11:10 a	5/28/80	310 ft.	439	---	---
43*	2:05 p	5/29/80	320 ft.	540	0.23 inch/second	0.09 inch/second
44	11:50 p	5/30/80	350 ft.	79	---	---

* Onsite analog recording

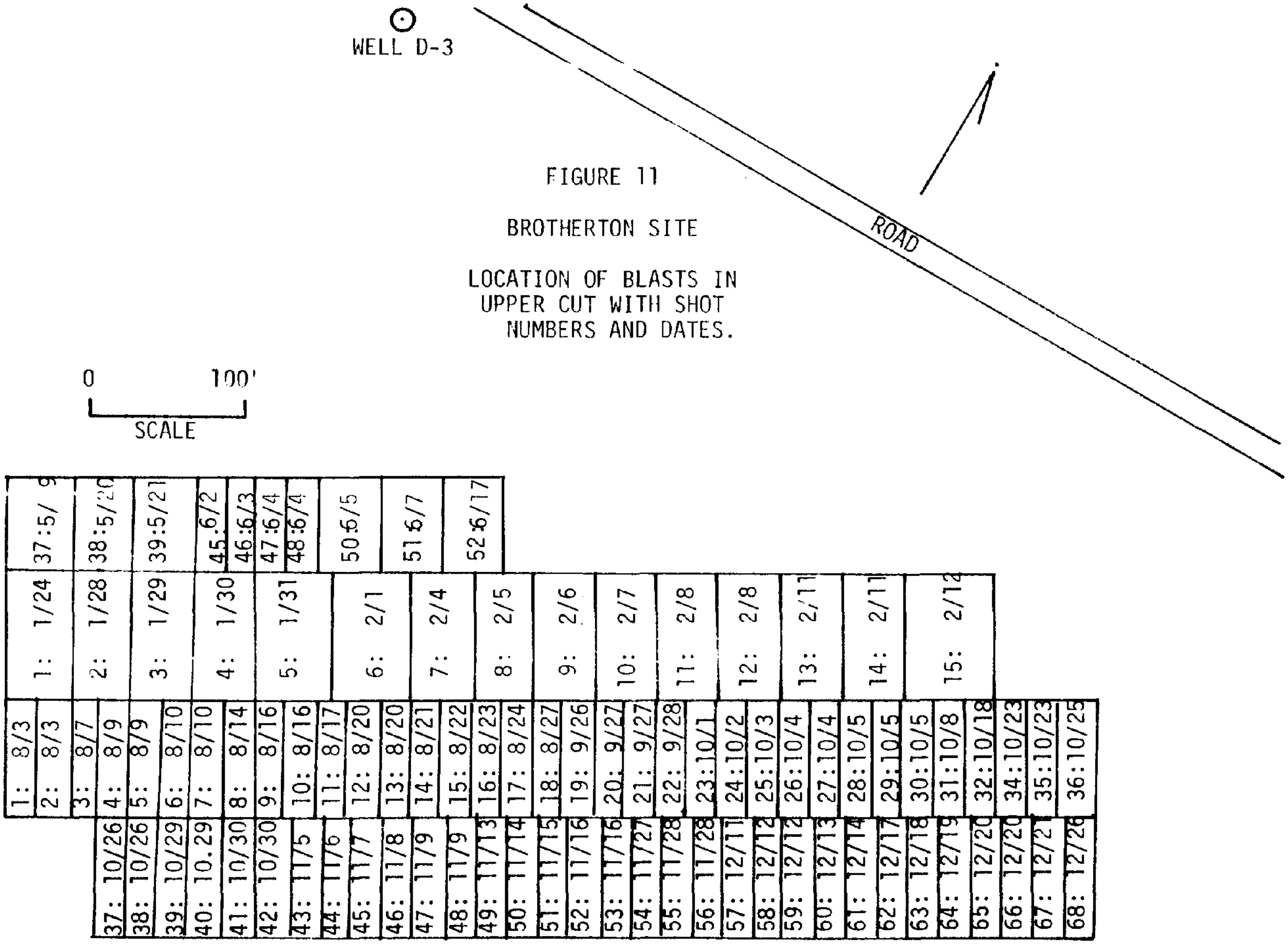


FIGURE 11

BROTHERTON SITE

LOCATION OF BLASTS IN UPPER CUT WITH SHOT NUMBERS AND DATES.

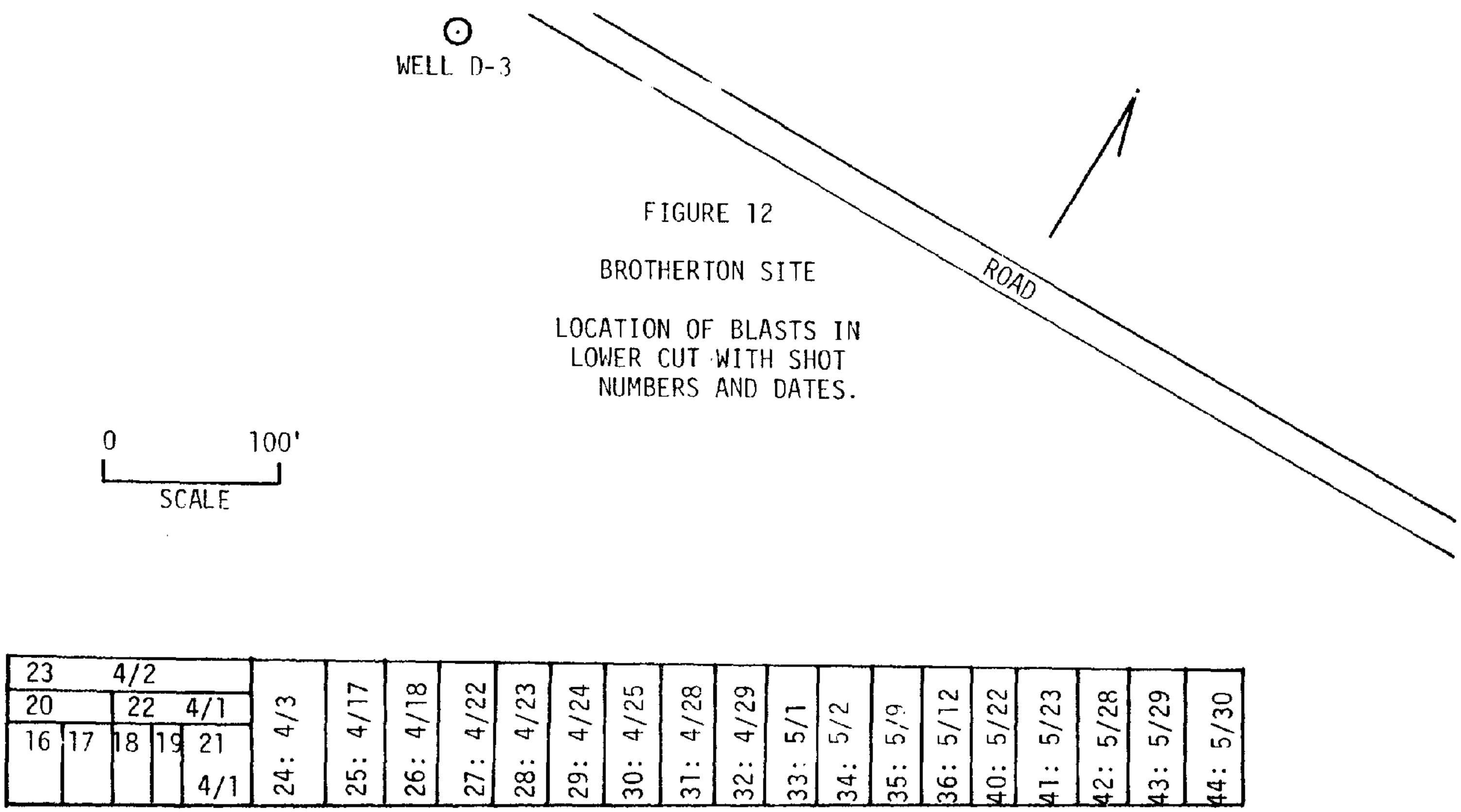


FIGURE 12

BROTHERTON SITE

LOCATION OF BLASTS IN LOWER CUT WITH SHOT NUMBERS AND DATES.

TABLE 4

BROTHERTON: UPPER COAL SEAM

SHOT NO.	DISTANCE	RPV SUBSURFACE / RPV SURFACE
3(79)	500 ft.	0.64
5	480 ft.	0.40
19	460 ft.	0.41
33	585 ft.	0.26
33A	595 ft.	0.20
35	620 ft.	0.42
36	630 ft.	0.17
48	520 ft.	0.33
52	530 ft.	0.24
53	530 ft.	0.31
4(80)	380 ft.	0.38
7	360 ft	0.30
8	370 ft.	0.26
10	380 ft.	0.38
		MEAN =0.34
		S.D. ±0.12

LOWER COAL SEAM

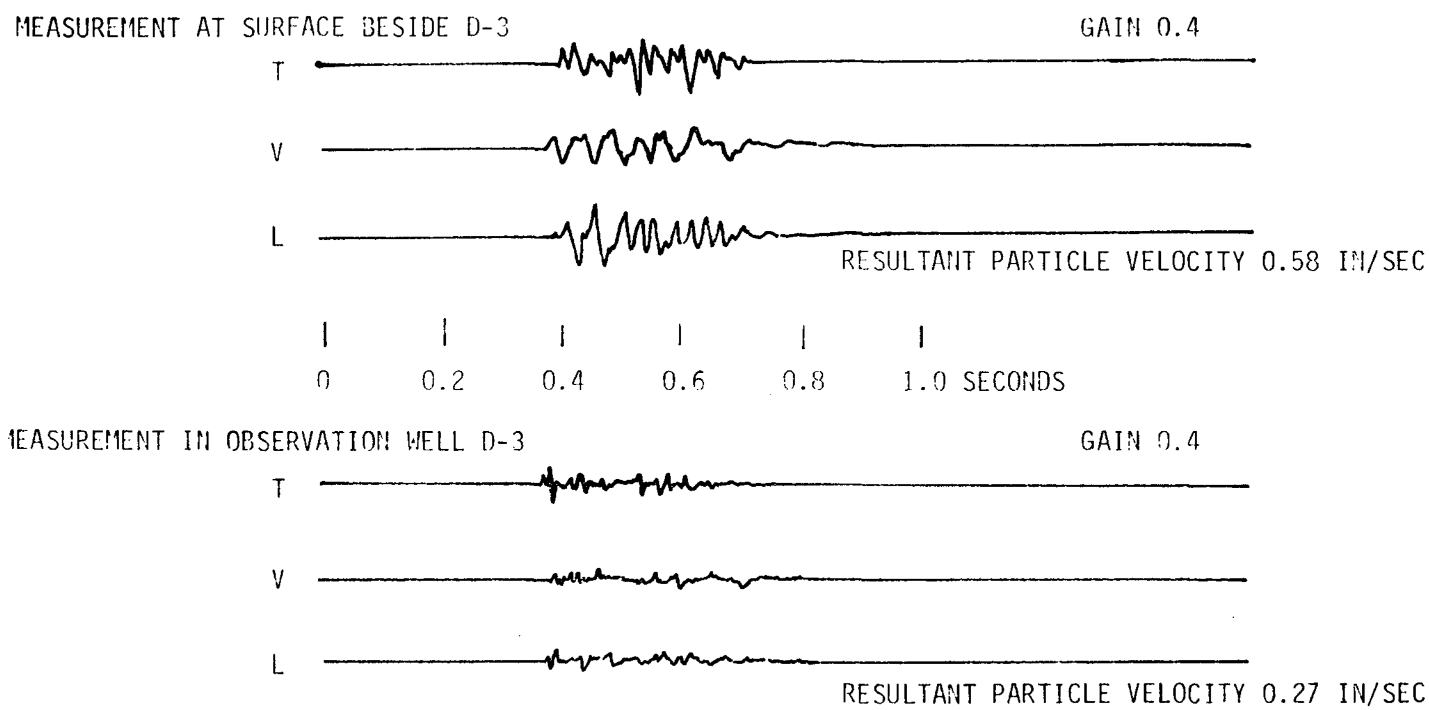
SHOT NO.	DISTANCE	RPV SUBSURFACE / RPV SURFACE
16	460 ft.	0.63
18	435 ft.	0.68
19	430 ft.	0.47
21	420 ft.	0.56
23	380 ft.	0.95
26	365 ft.	0.78
27	360 ft.	0.77
28	365 ft.	0.92
29	370 ft.	0.80
30	375 ft.	0.37
31	380 ft.	0.50
32	390 ft.	0.68
		MEAN =0.68
		S.D. ±0.18

TABLE 4

(CONTINUED)

BROTHERTON: UPPER COAL SEAM

SHOT NO.	DISTANCE	RPV SURFACE	MONITOR PPV
62	390 ft.	1.17	1.00
63	370 ft.	1.36	
64			.80
65			.75
66			.40
67			.60
68			.15
69			.23
70			.77
71			.75
72			.33
73	310 ft.	2.2	.66
74	300 ft.	1.8	
LOWER COAL SEAM			
75	350 ft.	1.75	



BROTHERTON, PA. SITE BLAST NO. 19 MARCH 28, 1980 11:30 AM 7 HOLES

DIAMETER OF HOLES: 6 3/4" DEPTH OF HOLES: 50' SPACING: 15' BURDEN: 15' STEMMING: 20'

TOTAL EXPLOSIVES: 1816 LBS. MAX. HOLES/DELAY: 1 MAX. LBS./DELAY: 259 LBS.

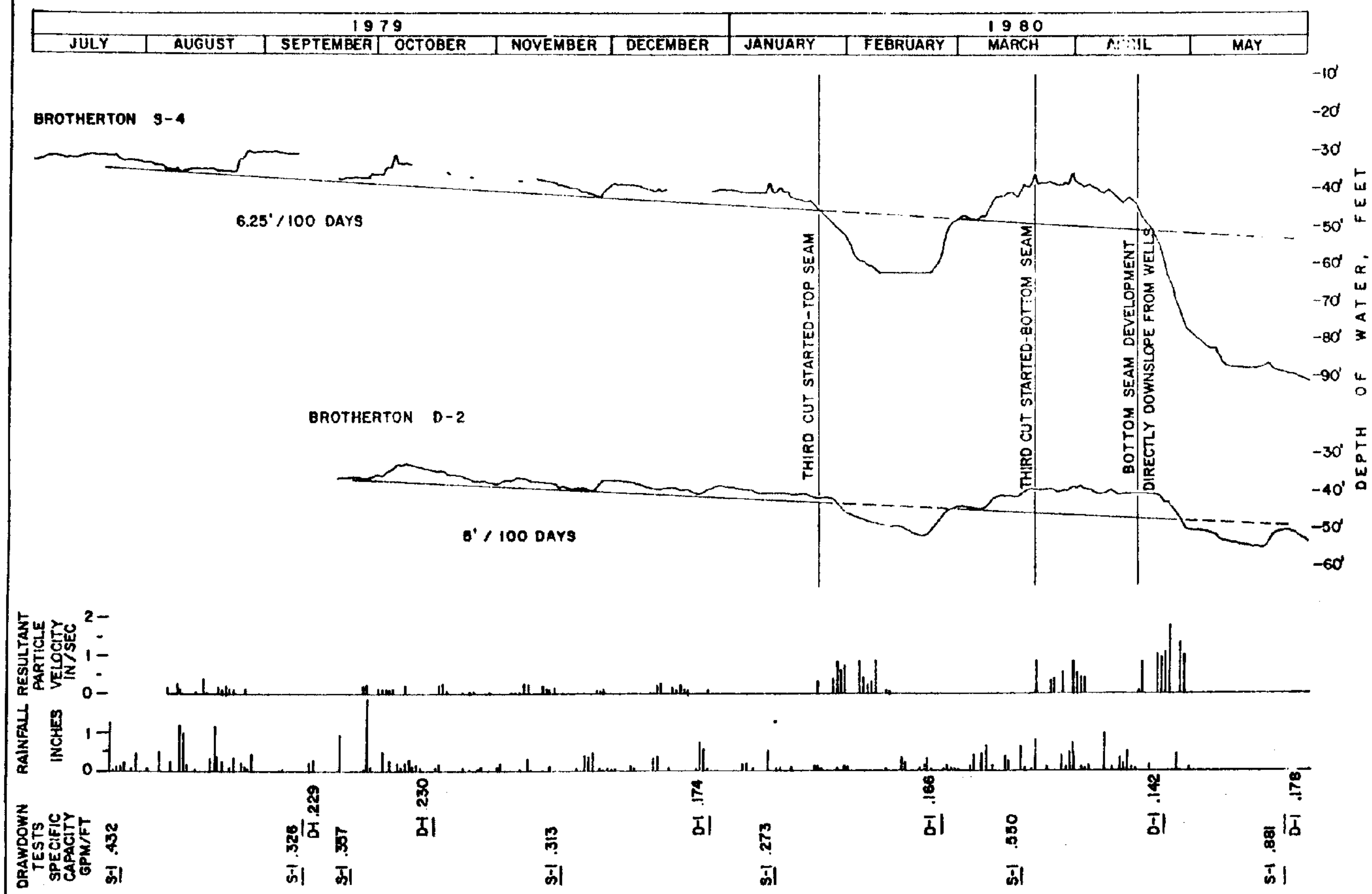
DISTANCE FROM BLAST: 430 FEET

FIGURE 13

TYPICAL VIBRATION RECORD

FIGURE 14

SUMMARY OF DATA FROM BROTHERTON SITE



Figures 15 and 16 are the detailed hydrographic charts for Well S-4 and D-2 covering the period when the sharp drop occurred in late January. On the shallow well chart the float was hung up at 40.8 feet on January 16 when preparations were being made for a drawdown test the next day. When the beaded line was freed, the recorder moved to a depth of 42.25 feet. The sharp upward spike on January 11 is the result of .52 inches of rain on that day, and the spike on January 14 results from 0.1 inches of rain and somewhat warmer daytime temperatures which may have added more water by thawing. Starting at the base of the spike on the 14th when the float was operating, a dashed line has been drawn to the point where the recorder started operating after the line was freed. This indicates that a fairly sharp drop had already started sometime shortly after January 14, 1980. There was no blasting during this time. The drop continued after the drawdown test and became abruptly steeper about noon on January 22. There had been no blasting at this site since December 26 so the drop was not related to any blast. The next blast occurred on January 24 after the well had been in sharp decline for 48 hours. The drop continued at the same rate until shortly after midnight on January 28 when the rate increased from 0.8 feet per day to 3.5 feet per day. Again this did not coincide with any blasting although it was followed by a blast 13 hours later at 1:00 pm on January 28. The evidence presented by the hydrographic chart from S-4 is clear that blasting did not cause the observed drop in static water level starting on or about January 14.

The evidence presented by the chart for Well D-2 is not so clear. First of all, the timing of the sharp drop is not coincident with the shallow well. Although the level in D-2 dropped about one foot from January 17 to January 28, this could be considered within the normal range of fluctuation. The blast on January 24 had a very slight effect causing a temporary drop of 0.2 feet, perhaps. The sharp drop commences on January 28, almost coincident with the blast at 1:00 pm. The drop accelerated on January 29, again approximately coincident with a blast. Ground vibrations at the surface for these two blasts were 0.87 in/sec and 0.61 in/sec maximum resultant particle velocity, respectively. At 11:05 am, January 31, a blast with a vibration level of 0.74 in/sec MRPV (maximum resultant particle velocity) caused the water level in the observation well to rise 0.45 feet before it continued to decline. The effect of subsequent blasts appeared to cause the water level to rise .2 to .3 feet temporarily but the decline continued although decreasing in rate of fall. Although a possible relationship between blasting and the declining water level is indicated by the evidence of D-2, the conflicting evidence of the shallow well and the possibility that the drop may not be caused by ground vibration but from some other factor causes concern. The point being that it could be wrong and misleading to attempt to find some vibration level, above which damage might occur, if in fact, the changes observed are really related to some other phenomenon inherent in the mining operation.

If one returns to Figure 11 in order find out <u>where</u> these blasts occurred, it is evident that the third cut for the upper seam was started with the blast of January 24. The blasts on January 28, 29, 30 and 31 were directly downslope from the test well site at a distance 85 feet closer than any mining to date. As these blasts initiated the removal of the supporting downslope material, the effect was the same as removing the toe of a slope. When excavation (of which blasting is but the initial phase) approaches close enough, the existing constraint on the downhill movement of the slope is partially removed and the soil and rock mass directly above the excavation move

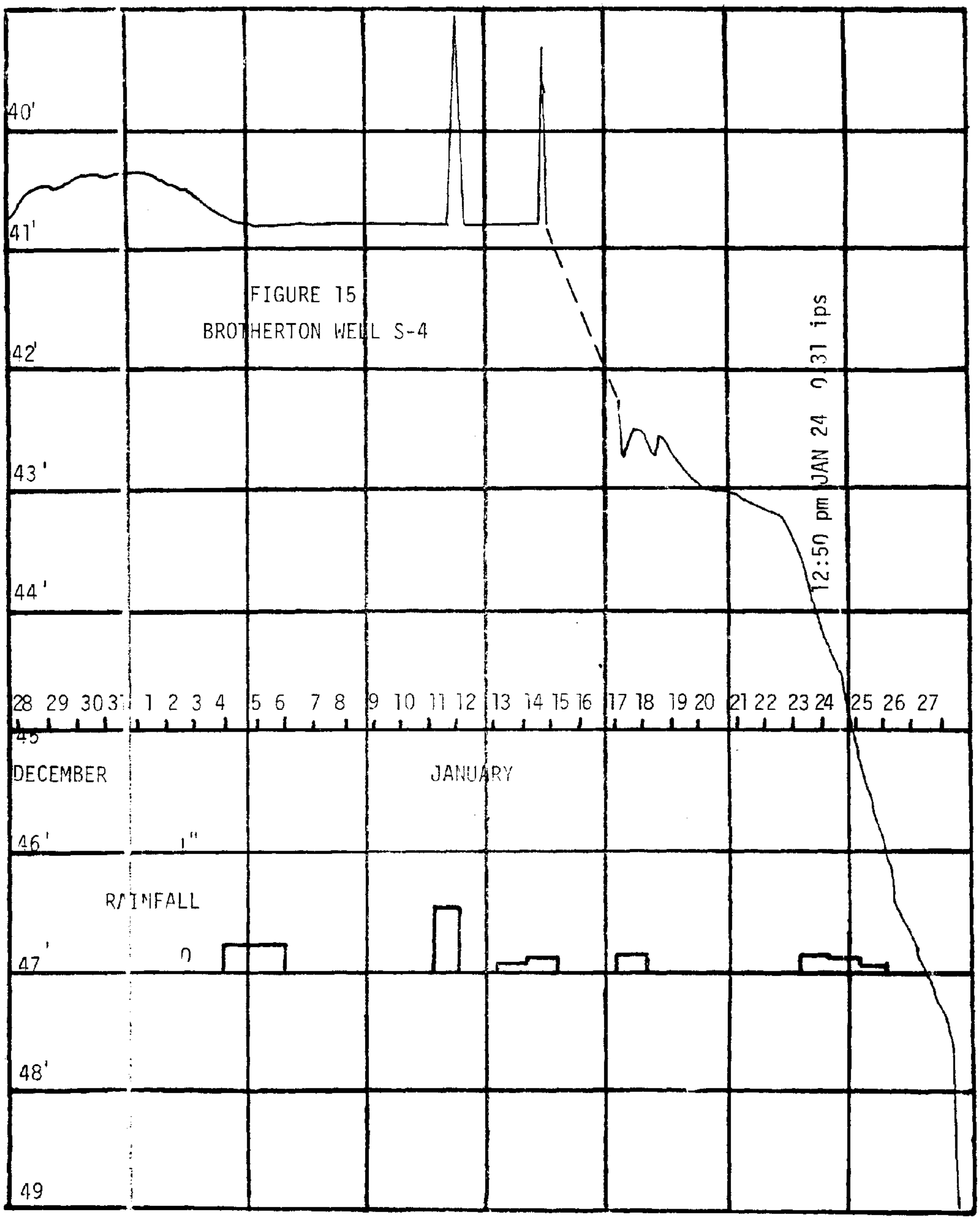


FIGURE 15
BROTHERTON WELL S-4
40'
41'
42'
43'
44'
45
46'
47'
48'
49
28 29 30 31 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27
DECEMBER
JANUARY
1"
RAINFALL
0
12:50 pm JAN 24 0.31 ips

FIGURE 15

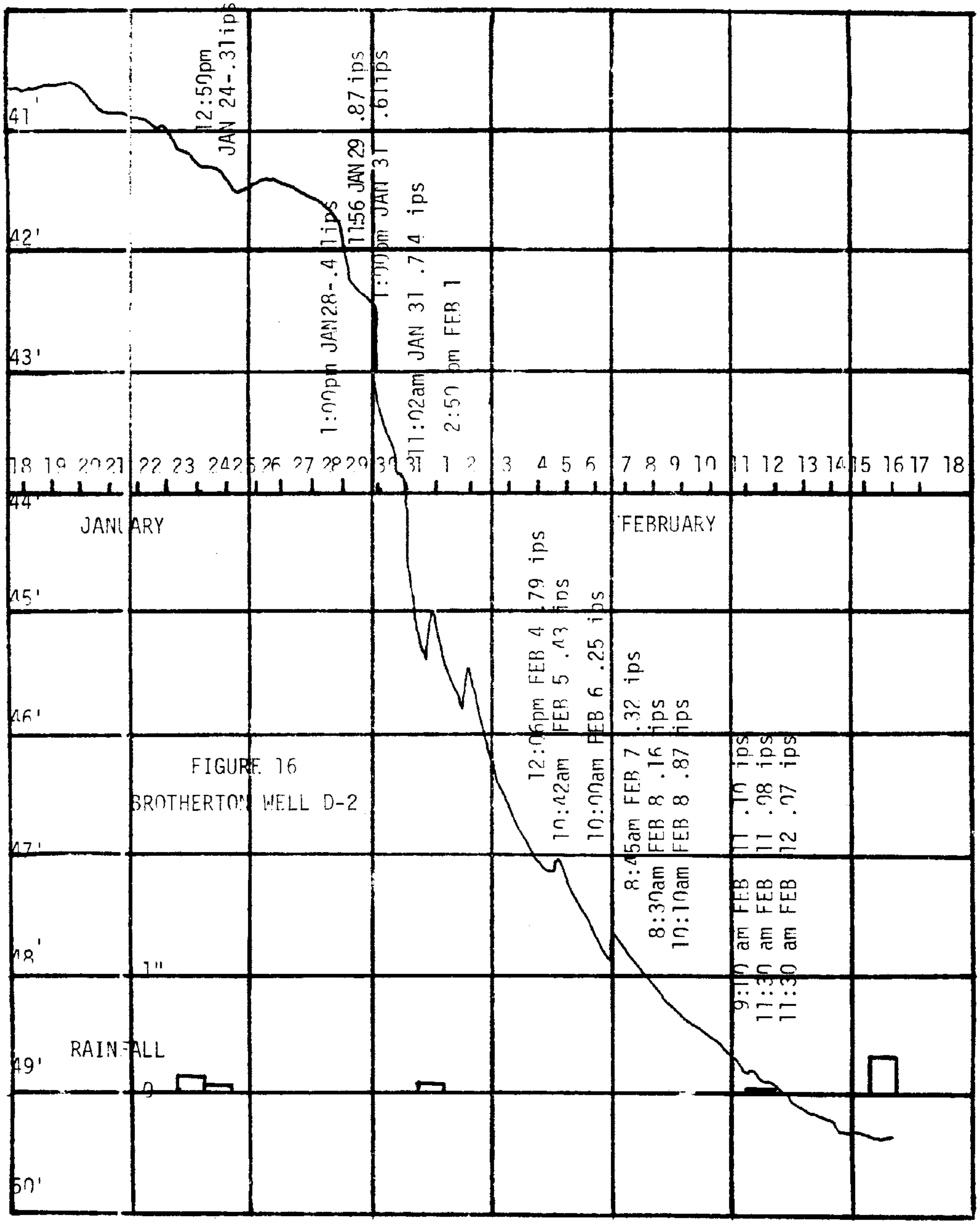

41'
42'
43'
44'
45'
46'
47'
48'
49'
50'
12:50pm JAN 24-.31ips
1:00pm JAN28-.41ips
11:56 JAN 29 .87 ips
1:00pm JAN 31 .61ips
11:02am JAN 31 .74 ips
2:50 pm FEB 1
18 19 20 21 22 23 24 25 26 27 28 29 30 31 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
JANUARY
FEBRUARY
12:06pm FEB 4 .79 ips
10:42am FEB 5 .43 ips
10:00am FEB 6 .25 ips
8:45am FEB 7 .32 ips
8:30am FEB 8 .16 ips
10:10am FEB 8 .87 ips
9:10 am FEB 11 .10 ips
11:30 am FEB 11 .98 ips
11:30 am FEB 12 .97 ips
FIGURE 16
BROTHERTON WELL D-2
1"
RAINFALL
0

FIGURE 16

slightly downhill. New fractures may be developed, but for the most part the movement probably causes the existing fractures to become more open.

This would improve the permeability as observed in the drawdown tests of S-1, but it would also increase the porosity, or storage space of the aquifer. Because this probably happens over the span of a few days, the water level in wells obtaining water from the affected strata would decline in direct proportion to the rate that new storage space is created. After movement ceased except for the normal hillside creep, and if recharge was available from rainfall, the fractures would be recharged, the water levels would rise, and one would find that the performance of the wells was noticeable improved. This scenario fits the observed events and it is substantiated by one further piece of evidence. Although both shallow and deep wells are obtaining water from the same water table aquifer, parts of the well bore are more productive than other parts as evidenced by the tendency for water to occur at the base of the coal seams, or perhaps more correctly, at the top of underclays which act as aquitards, but not as aquicludes. In other words, downward moving water is able to recharge the fractures below the underclay although the underclay may impede the rate of recharge. In Well D-1, the strata above 115 feet are behind an unperforated liner. Assuming that the packer is effective, water entering Well D-1 must do so below a depth of 115 feet, whereas in Well S-1, all of the water enters the well above a depth of 109 feet. In the lateral stress relief scenario, one would expect that the fractures near the surface would open up more than those at depth because the stress relief is acting at the surface. As previously stated in the quotation from Ferguson in the discussion of fractures created by lateral stress relief, "They also become less frequent with depth and they do not occur beyond the destressed zone in the valley wall." This is consistent with the drawdown performance of the two wells; Well S-1 has experienced significant improvement in permeability and Well D-1 has not, because the fractures below 115 feet have not opened up as much as those above 109 feet.

Figures 17 and 18 are the detailed hydrographic charts for the shallow and deep water level recorders for the period covering the sharp drop in the latter part of April, 1980. The chart for S-4 reveals several sharp spikes which correlate nicely with the rainfall indicated at the bottom of thechart. All of the blasts during this period are plotted at the appropriate time and it can be seen that there were nine blasts from March 21 to April 3 with ground vibration levels ranging from 0.37 to 0.86 in/sec MRPV. Some of these are associated with troughs, some with peaks, but no trend or relatively long-term change is associated with any of these blasts. During this period the water level fluctuated between 36 and 40 feet depending mainly on the occurrence of rain. Then on April 6 the level dropped below 40 feet and continued a downward descent, interrupted by two more rain spikes and accelerated on April 16. There was no blasting during this time and the next blast didn't occur until 12:08 pm on April 17 when the rate of decline was already at its greatest. Another blast on April 18 appeared to slow the decline down for about 12 hours but later the sharp descent continued. Although there is no one point where one can pick the start of the sharp decline, it does appear that it would have had to occur sometime well after the blast of April 3, and that it was not associated with some level of ground vibration being exceeded. In other words, not related to blasting per se.

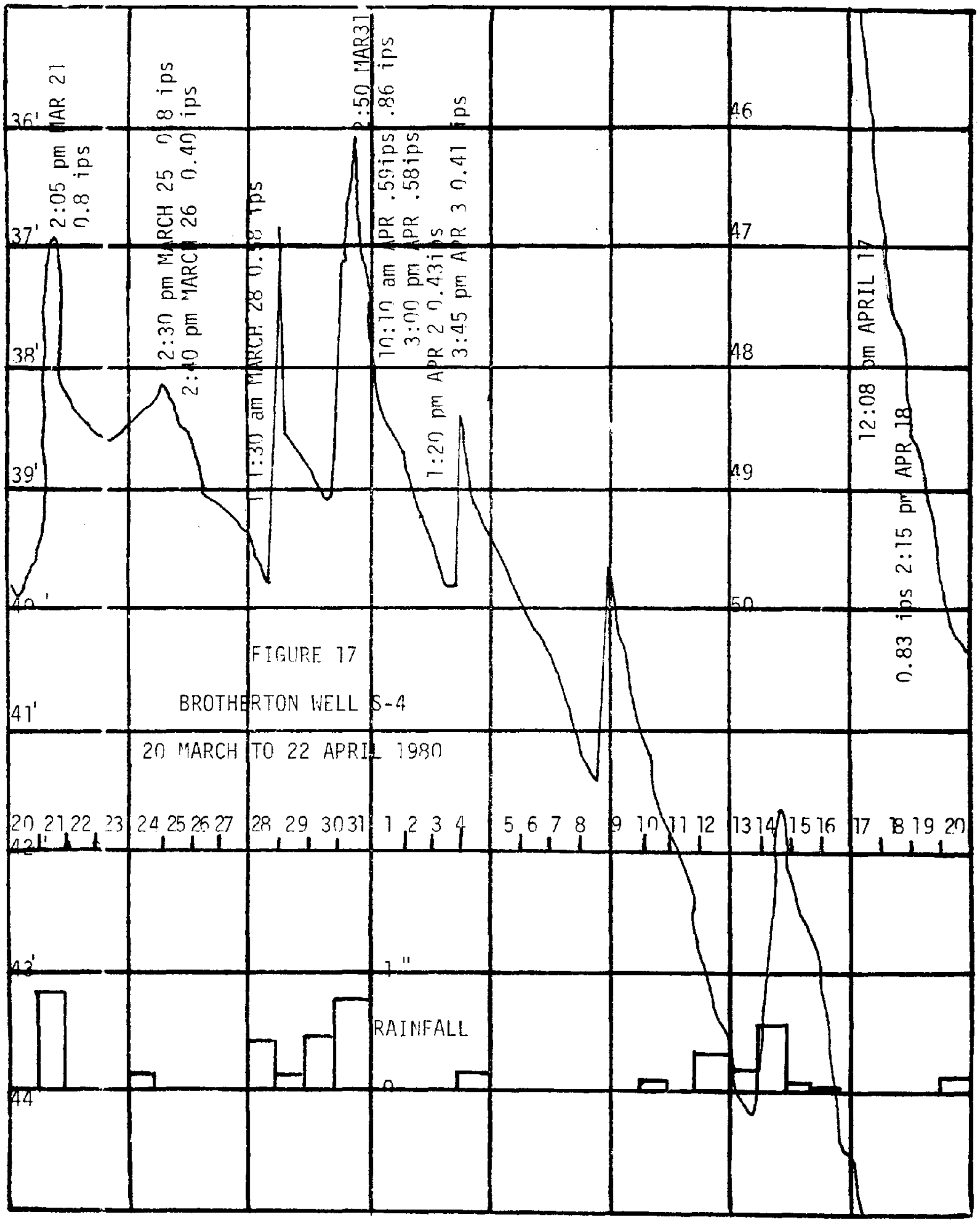


FIGURE 17
BROTHERTON WELL S-4
20 MARCH TO 22 APRIL 1980
RAINFALL
2:05 pm MAR 21 0.8 ips
2:30 pm MARCH 25 0.8 ips
2:40 pm MARCH 26 0.40 ips
10:10 am APR .59ips
3:00 pm APR .58ips
1:20 pm APR 2 0.43ips
3:45 pm APR 3 0.41 ips
12:08 pm APRIL 17
0.83 ips 2:15 pm APR 18

FIGURE 17

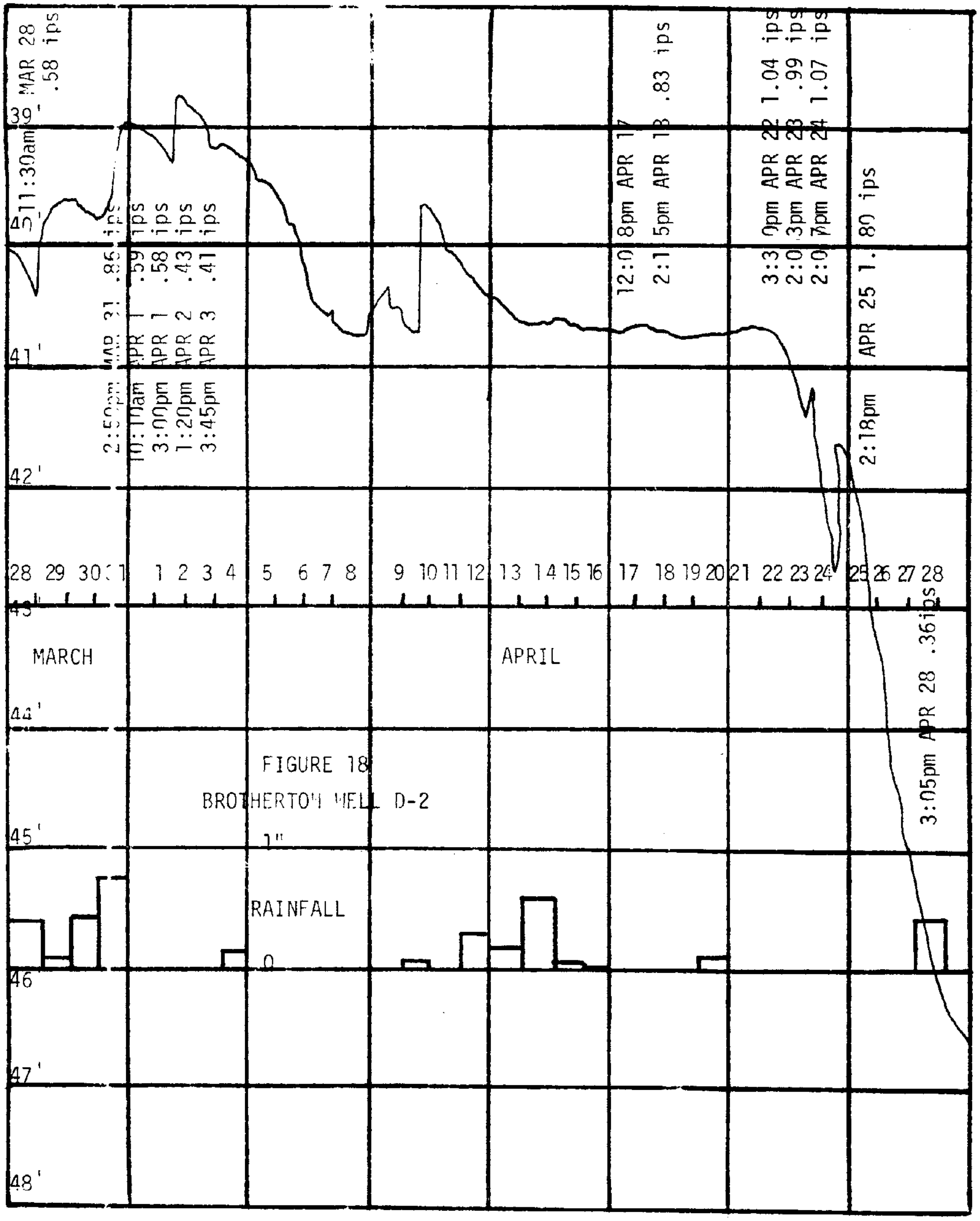


FIGURE 18
BROTHERTON WELL D-2
MARCH
APRIL
RAINFALL
1"
0
39'
41'
42'
44'
45'
46'
47'
48'
11:30am MAR 28 .58 ips
12:08pm APR 17
2:15pm APR 18 .83 ips
3:30pm APR 22 1.04 ips
2:03pm APR 23 .99 ips
2:07pm APR 24 1.07 ips
2:18pm APR 25 1.80 ips
3:05pm APR 28 .36 ips
10:10am APR 1 .59 ips
3:00pm APR 1 .58 ips
1:20pm APR 2 .43 ips
3:45pm APR 3 .41 ips

FIGURE 18

Again, the evidence on the deep chart is not as clear as that on the shallow one. The onset date of the decline is more clear and appears to have started late in the afternoon of April 22, at least 18 days after the decline commenced in the shallow well. There was a blast that afternoon at 3:30 pm with ground vibrations at a level of 1.04 in/sec MRPV. Additional blasts were detonated on April 23, 24, and 25 at respective levels of 0.99, 1.07, and 1.80 in/sec MRPV. The only interruption in the decline resulted from the blast of April 24 when the float recorder displayed a rise of 1.3 feet from readings taken immediately before and immediately after the blast.

In this case it is also instructive to look at where the blasts occurred rather than the level of vibrations generated by the blast. As before, the sharp decline in Well S-4 occurred when excavation was started in the lower cut directly downslope from the well and may have been as much as three days after any blasting. Excavation without blasting was the main activity from April 3 to April 22 when the decline in the deep well commenced. During this time there were only two blasts and these appeared to have no effect on the well, although one produced ground vibrations at the surface of 0.83 in/sec MRPV.

To establish that S-4 and D-2 are representative, Figures 19 and 20 show how the static water level of all wells varied during the test period based on measurements at different times. All of these data indicate that the changes observed in both the shallow and the deep wells can be attributed to lateral stress relief which has been described. They are related to the proximity and location of the excavation and have no relationship to the level of blasting vibrations. Of course, the blasting vibration levels are generally higher when the decline occurs but this is because they are associated with those blasts that are closer, which in turn are associated with the proximity of surface mining.

Chemical sampling to detect any changes in the waters was performed before and after those blasts where on-site recording was done. The sampling method was to lower a sampling bottle into one of the shallow wells and one of the deep wells. The pumps were not used because there was no power at the site and to start the pumps would require transporting the portable alternator to the site and setting it up. This is a two-man job. It was felt that the sampling bottle technique would provide the needed information particularly since it would be backed up by pumped samples taken when drawdown tests were performed.

Samples collected with the bottle were analyzed on site with a portable spectrophotometric device or shortly afterward. Drawdown samples were sent to a commercial laboratory where they were analyzed in accordance with "Standard Methods for the Examination of Water and Wastewater", Latest Edition, APHA, AWWA and WPCF. Drawdown samples were also analyzed by the spectrophotometric method to maintain acheck and a control on the field analyses.

This methodology worked fine for the chemical parameters and the results of all of these analyses are included in Appendix D. In general, there was no significant change in the chemistry of these waters although the iron and manganese concentrations were erratic. The pH stayed within a normal range, the sulfate concentration, the alkalinity, and nitrates remained about the same.

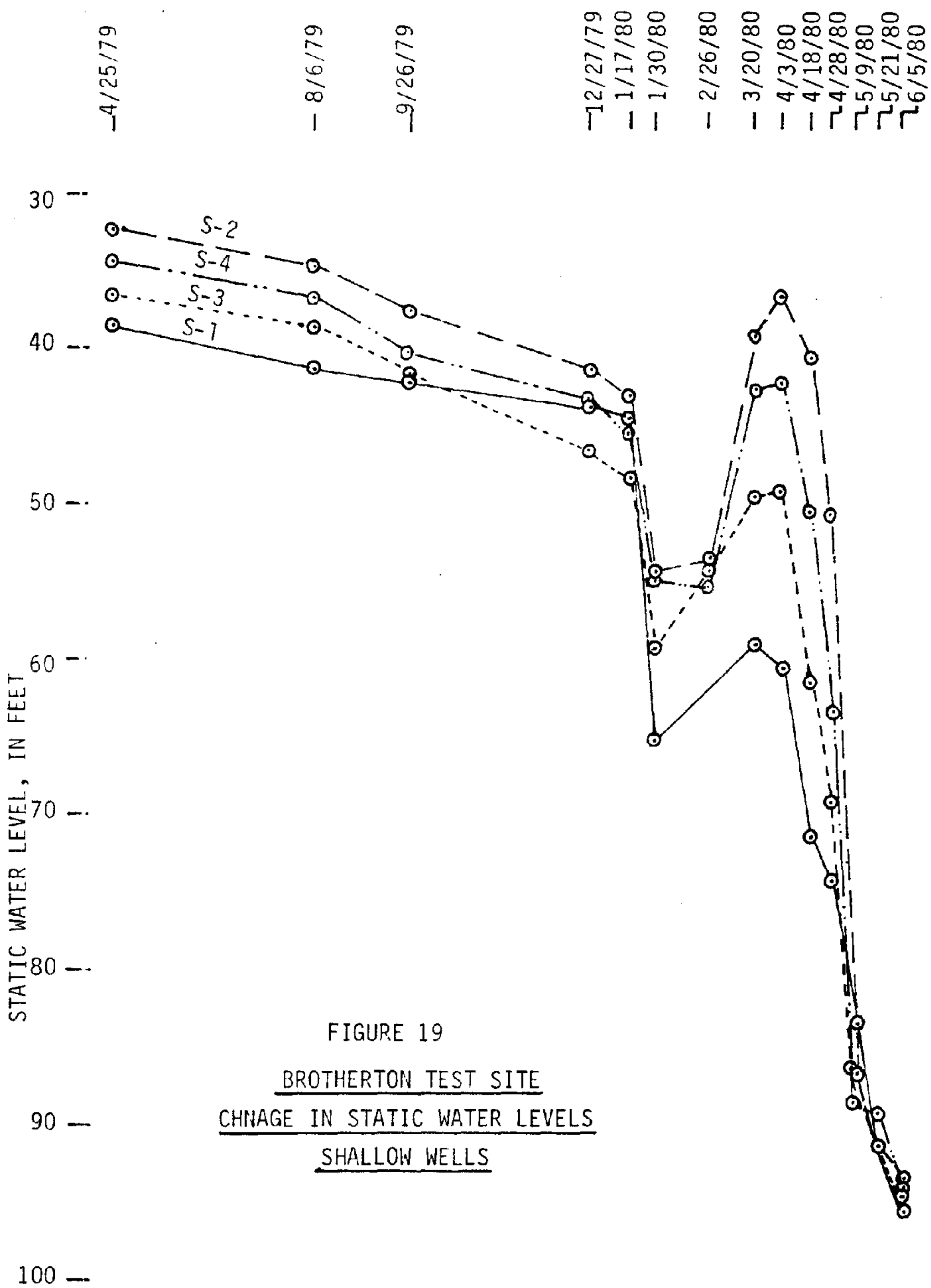


FIGURE 19

BROTHERTON TEST SITE

CHNAGE IN STATIC WATER LEVELS

SHALLOW WELLS

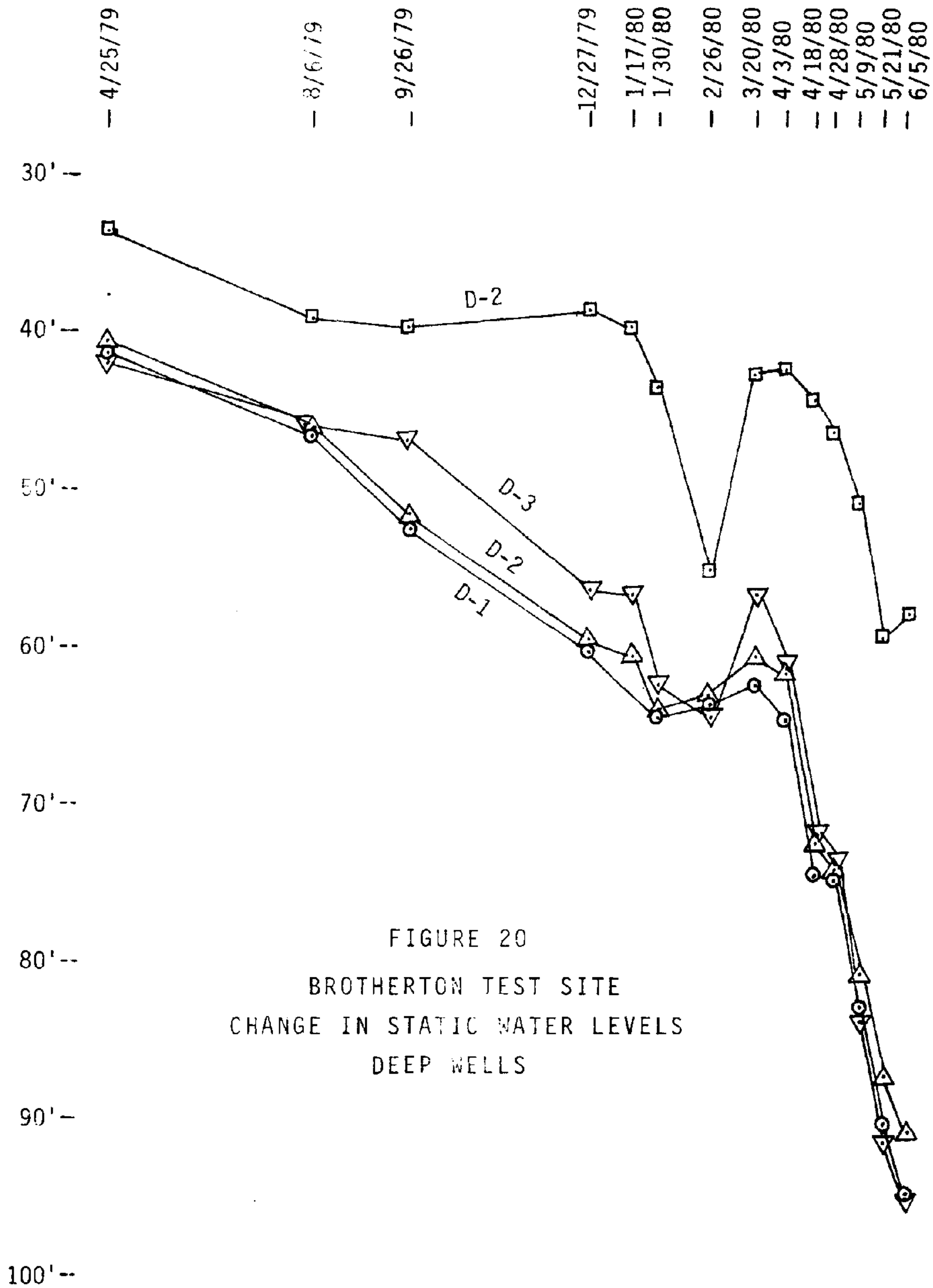


FIGURE 20

BROTHERTON TEST SITE

CHANGE IN STATIC WATER LEVELS

DEEP WELLS

The turbidity measurements are a different matter and the validity of the field measurements of this parameter is very questionable. There are several reasons for this.

At Brotherton, it was noticed that if the wells sat idle for only a few days, it was necessary to pump them for approximately one hour before the reddish-iron color would disappear. In retrieving the sample bottle, the water was commonly reddish and most of this material represented fine particles of iron suspended in water rather than being dissolved in it. This particulate matter undoubtedly affected the turbidity readings at times. Another factor was that these were new wells and they were not in use as frequently as domestic wells would be. Early turbidity readings even under controlled laboratory conditions were very high indicating that the effects of suspended drill cutting fines and sidewall sloughing were still significant up to six months after the drilling of the wells, although for most of this period there wasn't any blasting. In June, 1980, drill cuttings can still be observed plastered to the steel casing. If these were within the zone of water fluctuation, it would be difficult to estimate how long they would contribute to the turbidity of the water. More mature wells being used every day probably would not have this problem. Another factor is the turbidity created by the sampling itself. If the bottle strikes the sidewall it may knock drill cuttings down into the water and a turbid sample is retrieved. Or if it strikes the sidewall on the way out of the hole, the next sample will be deceptively turbid. In addition, it appeared that the reddish-iron particulate matter tended to be concentrated near the top of the water column. If the bottle was lowered slowly, the sample was very reddish. If the bottle was dropped through the water surface rapidly and allowed to sink to a depth of ten feet or more, the sample would be much clearer. This technique was of value in getting the first sample before the blast, but when the second sample was obtained, the segregation at the water surface had already been disturbed.

Where pumped laboratory samples were obtained both before and after a blast, the results indicate that the turbidity increased 5 NTU when the blast was at a distance of 460 feet and the ground vibrations were measured to be 0.22 in/sec MRPV, but undoubtedly this increase was only temporary.

Over the long term, the laboratory readings indicate a decrease in turbidity with time until March, 1980, when the values start to increase again. See Table 5.

More information is needed on the possibility of temporary turbidity being caused by blasting. This should be done at a site where samples can be pumped from the well and samples should be collected before the blast and then at ten-minute intervals after the blast to determine how long the condition persists. A water well meeting these conditions is to be drilled in southern Indiana and monitored as an extension of this project. Monthly drawdown tests are to be performed. To the greatest extent possible, drawdown tests will be planned to coincide with blasts so that samples can be taken to evaluate this possible effect. These results will be reported in another final report covering only that well.

TABLE 5

DATE	WELL S-1	WELL D-1
8/ 2/79	17.0 NTU	650.0 NTU
8/ 7/79	11.0 "	--
8/13/79	11.0 "	--
9/11/79	.45 "	3.8 "
9/26/79 Pre-blast	25.0 "	--
9/26/79 Post blast	30.0 "	--
10/16/79	--	4.0 "
11/19/79	7.1 "	--
12/27/79	--	0.4 "
1/17/79	1.0 "	--
2/20/79	--	0.12 "
3/20/79	2.0 "	--
4/24/79	--	11.0 "
5/27/79	4.0 "	3.5 "

TENMILE, WEST VIRGINIA TEST SITE

This site is located about ten miles southeast of Buckhannon, West Viginia. The Allegheny Group of the Pennsylvanian System occurs at the surface and the coals being mined are the Lower and Middle Kittanning seams. Dip of the strata is 2^{o} to the northwest. Topography at the site is illustrated on Figure 21 which also shows the relationship of the test well site to the area being mined. As of June, 1980, all mining directly below the test site was complete.

Mining of the coal at this site is only one aspect of the operation. A much larger stripping operation is contemplated about one mile to the east. The stripping in the area of the test wells is being done in conjunction with the construction of a very large sedimentation basin. The overburden will not be replaced but is being used for the construction of a dam. Eventually the area up to an elevation of about 2050 feet will be flooded. The test wells are at an elevation of 2080 feet approximately.

Figure 22 is a cross-section showing the relationship between the wells, the pit, and the seams being mined.

The specific test well site was selected because it was about 1000 feet from where the first blasting activity was planned and there was an existing road to the site. Blasting was to be done within about fifty feet of the wells as mining progressed. With a predominantly sandstone overburden this would provide an opportunity to evaluate the stability of the boreholes in this type of material as well as evaluating the effects of blasting on the ground-water resources in a geologic section considerably different than that at Brotherton. The strata at Tenmile are more typical of those found in southern West Virginia, eastern Kentucky, and Virginia although the strata at Tenmile are slightly younger in age. This would provide broader geographic significance to the project results.

When drilling started at Tenmile, drawdown tests had already been conducted at Brotherton. Tests at this site indicated that the information provided by observation wells (wells in addition to the pumped well) was minimal even with conditions of relatively good interconnection. This, coupled with the fact that the hillside was so steep that there wasn't sufficient flat space at the site to drill any pattern other than a series of wells in a straight line along the road, led to the decision to drill only three shallow wells and two deep ones. Accordingly, the wells were drilled in early May, 1979, in the pattern shown on Figure 23. Depths of the wells are shown beside the locations.

Approximately 20 feet of plastic casing was used at the top of each well, and after logging was completed, plastic liners were placed in the two deep wells. Liners were unperforated above the packers and perforated below, with packers set at 160 feet. Pump in Well S-1 was set at a depth of 146 feet and the pump in Well D-1 was placed at 187 feet. Flexible 1" plastic discharge line was run from the pump up to the casing collar where it joined galvanized iron well head fittings that were held in place by a standard split well seal cap.

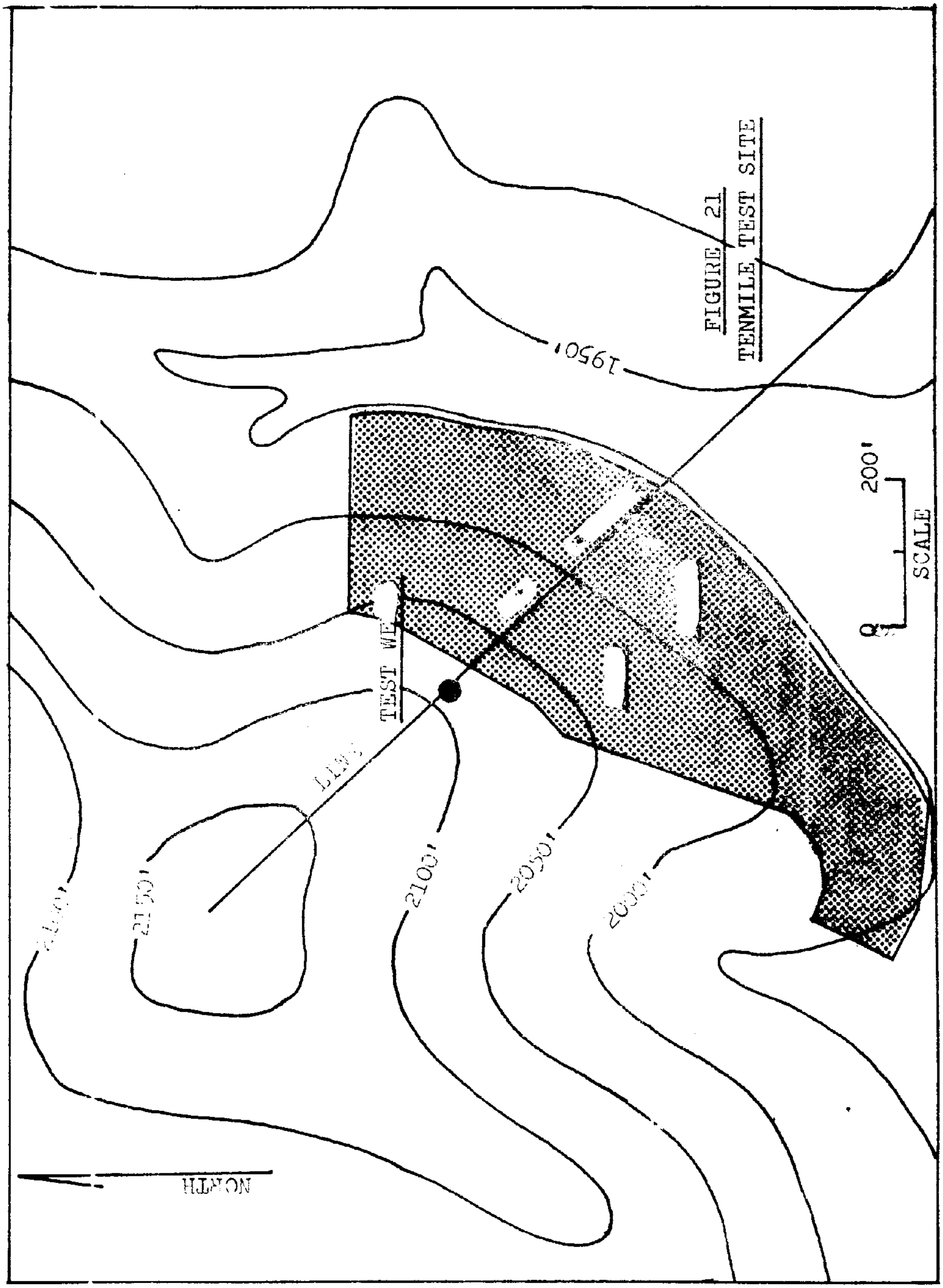


FIGURE 21
TENMILE TEST SITE

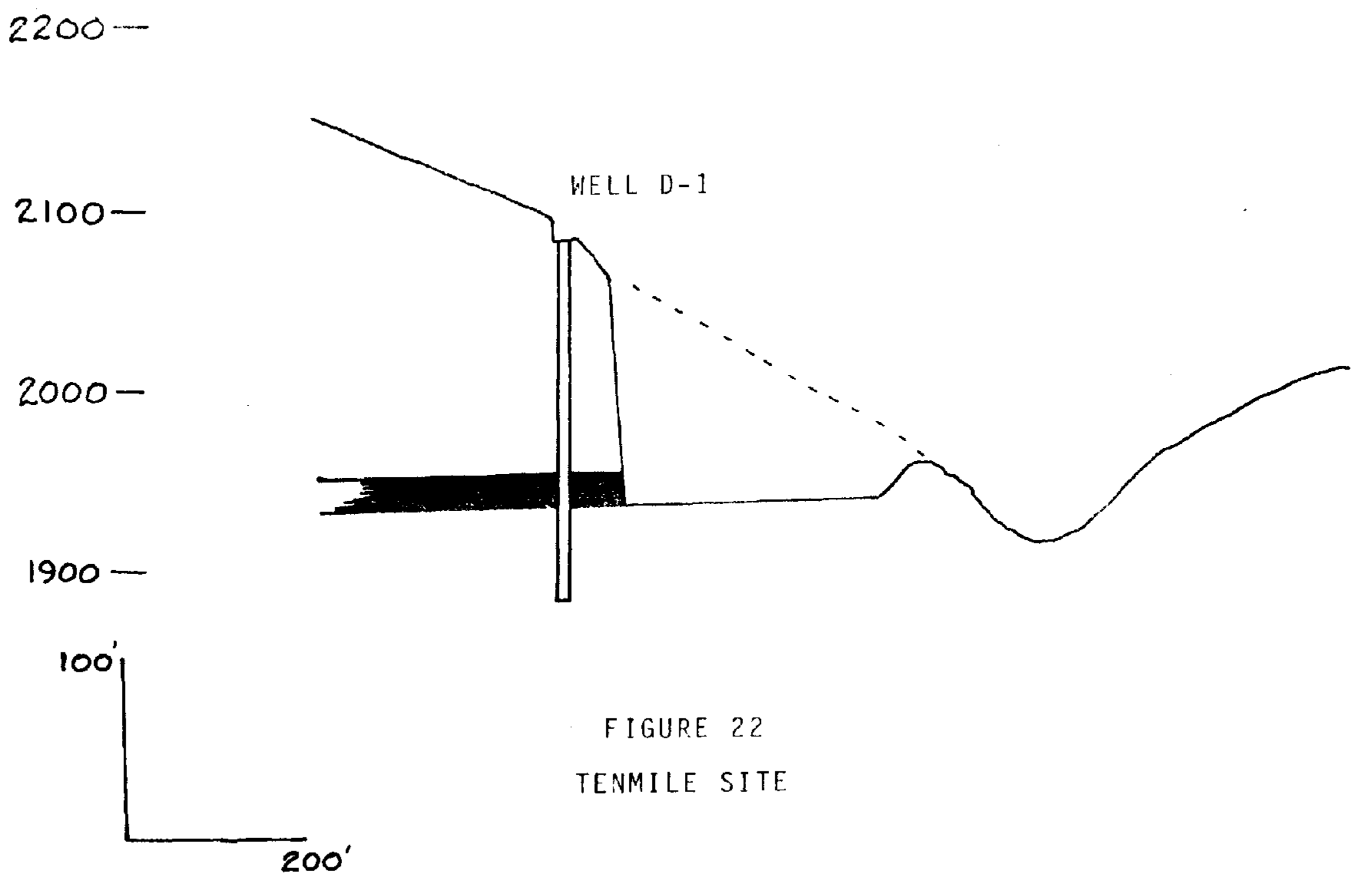
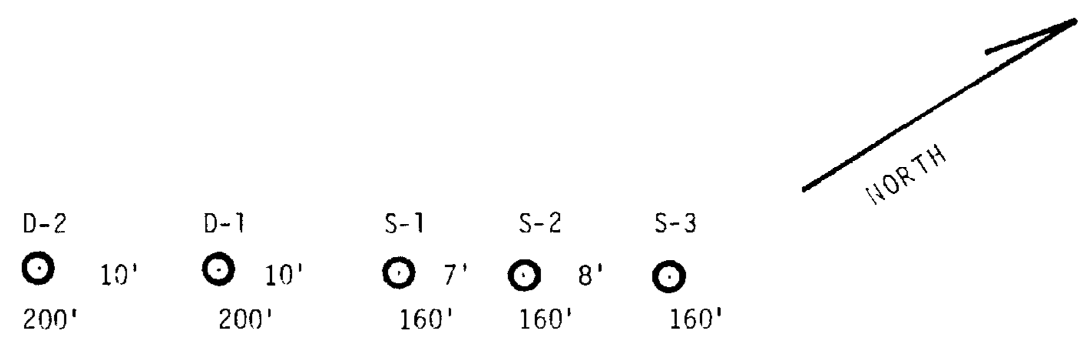


FIGURE 22
TENMILE SITE



SCALE: 1" = 10'

FIGURE 23
TENMILE, W.VA. SITE
TEST WELL PATTERN

In addition to the drilling time and lithologic logs that were made at the time of drilling. gamma ray, caliper, and density logs were run on Wells S-1 and D-1. Caliper logs were run on all others. Figure 24 is a composite of all of the logs.

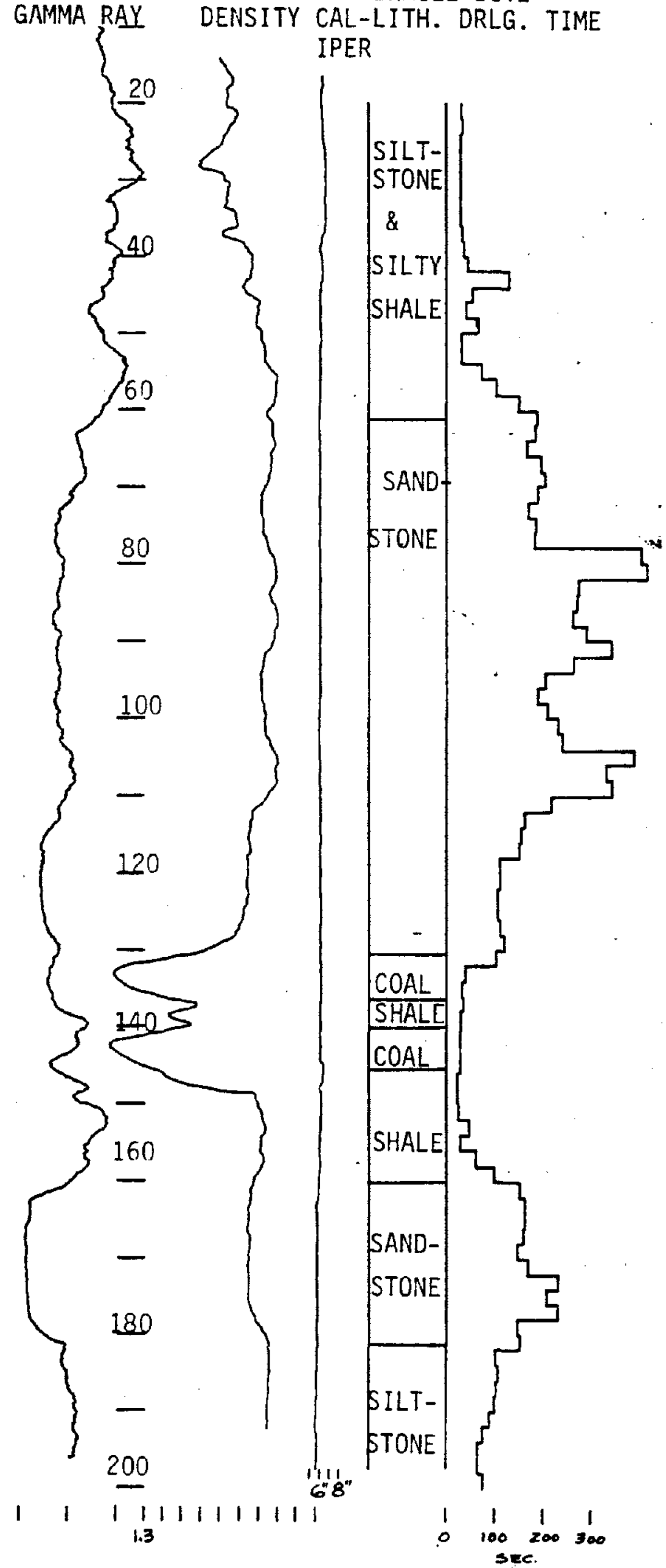
Water entry to the wells during drilling was very sparse and was restricted to the coal bearing zones. Generally, the water was only sufficient enough to keep the air return from dusting.

On May 30, 1979, an attempt was made to test Well S-1. The water level was pulled down to the pump in 20 minutes at a very low pumping rate. The exact rate could not be determined because the meter became jammed with sand. Several attempts were made to get some valid pre-blast information on this well. Finally on June 9, sufficient information was obtained prior to the blast to determine that the specific capacity was not more than .065 gpm/ft. after 20 minutes of pumping. The water level certainly had not stabilized at this point and was declining rapidly. The first blast was on this date but pumping of the well could not be continued after 20 minutes because the water level was then down to the pump intake. The main problem with Well S-1 was that there was not enough pump submergence to permit a test of any length.

A pre-blast drawdown test of Well D-1 was conducted on June 7, 1979, using a pump rate of .41 gpm. the water level was pulled down to the pump intake after 189 minutes. Two days later, another drawdown test of this well was conducted and the first blast was detonated 80 minutes into the test. The pumping rate was .42 gpm. which was used to give results as comparable as possible to the earlier test although it was established that the test would have to be terminated before the full 600 minutes. Time-drawdown plots of both of these tests are presented in Figures 25 and 26, respectively. There may be a very slight increase in the slope following the blast but this may be more apparent than real because the water level one minute after the blast (81 minutes after pumping started) may have risen a tenth of a foot or so which slightly disrupts the generally smooth curvilinear (slightly concave downward) nature of the curve after 13 minutes. A more abrupt change appears at the end of the pre-blast curve which probably represents the termination of part of the fracture system on the 25^{0} downslope of the hill. This would have the same effect as a partial barrier. Certainly, there is no significant change as a result of this blast which was 580 feet away and produced ground vibrations of 0.80 in/sec MRPV at the surface, and 0.33 in/sec MRPV at the bottom of Well S-3. Table 6 is a summary of the drawdown tests performed for Well S-1, and Table 7 is a similar summary for Well D-1.

Figure 27 is a composite of all the time-drawdown curves for Well D-1. It is immediately evident that there are generally two groups of slopes. The first includes the relatively steep slopes for June 7, 9, and July 24. The others are flat or at least at lesser slopes except for the one for July 10. If this latter test had involved a pumping rate approximating the .4 to .5 gpm. rate of the other June and July tests, it probably would have plotted with the other tests with the steep slopes. This is supported by the fact that the specific capacity for these four tests is 0.020 ± 0.002 gpm/ft. The significant point is that sometime between the test of July 24, 1979 and the test of August 29, 1979, a significant improvement occurred in this well. Although not as noticeable as the change in slope, the specific capacity for the test on August 29 also increased by about 50% over the previous four values.

FIGURE 24. COMPOSITE LOG. TENMILE SITE



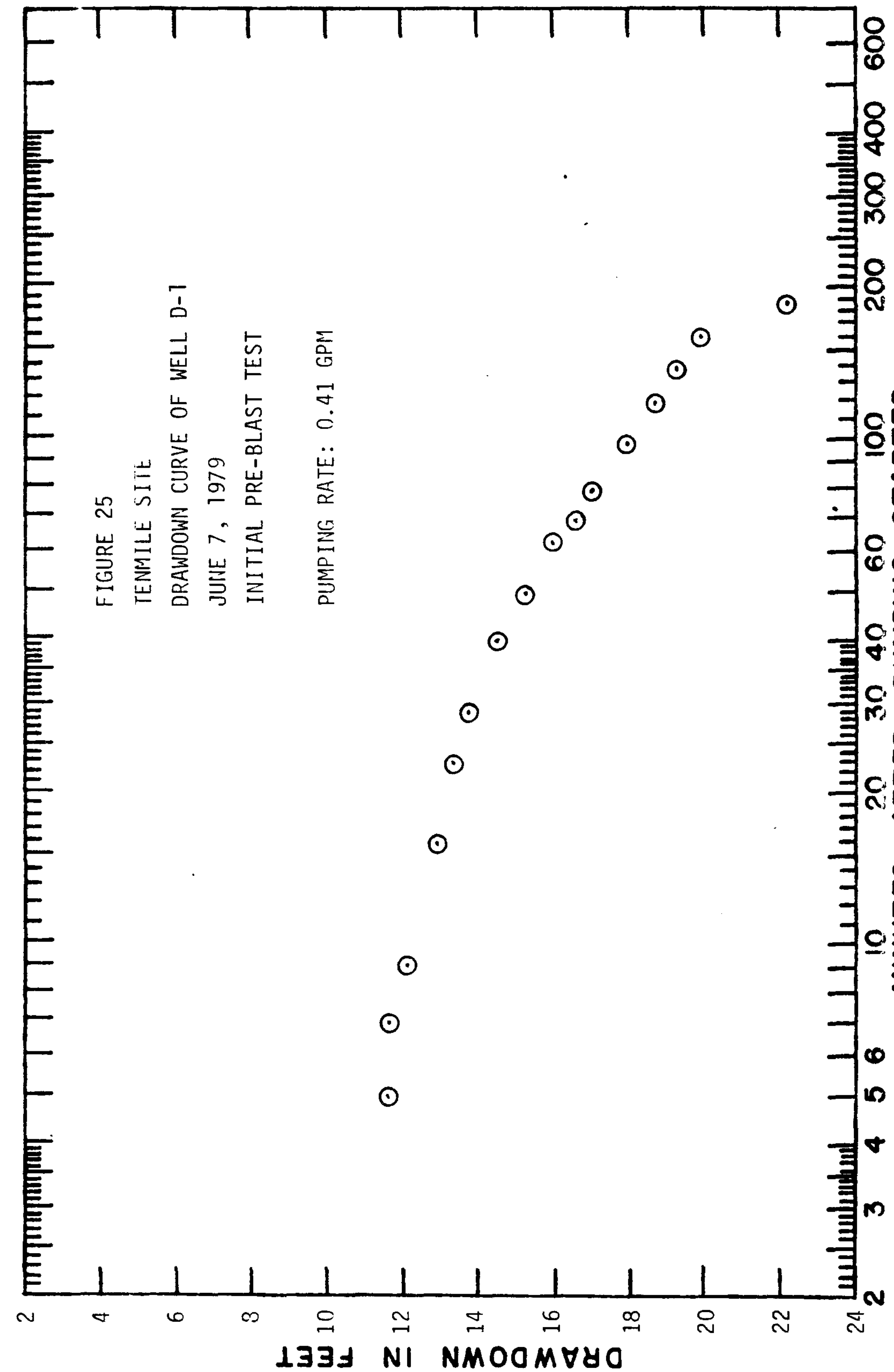


FIGURE 25
TENMILE SITE
DRAWDOWN CURVE OF WELL D-1
JUNE 7, 1979
INITIAL PRE-BLAST TEST

PUMPING RATE: 0.41 GPM

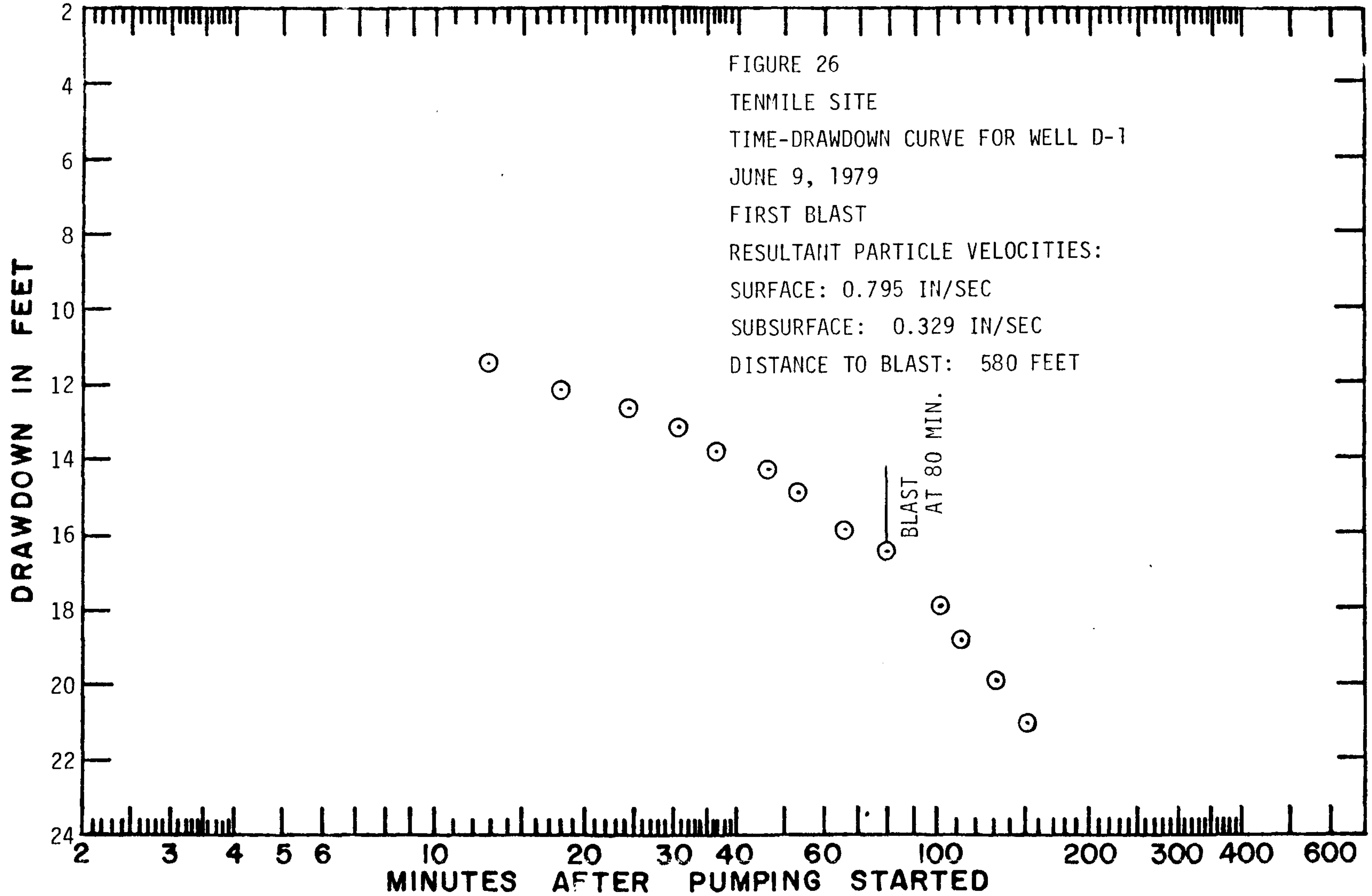


FIGURE 26
TENMILE SITE
TIME-DRAWDOWN CURVE FOR WELL D-1
JUNE 9, 1979
FIRST BLAST
RESULTANT PARTICLE VELOCITIES:
SURFACE: 0.795 IN/SEC
SUBSURFACE: 0.329 IN/SEC
DISTANCE TO BLAST: 580 FEET
BLAST
AT 80 MIN.
DRAWDOWN IN FEET
2
4
6
8
10
12
14
16
18
20
22
24
2
3
4
5
6
10
20
30
40
60
100
200
300
400
600
MINUTES AFTER PUMPING STARTED

TABLE 6

TENMILE: TEST SUMMARY WELL S-1

Depth of Well: 160 feet

Depth to Pump: 146 feet

DATE	PUMP RATE, Q	ADJUSTED DRAWDOWN, S'	$\frac{Q}{S'}$	STATIC WATER LEVEL AT TEST START	LENGTH OF TEST
5/30/79	Meter jammed with sand.	Water level to pump in 20 min.		129.60 ft.	20 min.
6/ 6/79	Meter intermittent.	Water level to pump in 10 min.		134.00 "	10 min.
6/ 7/79	Meter intermittent.	Water level to pump in 13 min.		138.40 "	18 min.
6/ 9/79	0.34 gpm	5.25 ft.	.065 gpm/ft.	139.75 "	20 min.
	Recovered 1.06 ft. in 161 min.				
7/ 9/79	0.21 gpm	5.67 ft.	.037 gpm/ft.	138.00 "	35 min.
	Recovered 1.12 ft. in 75 min.				
7/24/79	0.23 gpm	8.44 ft.	.027 gpm/ft.	137.24 "	60 min.
12/10/79	Meter jammed with sand.			129.15 "	3 min.
1/24/80	Meter froze			124.52 "	20 min.
3/ 4/80	2.09 gpm	4.96 ft.	.421 gmp/ft.	129.70 "	100 min.
4/29/80	2.78 gpm	5.32 ft.	.523 gpm/ft.	127.11 "	600 min.
	3.21 gpm	6.88 ft.	.467 gpm/ft.		
	4.08 gpm	10.21 ft.	.400 gpm/ft.		
	2.80 gpm	6.53 ft.	.428 gpm/ft.		
	Recovered 6.37 ft. in 30 min.				
6/ 6/80	2.65 gpm	4.01 ft.	.661 gpm/ft.	128.10 "	270 min.

TABLE 7

TENMILE: TEST SUMMARY WELL D-1

Depth of Well: 200 feet

Depth to Pump: 187 feet

DATE	PUMP RATE, Q	ADJUSTED DRAWDOWN, S'	SPECIFIC CAPACITY, $\frac{Q}{S'}$	STATIC WATER LEVEL AT TEST START	LENGTH OF TEST
6/ 7/79	0.41 gpm	22.27 ft.	0.018 gpm/ft.	149.96 ft.	189 min.
6/ 9/79	0.42 "	20.98 "	0.020 "	150.46 "	155 min.
7/10/79	0.25 "	12.99 "	0.019 "	149.11 "	600 min.
7/24/79	0.51 "	23.21 "	0.022 "	149.53 "	200 min.
8/29/79	0.48 "	14.05 "	0.034 "	149.68 "	140 min.
10/ 2/79	0.27 "	8.07 "	0.033 "	147.08 "	600 min.
10/31/79	0.32 "	8.67 "	0.037 "	146.22 "	600 min.
	0.49 "	12.20 "	0.040 "		
12/11/79	0.42 "	17.21 "	0.024 "	145.46 "	600 min.
1/24/80	0.41 "	15.26 "	0.027 "	144.91 "	600 min.
3/ 4/80	0.74 "	16.23 "	0.046 "	147.77 "	300 min.
4/28/80	1.02 "	19.09 "	0.053 "	142.45 "	240 min.
6/ 5/80	1.06 "	21.12 "	0.050 "	138.50 "	240 min.

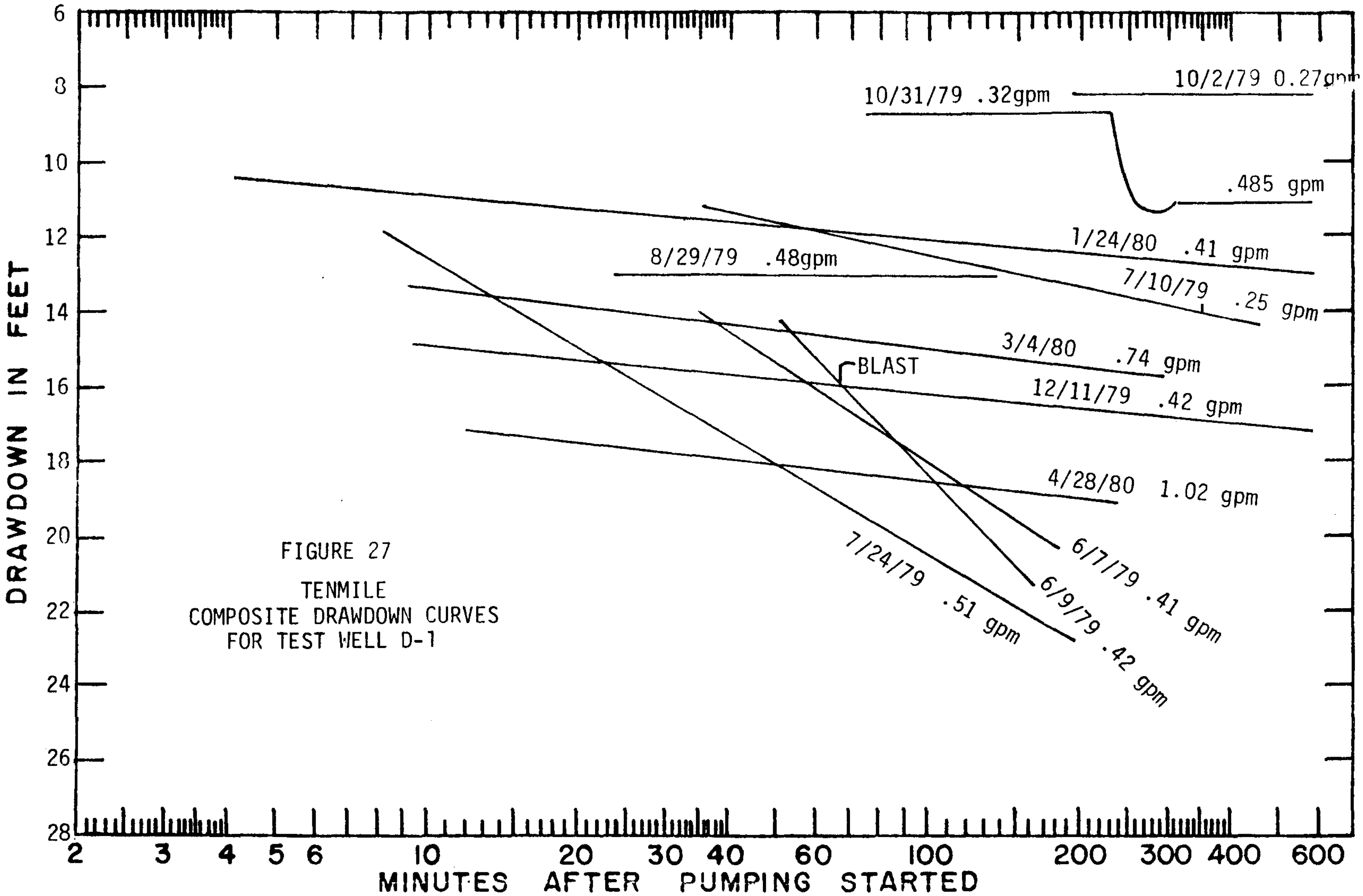


FIGURE 27

TENMILE
COMPOSITE DRAWDOWN CURVES
FOR TEST WELL D-1

Prior to the change, there was a blast on July 18 at a distance of only 200 feet. Ground vibrations from this blast were measured at the surface to be 3.34 in/sec MRPV, and at the bottom of Well S-3, 1.27 in/sec MRPV. This wasn't sufficient to cause any change in the slope as evidenced by the test on July 24. On July 25, another blast at a distance of 157 feet produced vibrations at the well site of 5.44 in/sec MRPV at the surface. Vibrations were not measured in uncased Well S-3 because of the possibility of losing an expensive piece of equipment. These blasts and others are listed in Table 8 which shows the proximity to the wells and the level of ground vibrations.

Supplementing this list is Figure 28 which shows the location of the blasts with respect to Well S-3. From this it can be seen that Shots 11 and 12 removed the support directly below the test site. These shots occurred on August 13 and 23, respectively. The stronger of these two blasts based on charge weight per delay at approximately equivalent distances is the blast on August 23. Ground vibration from this blast was 3.74 in/sec MRPV. Unfortunately, notification was not received from the operator and measurements were not made of the blast on August 13. Nevertheless, the stronger blast was measured and though the vibration level is substantial, it is not much greater than the blast of July 18 which did not cause any change.

Again, as at Brotherton, the first improvement in the specific capacity occurred when the support was removed immediately downslope, in this case 100 feet away. But unlike Brotherton there was no increase in the rate of decline in water levels, in fact, at Tenmile during this period there was no decline in the water level. After the strong blast of July 25 the water level rose from a depth of 138.6 feet to 135.75 on August 23 and continued to rise until September 6 when it was at a depth of 130.5 feet. There may be two reasons to account for this. The first is that the static water level in the wells at Tenmile never was very high and generally occupied a level opposite the coal section which started at a depth of 130 feet. There wasn't much possibility of further decline. The second reason is that these strata were initially so "tight" that surface water could not easily percolate downward and provide recharge. With an improvement in permeability resulting from more open fractures, the new availability of recharge may have far exceeded the water lost to fill the new storage space at lower levels.

Although Well D-1 improved, there was no noticeable improvement in Well S-1 at this time. Efforts to test it were futile because of the inadequate submergence. Pumping it would cause the meter to become jammed with sand, or the rate would have to be so minor that the meter would freeze in cold weather. Nevertheless, periodic efforts to pump it were made and on March 4, 1980, it was pumped for 100 minutes at a rate of 2.09 gpm. The test was terminated at that time because near-equilibrium conditions had been attained in only 20 minutes with a drawdown of 4.93 feet, and the pumping was starting to effect an on-going test of Well D-1. Subsequent testing on April 29, 1980, using a step-drawdown technique, definitely established that the specific capacity had improved and was now in the range of 0.450 gpm/ft. By June 6, 1980, with no further blasting or mining downslope, the specific capacity improved further to a value of 0.661 gpm/ft. The contrast between this test and the test of July 24, 1979, is best seen by comparing the time-drawdown curves in Figures 29 and 30.

TABLE 8

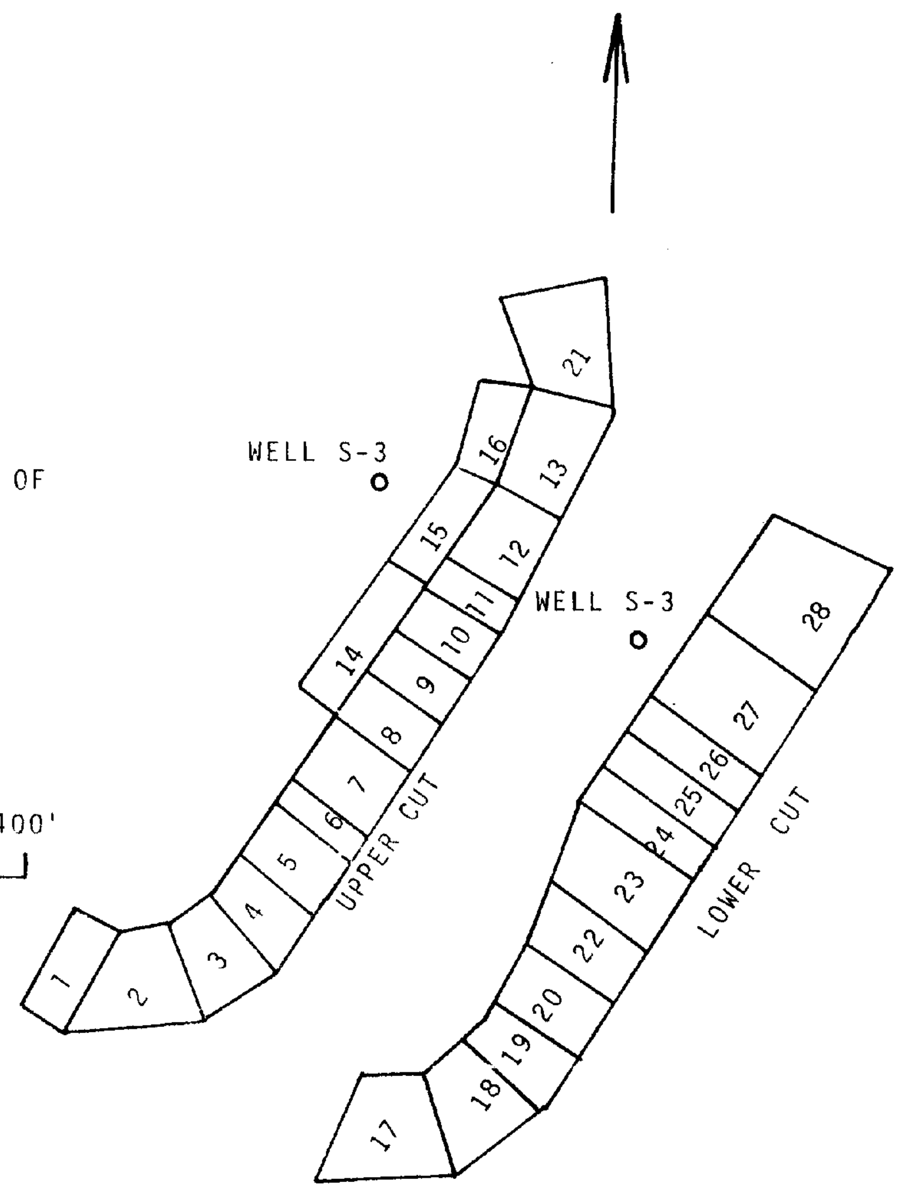
TENMILE

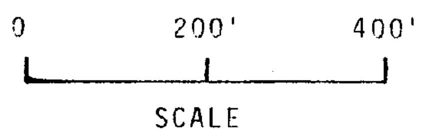
SHOT NO.	DATE	DISTANCE TO BLAST	CHARGE WGT./DELAY	RESULTANT AT SURFACE	RESULTANT IN WELL S-3
1*	6/ 9/79	580 ft.	286 lbs.	0.795 inch/second	0.329 inch/second
2*	6/12/79	540 ft.	556 lbs.	1.60 inch/second	0.53 inch/second
3*	6/15/79	500 ft.	598 lbs.	---	0.67 inch/second
4*	6/19/79	450 ft.	844 lbs.	2.08 inch/second	0.60 inch/second
5*	6/22/79	358 ft.	1002 lbs.	---	1.04 inch/second
6*	7/10/79	335 ft.	712 lbs.	1.60 inch/second	0.70 inch/second
7*	7/12/79	250 ft.	634 lbs.	2.22 inch/second	1.34 inch/second
8*	7/18/79	200 ft.	275 lbs.	3.34 inch/second	1.27 inch/second
9*	7/25/79	157 ft.	--	5.44 inch/second	---
10*	8/ 3/79	140 ft.	542 lbs.	3.29 inch/second	---
11	8/13/79	110 ft.	281 lbs.	Not Notified	
12*	8/23/79	114 ft.	568 lbs.	3.74 inch/second	---
13*	8/31/79	160 ft.	400 lbs.	1.78 inch/second	---
14	9/ 8/79	85 ft.	322 lbs.	Not Notified	
15*	9/18/79	64 ft.	738 lbs.	5.02 inch/second	---
16*	10/26/79	70 ft.	370 lbs.	4.72 inch/second	---
17	10/31/79	550 ft.	191 lbs.	0.11 inch/second	---
18	11/ 5/79	480 ft.	156 lbs.	0.33 inch/second	---
19	11/ 7/79	420 ft.	267 lbs.	0.62 inch/second	---
20	11/15/79	350 ft.	228 lbs.	0.67 inch/second	---
21*	11/21/79	225 ft.	120 lbs.	1.13 inch/second	---
22*	11/27/79	295 ft.	227 lbs.	0.654 inch/second	---

SHOT NO.	DATE	DISTANCE TO BLAST	CHARGE WGT./DELAY	RESULTANT AT SURFACE	RESULTANT IN WELL S-3
23*	12/10/79	250 ft.	173 lbs.	0.647 inch/second	.422 inch/second
24	12/11/79	150 ft.	766 lbs.	1.10 inch/second	---
25	12/13/79	110 ft.	336 lbs.	0.78 inch/second	---
26	12/15/79	70 ft.	407 lbs.	1.83 inch/second	---
27*	12/19/79	100 ft.	514 lbs.	4.43 inch/second	---
28	2/10/80	85 ft.	250 lbs.	$>$2.00 inch/second	---

* On-site analog recordings.

FIGURE 28
<u>TENMILE</u>
APPROXIMATE LOCATION OF
BLASTS





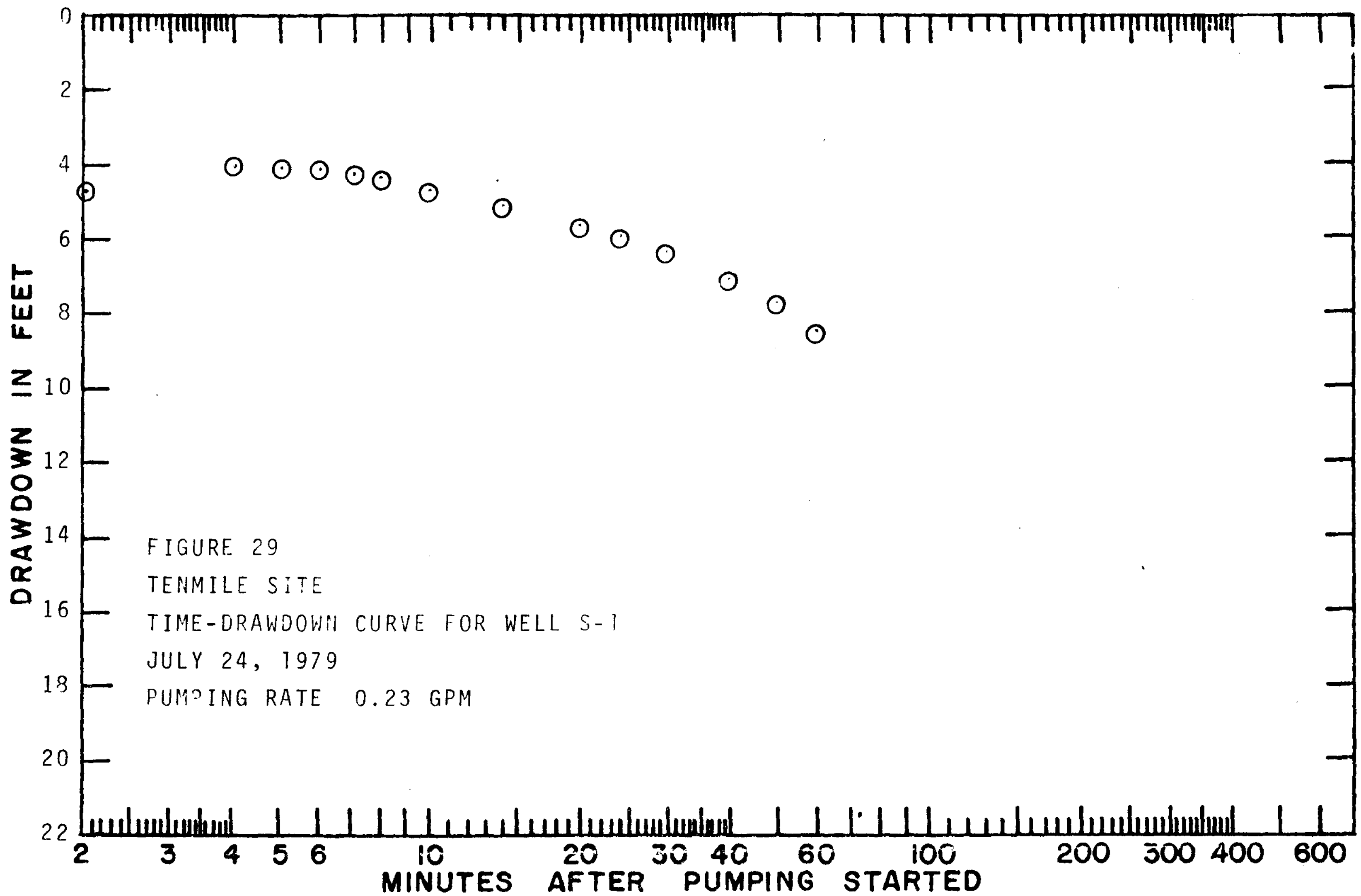


FIGURE 29
TENMILE SITE
TIME-DRAWDOWN CURVE FOR WELL S-1
JULY 24, 1979
PUMPING RATE 0.23 GPM

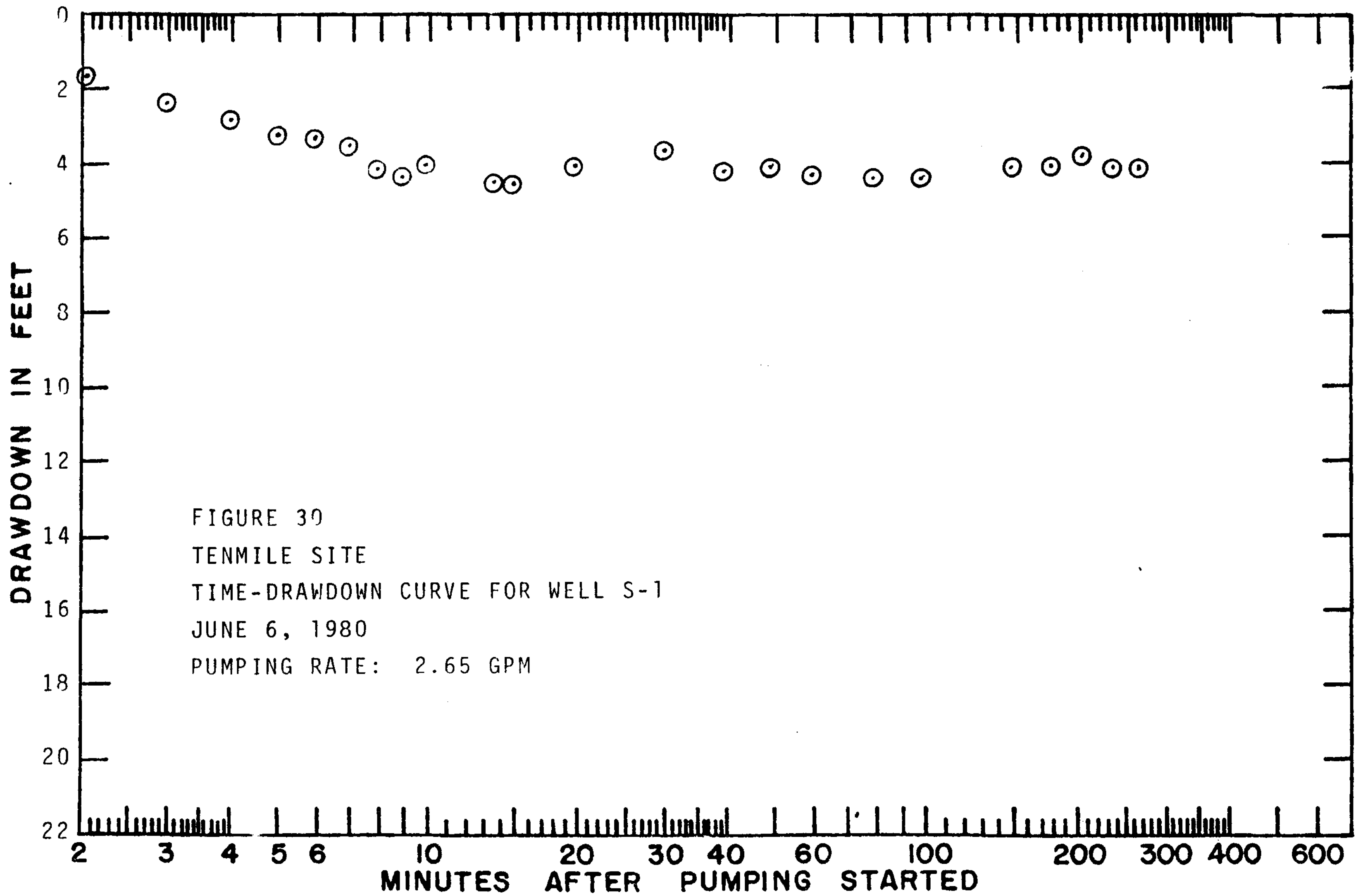


FIGURE 30
TENMILE SITE
TIME-DRAWDOWN CURVE FOR WELL S-1
JUNE 6, 1980
PUMPING RATE: 2.65 GPM

The drawdown test of Well D-1, also conducted on March 4, 1980 indicated that there was substantial improvement in that well since the last test on January 24, 1980. The specific capacity increased 17 times from an earlier value of .027 gpm/ft. to 0.46 gpm/ft. The time-drawdown curve is shown in Figure 31 for comparison with those in Figures 25 and 26. This was the second improvement in this well and this latter improvement was more significant than the former. Why did both Wells S-1 and D-1 show improvement on the same test date and was there any evidence that water levels may have been affected this time, in a manner similar to that at Brotherton? Reference to the plot of static water levels over the period of testing (Figure 32) provides the answer. Although there was a fair amount of rainfall throughout the period, the static water level started dropping in late January, 1980 and continued the decline until March 3, the day before the drawdown tests of the wells. From January 23 to March 3 the decline was 10½ feet, which is small in comparison to Brotherton but at Tenmile the water level was already at a low level opposite the coal being mined. The decline lowered the static water level to a point 7½ feet below any other low in the previous eight months. There was only one nearby blast during this time and that occurred on February 10. Nothing significant happened to the water level on that date. As at Brotherton, the water level change cannot be convincingly attributed to blast vibrations and at Tenmile, the absence of any blasting on this hill for the 35 days preceding the commencement of the decline makes the point clearly. Lateral stress relief resulting from removal of the downslope support is the most logical explanation for the improvement in the permeability and storage capacity of the water-table aquifer, which brought about a temporary decline in water level, followed by recovery and improved well performance. The reason that the major improvement did not occur within hours or days following the excavation is probably because the thick sandstone section has more tensile strength than the strata at Brotherton, and being stronger, required more time to fail.

Certainly, ground vibrations produced by blasting caused no deleterious effects on either Well D-1 and S-1, because both wells are better wells now than before any blasting or mining was performed. But it is very doubtful that the wells are better because of the elastic phenomenon such as ground vibration. Although the vibration levels were substantial, they probably had no direct effect on the wells with one possible exception. This possibility involves some difficulty in measuring the bottom of Well S-3. There is no difficulty in running a small diameter electric probe into the well to determine water level, but when an attempt was made on April 29, 1980, to sound the bottom with a 1" iron pipe on a plastic tape, the sounding device behaved as if its movement was restricted by a bridge at a depth between 65 and 90 feet. The tape would not go below 138.5 feet although the "feel" of the tape indicated that bottom had not been reached. On December 10, 1979, a 3" diameter geophone was lowered into this hole and no difficulty was experienced. On December 19, bottom was sounded in S-3 both before and after a blast on that date and no difficulty was encountered. There was no blasting after that date until the large shot on February 10 which was detonated only 85 feet from this well. Vibrations were recorded by a continuous monitor but this goes off-scale at 2 in/sec MRPV, which it did in response to this blast and for the second time the instrument shed was severely damaged. It is possible that this one blast may have been sufficient to cause a loose rock in the sidewall to shift into the hole causing a partial bridge. None of the other holes experienced any damage.

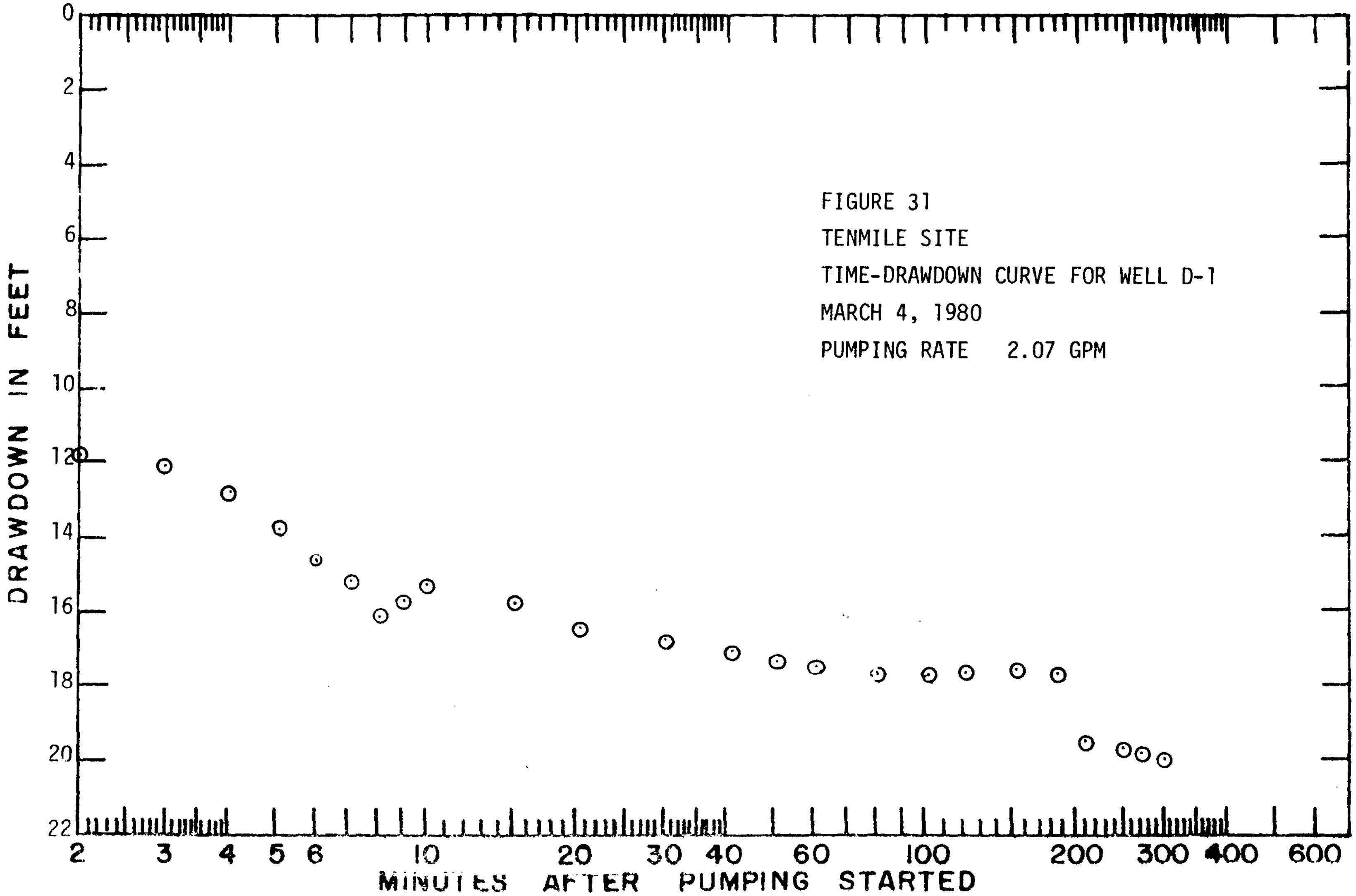


FIGURE 31
TENMILE SITE
TIME-DRAWDOWN CURVE FOR WELL D-1
MARCH 4, 1980
PUMPING RATE 2.07 GPM

FIG.32 SUMMARY OF DATA FROM TENMILE, W. VA. SITE

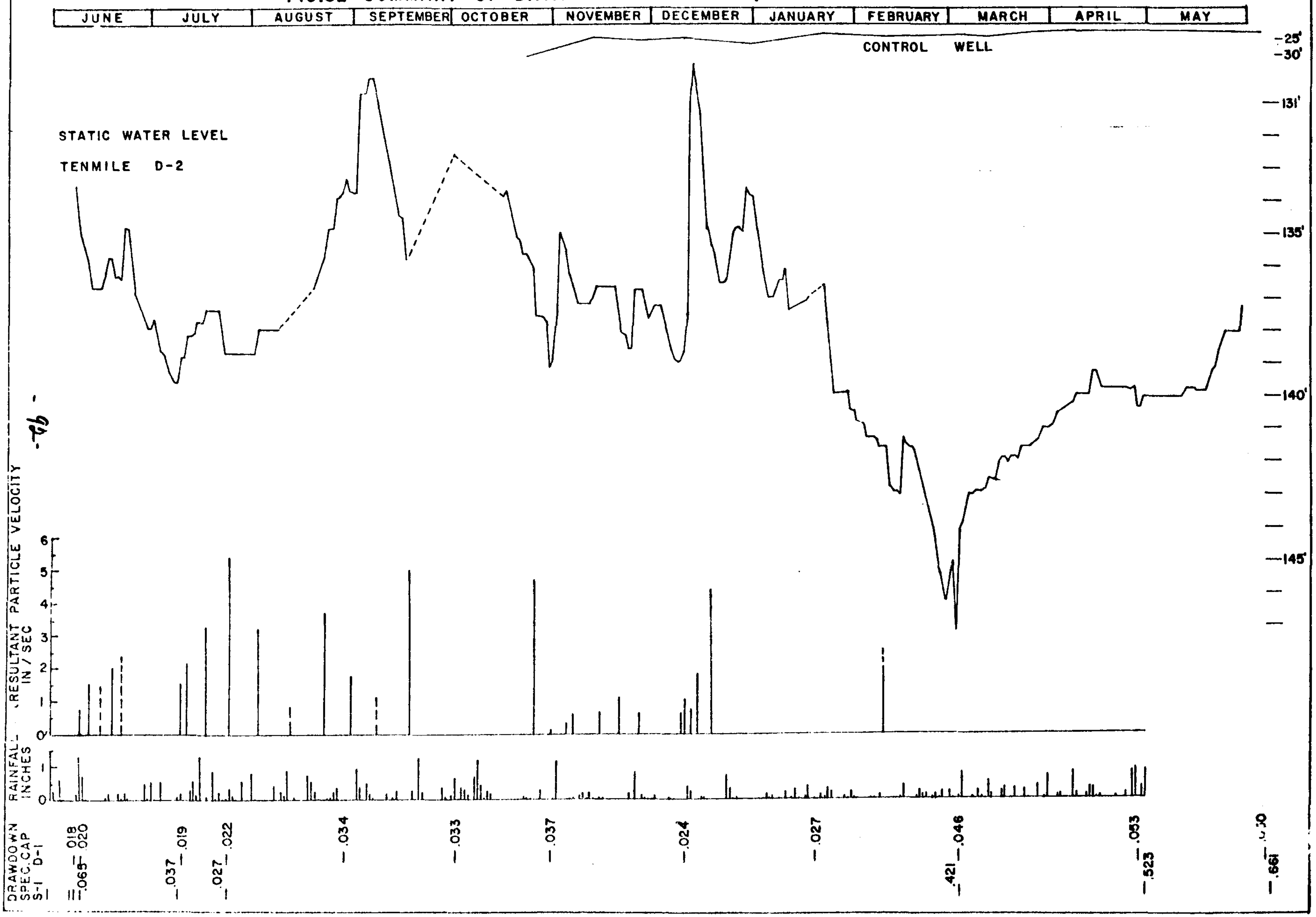


Table 9 indicates the depths of uncased Wells S-2 and S-3 at various times during the testing program. Upward fluctuations are, of course, impossible, and they represent the sounding weight hanging up on an uneven surface of cuttings at the bottom, or possibly, even on a shoulder near the bottom. The values must be viewed to see what they represent in the way of a rate of sloughing inasmuch as it is difficult to perceive of conditions short of some form of drilling through which the well could become deeper.

To the extent that time would permit, soundings were taken both before and after blasts where on-site vibration measurements were made. Without exception, these showed no significant change between the "before and "after" blast readings although variances of .2 or .3 feet were common. In Table 9, the maximum depth reading is used whether this occurred before the blast or after.

The difference between ground vibrations at the surface and those at the bottom of Well S-3 was measured for seven blasts. Table 10 shows the attenuation of these vibrations with depth. For all of these blasts the mean of 0.44 indicates that the vibrations at the bottom of Well S-3 were, on the average only 44% of those at the surface.

As to the changes in the chemistry of the waters the results are similar to those observed at Brotherton. The chemical nature of water varied insignificantly but the turbidity values varied wildly. Caliper logs indicate that about one inch of drill cuttings was left plastered on the sidewalls at the time of logging. This material continued to slough into the hole and at times the sampling bottle would return to the surface with cuttings inside the bottle, on the outside of the bottle, and on the retrieving line, regardless of the care taken in trying to get an uncontaminated sample. Consequently, for the reasons cited at Brotherton, the turbidity values have little validity and should be disregarded. On the other hand, there is a suggestion that <u>turbidity</u> increases temporarily immediately after a close-in blast (less than 300 feet) and additional data would be desirable. Considering the sampling problems, it appears that this can best be done at the site in southern Indiana. Results of the chemical analyses, both those made in the laboratory and those made in the field, are contained in Appendix C.

TABLE 9

TENMILE SITE

DRILLED DEPTH	WELL S-2	WELL S-3
5-30	146.30'	154.6'
DATE		
6-09	--	153.70'
6-15	--	153.80
6-19	--	153.00
7-09	147.45'	152.80
7-10	--	152.50
7-12	147.20	152.74
7-18	147.20	152.40
7-25	147.08	151.62
8-03	146.90	151.40
8-23	147.77	151.26
8-31	147.00	150.55
9-18	147.00	150.03
11-21	146.88	150.15
12-19	--	150.38
4-29	147.00	138.50+*

* Partial obstruction in hole between 65 and 90 feet prevented reaching bottom with sounding tape. Another effort will be made with a heavier device.

TABLE 10

TENMILE

SHOT NO.	DISTANCE	RPV SUBSURFACE / RPV SURFACE
1	580 ft.	0.41
2	542 ft.	0.33
4	450 ft.	0.29
6	712 ft.	0.44
7	250 ft.	0.60
8	200 ft.	0.38
24	250 ft.	0.65
		MEAN =0.44
		S.D. ±0.13

ROSE POINT, PENNSYLVANIA TEST SITE

This site is located about ten miles east of New Castle, Pennsylvania. The Allegheny Group of the Pennsylvanian System occurs at the surface and the coal that was mined was the Middle Kittanning seam. Dip of the strata is very gentle to the southeast. Topography at the site is illustrated on Figure 33 which also shows the relationship of the test well site to the area that was mined. All blasting at this site was completed on March 3, 1980, and the area near the wells was backfilled on April 10. The nearest blast was at a distance of 175 feet but mining was continued up to a distance of 49 feet from the test wells. This difference in distance is because the overburden could be ripped without blasting for the area between 49 and 175 feet.

Figure 34 is a cross-section which shows the relationship between the wells, the coal being mined, and the Van Port limestone, which is at a depth of 93 feet in Well D-1. Although water was encountered in scattered zones above this limestone, most local residents case off the strata above it and obtain their water generally from a zone at the base of the limestone. Reportedly this is because the water obtained from the shallower zones tends to have a higher iron content and the water tends to be reddish. There is a 6 to 9" coal at the base of the limestone at a depth of 116 feet.

This situation provided an opportunity to test a well which obtained ground water from a relatively high-yield deep source but without the complicating factor of having the mined seam intersect the well-bore. The mined seam cropped out about ten feet northwest of the wells. The site also presented a situation where downslope stress relief would not be a factor because all of the mining and overburden removal was above the elevation of the wells. This situation is analogous to the common situation in Appalachia where the well is below the contour stripping or mountain-top removal.

Because there was no above-coal section present, no shallow well set was drilled and the test well group consisted of four deep wells which were drilled in the pattern shown in Figure 35. Water entry below the limestone was at a depth of 125 feet and this was the zone developed in the wells.

Approximately 20 feet of plastic casing was used at the surface for each well, and after logging was completed, plastic liners were placed to the bottom of all four wells. Packers were cemented in place at a depth of 100 feet with perforated liner below that depth and unperforated liner above. The wells were drilled to a depth of 168 feet and the pump was set in Well D-1 at a depth of approximately 158 feet. Flexible 1" discharge line was installed from the pump up to the surface where it joined galvanized pipe fittings which ran through a standard split well-seal cap. The check valve was removed from the pump before placement in order to facilitate removal of the entire assembly by hand.

In addition to the drilling time and lithologic logs which were made at the time of drilling, gamma ray, caliper, and density logs were made in Wells D-1 and D-4. A composite of these is shown in Figure 36.

Unlike the other three sites, surface mining had already started at this location when the wells were drilled. Drilling was completed, logs were run, liners and pump were installed, and the initial drawdown test was run, before the next blast occurred.

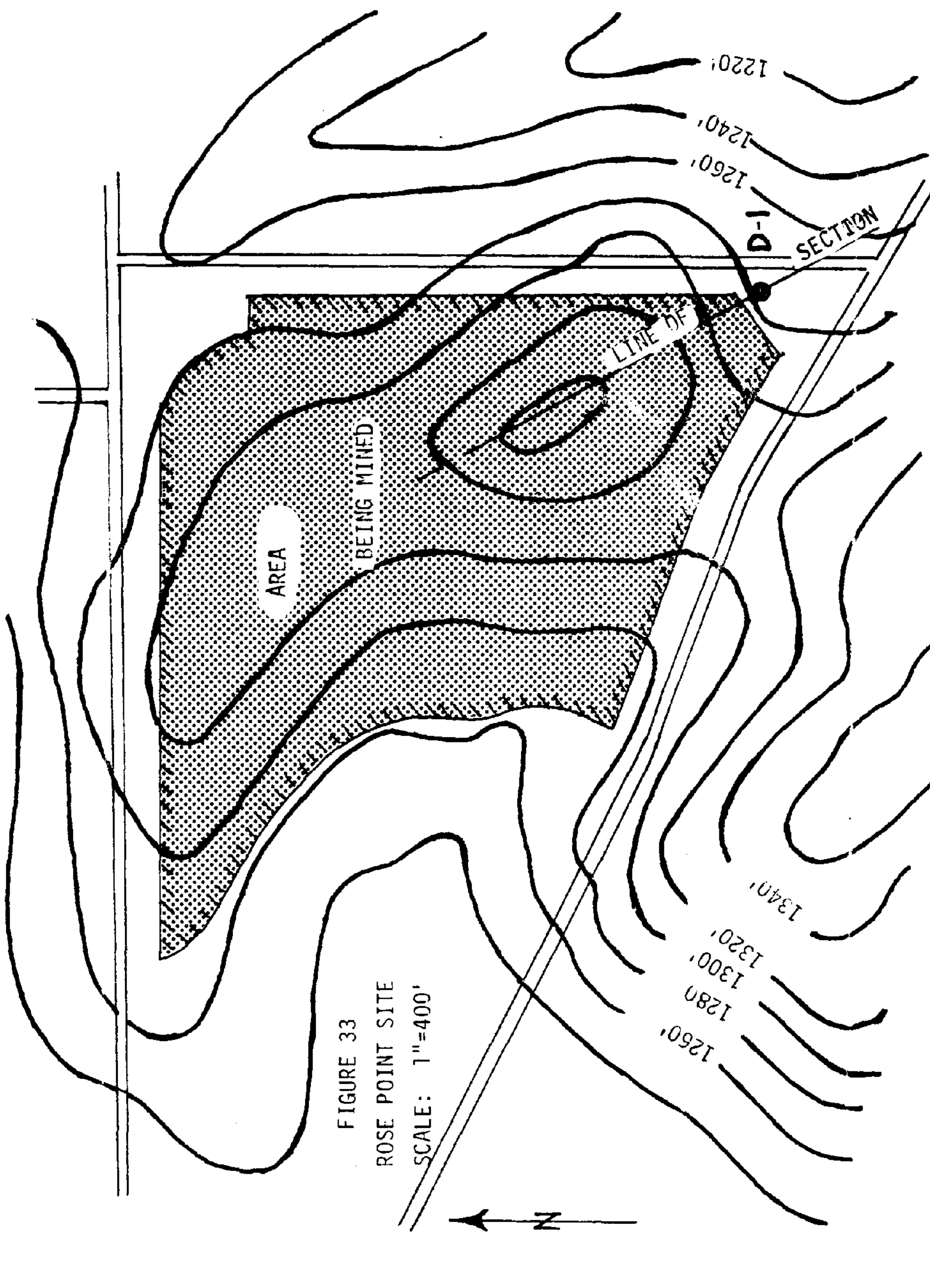
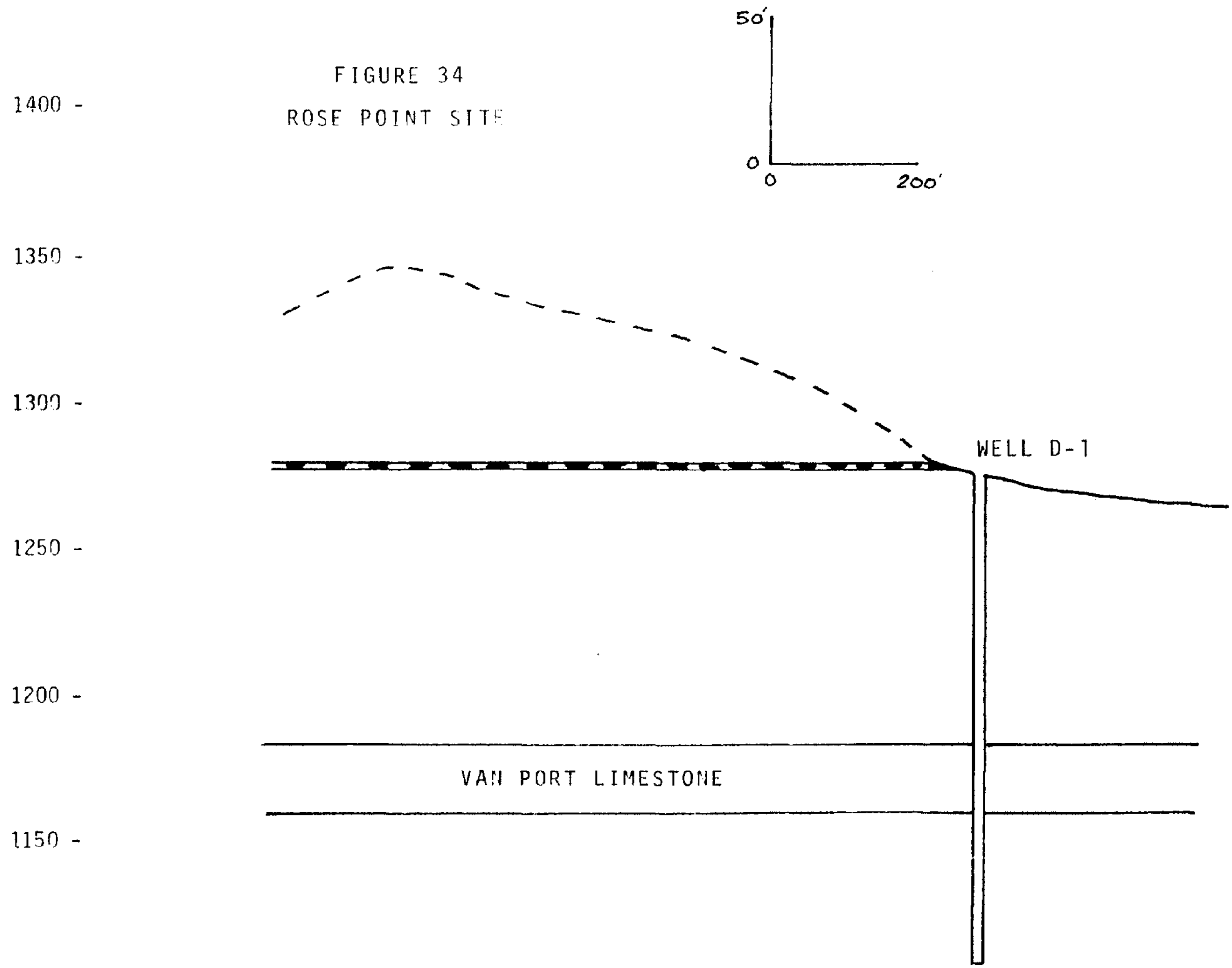
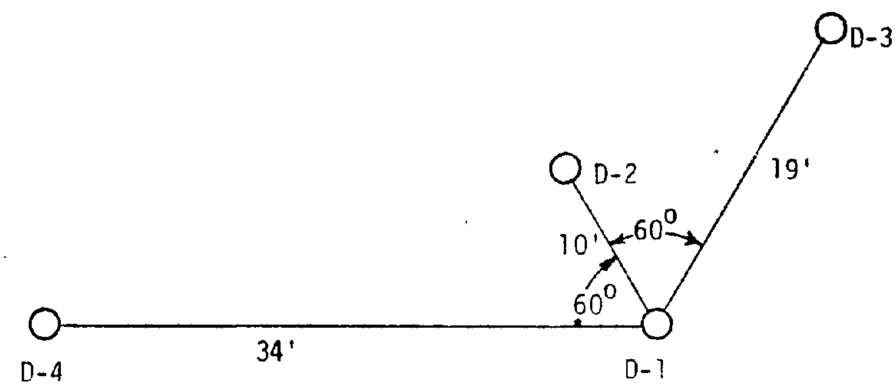


FIGURE 33
ROSE POINT SITE
SCALE: 1"=400'

FIGURE 34
ROSE POINT SITE

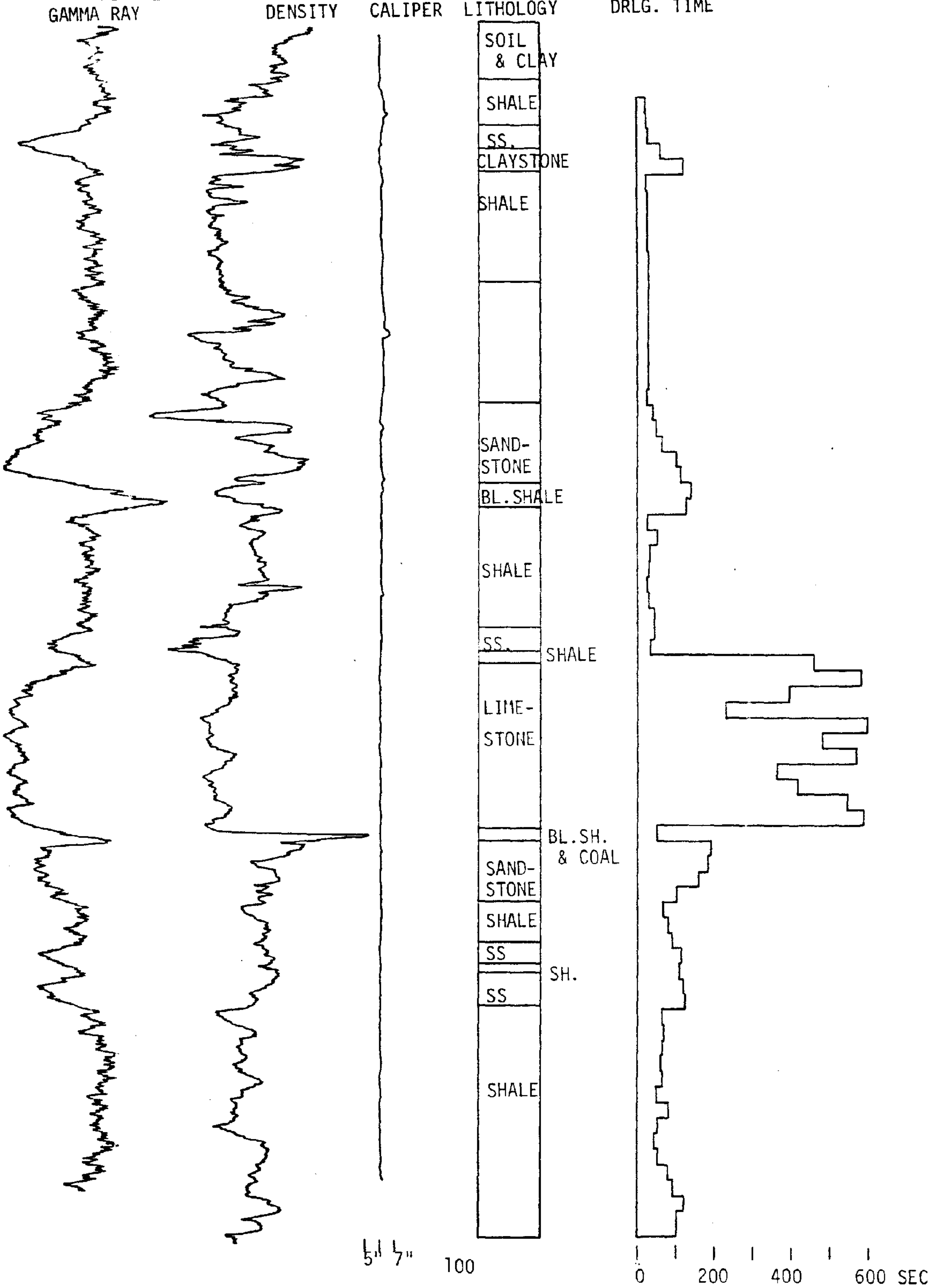




SCALE: 1" : 10'

FIGURE 35
ROSE POINT SITE
TEST WELL PATTERN

FIGURE 36. COMPOSITE LOG. ROSE POINT SITE



On August 16, 1979, Well D-1 was pumped at the rate of 5.04 gpm for 600 minutes after which time the adjusted drawdown was 17.53 feet. Specific capacity was 0.288 gallons per foot of drawdown. The time-drawdown curve for this initial test is shown is Figure 37.

The first blast following the installation of the wells occurred on August 21, 1979. Well D-1 was pumped at the rate of 5.07 gpm and the test had been underway for 87 minutes when the blast was detonated. Pumping was continued but after a total of 115 minutes of pumping a wire vibrated loose from the alternator and interruped the flow of power to the pump. This was not immediately apparent and it took some time to locate the source of the trouble and this test was terminated. The time-drawdown curve for this test is shown in Figure 38.

Two and one-half hours later, the well was pumped at the rate of 6.49 gpm and the resulting curve conformed closely to the initial test curve for the first 170 minutes then dropped off more suddenly. Because the recharge area of the well may not have had time to recover from the earlier pumping, little significance is attached to this drop off because it did not occur on any of the subsequent tests. More important was the conformity of the early part of the curve which indicated that no damage to the well or to the water bearing strata had occurred.

In view of the difficulties encountered with this drawdown test during the first blast, it was decided to repeat it for the next blast on September 21. On this 600 minute test, the pump rate was very uniform before and after the blast. The maximum resultant particle velocity at the surface was .68 in/sec for this blast which was 700 feet away. The effect on the pumped well and the observation wells was so insignificant that it is better to indicate the effect by listing the data for the pumped well in Table 11 rather than with a time-drawdown curve.

As experienced at all of the other sites, the observation wells were of limited value. Designed to provide for definition of the cone of depression and facilitate determination of the coefficients of transmissivity and storage capacity by the Theis method, and to provide data for distance-drawdown curves for determination of the well efficiency, the drawdown in these wells was generally less than 1½ feet in the most affected well. Frequently there would be no apparent drawdown at a distance of 10 feet. Usually the most affected well would be one of the most distant. The data for the observation wells is included in the Appendix and the drawdowns indicated for those data are not adjusted because the decreases in saturated thickness upon drawdown are insignificant. The observation wells were very useful in providing accessible wells for the downhole geophone and the float recorder installations.

A summary of all drawdown tests is given in Table 12 and a composite of the time-drawdown curves is illustrated in Figure 39. Table 13 is list of all blasts with corresponding blast vibration measurements, and Figure 40 shows the location of these blasts.

From the test summary it is evident that the specific capacity remained around .350 ± 13% gpm/ft. until February 20, 1980, when it increased by 77% to .585 gpm/ft. Why this occurred is less clear that at the Brotherton

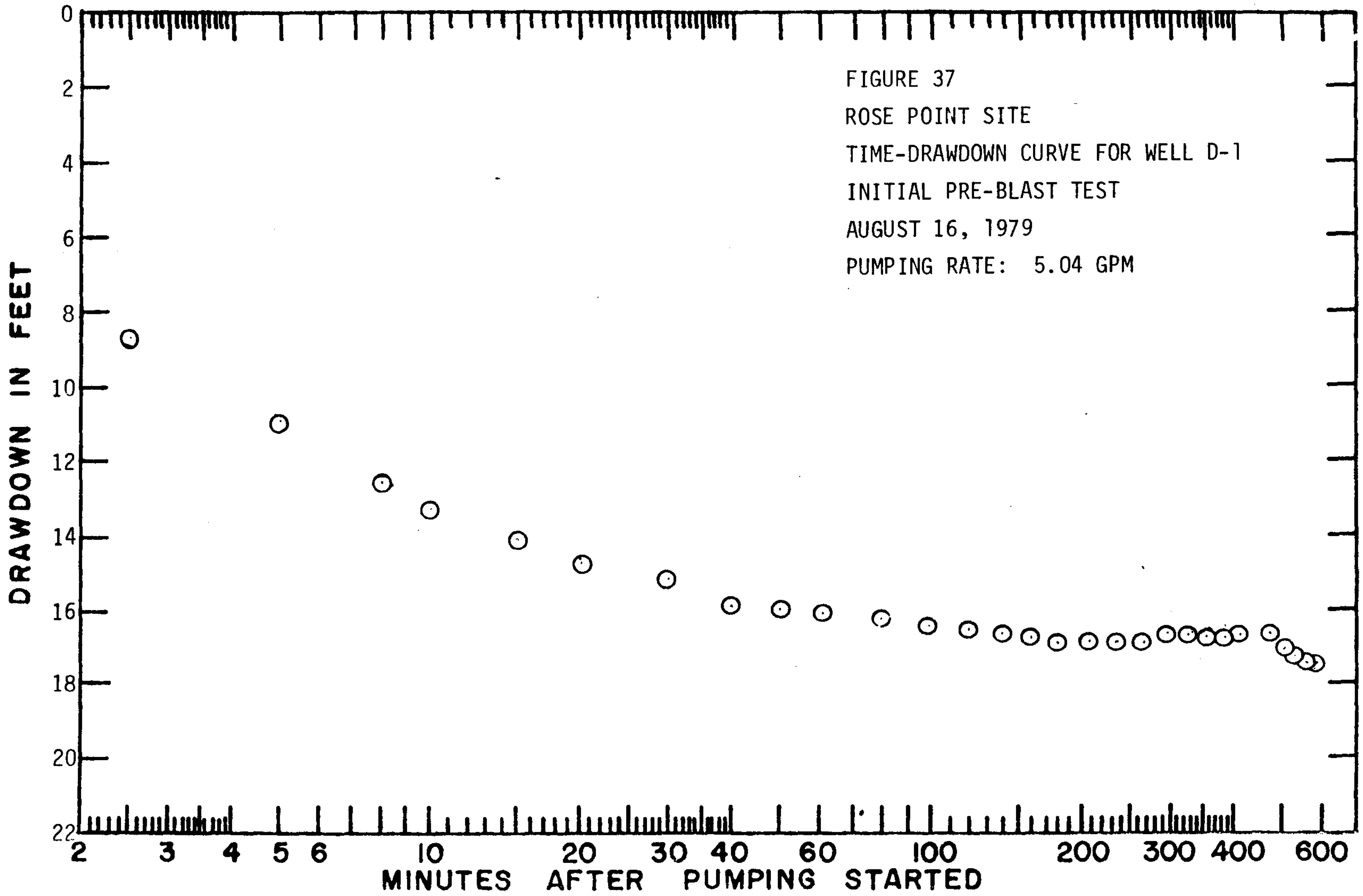


FIGURE 37
ROSE POINT SITE
TIME-DRAWDOWN CURVE FOR WELL D-1
INITIAL PRE-BLAST TEST
AUGUST 16, 1979
PUMPING RATE: 5.04 GPM
DRAWDOWN IN FEET
0
2
4
6
8
10
12
14
16
18
20
22
2
3
4
5
6
10
20
30
40
60
100
200
300
400
600
MINUTES AFTER PUMPING STARTED

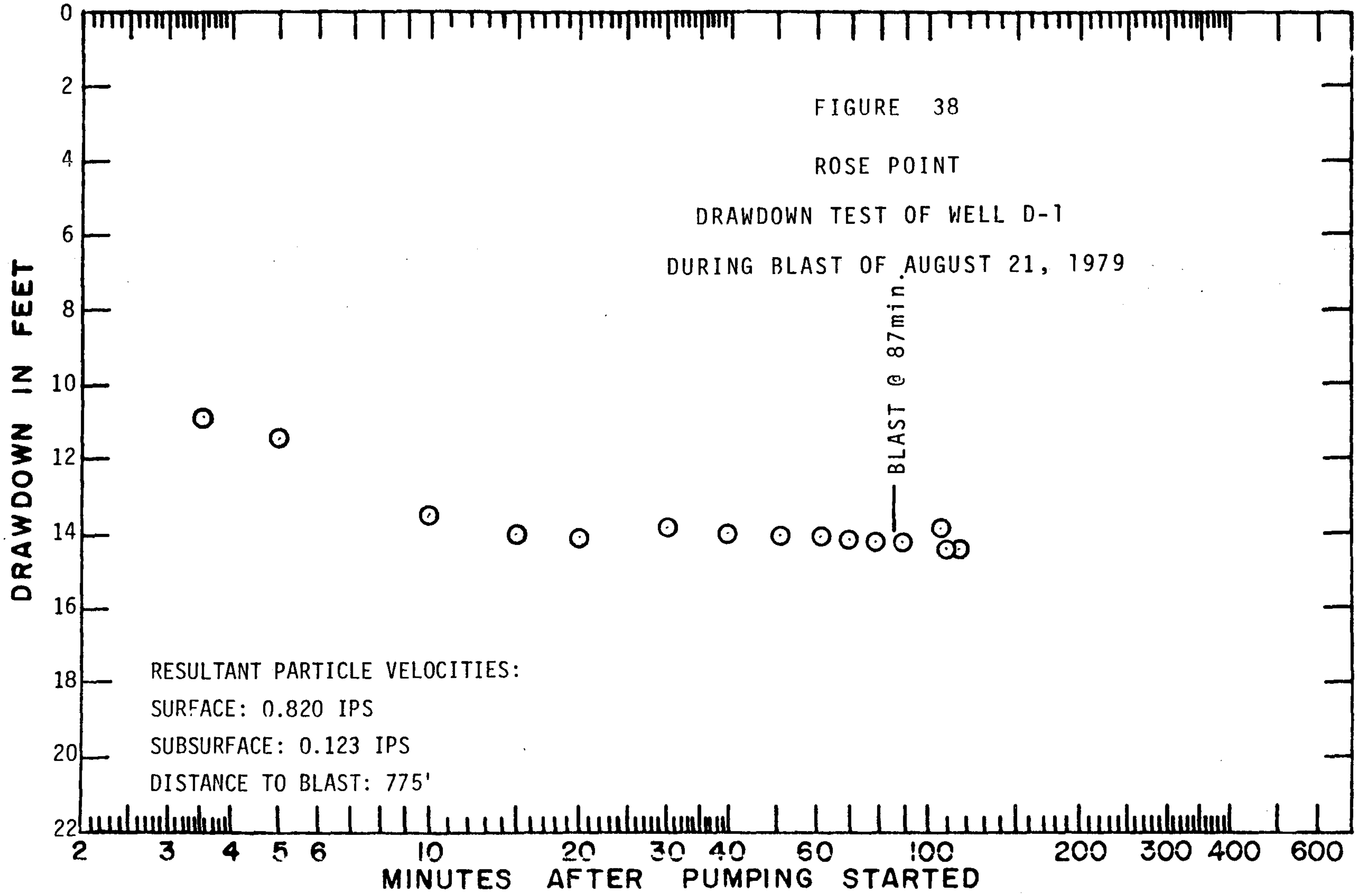


FIGURE 38
ROSE POINT
DRAWDOWN TEST OF WELL D-1
DURING BLAST OF AUGUST 21, 1979
BLAST @ 87min.
RESULTANT PARTICLE VELOCITIES:
SURFACE: 0.820 IPS
SUBSURFACE: 0.123 IPS
DISTANCE TO BLAST: 775'
DRAWDOWN IN FEET
0
2
4
6
8
10
12
14
16
18
20
22
2
3
4
5
6
10
20
30
40
60
100
200
300
400
600
MINUTES AFTER PUMPING STARTED

TABLE 11

ROSE POINT

EFFECT OF BLAST OF 21 SEPTEMBER 1979 ON WELL D-1
WELL PUMPED AT 6.81 GPM DURING BLAST

TEST TIME	DEPTH OF WATER
480 min.	116.64 ft.
490 min.	116.58 ft.
500 min.	116.60 ft.
510 min.	116.63 ft.
520 min.	116.74 ft.
BLAST AT 526 MINUTES	
528 min.	116.93 ft.
540 min.	117.33 ft.
550 min.	117.30 ft.
560 min.	117.42 ft.
570 min.	117.29 ft.
580 min.	117.26 ft.
590 min.	117.24 ft.
600 min.	117.16 ft.

TABLE 12

ROSE POINT: TEST SUMMARY WELL D-1

DATE	PUMP RATE, Q	ADJUSTED DRAWDOWN, S'	STATIC WATER LEVEL AT TEST START	SPECIFIC CAPACITY $\frac{Q}{S}$	LENGTH OF TEST
8/16/79	5.04	17.53	97.48	.288	600 min
8/21/79	5.07	14.47	98.40	.350	115 min.
8/21/79	6.49	19.84	98.40	.327	200 min.
9/21/79	6.81	20.94	98.52	.325	600 min.
10/29/79	6.62	20.24	97.75	.327	600 min.
12/04/79	6.50	17.76	94.05	.366	600 min.
1/15/80	6.46	19.50	95.83	.331	600 min.
2/20/80	6.54	11.17	98.12	.585	600 min.
3/11/80	6.73	11.37	98.11	.592	600 min.
4/10/80	6.52	12.39	96.10	.526	600 min.
5/22/80	5.98	42.08	80.00	.142	30 min.
8/6/80	1.80	4.35	97.7	.414	300 min.
8/6/80	6.20	20.90	97.7	.297	335 min.

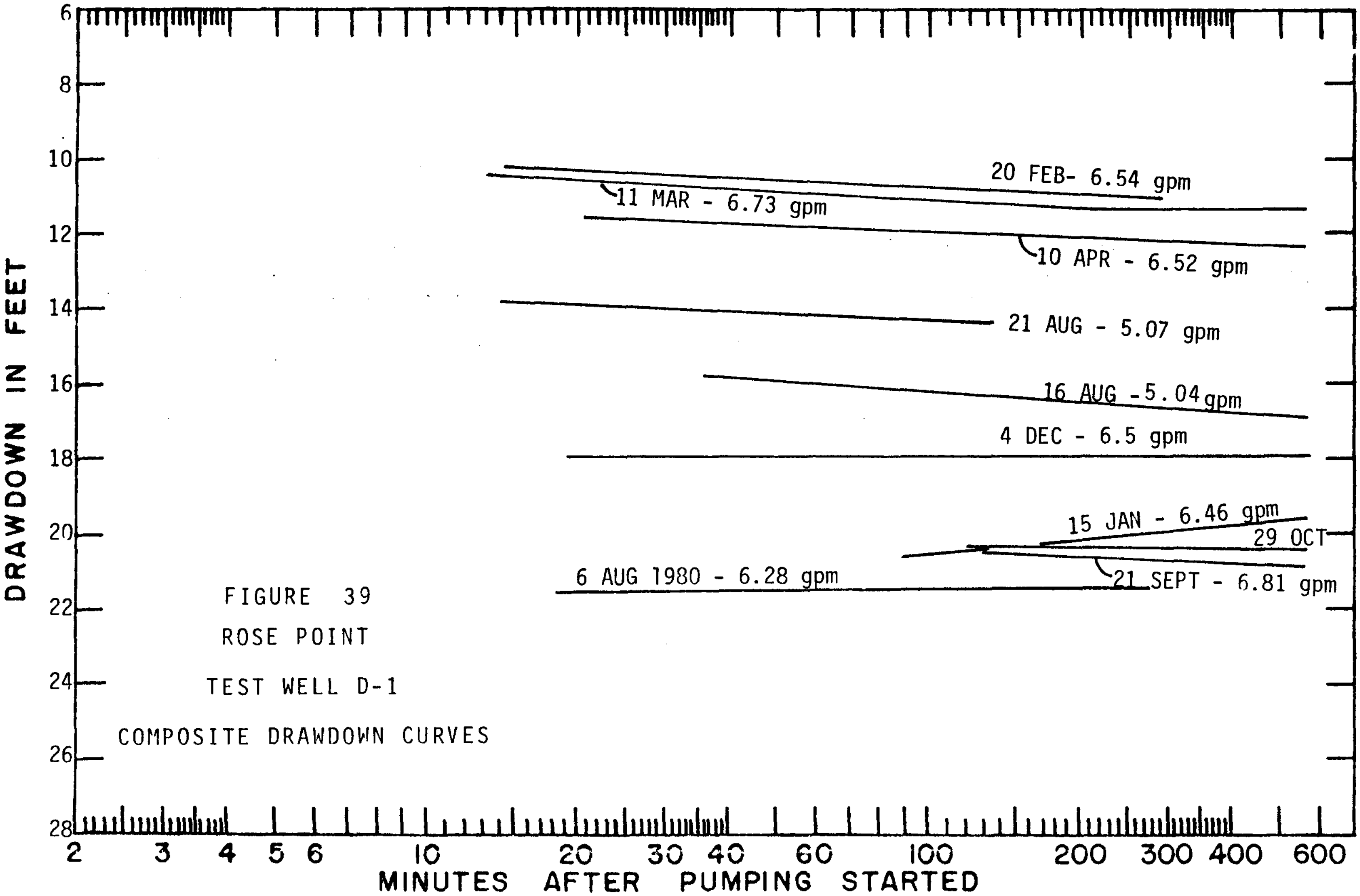

DRAWDOWN IN FEET
6
8
10
12
14
16
18
20
22
24
26
28
2
3
4
5
6
10
20
30
40
60
100
200
300
400
600
MINUTES AFTER PUMPING STARTED
20 FEB- 6.54 gpm
11 MAR - 6.73 gpm
10 APR - 6.52 gpm
21 AUG - 5.07 gpm
16 AUG -5.04 gpm
4 DEC - 6.5 gpm
15 JAN - 6.46 gpm
29 OCT
21 SEPT - 6.81 gpm
6 AUG 1980 - 6.28 gpm
FIGURE 39
ROSE POINT
TEST WELL D-1
COMPOSITE DRAWDOWN CURVES

TABLE 13

ROSE POINT

SHOT NO.	DATE	DISTANCE TO BLAST	CHARGE WGT./DELAY	RESULTANT AT SURFACE	RESULTANT IN WELL D-3
1	8/21/79	775 ft.	205 lbs.	.820 inch/second	.123 inch/second
2	9/21/79	700 ft.	203 lbs.	.680 inch/second	T = 0.1 Peak Inst. Malfunction.
3	9/24/79	700 ft.	250 lbs.	.928 inch/second	.081 inch/second
4	10.16/79	650 ft.	200 lbs.	.804 inch/second	Not Monitored
5	10.18/79	600 ft.	200 lbs.	1.17 inch/second	.112 inch/second
6	10.26/79	600 ft.	200 lbs.	1.27 inch/second	.14 inch/second
7	11/13/79	600 ft.	100 lbs.	.640 inch/second	.11 inch/second
8	11/13/79	550 ft.	150 lbs.	1.84 inch/second	.163 inch/second
9	11/20/79	550 ft.	150 lbs.	1.54 inch/second	.118 inch/second
10	12/06/79	540 ft.	105 lbs.	.705 inch/second	.091 inch/second
11	12/07/79	500 ft.	155 lbs.	1.62 inch/second	.134 inch/second
12	12/12/79	470 ft.	150 lbs.	1.83 inch/second	Not Monitored
13	12/19/79	460 ft.	155 lbs.	1.70 inch/second	Film Trace Too Light Not Able To Develop
14	1/03/80	450 ft.	105 lbs.	1.00 inch/second	.217 inch/second
15	1/08/80	400 ft.	98 lbs.	1.12 inch/second	.159 inch/second
16	1/10/80	400 ft.	155 lbs.	2.14 inch/second	.194 inch/second
17	1/10/80	410 ft.	105 lbs.	1.36 inch/second	.169 inch/second
18	1/24/80	380 ft.		1.00 inch/second	.214 inch/second
19	1/25/80	320 ft.	150 lbs.	1.65 inch/second	.294 inch/second
20	1/30/80	320 ft.	105 lbs.	1.979 inch/second	---

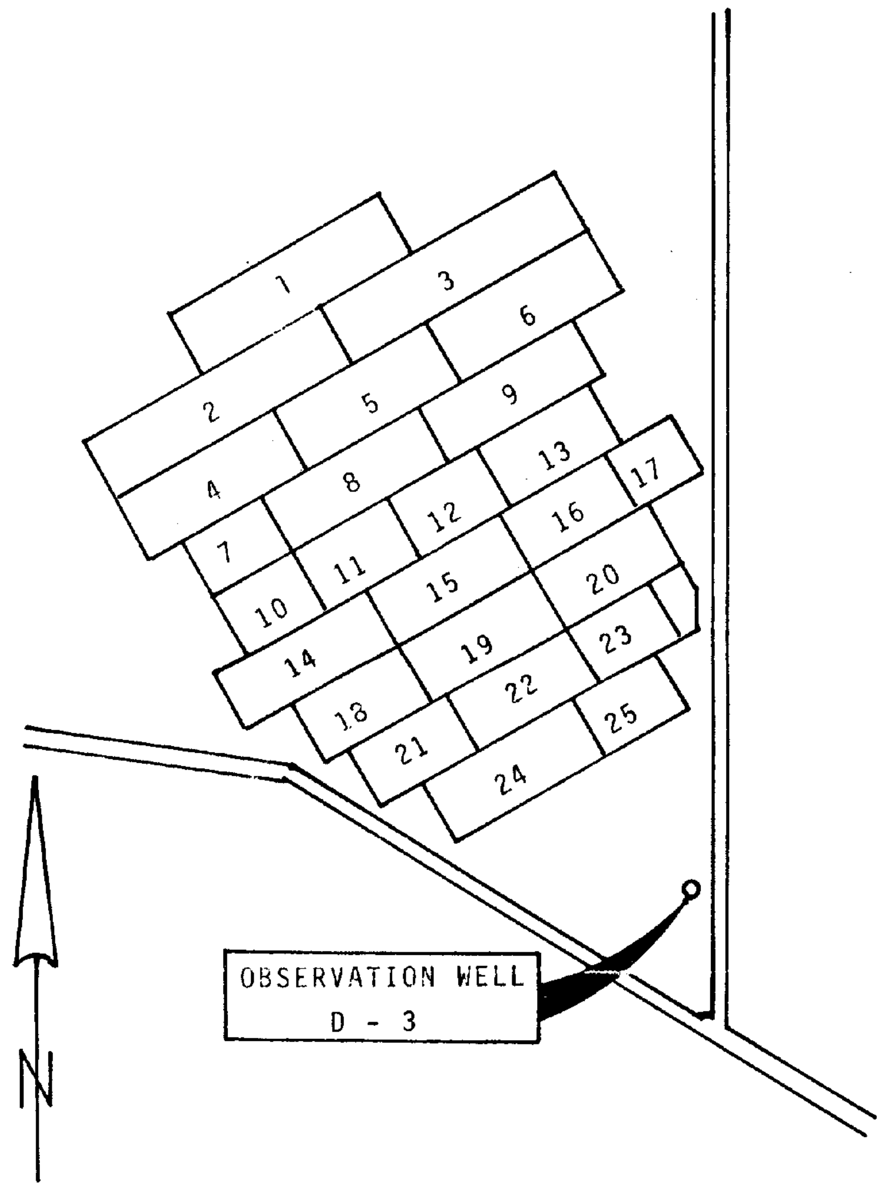
SHOT NO.	DATE	DISTANCE TO BLAST	CHARGE WGT./DELAY	RESULTANT AT SURFACE	RESULTANT IN WELL S-3
21	2/08/80	320 ft.	105 lbs.	1.02 inch/second	.17 inch/second
22	2/12/80	250 ft.	103 lbs.	1.42 inch/second	.226 inch/second
23	2/14/80	250 ft.	105 lbs.	1.313 inch/second	.204 inch/second
24	2/18/80	280 ft.	103 lbs.	1.49 inch/second	.277 inch/second
25	2/22/80	180 ft.	195 lbs.	2.05 inch/second	.233 inch/second
26	3/03/80	175 ft.	76 lbs.	1.44 inch/second	.227 inch/second

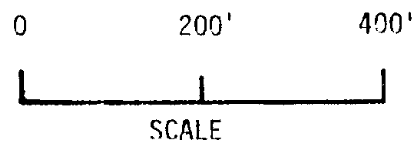
FIGURE 40

ROSE POINT

APPROXIMATE LOCATION OF

BLASTS





and Tenmile sites. There was no removal of downslope support but there was relocation of overburden at distances between 250 and 380 feet during the time between the previous test on January 15 and this one.

The highwall was advanced toward the well-site and after the overburden was blasted, it was pushed in a direction away from the wells by bulldozers. This would remove some of the vertical stress on the rocks below those areas where the overburden had been removed and not replaced. Upward arching in response to this stress relief could have caused existing fractures in the underlying strata to become more open and permit more recharge, and improved permeability. Whether this effect would extend downward to a depth of 125 feet and laterally for a distance of 250 feet is conjectural.

The previous test on January 15, 1980, was unusual. The pump rate was maintained very uniformly after the first three minutes of the test and the water level in the pumped well declined to an adjusted drawdown of 23.11 feet in 30 minutes. After 30 minutes, the water level began to rise and continued to do so until the end of the test when the adjusted drawdown was 19.50 feet, a rise of 3.61 feet. Was there some development of the well during the test such as the flushing and clean-up of additional fractures or perforations? Or, possibly, did the rise reflect some permeability improvement as a result of nearby vertical stress relief following the relocation of overburden? Because of the unusual character of this test, the time-drawdown curve is shown in Figure 41.

The summary chart in Figure 42 may shed some light on events from January 15 to February 20, 1980. The long-term graph of static water level indicates that the water level is very stable and the total range of fluctuation from August 10, 1979 to June 1, 1980 is only 2½ feet. The chart shows a rather abrupt drop on February 8,1980 but the decline may not have been as abrupt as shown. There was a blast on that date and an on-site measurement of the ground vibrations was made. In conjunction with that, the water levels were checked and water samples taken. It was noticed before the blast that the float recorder was hung up on something. When it was freed the float dropped 1.29 feet. The last observed movement was on January 30 when the recorder was checked during another on-site recording so this amount of decline could have occurred anytime during the nine-day period. Even so, the decline is greater than any observed previously at this site and it may be more significant than the magnitude suggest because of the stability of this well. The drop did occur after a two or three week period of diminished rainfall. Recovery since the decline has brought the static water level in the well to the highest point observed during the test period. Of course, rainfall during this recovery period was heavy and it is difficult to determine cause and effect.

It is clear that the well performance did improve sometime between January 15 and February 20, 1980, that overburden was being excavated at distances between 250 and 380 feet, and that the static water level declined during this period. Although the case is weaker, these events do fit the scenario of stress relief but in this case the relief is vertical rather than lateral. This difference may necessitate a more subtle response because of the greater confinement.

This well continued to exhibit improved performance on March 11, eight days after the last blast at this operation, and on April 10, when the area

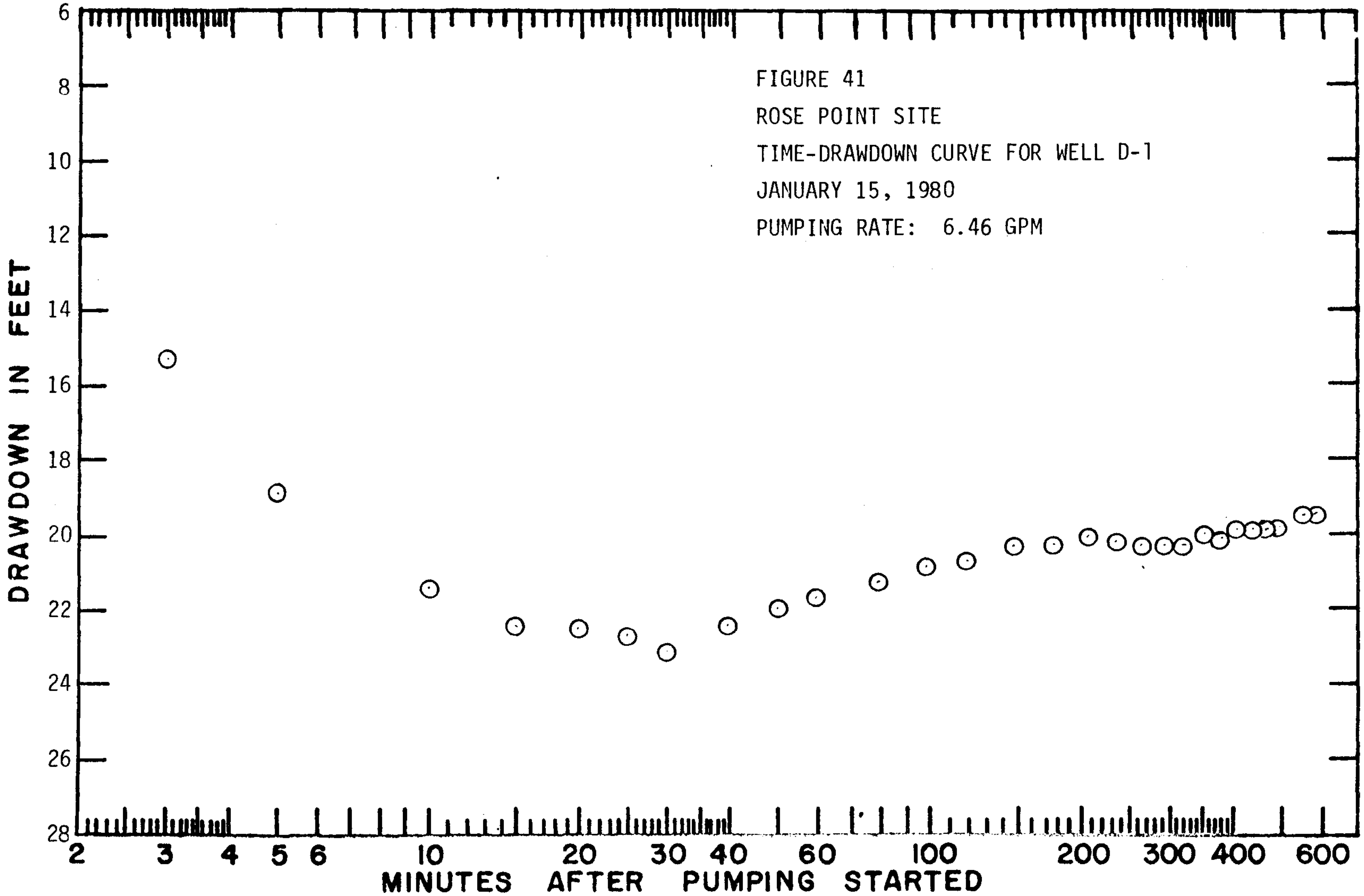


FIGURE 41
ROSE POINT SITE
TIME-DRAWDOWN CURVE FOR WELL D-1
JANUARY 15, 1980
PUMPING RATE: 6.46 GPM

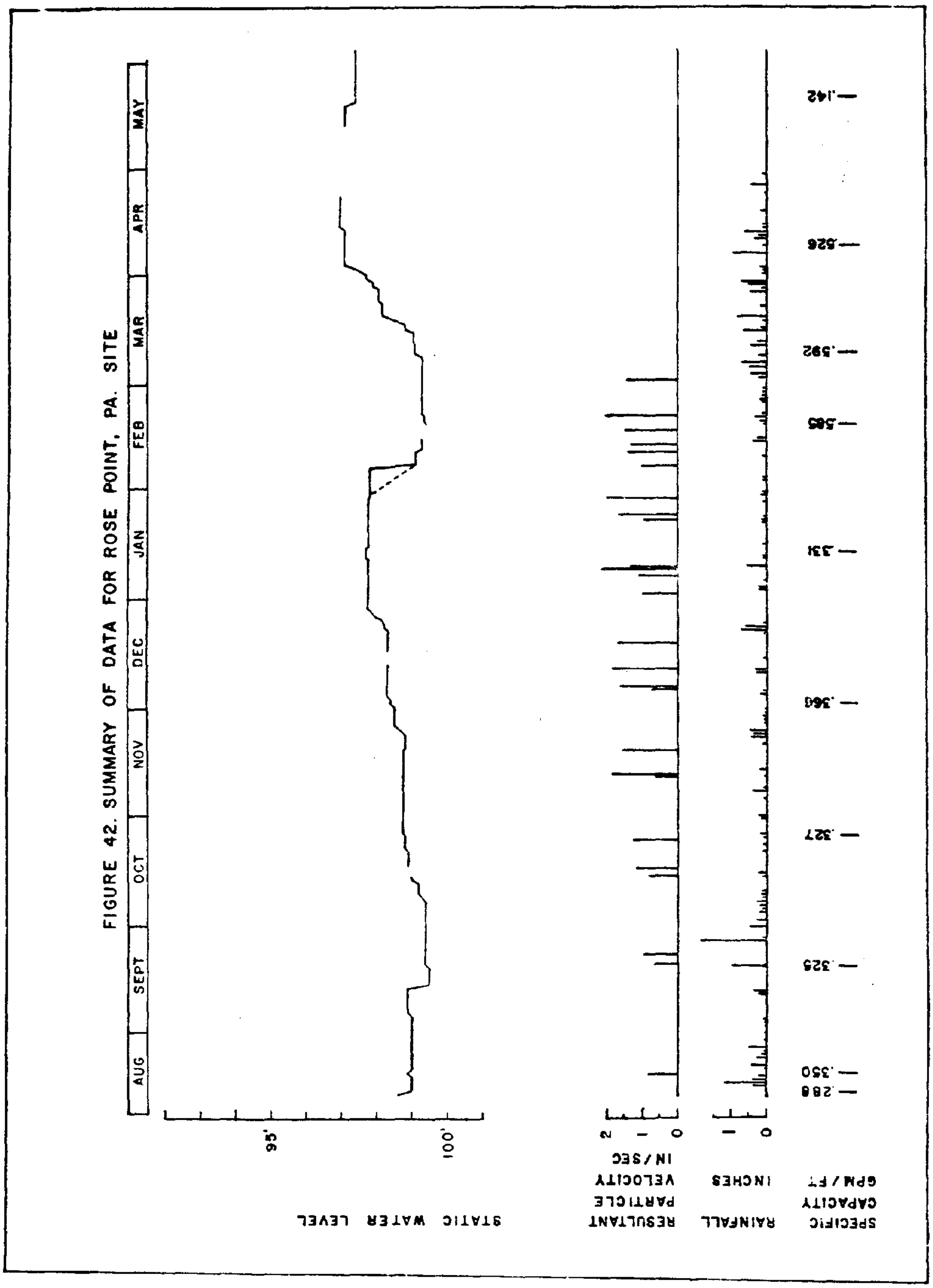


FIGURE 42. SUMMARY OF DATA FOR ROSE POINT, PA. SITE

around the site was being reclaimed. On May 22, however, the well was pumped at the rate of 5.98 gpm and the water level was pulled down to the pump in only 30 minutes. This performance is considerably worse than any previous test and it is not clear as to what has happened. Perhaps the backfilling of the pit permitted fines to be washed down into the fractures and partially plugged them. Perhaps the replacement of the overburden caused the fractures to close again when the vertical stress was restored.

A subsequent test on August 6, 1980 was performed at two different pump rates. This test indicated that the specific capacity recovered to its' original value possibly as a result of flushing out of the fines.

As at the other sites, vibration measurements were made at the bottom of one of the wells to determine the difference between the vibration level at that point and the vibration level at the surface. At Rose Point the measurements were made at the bottom of Well D-2. To determine an attenuation factor, the resultant particle velocity measured in the well is divided by the resultant particle velocity measured at the surface. These data are in Table 14. The average for the RPV subsurface to RPV surface ratio is 0.14 with a standard deviation of +0.04. In other words, the vibration level at the bottom of Well D-2 for these blasts was only 14% of that on the surface.

The chemistry of the well water at Rose Point was essentially unchanged based on the results obtained by the commercial laboratory, although the pH did vary from 6.3 to 7.6, and there was a fair amount of fluctuation in carbon dioxide levels. In contrast, the field determinations of samples from Well D-2 show an abnormally high pH and phenolphthalein alkalinity after December 4, 1979. Other field tests and laboratory tests of waters in Well D-1 or Well D-4 do not show these abnormalities. A contaminant must have been introduced into Well D-2 at that time and there hasn't been enough circulation through the well to remove it. These data are included in the Appendix but the reader is cautioned that the field test results are erroneous for the pH and alkalinity readings because of the large discrepancy with the laboratory results. The other parameters seem fairly reasonable however. Perhaps because the wells had liners, the turbidity readings appear more reasonable and consistent.

TABLE 14

ROSE POINT

SHOT NO.	DISTANCE	RPV SUBSURFACE / RPV SURFACE
1	775 ft.	0.15
3	700 ft.	0.09
5	600 ft.	0.10
6	600 ft.	0.11
7	600 ft.	0.17
8	550 ft.	0.09
9	550 ft.	0.08
10	540 ft.	0.13
11	500 ft.	0.08
14	450 ft.	0.22
15	400 ft.	0.14
16	400 ft.	0.09
17	410 ft.	0.12
18	380 ft.	0.21
19	320 ft.	0.18
21	320 ft.	0.17
22	250 ft.	0.16
23	250 ft.	0.16
24	280 ft.	0.19
25	180 ft.	0.11
26	175 ft.	0.16
		MEAN = 0.14
		S.D. ± 0.04

ST. CLAIRSVILLE, OHIO TEST SITE

This site is five miles southwest of St. Clairsville, Ohio. The Washington Formation of the Permian System and the Monongahela Group of the Pennsylvanian System occur at the surface. The coals being mined are the Waynesburg (No. 11) and the Uniontown (No. 10) seams. Dip of the strata is about 25 feet per mile to the south. Topography at the site is illustrated in Figure 43 which also shows the relationship of the test well site to the area being mined as of June, 1980. Eventually mining will proceed through the well-site and destroy the wells. A cross-section showing the relationships between the seams being mined, the test wells, and the pit is included as Figure 44.

Ground water in this general area is very sparse. Maps published by the Ohio Department of Natural Resources, Division of Water, indicate that this site is situated in an area where wells seldom yield as much as 5 gallons per minute. More specifically, for the strata present at this site, the text that accompanies the map states that the Washington formation and the Monongahela group are generally considered to be a meager source of underground water and that yields of less than 1 gpm are common. Although this is not encouraging as to the possibilities of getting a group of good wells, it was attractive for a project test site. This is because it is in such areas where water is so scarce that any activity which threatens the supply creates fear and apprehension. It is in such areas that it is most important to determine the effects of nearby blasting on ground water sources. The specific test-well site was selected because it was about 70 feet higher in elevation than where mining was to commence and about 1,400 feet away. Mining was to progress directly up the hill toward the wells and it was estimated that it would be about one year before the test-well site would be mined.

Mining was to commence in late May, 1979. Bad economic conditions for the relatively high sulfur Ohio coal delayed the commencement of mining until November, 1979, and in the meantime the mining plan was changed. Instead of starting on the hill where the test wells were located, initial activity was across the valley to the southwest where another shaded area is shown on the Site map.

The delay and the change in plans created a problem for the test program because it meant there might not be sufficient time remaining in the project to collect the required data. Extensions were granted by the Bureau of Mines and data gathering continued to September, 1980.

Eight test wells were drilled in March, 1979, in accordance with the test well pattern and well numbering system described in Chapter 6, and illustrated in Figure 1. Initial depth of the test wells is as follows:

Shallow Well Group		Deep Well Group	
S-1	80 Feet	D-1	180 feet
S-2	80 feet	D-2	180 feet
S-3	80 feet	D-3	184 feet
S-4	80 feet	D-4	180 feet

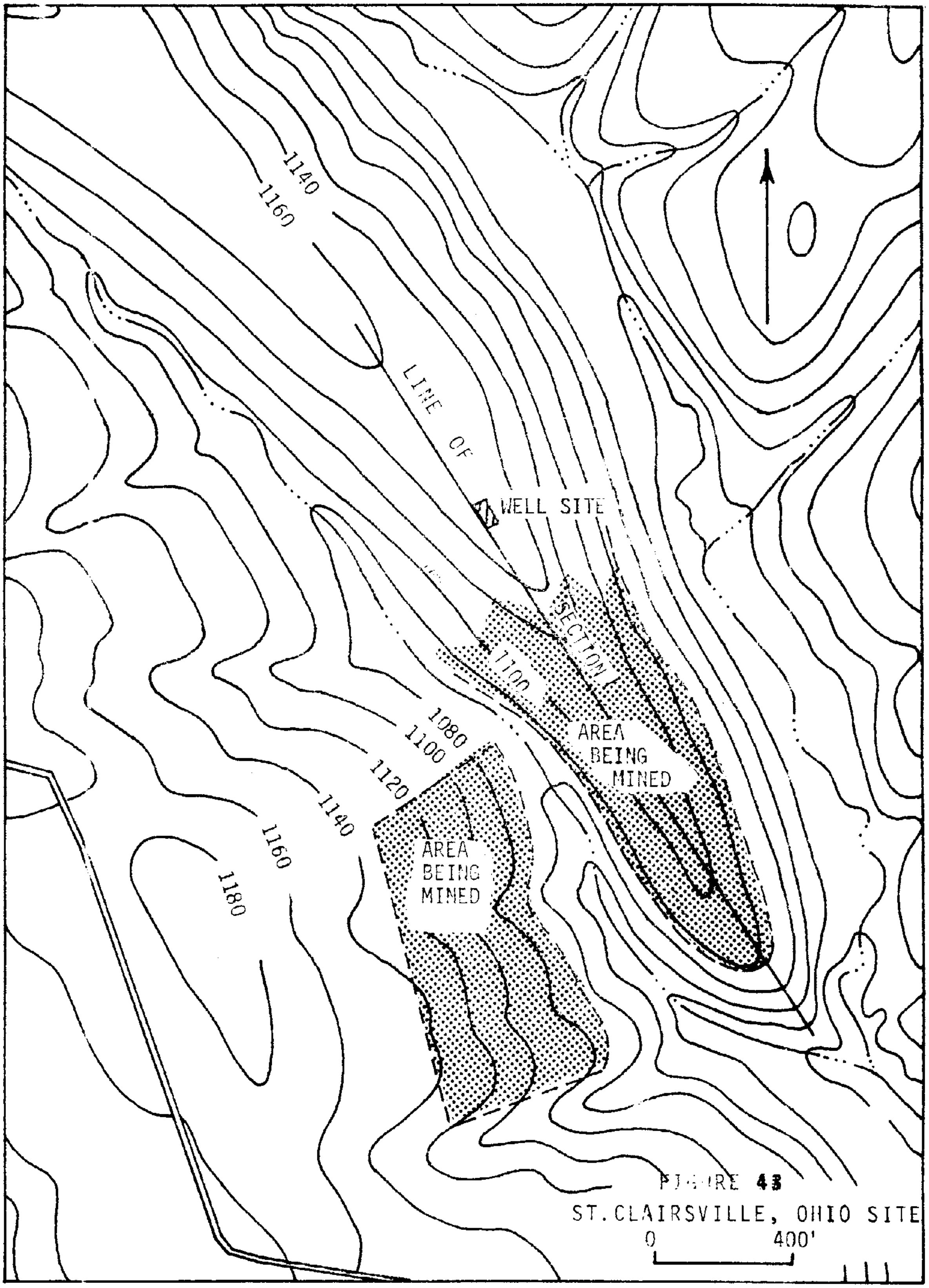


FIGURE 43
ST.CLAIRSVILLE, OHIO SITE

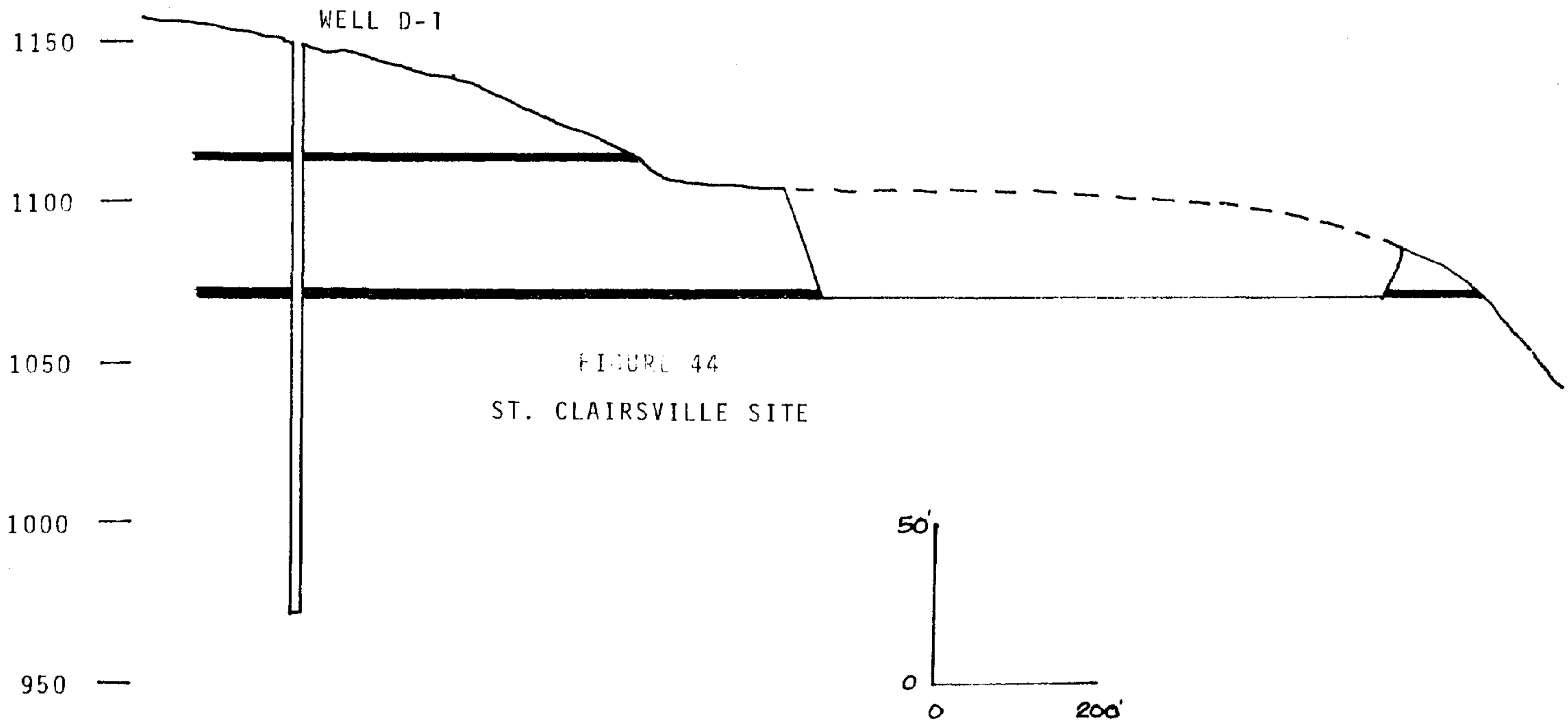


FIGURE 44
ST. CLAIRSVILLE SITE

Water was encountered in all wells at a depth of about twenty feet where the Waynesburg coal was penetrated. This is the source of water for the shallow wells. The deeper wells were lined with plastic liners and packers were set at 100 feet with unperforated liner above that point and perforated liner below. This sealed off the water at 20 feet at the deep wells and their source was primarily from a coal seam at a depth of 172 feet, which would be the Sewickley (No. 9) coal. Static water levels indicate that D-1, D-2, and D-3 are isolated from the shallow group, but D-4 may have some interconnection through the Uniontown coal at 64 feet possibly because of a break in the liner.

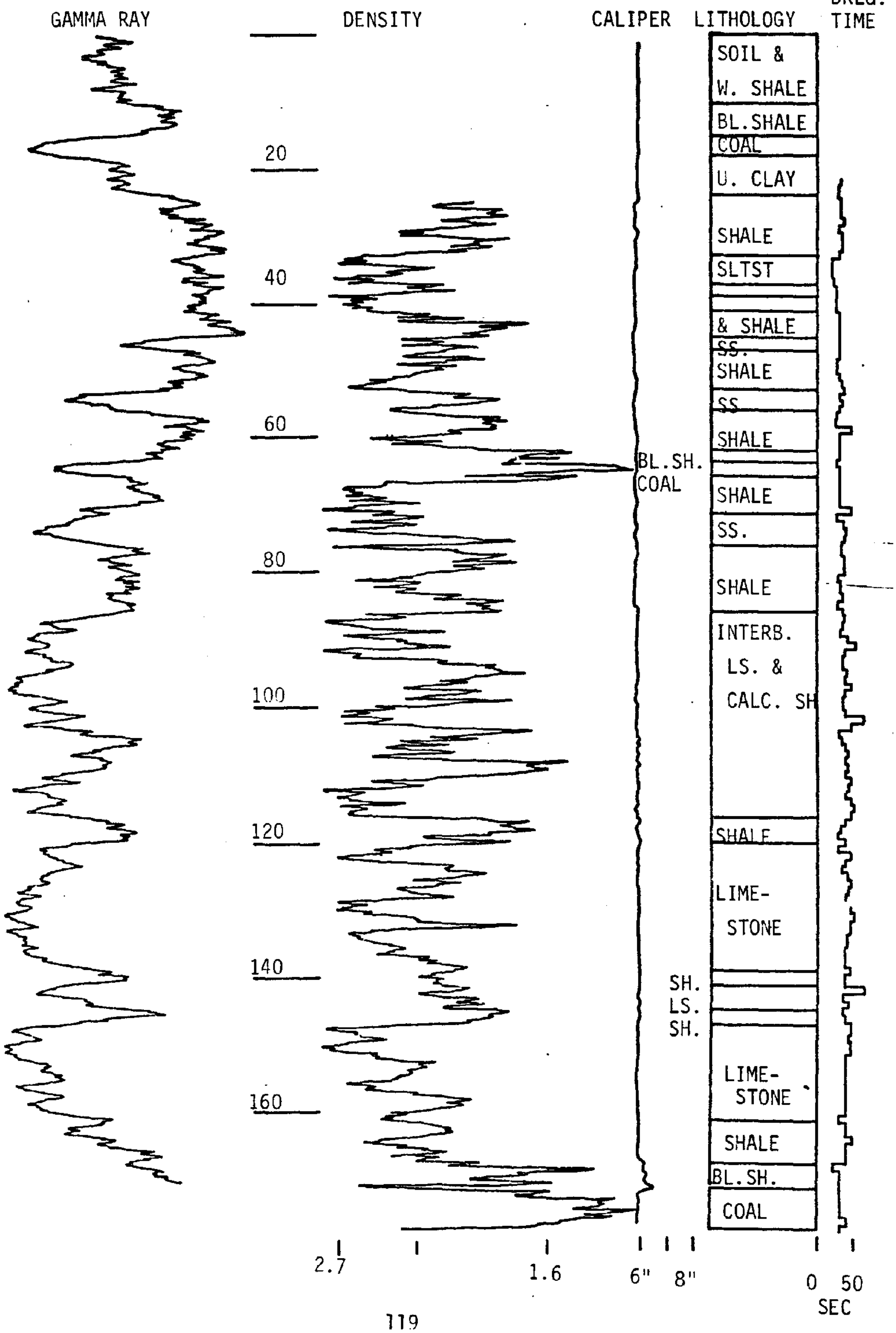
In addition to the drilling time and lithologic logs made at the time of the drilling, gamma ray, caliper, and density logs were run on Wells S-1 and D-1. Caliper logs were run on all of the others. Figure 45 is a composite of all these logs.

On May 10, 1979, both Well D-1 and Well S-1 were pumped down for a pre-mining determination of the productive capability. Well S-1 was pumped at the rate of 0.86 gpm for a full test period of 600 minutes. The adjusted drawdown after 600 minutes was 20.92 feet. Specific capacity as determined by this test was .041 gpm/ft.

Well D-1 was pumped at the rate of 0.64 gpm and the well could only be pumped for 62 minutes at this rate before the water level had declined almost to the pump intake. The adjusted drawdown at that time was 23.04 feet but the water level was still in fairly rapid decline so the specific capacity determined from these figures gives an erroneous impression of the capability. Because of this, the well was tested again on June 27 at a pump rate of only 0.21 gpm. This rate could be continued for 300 minutes before the water level approached the pump intake. Recovery was observed for the next 300 minutes. Recovery was at a constant rate per minute indicating that water entry point was still above the water level after it had recovered to a depth of 145 feet. Recovery rate was only .04 gpm. While this may seem to be absurdly low, one of the authors has measured a constant recovery rate of only 0.07 gpm for a well which was serving as a domestic supply.

Well S-1 was also tested again on June 27 to confirm the data obtained on the previous test. No blasting or mining had taken place at the site in the interim. Well S-1 was pumped at the rate of 0.96 gpm and it was surprising that the water level was drawn down to the pump intake in only 110 minutes. The pumping rate was slightly higher on the second test but not enough to account for the significant change in performance. Again on September 18 the well was tested again. There still had been no blasting or mining activity. At a pumping rate of 0.76 gpm, slightly less than the initial test, the water level was pulled down nearly to the pump in 120 minutes. At that time, the rate was reduced to 0.37 gpm and the well stabilized after rising about four feet. A possible explanation of this deterioration in performance is that the first test allowed air to enter the fracture system in the upper coal (Waynesburg seam) and perhaps became trapped in a small domal structure within the area of influence of the well. This would eliminate or reduce the flow of water coming from that area and thus reduce the yield of the well. This is significant because it is an example of a well which initially appeared to be adequate for domestic needs on the basis of a ten-hour test, and then with no intervening mining activity, deteriorated to a point where it was inadequate.

FIGURE 45. COMPOSITE WELL LOG ST. CLAIRSVILLE SITE



Summaries of the drawdown tests performed in Well S-1 are listed in Table 15, and for Well D-1 in Table 16. Field data are presented in the Appendix.

TABLE 15

ST. CLAIRSVILLE: TEST SUMMARY WELL S-1

Depth of Well: 80 feet

Depth to Pump: 69 feet

DATE	PUMP RATE Q	ADJUSTED DRAWDOWN, S'	$\frac{Q}{S'}$	STATIC WATER LEVEL AT TEST START	LENGTH OF TEST
5/10/79	0.86 gpm	20.92 ft.	0.041 gpm/ft.	22.79 ft.	600 min.
6/27/79	0.96 gpm	29.55 ft.	0.033 gpm/ft.	23.07 ft.	110 min.
9/18/79	0.76 gpm	29.23 ft.	0.026 gpm/ft.	22.89 ft.	120 min
9/18/79	0.37 gpm	27.87 ft.	0.014 gpm/ft.	22.89 ft.	480 min.
11/13/79	0.41 gpm	25.29 ft.	0.016 gpm/ft.	22.61 ft.	600 min.
4/08/80	0.44 gpm	25.63 ft.	0.017 gpm/ft.	19.78 ft.	600 min.
6/12/80	0.24 gpm	1.50 ft.	0.160 gpm/ft.	21.24 ft.	240 min.
6/20/80	0.57 gpm	29.48 ft.	0.019 gpm/ft.	21.66 ft.	210 min.
6/20/80	0.39 gpm	29.75 ft.	0.013 gpm/ft.	21.66 ft.	240 min.

TABLE 16

ST. CLAIRSVILLE: TEST SUMMARY WELL D-1

Depth of Well: 180 feet

Depth to Pump: 163 feet

DATE	PUMP RATE, Q	ADJUSTED DRAWDOWN, S'	$\frac{Q}{S}$	STATIC WATER LEVEL AT TEST START	LENGTH OF TEST
5/10/79	0.64 gpm	23.04 ft.	0.028 gpm/ft.	126.87 ft.	62 min.
6/27/79	0.21 gpm	29.80 ft.	0.007 gpm/ft.	112.68 ft.	300 min.
4/17/80	0.27 gpm	32.21 ft.	0.008 gpm/ft.	102.67 ft.	230 min.
7/30/80	0.25 gpm	31.95 ft.	0.008 gpm/ft.	110.20 ft.	240 min.
9/05/80	0.24 gpm	34.80 ft.	0.007 gpm/ft.	106.40 ft.	240 min.

General slopes of the time-drawdown curves for these tests and the others conducted at this site are shown in the Figures 46 and 47. For Well S-1, the slopes increase as the pumping rate progresses from 0.24 to 0.44 to 0.57 to 0.76 and then 0.96 gpm. Exceptions to this are the initial test and the test of November 13, 1979. In the latter, the pumping rate during the first few minutes of the test was allowed to increase and pull the water level down rapidly and distort the slope of the remaining curve. At the end of the November 13, 1979 test, the adjusted drawdown was very close to that of the April 8, 1980 test which was pumped at about the same rate.

Similarly for Well D-1, all of the slopes are steep but they increase as the pumping rate increases.

The reason for this increase in slope with increase in pumping rate is that the static water level is approximately the same as the depth of water entry into the well. When the water level is drawn down below the water entry, the contribution from the aquifer is constant and if the pumping rate exceeds this contribution, the remainder is made up from well storage, that is, the water which has built up over time in the well bore. Consequently, under these conditions, at pumping rates which exceed the water entry, the increase in slope simply reflects faster withdrawal of well storage water. Examination of the time-drawdown curve for the test of June 12, 1980 makes this point clear. At a pumping rate of 0.24 gpm, the well reached near-equilibrium in 5 minutes with a drawdown of about two feet. By comparison, the test of April 8, 1980 was pumped at a rate of 0.44 gpm and the time-drawdown curve is relatively steep, linear, and with no indication that equilibrium is being approached. From these curves, and knowing that the water is entering the hole around a depth of 20 feet, one can deduce that the water entry is between 0.24 and 0.44 gpm. Effort to stabilize the well on the September 18, 1979 test after the water level was drawn down to just above the pump, indicates that the rate of entry was 0.35 gpm.

For these low yield wells, the above explanation points out one of the possible sources of error if one uses the slope of these time-drawdown curves to determine the transmissivity and storage coefficients.

On tests such as these when the water level doesn't approach equilibrium, the specific capacity is also a poor index because its value is dependent on the time at which the drawdown is determined. In these circumstances, the best index is to draw the water level down to a few feet above the pump and observe the recovery. If the incremental recovery rate is constant, the water entry is above the observed water level. Thus, in a 6" diameter hole, the rate of water entry in gallons per minute can be determined by multiplying the recovery rate in feet per minute by 1.5 gallons per foot. This rate should remain fairly constant from test to test. Alternatively, under these conditions, if the well has been drawn down to just above the pump at a pumping rate that exceeds the water entry rate, one can determine the water entry rate by decreasing the pumping rate gradually until equilibrium is attained. When this is reached, the water entry rate is equal to the pumping rate.

On April 8, 1980, the first blast on the test-well hill was detonated. A drawdown test of Well S-1 was in progress at the time and the blast occurred 423 minutes after the test started. Fluctuation in pumping rate caused

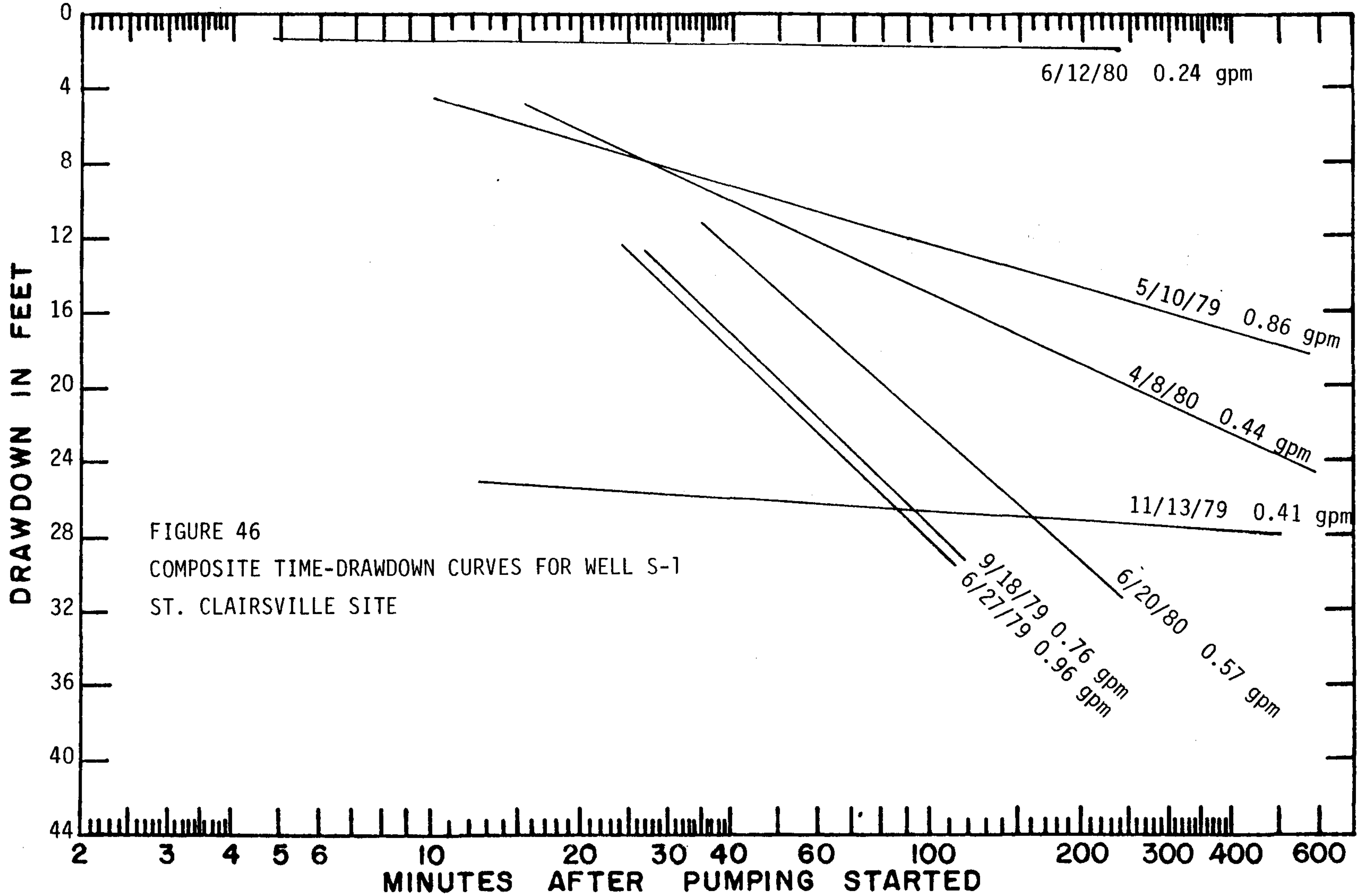


FIGURE 46
COMPOSITE TIME-DRAWDOWN CURVES FOR WELL S-1
ST. CLAIRSVILLE SITE

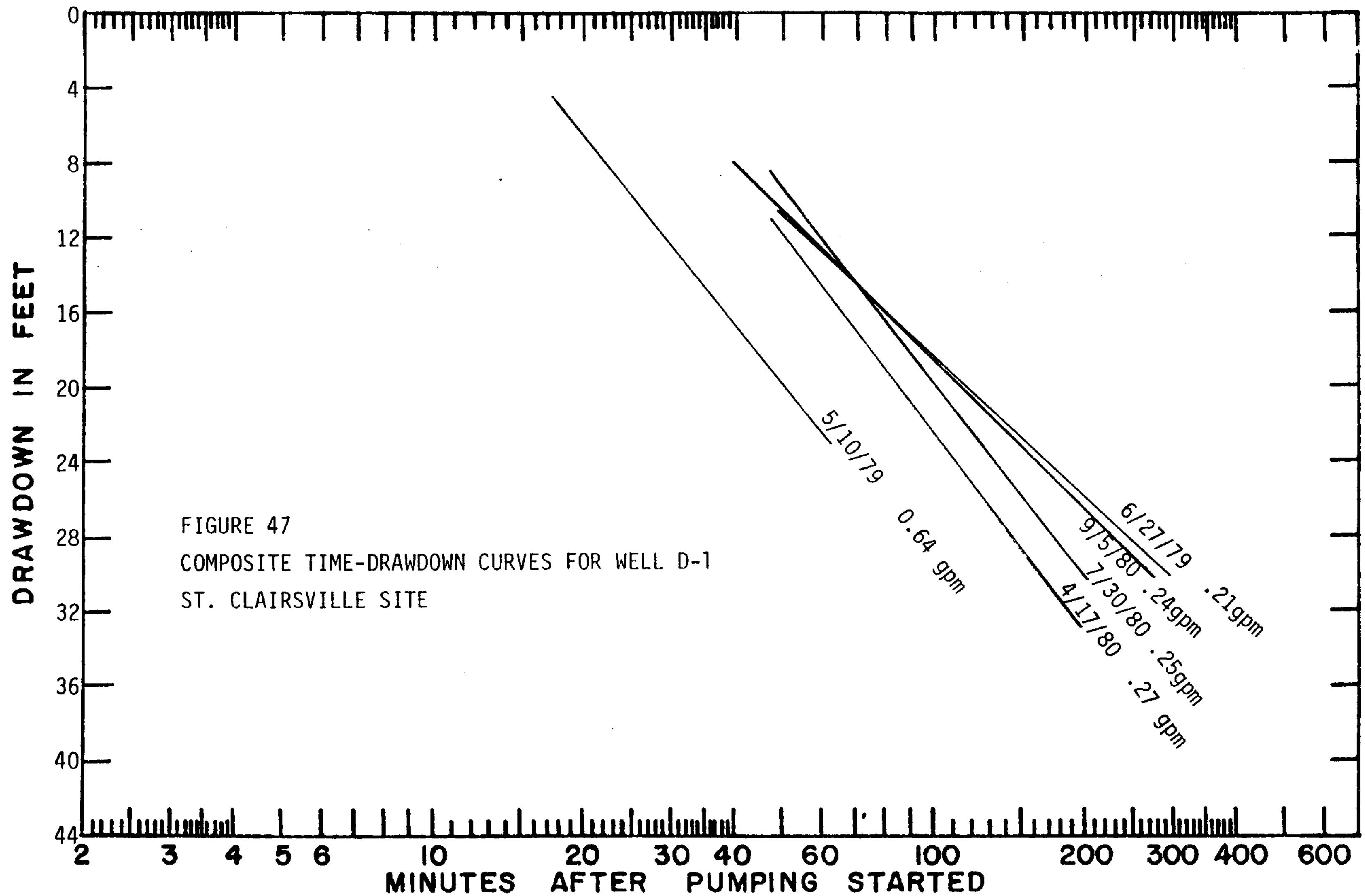


FIGURE 47
COMPOSITE TIME-DRAWDOWN CURVES FOR WELL D-1
ST. CLAIRSVILLE SITE

the time-drawdown to vary prior to the blast, but after the blast the plotted points fell on the extension of the initial slope indicating no change. A detailed plot of this time-drawdown curve is shown in Figure 48.

During the test of Well S-1 on June 12, 1980, the fourth blast on this hill was detonated at a distance of 425 feet from the well. On this test, the well was being pumped at the rate of 0.24 gpm and near-equilibrium had been attained. The blast occurred 170 minutes after the test started and the water level rose 0.8 foot in the 60 minutes following the blast. Figure 49 is the time-drawdown curve for this test.

On April 17, 1980, the second blast on this hill was detonated 135 minutes after a drawdown test of Well D-1 had started. Maximum resultant particle velocity for this blast at the surface by Well D-3 was 0.20 in/sec. This blast had no significant effect on the performance of this well.

The blasts on the test-well hill are listed in Table 17 and the maximum resultant particle velocities at the well site are indicated. The location of the blasts is shown in Figure 50.

Data are too sparse at this time to determine a valid subsurface to surface attenuation ratio but it appears to be approximately 0.25.

Static water level for Well S-2 is shown in the Data Summary Chart in Figure 51. There was also a continuous float gage recorder on Well D-2 but the record is very intermittent because the protective shed and the recorder were damaged by cows. The instrument was replaced but the new device had a short in the clock mechanism which caused the batteries to run down after a few days. A third instrument is now at the site and seems to be functioning properly. There should be an adequate record for both wells as the mining approaches.

As of September 1980, there was no apparent change in either of the wells as a result of the blasting.

As at the other sites, the chemical analyses of the ground water at this site show little variation and no significant long-term trend. There are more pre- and post-blast pairs of turbidity data from pumped samples but not enough to draw any conclusions. Typically, iron and manganese show the most variation but there is no trend.

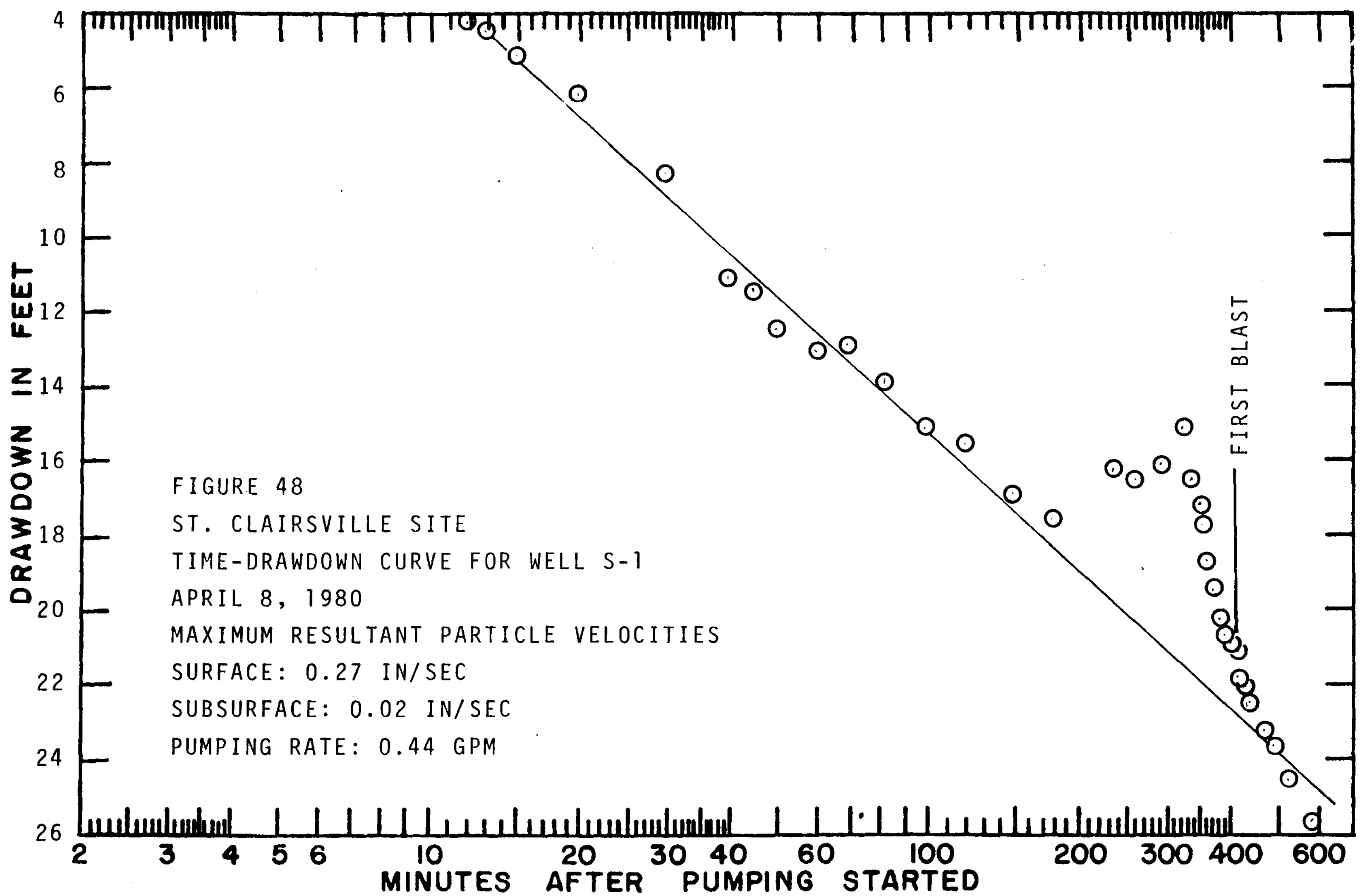


FIGURE 48
ST. CLAIRSVILLE SITE
TIME-DRAWDOWN CURVE FOR WELL S-1
APRIL 8, 1980
MAXIMUM RESULTANT PARTICLE VELOCITIES
SURFACE: 0.27 IN/SEC
SUBSURFACE: 0.02 IN/SEC
PUMPING RATE: 0.44 GPM

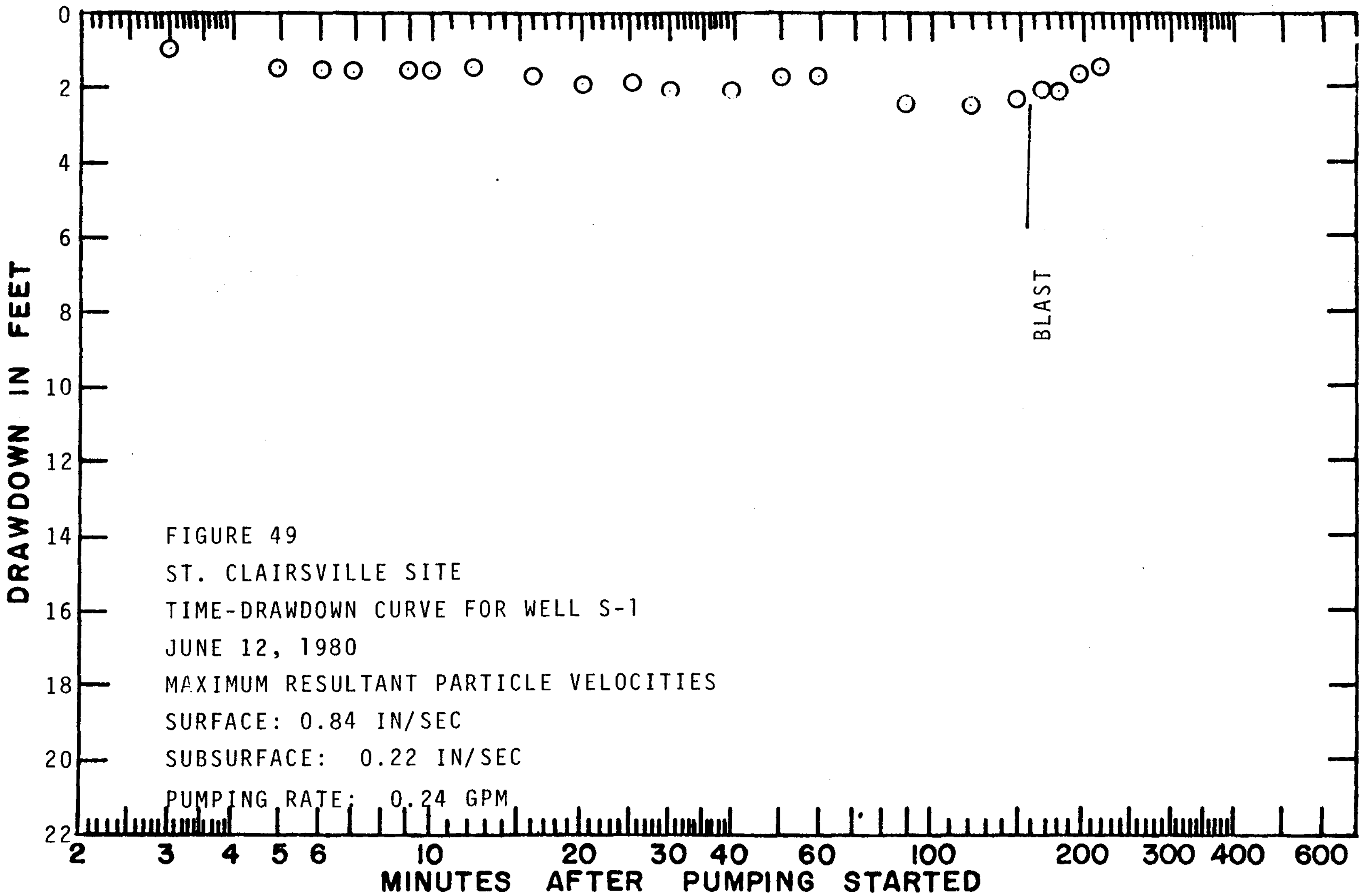


FIGURE 49
ST. CLAIRSVILLE SITE
TIME-DRAWDOWN CURVE FOR WELL S-1
JUNE 12, 1980
MAXIMUM RESULTANT PARTICLE VELOCITIES
SURFACE: 0.84 IN/SEC
SUBSURFACE: 0.22 IN/SEC
PUMPING RATE: 0.24 GPM

TABLE 17

ST. CLAIRSVILLE

SHOT NO.	TIME	DATE	DISTANCE	LBS/DELAY	MRPV AT SURFACE	MRPV IN WELL D-2
1	3:20 p	4/8/80	1000 ft.		0.27 inch/second	0.02 inch/second
2	3:15 p	4/17/80	800 ft.	116	0.25 inch/second	0.07 inch/second
3	3:32 p	5/ 8/80	720 ft.	66	Not Recorded	Not Recorded
4	3:52 p	5/ 8/80	720 ft.	66	Not Recorded	Not Recorded
5	11:12 a	5/ 9/80	720 ft.	66	Not Recorded	Not Recorded
6	2:30 p	5/28/80	600 ft.	200	0.45 inch/second	0.10 inch/second
7	3:05 p	5/12/80	425 ft.	166	0.84 inch/second	0.22 inch/second

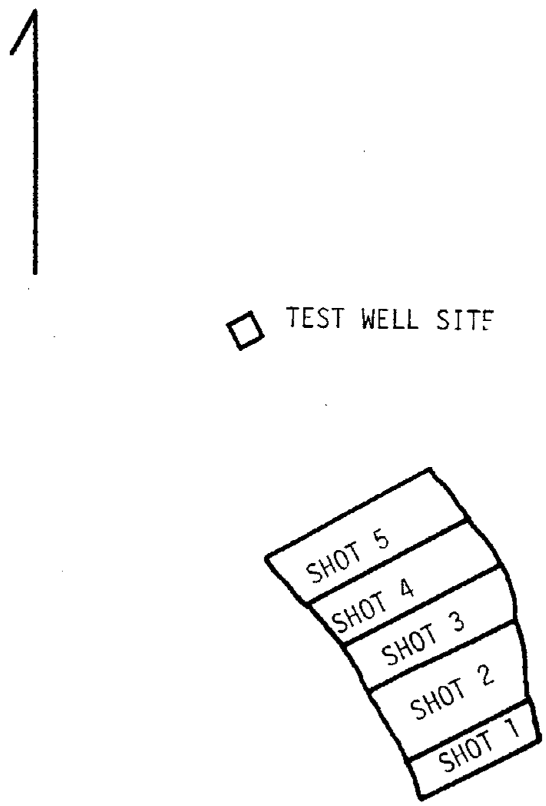


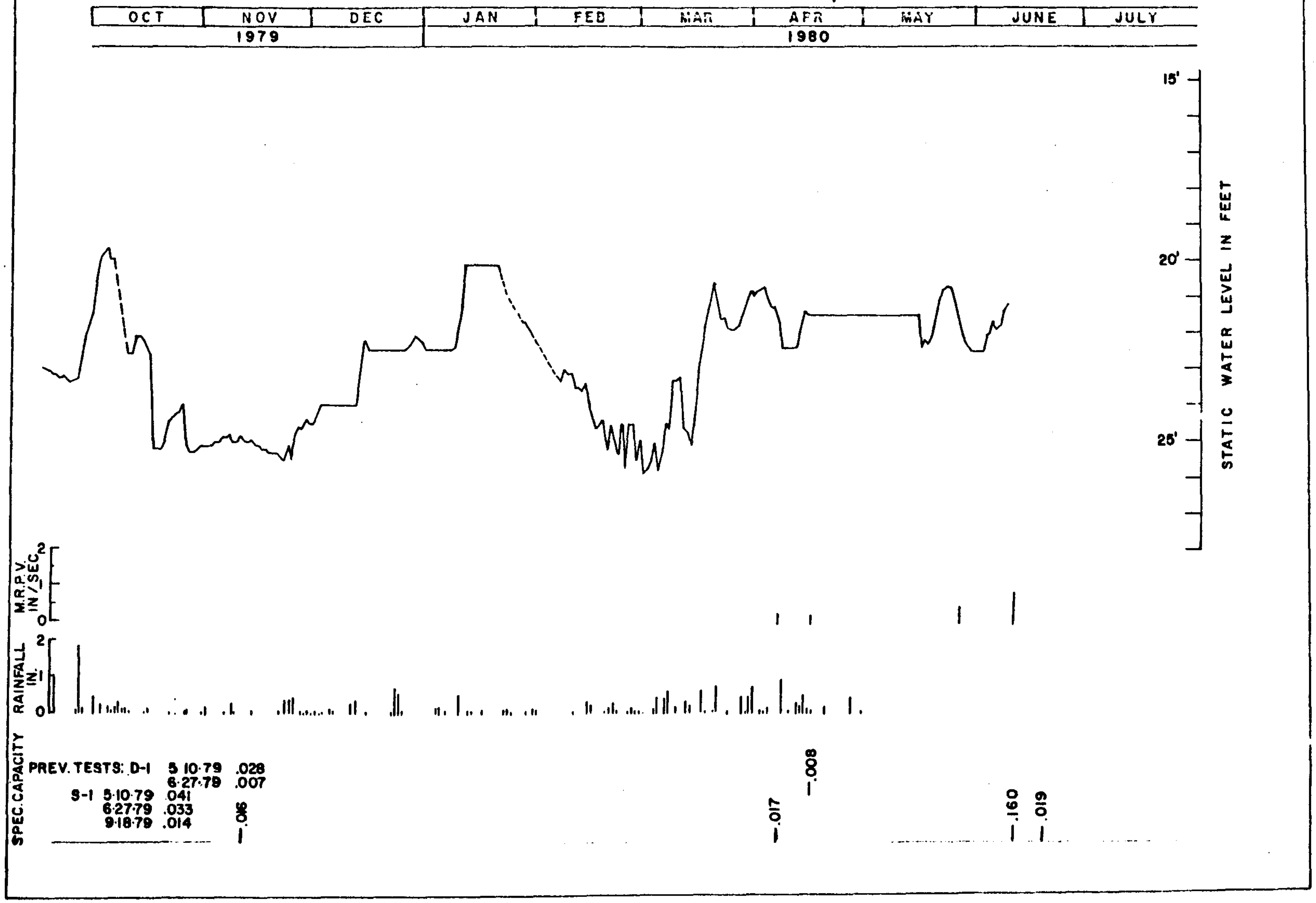
FIGURE 50

BLAST LOCATION MAP

ST. CLAIRSVILLE SITE

SCALE: 1" = 400'

FIGURE 51. SUMMARY OF DATA FOR ST. CLAIRSVILLE, OHIO SITE



GENERAL CONCLUSIONS

The history of events at three of the four sites indicates a pattern of change in the water producing characteristics of the low yield, fractured, water table aquifers which typically are the source of water for domestic water wells in the coal producing regions of Appalachia. As mining approaches to within approximately 300 feet, it is expected that this pattern of change will occur at the fourth site.

The sequence of events is as follows:

1. PRE-MINING PHASE

   The water well is drilled to a depth of 100 to 150 feet with only 20 feet of casing at the surface. Water entry is typically associated with the coal seams but appears to have vertical connection to the surface through fractures. The well is commonly developed with a submersible pump and if the pumping rate is properly regulated (rarely done in practice), the pump will draw the water level down fairly rapidly for the first 10 to 20 minutes of pumping, followed by near equilibrium conditions. Where these conditions prevail, specific capacity is a simple but good index for evaluating the consistency of performance.

2. MINING AND BLASTING PHASE

   When nearby mining commences and blast-induced ground vibrations are relatively low (say, less than 1.0 in/sec maximum resultant particle velocity), the response of the well is limited to a slight variation in water level on the order of one- or two-tenths of a foot either up or down. The effect is temporary and when the water well is tested by drawdown at a later date, the specific capacity is essentially unchanged.

   If a well has been pumped for several hours before the blast, and is pumped during the blast and for several hours afterward, a crude, long period oscillation of the water level sometimes develops about one to two hours after the blast. This oscillation may involve alternate lowering and rising of the water level on the order of about one foot. Because of the length of time after the blast, this oscillation does not appear to be the result of blast-induced ground vibrations but more likely is caused by the relocation of the blasted rock mass. This oscillation phenomenon is not always observed and it was never observed in a well that was not being pumped continuously over a period of several hours.

   Blasting may cause some temporary increase in turbidity but this effect is difficult to evaluate because increases in turbidity can be observed when there has been no blasting because of normal intermittent sloughing of the sidewall into the hole. Proper sampling of static wells is also difficult and the results are ambiguous. The possibility of increases in turbidity from whatever cause appears to be lessened by the use of plastic well liners.

3. STRESS RELIEF AND WELL IMPROVEMENT PHASE

The well continues to perform in the same manner although blast-induced ground vibrations at the surface may approximate or exceed 2.0 in/sec maximum resultant particle velocity, until surface mining approaches to within about 300 feet of the water well. This distance may be somewhat less if the mining is being done upslope from the well. At this distance, the strata respond to the removal of downslope support, or to the relocation of upslope overburden load, by gross expansion of the rock mass in which the well has been drilled. The mode of expansion involves increased opening of existing fractures, and perhaps the creation of some new fractures. Because the ground water of concern resides and moves in these fracture openings for the most part, a change in the openings causes two changes which affect the performance of the well.

First, the larger openings create more storage space for the ground water and the existing supply moves downward to fill the new voids. This causes the water level in the well to decline at a relatively rapid rate for a period of a week or two. If recharge from rainfall is available, after this time, the water level in the well will recover and possibly be at a higher level than before, unless communication with the pit has been improved to the extent that the ground water drains into the pit at a rate greater than the rate of recharge. Fortunately, the primary existing fractures are parallel to the contour of the slope. If the mining is downslope and the coal is roughly horizontal, the pit will be roughly parallel to the primary fractures. As they open up the communication to the pit will not be necessarily improved. Because the direction of stress relief is more or less parallel to the secondary set of fractures, they may not open up appreciably by the mechanism described.

Second, the more open fractures improve the permeability of the rock mass. If the water level is still high enough to permit a drawdown to near-equilibrium, the well will exhibit improved performance which will be indicated by a higher specific capacity.

4. REPETITION PHASE

If a second, deeper cut is made, the sequence involving stress relief may be repeated, resulting in more improvement in the well performance, if there is still sufficient submergence for the pump.

5. POST-BACKFILL STAGE

At one site there was evidence that a post-improvement phase may exist. After backfilling was completed the performance of the well deteriorated to a level about half as good as originally. The reasons for this are not clearly understood at this time but may have something to do with the reapplication of stress, or to clogging of the fractures with fines. At the other sites, the wells will be destroyed by mining, or at Tenmile, there will be no backfill of the sedimentation pond, so there will be no opportunity to determine if this effect is general. This phenomenon deserves more investigation.

These effects tend to be more pronounced in wells where the water is obtained from relatively shallow fractures. At Tenmile and Brotherton, the shallow wells exhibited substantially improved permeability while the deeper wells indicated improvement to a lesser degree. This is entirely consistent with the stress relief mechanism and is what one would expect.

None of these events occurred catastrophically as the result of a blast. Water level measurements taken before and after the blast did not indicate any immediate change. The changes occurred over days or weeks. Nor did there appear to be any ground vibration threshold level associated with the events. Because ground vibration levels are dependent on charge weight per delay and distance to the blast, the ground vibration levels were generally higher as mining approached the wells but because there was no significant immediate response to the transient vibrations, they are not the cause of the events per se.

The events are caused by the removal of support or by relocation of the overburden load and it is only to the extent that blasting is commonly the initial step in this process that it can be related to the events observed.

The location and the proximity of the excavation are the factors that control the timing of stress relief. The depth of the cut, the steepness of the slope, the tensile strength of the strata, and the dip of the strata are factors which determine the critical distance and more research should be done to establish the interrelationships. From this project a distance of roughly 300 feet appears to be a reasonable average for Appalachia. When the stress relief occurs as the result of removal of downslope support, it appears that nothing occurs until the excavation has moved within roughly a 30° arc on either side of a line running directly downslope from the well. There is a suggestion that with this type of relief, location is more important than distance. Effects caused by upslope overburden relocation are more subtle and conversely, distance is probably more important than location. Although not included among the first four sites, a well along the contour to one side of the pit may show only minimal effects. The situation would be analogous to area stripping which will be tested in Southern Indiana.

Because the sequence of events includes the probabilty that the water level may drop significantly, the importance of having adequate pump submergence should be clear. At Brotherton, a good 8 gpm test well is now dry simply because the water level is now below the pump. If the well had been drilled 50' deeper to provide for more submergence, the well would be productive today.

Vibration measurements made at the surface and in the bottom of one of the observation wells indicate that vibration levels are always lower in the well. How much lower depends on the geometric relationship between the well and the blastholes and the degree of confinement of the blast. If the blast is downslope and the degree of confinement is high, the ground vibrations at the bottom of the well may be 68% as strong as those at the surface. If the elevation of the blastholes are entirely above the casing collar of the water well, the vibrations at the bottom of the well may be as little as 14% of those at the surface.

Chemical analyses of water samples taken before and after the blasts, and at periodic intervals throughout the testing period, reveal that no significant chemical change occurred. Only turbidity showed considerable fluctuation but a large part of this may have been the result of the sampling method. Further investigation of the effects of blasting on this parameter will be performed at the site in Southern Indiana.

All of the data collected in this study indicate that the commonly accepted limit of 2.0 in/sec peak particle velocity is adequage to protect water wells from any significant damage. There is a possibility that temporary turbidity may be caused at lower levels from time to time but not at any constant threshold level. At this point, the increase in turbidity appears no more significant than that caused by the normal sloughing which occurs in these uncased holes all of the time.

A better understanding of the role that stress relief plays as surface mining is conducted in Appalachia would do much to explain many of the problems that occur not only with water wells but houses and structures as well, and would suggest the best preventative and remedial measures.

PRE-MINING PRECAUTIONS AN OPERATOR SHOULD CONSIDER

Regulations promulgated as the result of the Federal Surface Mining Control and Reclamation Act of 1977 require extensive investigation of pre-mining ground water conditions and periodic monitoring as mining proceeds. Much of the required information is only available by contacting neighbors and asking questions about their wells. Assessment of neighboring wells and other groundwater system equipment is reasonably limited to surface condition and other readily available data. As stated previously, residents generally know very little about their wells. Consequently the data collected consists essentially of the well depth and an analysis of a sample collected during the investigation. In some states, the water well driller is required to file a report which indicates the strata penetrated and usually includes some estimate of the yield, usually in gallons per minute. In general the estimates are based on improper test procedures and usually overstate the actual yield by a considerable amount. An operator who is planning a surface mine operation near some water wells would do well to obtain these records and try to verify the accuracy of some of the indicated yields before mining commences.

For all wells in the vicinity of a surface mining operation, the operator in the pre-mining investigation should try to obtain at least the following data:

Depth of well

Depth of pump below surface

Type of pump

Casing length

Date drilled

Name of driller

Is a storage tank employed? How large?

Pump capacity in gallons per minute

Static water level

Well liners?

Diameter of well

Clean-out history

Distance of well from ultimate pit limit

Number of households depending on supply

Number of people depending on supply

Any large volume needs, such as a dairy farm?

Any previous history of discoloration or temporary turbidity

Is well in valley alluvium?

Is well on hillside and above or below planned mining?

Do reported depths of encountering water coincide with depth to a coal seam or a sandstone.

Is water possibly being obtained from flooded underground workings?

Analysis for pH, iron, sulfate, alkalinity and turbidity

If feasible, the operator should determine the static water level by relying on his own measurements. Determining static water level in wells that have a pitless adapter is relatively easy. The cap is removed and an electric probe can be lowered directly into the well. The main problem is in making the measurement when the well has completely recovered from a previous pump cycle. With most Appalachian wells, the recovery is fairly rapid and if subsequent measurements indicate that the water level is still rising, one will know that recovery is not complete. By leaving the probe in the well and plumbing the water level at five minute intervals for 30 minutes, one can usually tell if recovery is complete (no change, or small fluctuation) or if one is dealing with a very poor well (say, with a recovery rate of about 0.25 feet per five minute interval in a 6" diameter well).

Wells with a pit generally have a split well-seal cap with a 5/8" or 3/4" entry hole on one side sealed with a threaded plug. By removing the plug, an electric water depth probe can be lowered into the well and the static water level determined. Care should be taken to avoid any excess bobbing of the probe because it may become entangled in the electric lines in wells with submersible pumps. Of course, the measurement should be made when the well has had an opportunity to recover. It the pit is a cribbed structure with a cover, the measurement is relatively easy to perform. If the pit has been back-filled with soil with only a "breather" pipe protruding above the ground surface, it may require considerable effort and time to gain access to the well through the opening in the split well-seal cap. Furthermore, the home owner may not permit the necessary digging to be done. In such cases, it may be possible to run a special small diameter probe into the breather pipe. If this cannot be done, a chalked line with a small diameter sinker can be lowered into the breather pipe and left for a 24-hour period. When removed, measurement of the highest water level over a 24-hour period can be obtained by measuring the distance from where the water removed the chalk to the point at the top of the breather pipe.

If it appears that some well owners may have an exaggerated opinion as to the capacity of their well, it may be prudent to obtain some quantitative determination of the yield before mining commences, either by observation of water level fluctuations during a pumping cycle or by recovery after the pump stops with respect to time. If the pumping rate is known, or can be determined, and the pumping rate can be maintained for 30 minutes or more, one will probably observe an equilibrium point which can be used in determining the specific capacity. If the specific capacity can be determined, it will afford a basis for comparing different wells in the neighborhood as well as indicating any difference in the performance of the well in which it was obtained. If the system includes a storage tank, however, it is usually difficult to obtain the actual pumping rate and one should remember that pump capacity and actual pumping rate are not the same thing. In such cases, if water levels are observed at the start and at one minute intervals while the well is being pumped for 30 minutes or more, a characteristic curve can be developed even if the pump rate is not known. At a later date, provided that the same pump is still in the well and no other changes have been made to the system, a similar test should provide essentially the same curve if no change has occurred in the well. In plotting such curves, semi-log graph paper should be used with feet of drawdown plotted on the linear scale for both drawdown and recovery. For drawdown, the logarithmic scale is used for the time in minutes after the pump started. For recovery, the logarithmic scale is used for t/t', where t equals number of minutes after pumping started and t' equals number of minutes after pumping stopped. Both drawdown and recovery curves can be plotted on the same piece of paper and kept for future reference. The total time to perform such a field test would be slightly more than one hour and would require only a watch, an electric water probe, and a measuring stick to determine distances between the five foot markers on the electric probe. Alternative systems can be divised using a rubber hose in the well, a pressure gage and a bicycle pump, or through the use of depth-recording pressure transducers, or even sonic devices.

If the operation is to approach to within 500 feet of a well, the operator may wish to consider having a low-cost plastic liner installed in the well prior to mining if agreeable with the owner. If the operation is to involve excavation between 300 and 500 feet of a well with little pump submergence, the operator may want to consider deepening such a well in advance of mining in order to increase the well storage because, if lateral stress relief occurs, the owner of such a well will probably lose his source of supply until recharge occurs. By anticipating the problem, it doesn't occur. Such forthought also allows the operator to arrange for the deepening when it is convenient to his schedule, instread of being faced with a serious neighbor problem in the midst of a busy period of mining activity.

RESPONSE TO COMPLAINTS

Many things can happen to affect the quantity or quality of water being delivered by a well most of which have no relation to nearby mining. Nevertheless, because of general ignorance as to the occurrence of ground water, proper well design and maintenance, and the real effects of nearby surface mining, coal operators usually receive complaints if any change occurs.

Anyone responding to such a complaint should have a good working knowledge of water well systems and an understanding of the ground water situation in the area. There are numerous consultants in the area of groundwater hydrology and there are some very capable water well drillers who have special expertise in the design and installation of water well systems. Many times, though, these people may not be available for immediate response to a complaint. In such instances, the operator is fortunate if he has a knowledgeable employee who can make a preliminary investigation of the situation and perhaps determine the source of the problem. If not, data can be obtained which may be sufficient for an expert to offer a solution by telephone. In any case, pre-mining bench mark data such as that discussed in the previous chapter is essential in determining what has happened to the well. For example, if in response to a complaint, the static water level is measured again and found to be roughly at the same level as before mining began, the problem is likely to be related to the pump, lines, or some other part of the system, but not the aquifer.

To provide a good working background in this area for anyone who may be involved with such problems, there are two excellent references in easily understood language. The first is a publication of the West Virginia Geologic and Economic Survey, "A Practical Handbook for Individual Water-Supply Systems in West Virginia" by Ronald A. Landers. Although especially useful in West Virginia, the content is largely applicable to all areas in Appalachia. Of particular interest is a section on problem prevention, problem diagnosis, and problem solution. There is also an excellent list of general references. Copies may be obtained for $5.00 from the Survey at P. O. Box 879, Morgantown, WV 26505.

The other publication is "Ground Water and Wells" published by the Johnson Division, UOP Inc., P. O. Box 43118, St. Paul, MN 55164, available at a cost of $8.00. This book is applicable for all areas of the United States and the only problem in applying the contents to residential wells in Appalachia is that these wells yield considerably less water.

Many other references are listed in the accompanying bibliography but many of these are technical in nature and are of value primarily to ground water hydrologists.

If the person who is responsible for investigating groundwater complaints around surface mining operations will study these two references and apply that knowledge along with the concept of the effects of lateral stress relief, one will not be able to solve all residential well problems but should be able to make a good preliminary diagnosis and determine if, and what kind of, expert advice may be necessary.

ADDITIONAL RESEARCH NEEDS

As a result of the program carried out in this project, several problems became apparent where additional research should be done. These are not related to the effects of blasting on groundwater supplies and hence are beyond the scope of this project.

1. Quantitative data on the phenonmenon of lateral stress relief following excavation. This would be applicable to any type of excavation including mining and construction. The current study indicates that the effects are present for a distance of about 300 feet from the excavation. This probably will vary depending on whether the excavation is upslope, downslope, or at the same elevation. Steepness of the slope and the type of material probably determine the effects too. Not only does the phenomenon affect the performance of water wells, but it might be of significant value in designing in situ leaching or combustion projects. Attempts to measure the amount of movement during this project were unsuccessful but the probable magnitude of the increase in porosity, judged by the drop in static water levels, suggests that the amount of movement could be measured with precision distance measuring equipment.

2. Normal variation in the turbidity of well water in uncased wells. How great is the range in turbidity of water under conditions of normal household use? The continuation of the project at the Evansville, Indiana site will provide better data on the turbidity levels immediately before and immediately after nearby blasting. It would be desirable to know how any variation indicated by these data compared with normal household fluctuation.

3. Normal sloughing rate of uncased wells. For the test wells utilized in this project, there was little or no sloughing of sidewall material into the hole. Investigation of some well damage complaints indicate, however, that there are some geographical areas where sloughing mudstones are a problem requiring periodic clean-out. These sloughing mudstones are commonly involved in landslide phenomena and the tendency to slough is worsened when the mudstones are dewatered and air is permitted to oxidize some of the material. Lengthy periods of drawdown might cause the mudstone within the cone of depression to oxidize and slough. Because surface mining frequently occurs in such areas, a better understanding of this mechanism is desirable.

4. Better understanding of red water. Red water was encountered at two test sites at the start of drawdown tests. The water would normally be red for the first 30 to 50 minutes of pumping. This occured even in the pre-mining tests. On no occasion did the water turn red immediately after a blast. Nevertheless, several sites were investigated in the Phase I part of the project where the owners of water wells claimed that their well water turned red immediately after a blast. In all of these cases, there were abandoned underground workings nearby and there is a possibility that the well water was coming from flooded portions of these old mines.

The red water encountered in the project wells at the commencement of pumping, was not abnormally high in dissolved iron. The red material is apparently suspended discrete particles and the origin appears to be bacterial. In some wells, red slimes will form on the sidewalls and on discharge lines necessitating periodic cleanup. Because this didn't occur to any significant extent in the test wells, there was no direct opportunity to determine if blast induced ground vibrations might cause some slime to slough into the pump intake.

It might be possible to develop laboratory experiments to determine the effect of transient vibrations in causing these slimes to slough, using host surfaces of different material and roughness.

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INVESTIGATION OF BLAST-DAMAGED WELL COMPLAINTS

Letter inquiries were sent to the surface mining regulatory agencies in each state in Appalachia where coal is mined. These inquiries asked for data on water wells where the agency had received a complaint of blast damage.

Inquiries were also sent to many coal mining companies, insurance companies, trade associations, and explosive suppliers. In all, about 150 inquiries were made.

Responses were received from all states except Kentucky and Tennessee, although the Kentucky Geological Survey was most helpful in supplying geologic data pertaining to a complaint near Prestonsburg, Kentucky. Ohio, Pennsylvania, Virginia, and West Virginia presented 22 case histories. Coal companies provided 10 complaint histories, and 4 examples were obtained from correspondence between the Center for Science in the Public Interest and the U. S. Bureau of Mines. In addition, there were 10 replies indicating no knowledge of any blast damaged wells.

Of the total of 36 wells reported as damaged by blasting, field visits were made to 24 of the sites and additional information obtained from either direct well measurement, discussion with the owner, or individuals handling the complaints for the coal company.

In many cases, it was apparent that the damage claimed was caused by something other than blasting. In some cases, leaks in near surface water lines had caused the pump to run continuously resulting in a lower static water level or a burned out pump.

In other cases, it was apparent that there was a general lowering of the water table which could have been due to a variety of causes but probably not blasting. Some of these causes might have been unplugged flowing test holes, interception of the aquifer in the pit highwall and subsequent draining, or a two-to-threefold increase in the number of residences utilizing a limited supply, combined with seasonal changes.

In nearly every case, there was a lack of good benchmark data. Many residents have only a vague idea of the depth of their wells and if measurements are made there may be a large discrepancy. Fewer have knowledge of the depth of casing. None of the residents interviewed knew the source aquifer in their well. About fifty percent had a vague idea of the static water level when the well was originally completed. Only one well had been tested in any quantitative way on completion and that test was inadequate. (The well was pumped dry in thirty minutes at a pumping rate of 30 gpm. The completion report indicated that the capacity was 30 gpm.)

Consequently, it is very difficult to confirm or deny that blast damage has occurred. In making these investigations, the owner's statements, perhaps amplified by a measurement of static water level or an observation of present quality, are the only data available. If the owner is convinced that blasting caused his problem, his account of the facts is not only limited by his understanding of wells and groundwater, but may be somewhat less than objective.

With this caveat in mind, the readily available "data" from the 36 wells are summarized in Table No. 1 and the locations shown on the map in Figure 1. The well data are analyzed in three matrices in Tables 2, 3, and 4. Totals are greater than 36 because two types of damage are claimed for some wells. Totals vary because data were not always available.

The size of the sample and the quality of the data eliminate the possibility of drawing any firm conclusions, but the matrices do suggest some hypotheses. In Table No. 2, 75% of the wells were within 1,500 feet of the coal strip blasting. The remaining 25% were at a distance greater than 2,400 feet, leaving a gap of 900 feet. Of the 10 wells at 2,400 feet or greater, the 5 with the lower static water level definitely appeared to have been affected by an unplugged flowing well from the same aquifer at a lower elevation. In one of the two wells with diminished flow, the inlet and discharge lines for the jet pump have not been pulled from the well since installation thirteen years ago. Normally, with jet pumps in Appalachia, it is necessary to clean out the lines and replace the foot valve every two or three years. In addition, this well originally served one dwelling but now serves another house and seven trailers. The diminished flow may be more apparent than real. The other instance of diminished flow at a distance of 2,400 feet or more involves a well system with a history of broken water lines which were buried at a depth of only two feet. This has caused the pump to run continually at times and unnecessarily deplete the resource.

The well where the sides were claimed to collapse was reported by a coal company. It was investigated by the Ohio Department of Natural Resources. Apparently, they decided the claim was not justified.

Therefore, it appears that in at least 8 of the 10 wells at distances greater than 2,400 feet, the observed effect is more likely to have been caused by something other than blasting. As one would expect, proximity to the blast must be an important factor in determining whether or not the well will be damaged.

Because residents were unable, in most cases, to recall the date of damage, blast data could not be determined but it is obvious that as in other studies of blast damage, explosive charge weight per delay will also be an important factor.

As with blast data, vibration measurements were not available because they weren't generally recorded even if the date of the blast had been known. Thus, no relation between these damage claims and peak particle velocity can be established or with length of vibratory effect. These items will be measured, of course, in the field test phase of the program. Attenuation of vibrations with depth will also be investigated.

If blasting is the cause of the damage, abruptness of problem onset should certainly exist. Table No. 3 relates the type of damage claimed to the approximate time interval between blast and onset of the problem. This table suggests that lowering of the static water level is probably more related to causes other than blasting. However, one specific case, not related to coal mining, was encountered in which a water well, at a distance from the blast of 150 ± feet and topographically higher, experienced a significant drop in static water level immediately after the blast. The

TABLE 1 - List of Water Wells Claimed to Have Been Damaged by Blasting

	Location	Depth, Feet	Casing, Feet	Type Damage*	Problem Onset	Approx. Distance from Blasting, Feet
1.	Eldred Twp., Jefferson Co., PA	185	20	C	Abrupt	17,000
2.	Mineral Co., WV	300	45	A	Gradual	1,000
3.	" " "	240	?	A	Gradual	1,000
4.	" " "	50	40	A	Gradual	1,000
5.	" " "	95	35	A	Gradual	1,000
6.	" " "	115	?	A	Gradual	1,000
7.	" " "	160	?	A	Gradual	5,000
8.	" " "	58	?	A	Gradual	5,000
9.	" " "	65	?	A	Gradual	5,000
10.	" " "	260	33	A	Gradual	5,000
11.	" " "	143	10	A	Gradual	5,000
12.	Quaker City, OH	69	?	C	Abrupt	700
13.	" " "	?	?	C	Abrupt	1,270
14.	New Concord, OH	140	?	B & C	Abrupt	850
15.	" " "	105	?	C	Abrupt	850
16.	Kirkwood Typ., Belmont Co., OH	100	?	B & C	Abrupt	4,500
17.	Rayland, OH	80	Est. 20	E	Intermediate	300
18.	Roy Meadows, Richland Dist., WV	117	?	D	Abrupt	1,200
19.	Clintwood, VA	88	37	D	Abrupt	300
20.	" "	Est. 100	?	D	Abrupt	300

List of Water Wells Claimed to Have Been Damaged by Blasting - Continued

	Location	Depth, Feet	Casing, Feet	Type Damage*	Problem Onset	Approx. Distance from Blasting Feet
21.	Norton, VA	400	16	C	Abrupt	165
22.	Claude Ryan, Prestonsburg, KY	110	20	B & C	Abrupt	900
23.	" " " "	110	?	B	Gradual	2,500
24.	" " " "	10	Dug	F	Intermediate	900
25.	Westmoreland Co., PA	200	25	B & C	Abrupt	900
26.	" " "	240	20	A & B	Intermediate	800
27.	" " "	55	?	A	Gradual	1,000
28.	Boyers, PA	45	?	C	Abrupt	200
29.	" "	95	?	C	Abrupt	200
30.	Bristol Twp., Morgan Co., OH	?	?	G	Abrupt	6,000
31.	Lisbon, OH	200	Est.20	C & E	Abrupt	?
32.	" "	125	?	D	Abrupt	900
33.	Warnock, OH	78	30	B	Intermediate	300
34.	" "	80	?	B	Intermediate	300
35.	" "	50	?	B	Intermediate	300
36.	" "	98	40	B	Intermediate	175

* Types of Damage

A. Lower static water level
B. Diminished yield
C. Temporary turbidity
D. Permanent quality change (iron, sulfur, color, and/or pH)
E. Intermittently dry
F. Permanently dry
G. Hole collapsed

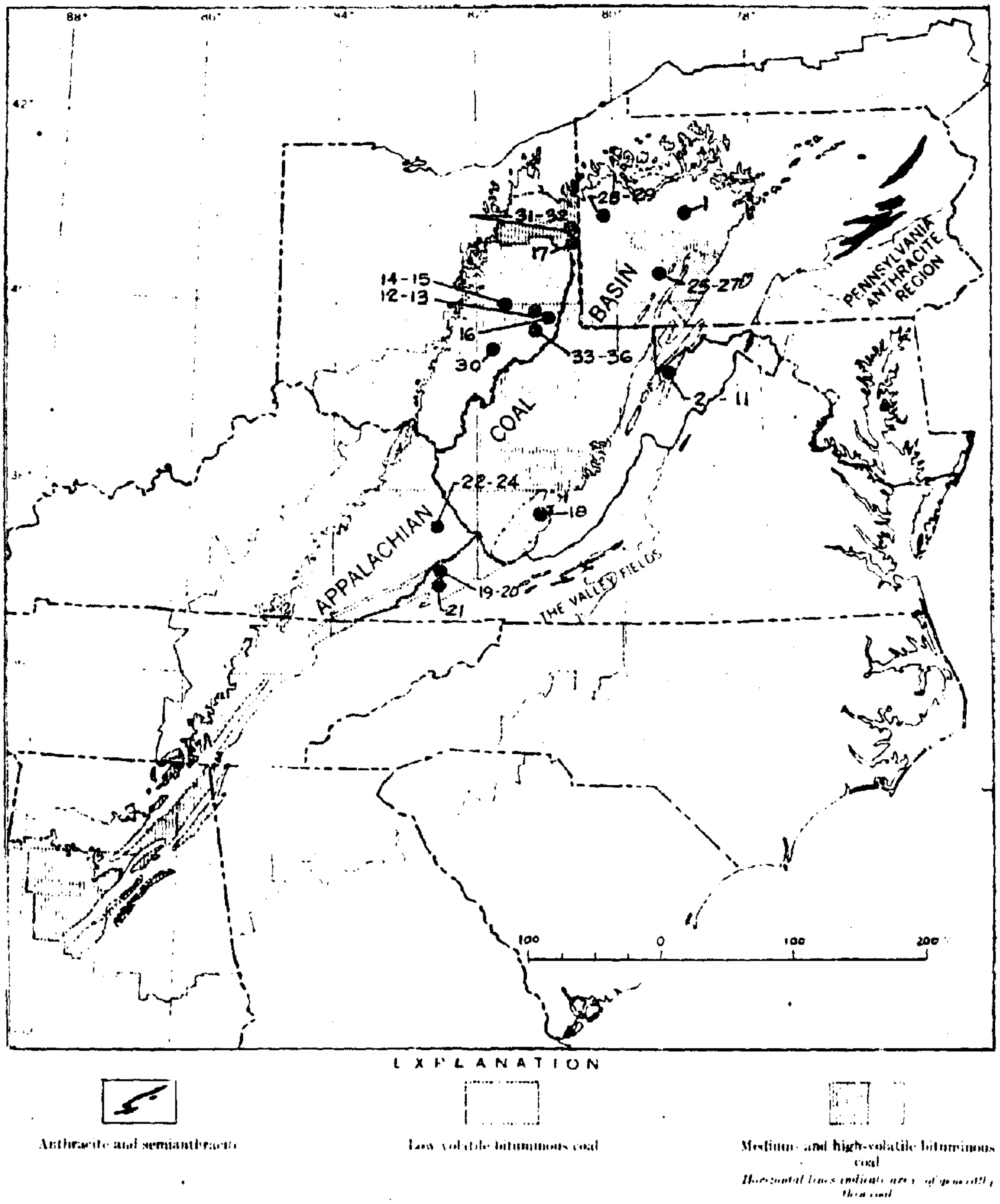

FIGURE 1

MAP SHOWING LOCATION OF WATER WELLS WHICH WERE REPORTED AS DAMAGED BY BLASTING
Numbers correspond to numbers used in Table 1

From USGS Prof. Paper 580

TABLE 2 - Matrix Showing Type of Damage Claimed Versus Distance from Blast

Damage Claimed	Distance from Coal Surface Mine, Feet 0 - 300	301-600	601-900	901-1200	1201-1500	1501-1800	1801-2100	2101-2400	Over 2401
Lower SWL			1	6					5,
Diminished flow	4		4						2
Temp. turbidity	3		5		1				2
Perm. qual. change	2		1	1					
Intermittently dry	1								
Permanently dry			1						
Hole collapsed									1
Total	10		12	7	1				10

TABLE 3 - Matrix Showing Type of Damage Claimed Versus Time Interval Between Blast and Onset of Problem

Damage Claimed	Abrupt Change (within 24 Hrs. of Blast)	Intermediate (Change Noticed After a Day or so)	Gradual (Indefinite Onset of Problem)
Lower SWL		1	11
Diminished flow	4	5	1
Temp. turbidity	12		
Perm. qual. change	4		
Intermittently dry	1	1	
Permanently dry		1	
Hole collapsed	1		
Total	22	8	12

blast occurred at 3:00 P. M. on July 17, 1972 in a limestone quarry in Hardy County, West Virginia. There was a float recorder in the well. Water was obtained from fractured limestone. The water level dropped two feet in the following twenty-four hours and then continued to drop at the rate of about 0.5 feet per day until the end of July when it leveled off for about eight days, then continued to decline until September. A large part of this may have been normal seasonal decline because the static water level recovered to previous levels in December. A graph of the available data is presented in Figure 2.

For the reasons previously stated, it is not likely that the blast-induced fractures extended out to this well, but they may have extended 10 to 15 feet and intercepted the natural fracture system from which water was being obtained, permitting water to flow into lower unsaturated areas. Apparently, these became saturated, or sealed off, in some manner and the static water level recovered.

It may be that such events are more common but are not detected in normal residential water well use. Because of the low yield of Appalachian aquifers, most residents probably operate their households from the readily available water in the well bore, generally known as casing storage. In a 6-inch diameter well, 100 feet deep, this could amount to 90 gallons if the static water level prior to pumping was at 40 feet. Most residents wouldn't detect a change until the casing storage had fallen to a level that would not sustain normal intermittent use.

Table No. 4 indicates the depth of wells in relation to the type of damage claimed. This matrix does not suggest much of anything except that temporary turbidity may be more evident in the deeper wells (with more open hole section). The total at the bottom indicates the distribution for this small sample and tends to confirm the intuitive impression that the average Appalachian water well is about 100 feet deep.

These matrices and the general observations made in the field suggest two main damage scenarios:

1. The long uncased sections and the number of people reporting cloudy or muddy water suggests that if blasting vibrations are sufficiently high, parts of the well bore may slough into the well. When the well is rotary drilled with air, fine dust and cuttings are plastered on the sides of the well. Water is introduced for clean-up but some of this material probably remains to form an unstable mudcake, particularly above the static water level. In addition, sloughing shales which are common in Pennsylvanian System sediments may cave into the hole. These effects could occur naturally with time or be influenced by water surges, earth tides, vibration of down-the-hole pump parts and lines, passing trains or trucks, stress redistribution from building, or blasting vibrations.

   An uncased borehole consisting of 80 feet or so of shale, mudstone, siltstone, and/or standstone is an unstable situation. Eventually, some material will cave into the well. If there is a submersible pump at the bottom, the material may jam the pump and no water will

FIGURE 2

GRAPH OF STATIC WATER LEVEL IN WELL IN HARDY COUNTY, WEST VIRGINIA

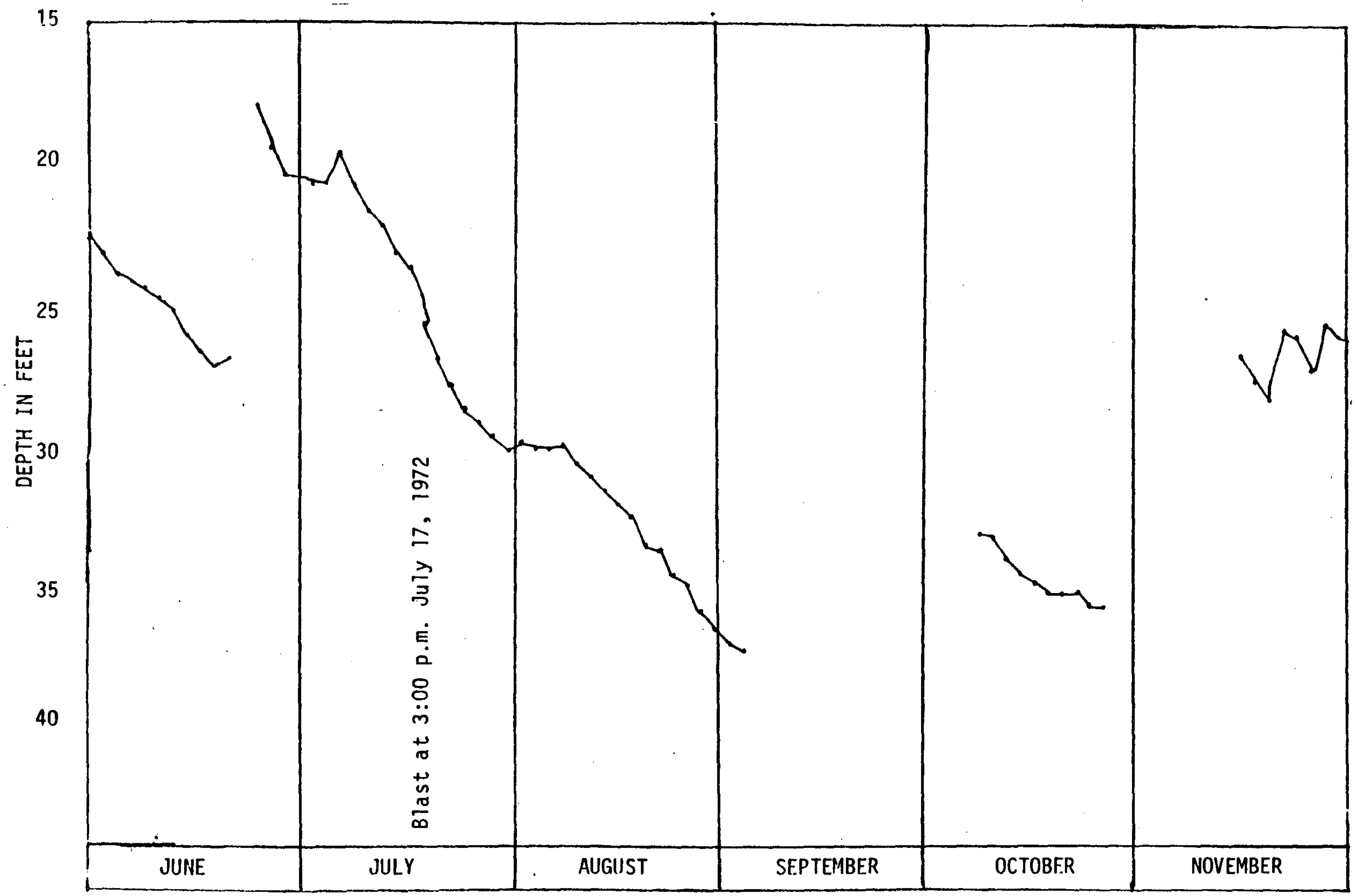

TABLE 4 Matrix Showing Type of Damage Claimed Versus Depth of Water Well

	Depth of Well, Feet												
Damage Claimed	0-25	26-50	51-75	76-100	101-125	126-150	151-175	176-200	201-225	226-250	251-275	276-300	Over 300
Lower SWL		1	3	1	1	1	1			2	1	1	
Diminished flow		1		4	2	1		1		1			
Temp. turbidity		1	1	2	2	1		2	1				1
Perm. qual. change				2	2								
Intermittently dry				1					1				
Permanently dry	1												
Hole collapsed													
Total	1	3	4	10	7	3	1	3	2	3	1	1	1

be obtained. Eventually, the caved material may pass through the pump and appear as mud, or in some cases, as shale particles. In such cases, the water usually clears up in a day or two. If there is a lot of caving at one time or a small amount of caving from time to time, it may bypass the pump and settle deeper in the hole. If it falls against the aquifer, it may diminish or seal off the flow. This scenario is primarily concerned with quantity effects except for the temporary turbidity. High iron content, acid pH, or sulfur odor is not involved.

2. A fewer number of people complain of an abrupt change in quality which involves high iron content, acid pH, and/or sulfur odors. In general, these wells appear to be associated with better yields. The change is relatively permanent. Usually, the change is too abrupt and the distance too great to call upon seepage of acid mine drainage from the pit. In most cases investigated, there was evidence of abandoned nearby deep mining, possibly with accumulation of mine water in low areas or in downdip localities. This water can become stratified with the acid mine drainage at the bottom and relatively potable water at the top (personal communication, D. R. Thompson, Pennsylvania Department of Environmental Resources). Such abandoned workings are generally unstable with roof falls being common. For any well which is obtaining water associated fairly directly with such a system, an abrupt change in quality could occur if a roof fall disturbed the water stratification either directly or by changing the flow pattern. Verification of the likelihood of this scenario is the fact that one such complainant indicated that he had to clean coal silt out of the well lines about every month or so.

   Because of the long history of underground coal mining in Appalachia on both large and small scales, it is probably impossible to determine exactly all of those areas underlain by abandoned workings.

   For the same reasons that sloughing or caving of the unstable well bore may occur, sloughing and caving can occur in the unstable abandoned mine workings.

Note.-

Appendix A "Investigations of Blast Damage Well Complaints" was written before the drawdown tests were conducted at the test sites and any conclusions had been arrived at from that information. It is now felt that the steady drop of the water level in the well in Figure 2 was caused by lateral stress relief.