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THE DEVELOPMENT OF A CONTINUOUS DRILL AND BLAST TUNNELING CONCEPT
PHASE II

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16. Abstract

A spiral drilling pattern is described which offers high efficiency drill and blast tunneling via frequent small blasts rather than occasional large blasts. Design work is presented for a machine which would stay at the face to provide essentially continuous drilling, loading, blasting, and mucking. Field tests provide the concept are described and photos of the spiral tunnel advance are provided. Successful testing of a suitable blast shield is also described and photos provided. Advance rates of four times conventional drill and blast practice are projected at about half the conventional cost per foot.

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The Development of a Continuous
Drill and Blast Tunneling Concept
Phase II

Preface

One of the goals of the Rapid Excavation development effort has been development of a continuous drill and blast tunneling capability in recognition of the fact that conventional drill and blast practice, while economical in many situations, suffers badly from its cyclic nature. The RAPIDEX spiral blast concept offers an attractive approach to this goal while maintaining many of the virtues, such as economy and flexibility, of the conventional method. Preliminary studies of the concept were funded by the ARPA Rapid Excavation program, monitored by the Bureau of Mines. Field testing of critical aspects of the concept were successfully completed under Department of Transportation funding and are reported herein. Economical blasting according to the spiral pattern, and the required machine shielding, were both successfully demonstrated in underground tests at the White Pine Copper Company mine in White Pine, Michigan. Preliminary machine design was completed for which performance projections indicate the possibility of a fourfold increase in advance rate at half the cost compared to conventional practice.

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1. Program Summary

The RAPIDEX continuous spiral blast concept replaces the occasional heavy blasting of conventional drill and blast tunneling with frequent, relatively light blasts while maintaining the high blast efficiency of the best conventional geometries. Individual light blasts, together with the spiral face geometry itself, permit the use of a shielded automated drill and blast machine that stays at the tunnel face to provide virtually continuous advance, exceeding the economy and performance of the conventional drill and blast practice while retaining its flexibility. Performance and cost estimates indicate an advance rate approximately four times conventional practice at roughly half the cost based on one mile long 18' x 18' tunnel.

The drilling pattern establishes and maintains a plane-free surface that rotates and advances in spiral fashion as the tunnel advances. Every individual blast occurs adjacent to this surface, producing rock fragments largely by a highly efficient slabbing action. Tunnel sections of any common shape--circular, horseshoe, rectangular, or whatever--may be produced, and in fact, tunnel shape and size may be readily changed without machine modification.

An early study (1) indicated an attractive performance potential for the concept and provided a preliminary machine design. The spiral blast geometry, per se, seemed feasible, as it was discovered that the geometry had been used in circular shaft sinking operations. However, no horizontal or noncircular work had been done, and the unique suitability of the pattern for use with a shielded machine which remained at the face had not previously been recognized. The present program, then, was undertaken to study spiral blast performance in a horizontal, horseshoe entry to determine both basic workability and quantitative performance data and to see if blast action would indeed be compatible with a "continuous" tunneling machine at the face.

Experimental blasting was done at the White Pine copper mine in White Pine, Michigan, utilizing the facilities, equipment, and highly skilled personnel of that operation. A 10 x 10 foot horseshoe entry was driven to a depth of about 30 feet, and for later special tests, a second 10 x 10 foot heading was driven to about a 10-foot depth. A powder factor comparable to good conventional practice, as low as 1.05 pounds/ton and averaging 1.8 pounds/ton, was demonstrated along with a hole factor, 3.9 feet/ton, comparable to production underground mining experience in a similar size heading. After some practice, those directly associated with the experimental work found it easy to maintain the desired 5-foot advance of the entry per revolution of the spiral.

Most experimental blasting was done with stick explosive, but highly satisfactory, even superior, performance was also demonstrated with ANFO. Collar initiation of the explosive, considered desirable for remote operation, was as satisfactory as more conventional hole-bottom initiation.

At a fairly early date, it became evident that the spiral blast geometry was quite workable, and that while much remained to be learned about the "optimum" combination(s) of explosive(s), loading and geometry, these questions would not be of critical importance. Furthermore, explosives advisors indicated that any of a wide variety of explosives would be satisfactory, with a final choice dependent upon handling safety and convenience rather than rock behavior. Accordingly, the final portion of the present effort was redirected from the originally proposed blasting study to consideration of the next most critical problem--the provision of a suitable blast shield. Aside from workability of the basic geometry, machine survivability is clearly the most important ingredient in satisfactory performance.

The RAPIDEX spiral blast machine utilizes a relatively light-weight shield aligned axially in the tunnel, taking advantage of the spiral geometry which throws most blast fragments away from the shield and other forward machine components. A preliminary shield design was completed, consisting of a 4 1/2 x 10 foot wire mesh supported on a steel frame and pivoted about one 10 foot edge at the centerline of the tunnel as the spiral face configuration "rotates." The shield was fabricated and tested through one full blasting revolution. No significant shield damage was sustained, and although minor changes in shield shape are suggested, it is evident that satisfactory performance can be attained.

Remaining obstacles in the development path, and there are no doubt many, cannot be overcome on paper. Development of a prototype machine is recommended, including as a first step, provision of all necessary machine functions, except monitoring for remote control. It is felt that all mechanical problems, including proper functioning, control, shielding, and over-all survivability, should be worked out with "on-board" controls prior to attempting remote control. As appropriate, one or more development programs for the necessary remote explosive loading and initiation components should also be undertaken, with the ongoing prototype development equipment serving as the field test vehicle for these components. With an adequate effort, a prototype can be ready for installation of monitoring and remote control elements in about one year.

2. Introduction

The need for substantial advances in underground excavation technology has produced considerable research activity on a wide variety of concepts under a variety of Government funded programs. One goal of this "Rapid Excavation" effort has been the development of a means to apply the well-known virtues, both technical and economic, of the drill and blast method in a continuous process. The spiral blast concept, aimed at this specific goal, has been funded for initial studies (1) by the ARPA Rapid Excavation Program and, for the experimental work reported herein, by the Department of Transportation.

The economy enjoyed by the drill and blast method stems from two factors: explosive energy is relatively cheap; and this energy is released so as to cause rock fragmentation largely through tensile failures. The relative ease and efficiency of tensile rock failures have long been recognized and studies have been undertaken to better understand this behavior (2,3).

The drill and blast process of course cannot be truly continuous since drilling and blasting (and other necessary functions) simply are separate, distinct, operations. Although some surface explosive work has been done to avoid the need for drilled blast holes (4) it does appear that the high performance associated with explosive excavation requires placement of the explosive beneath the rock surface. This report describes an experimental study of a new blasting pattern which, in simplest terms, replaces the occasional heavy blast of conventional practice with frequent, much smaller blasts. The objective, of course, is to reduce the size of individual blasts to a level which can be withstood by a properly shielded machine adjacent to the face. This machine, which would perform drilling, loading, and mucking functions, would not be withdrawn for blasting, and a virtually continuous process could be carried out. The result, as viewed in terms of muck flow and heading advance, would for all practical purposes be continuous.

2.1 The Spiral Blast Concept

One cannot simply reduce the size of individual blasts while maintaining a high blasting efficiency (and economy). The blasting pattern must be designed to provide a favorable geometry for each individual shot. The spiral blast pattern is an unique arrangement that places a plane free face adjacent to every shot, thus allowing each hole to "slab" its burden much like a bench round in open pit mines. This is opposed to a conventional "V-cut" round or "burn cut" round which must first open up the center of the round before slabbing can take place.

The concept is illustrated schematically in Figure 1, repeated from Reference (1). The blast hole pattern consists of essentially axial holes bored in radial rows or "spokes." All holes along one spoke of the pattern are drilled to the same depth, with the depth gradually increasing from spoke to spoke. The locus of the hole bottoms at any particular radius would be a spiral.

Explosive is loaded into boreholes along one spoke and shot, thus producing an essentially plane surface, parallel to (and containing) the axis of the tunnel. The next row of holes is then loaded and shot, and so on, with each "pie shaped" section being rather easily removed because of the adjacent free surface. The advancing tunnel geometry will be a combination of a spiral face formed by the holebottom

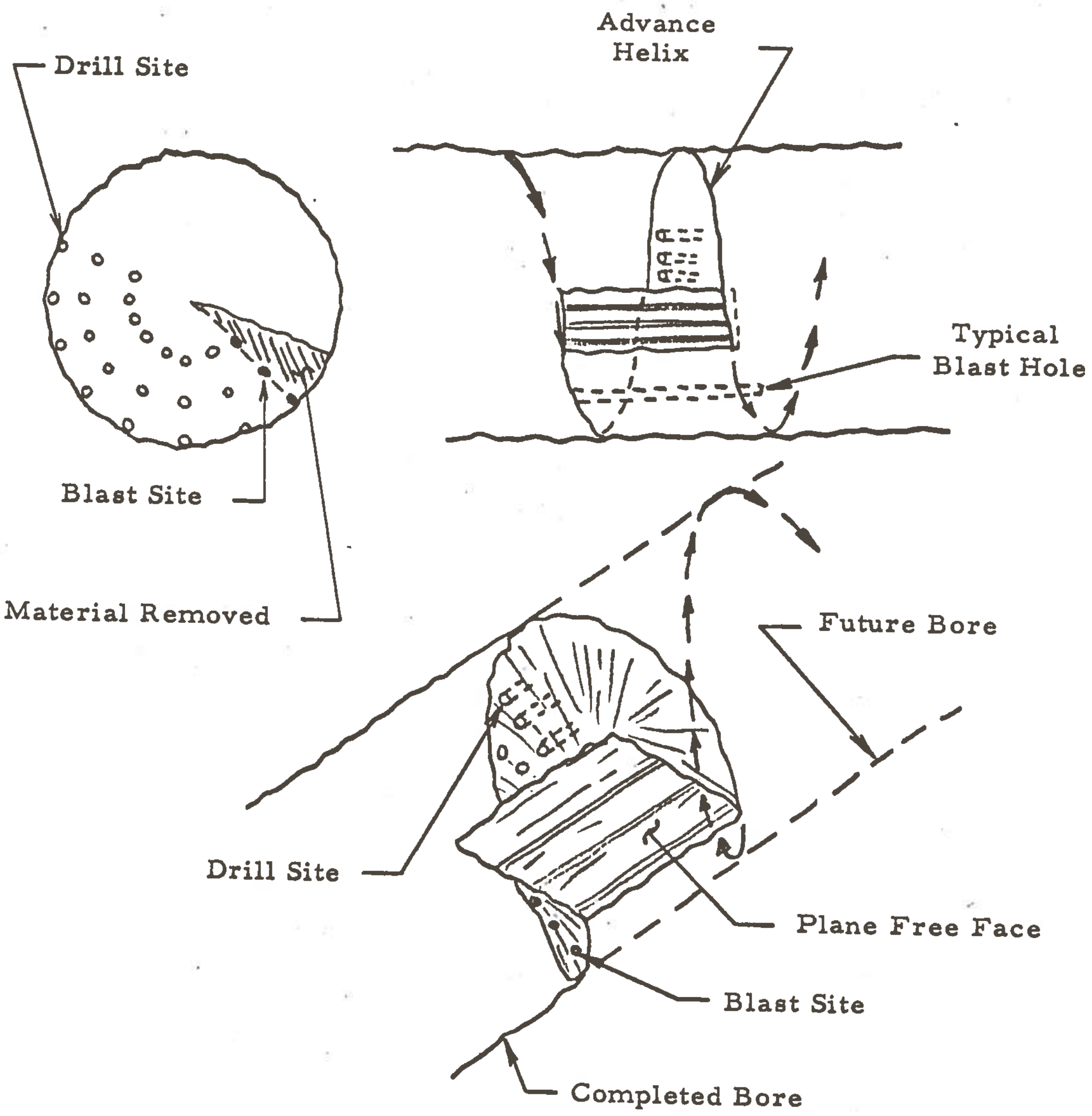


FIGURE 1
BASIC SPIRAL BLAST CONCEPT

distribution (like one turn of a screw conveyor blade) and the intersecting rectangular plane surface. Of course, the outermost boreholes must diverge slightly from the tunnel axis to provide wall clearance for the drill, as in any drill pattern.

In concept the complete spiral blast tunneling machine would employ one or more automated drills, drilling in advance of the loading and shooting position. Drilling equipment and explosive loading equipment would be mounted on a radial arm which may be rotated about the tunnel axis. Mucking would of course occur at the tunnel floor. Mucking equipment can be relatively small since, with nearly continuous blasting, it will never face a large muck pile as occurs with the conventional system.

In addition to providing an efficient blasting geometry, the spiral geometry also enhances the shielding of machine components. By working ahead (i.e., in the circumferential direction) of the blast area, drills are substantially shielded by in-place rock and, in addition, major blast fragments are projected away from the drills in a generally tangential direction. A relatively light shield, aligned axially and movable with respect to both the blast site and the drills, can provide the necessary additional shielding. This is in sharp contrast to recently patented devices and methods (5, 6) which enclose drilling, loading and initiation equipment in "modules" which are required to stand directly in front of the blast. In fact, it is anticipated that with proper design the spiral blast concept will permit simultaneous drilling and blasting.

The spiral blasting pattern, per se, is not new. It was patented by Ronald C. Baldwin (Patent No. 3,098,641, assigned to Ingersoll-Rand Company) in 1963 and used in sinking very large (65 feet in diameter) shafts for Atlas missile silos in northern New York. It has also been used for smaller shafts in Sweden where it is known as the "Swedish spiral shaft sinking method" (7). Curiously enough, that Swedish work is directly traceable to the Baldwin concept as carried to Sweden by an Ingersoll-Rand employee. However, neither the Baldwin Patent and his application of the concept in New York nor the Swedish applications recognize and/or teach the unique suitability of the spiral blast pattern for firing efficient, single, shots in combination with a shielded machine which stays at the face.

This shaft work and the sketch of Figure 1 all relate to cylindrical geometries, but the spiral blast method is not limited to that shape. Indeed, one of the major advantages of the method is that it can produce any reasonable shape and, in fact, shape and size can be varied within a single bore without machine alterations.

2.2 Phase I. ARPA-Funded Work

The first phase of the spiral blast work was funded within the ARPA Rapid Excavation program and is reported in detail in Reference (1). Briefly, that work was a feasibility study of the spiral blast pattern and a preliminary design study of a machine to provide continuous tunneling capability.

At the inception of the feasibility study, it was not known that the spiral blast pattern had been used. Knowledge of this fact of course established feasibility of the drilling pattern per se, and the study then moved on to estimation of specific drilling patterns, machine requirements and performance.

An 8 x 8 foot horseshoe section tunnel was assumed and, based on a four-foot advance per revolution of the spiral and reasonable component performances, an advance rate of 8 to 13 feet per hour was predicted. This performance requires the development of a suitable explosive loading and initiation capability, but in all other respects off-the-shelf conventional components can be used.

2.3 Goals of Phase II

The present, or Phase II program, was undertaken to experimentally study the spiral blast pattern. All drilling, blasting, and mucking work were to be done by conventional equipment, with test work carried out at the White Pine Copper Mine in White Pine, Michigan. A cooperative mine is an ideal tunneling test facility, providing a place to put the tunnel (they are not that easily found), skilled personnel, and all necessary equipment.

Knowledge of prior use of the spiral blast pattern in shaft sinking indicated that rock could be excavated in a spiral geometry although, to our knowledge, it had never been used to drive a horizontal entry. However, much remained to be learned regarding specific drilling patterns, hole loading, muck behavior and so on.

The blasting work was to begin with common stick explosives for convenience and move on to other explosives more suitable for remote loading. Actually, the work moved directly from stick explosive to ANFO and, having success with the latter, it did not seem necessary at this time to explore the wide variety of pumpable explosives available (all more costly than ANFO).

With the successful development of spiral blasting the original progress goals were changed to include design, fabrication, and testing of a suitable blast shield. This shift in goals is not an indication that blasting research for the spiral geometry is completed. In fact, much remains to be learned, but it becamse clear that no insurmountable obstacles would be found in the spiral blasting geometry. Thus the program was shifted to explore the most obvious remaining obstacle in the path of an operational spiral blast machine; the development of the necessary blast shield.

3. Experimental Blasting

Preliminary work on Phase I (1) lead to the selection of an 8 x 8 foot, horseshoe tunnel as a desirable cross section for preliminary blasting work. In addition to being of practical interest, this shape would demonstrate the ability of the spiral blast system to produce other than round tunnels, while the flat floor would provide needed space for an eventual prototype machine. The eight-foot size was erroneously selected on the assumption that a smaller heading would be more economical. In order to permit the use of available equipment at White Pine (particularly mucking equipment) this was later changed to a 10 x 10 foot section.

3.1 Development of the Drilling Pattern

Experimental blasting work was done under subcontract to the Copper Range Company at their White Pine Mine in White Pine, Michigan. The subcontractor provided skilled miners, mining engineers, the test site, equipment and supplies for all experimental work.

The test was located at the White Pine "Phase I longwall site," a region which was mined in 1966 and has since seen a wide variety of experimental work. The mine workings are located near the base of a deposit known as the Nonesuch Shales. The test site was at a depth of 400 feet. Rock (ore) is laminated shale, siltstone, and fine to coarse grained sandstone, having a range of compressive strength from 13,000 to 26,000 psi. Jointing is heavy, with spacing somewhat less than six inches.

The blasting pattern anticipated in preliminary design work (for an 8 x 8 foot heading) is shown in Figure 2. In keeping with the spiral blast concept, blast holes are arranged in radial rows or "spokes." Unlike conventional practice, it was felt that, in comparison to that hole pattern which gives minimum explosive consumption, some compromise in the exact hole spacing may be desirable in the interest of machine simplicity (see Section 4). Thus, the drilling pattern of Figure 2 was evolved for the drill support system shown in Figure 3 in which three drills are mounted on a single, radially extendible, arm. Two drills are held in fixed position relative to each other while the third is held on a simple pivoting arm to accomodate the variable angle between wall and radial directions for the non-circular cross section.

Experimental work at White Pine was done with a single drill, either jack-leg mounted or, for most work, carried on a conventional crawler mount. While this allowed complete freedom in hole placement, the ultimate needs of a simple, automated system were kept in mind as experimental work progressed.

Lingering doubts of the basic feasibility of the spiral blast concept in a horizontal entry were eliminated in the first revolution of the test spiral. This revolution took the face from a flat surface to the desired spiral shape with a "left-hand" (counterclockwise) rotation. Each hole was able to break the rock beyond the previously established face, providing the necessary advance from spoke to spoke.

As stated, experimental work was done in a 10 x 10 foot horseshoe entry to accomodate the mucking equipment available at White Pine. An advance per rotation of five feet was anticipated and, while this was accomplished with ease, no attempt to produce greater advance per revolution was made.

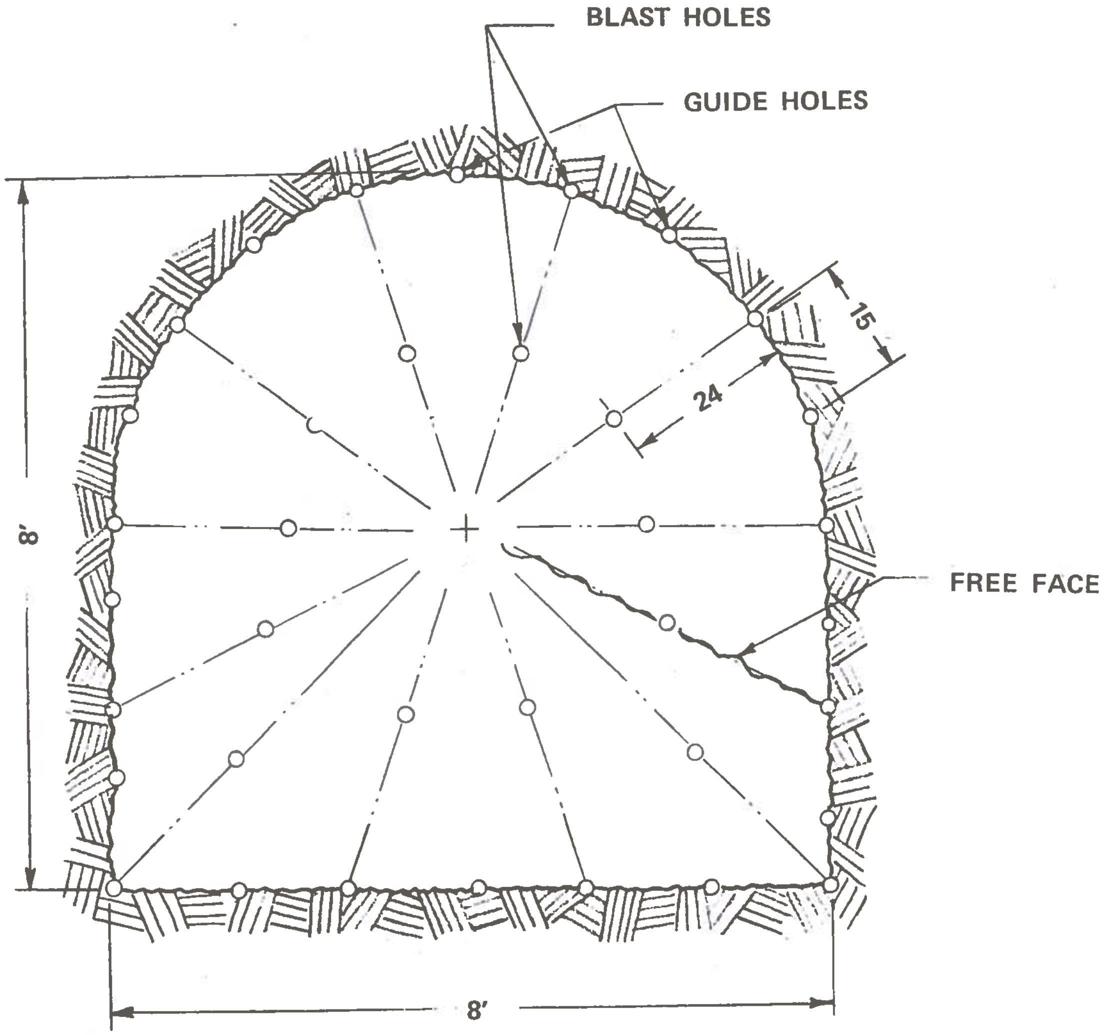


FIGURE 2
PRELIMINARY HORSESHOE TUNNEL BLAST PATTERN

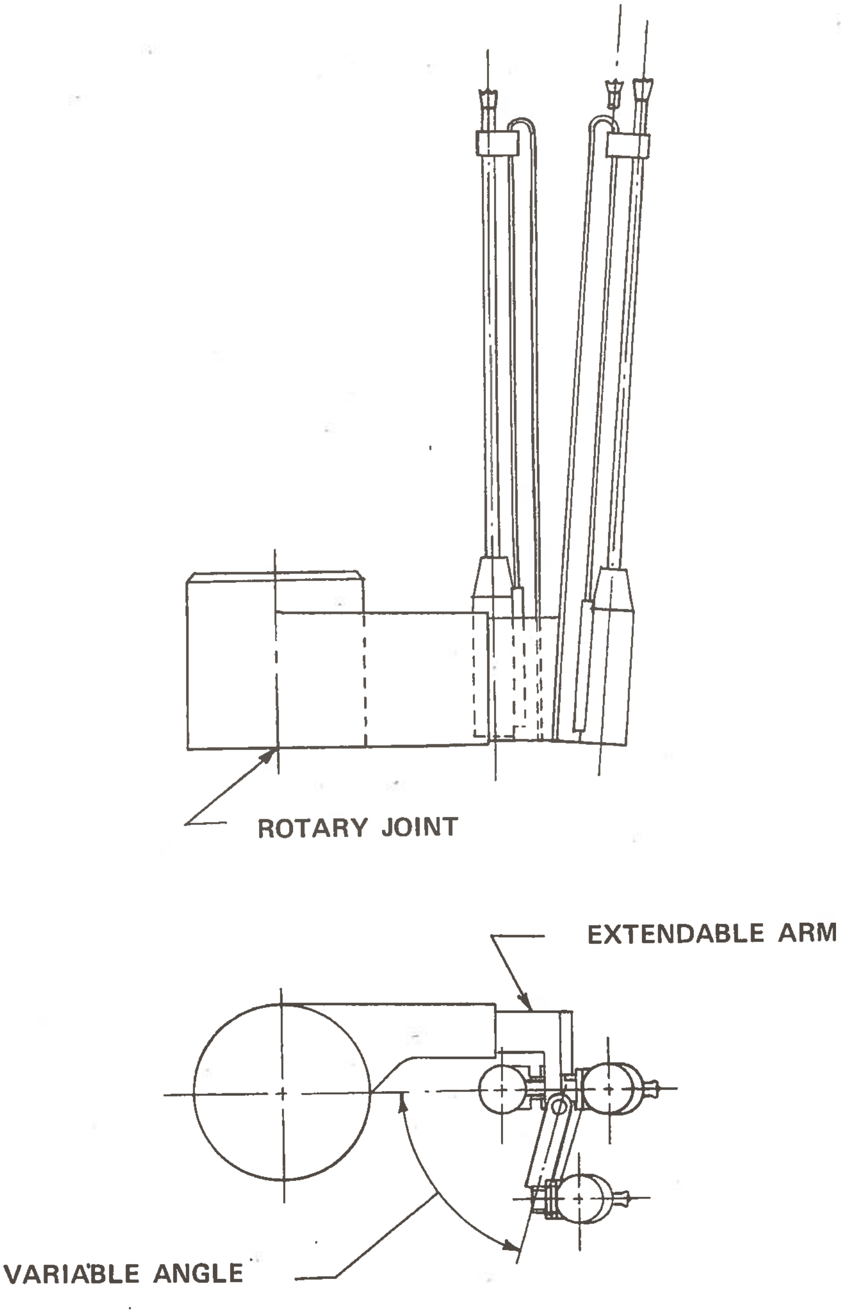


FIGURE 3
ROTATING DRILL MOUNT ARM

Ultimately holes will be drilled in groups, depending upon the number and mounting of drills, and fired individually at evenly spaced intervals to minimize blast effect and to provide nearly continuous advance. In this experimental work, holes were drilled individually, there being only one drill in use, and fired in small groups to avoid the excessive loading and ventilation delays of individual shots. Within each group, however, each hole was fired independently of the others by using standard delays. Groups were defined by an arbitrary division of the face into eight "pie-shaped" segments. Thus, for an advance of five feet per revolution, each segment must provide an advance of 5 x 12/8 or about 7 1/2 inches.

No problems were experienced in starting the spiral although, as in many experimental blasting programs, the first holes were overpowdered. Eleven holes were drilled in the first group, each about 8 inches deep and powdered with one-half stick of 60-extra powder. This gave a powder factor for this group of about 12 pounds of explosive per ton of rock. The powder consumption was reduced by the end of the first revolution to approximately 1.3 pounds per ton in six holes.

By the end of the second revolution a firm drilling pattern had evolved, as shown in Figure 4. Each group included two "spokes," one of three holes and another of two. Discounting the central hole, which usually is not needed, this pattern contains forty holes as compared with thirty-six in the tentative 8 x 8 foot heading. In the 10 x 10 foot heading all holes were powdered, whereas the smaller pattern assumed twelve unpowdered "guide holes" in the periphery. Guide holes were not found to be necessary for the drilling pattern shown in the particular rock at White Pine.

Radial spacing of the holes in each spoke of the pattern shown in Figure 4 was about as shown, but the exact placement of any individual hole was selected after examination of the particular rock configuration encountered. This freedom to adjust the drilling pattern slightly as variable conditions require (or permit) is considered a virtue of the spiral blast system since variable conditions will in fact be the rule. Of course, this freedom can only be exercised if the tunneling machine is monitored and controlled by an experienced operator, suggesting that, at least for the present, it would be unwise to attempt development of a fully automated machine.

In any production blast there are two classes of breaking mechanism. First a relief area or free face must somehow be formed. This free face or cut may be formed by taking advantage of angle relief on the cut holes such as a V-cut, pyramid-cut, or draw-cut. The relief area may also be formed by blasting into one or more uncharged holes. All the holes in this type of cut, whether charged or uncharged, are drilled parallel. Burn cuts, cylinder cuts and crater cuts fall under this classification. A relief surface may also be formed by mechanically cutting a slot. This method can only be used in softer rock such as coal.

Once a cut has been opened up, it is possible to use the second class of rock breaking mechanism--slabbing. In a slabbing operation, holes which run roughly parallel to a free face are blasted. The free surface provides the relief necessary to break the rock.

A conventional mining or tunneling round includes both the above breaking mechanisms. A small relief opening, generally in the center, is opened by one of the cuts and then the remaining rock is slabbed into this

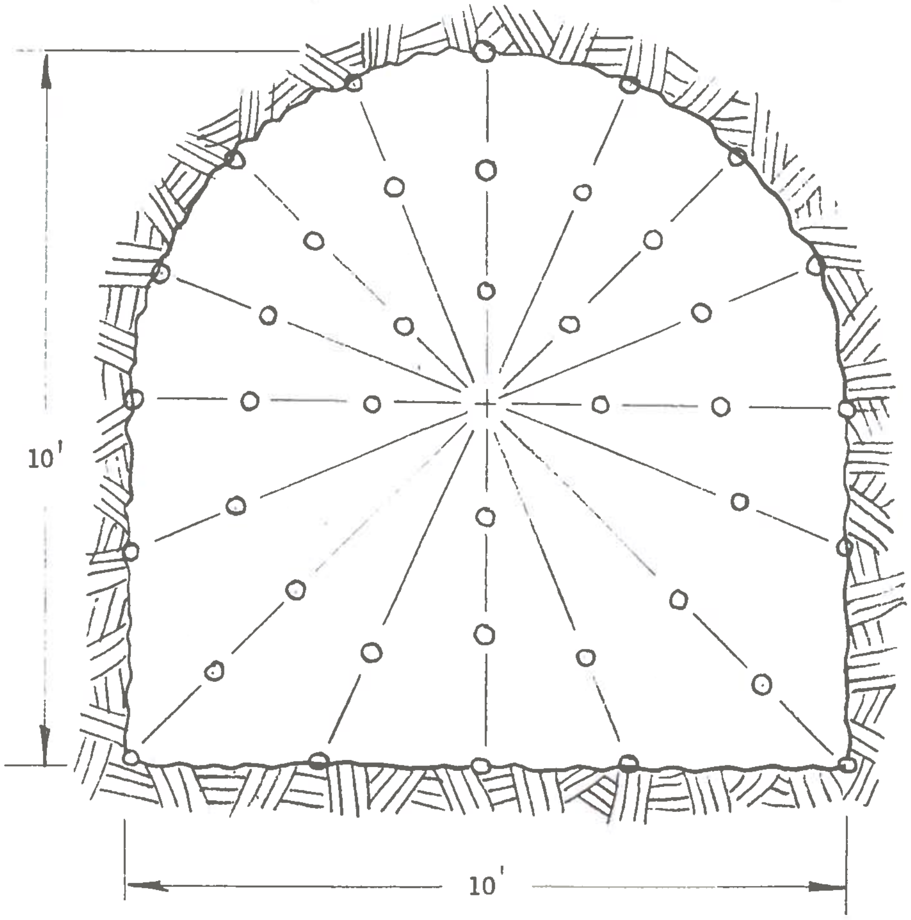


FIGURE 4
EXPERIMENTAL DRILLING PATTERN

opening. Because cratering the cut is much less efficient than slabbing into it, more explosive per ton of rock removed is required in the cut area. In a typical V-cut, for example, approximately 2.5 times the powder per ton of rock is used in the cut as in the slabbing.

In analyzing the breaking action in the spiral blast round, these same two breaking mechanisms are present. Each hole in the spiral blast must both slab and cut. The first four feet four inches of each five-foot hole has a free surface to break to. The bottom eight inches has no free surface. In order for advance, there must be a cratering action in the bottom of the hole (see Figure 5).

Because the cratering is less efficient than the slabbing, a higher concentration of powder is required at the bottom of each hole. Since it is impractical to use two different types of explosives in this operation, the drill hole pattern is in fact controlled by the bottom eight inches of each hole.

The drill pattern illustrated in Figure 4 was developed by combining the experience gained in the first eleven wedges and the cratering effect as stated above. The powder factor in the last eight inches of hole was calculated for each of the first eleven wedges. These may be seen in the following table:

(See Page 21)

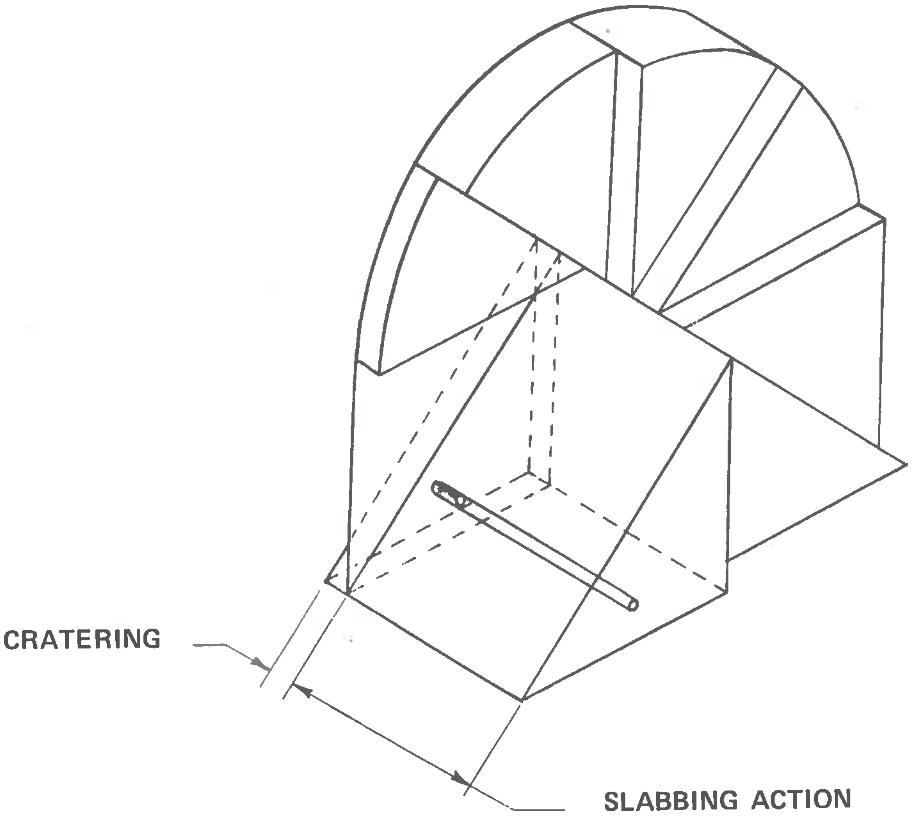
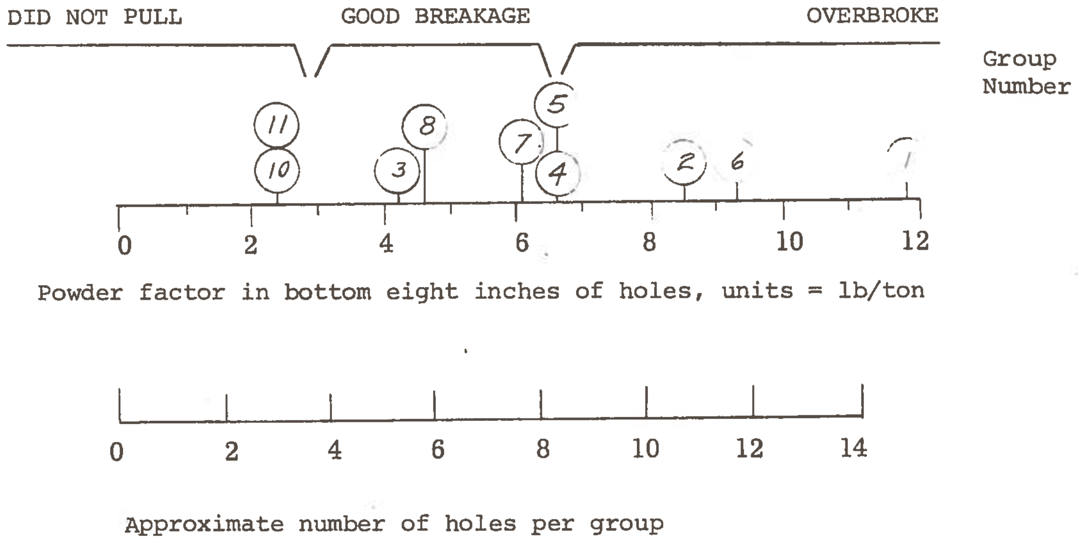


FIGURE 5
SPIRAL BLAST ACTION

TABLE I. HOLE-BOTTOM POWDER FACTOR



The table shows that four holes per group was the most efficient pattern possible for the White Pine rock; however, it left so little margin for error that the five hole pattern was chosen as a practical minimum.

This five hole per group pattern was used to drive the tunnel through revolutions 3 and 4. During this time no bad pulls or bootlegged holes were encountered.

Because the spiral blast technique was intended to be used in production, it was desirable to learn something about the system's efficiency. The data collected during this test give some clues as to the suitability of this system for production. The following table summarizes the data for revolutions 2 through 4.

(See next page)

TABLE II. OVER-ALL BLASTING PERFORMANCE

	2nd Rev.	3rd Rev.	4th Rev.	Total
Advance	5 feet	5 feet	5 feet	15 feet
Rock Removed	43.5 tons	43.5 tons	43.5 tons	130 tons
Holes Drilled	31	37	33	101
Footage of Holes	155 feet	185 feet	170 feet	510 feet
Pounds of Powder (RXL)	49	83.3	69	201.3
Pounds of Powder (Primer)	4.2	15.5	14	33.7
Powder Factor	1.05	2.27	1.9	1.8 (average)
Hole Factor	3.6	4.25	3.9	3.9 (average)

One performance indicator of a drill round is the amount of explosives used to remove a ton of rock. This index is called the powder factor, having units of pounds per ton. The average powder factor for the fifteen feet of tunnel was 1.8 pounds/ton. This compares to powder factors used to drive most tunnels of .68 to 2.8 pounds/ton for conventional drill and blast practice (8), and 188 pounds/ton for recent work (4) with surface explosives.

Another index that could be used to measure a drill round's performance is the footage of hole drilled per ton of rock removed. This index, called the hole factor, has units of feet per ton. In driving this tunnel, it was necessary to drill about 3.9 feet of hole for every ton of rock removed. Typically, a 30 hole burn cut or V-cut round in the same size tunnel would have a hole factor of around 3.8 feet/ton. For the spiral blast geometry each hole pulled essentially its entire length. Occassionally, a "boot" of an inch or two was observed.

Some difficulty was experienced, as might be expected, in pulling the holes in the lower corners of the horseshoe heading. However, this difficulty was easily avoided by shooting the corner hole after the spoke beyond the corner had been fired. That is, the spiral advance continues past the corner in an essentially circular fashion, after which the corner hole is fired to "square up" the corner.

A note of explanation on the number of holes actually drilled per revolution: as stated, a five hole per group pattern was selected for revolutions 3 and 4. As also stated, it was felt that a four hole round could do the job under ideal circumstances. Revolutions 3 and 4 were actually driven using an average of 4.4 holes per wedge. Overbreak from several of the five hole groups along with a heavily jointed geological structure allowed the use of 4 holes in several groups. Again, the freedom to adjust the patterns as progress is observed is of value.

The data indicate that the explosives consumption and the number of holes drilled are roughly the same as used in driving a conventional tunnel. It can be concluded from this that the costs of consumables for drilling and blasting would be about the same.

The actual spiral geometry is not the ideal geometry shown thus far in sketches and models. Figures 6 through 9 are photos of the face during the second revolution of the spiral, showing typical face configurations. Note that this tunnel was driven with a "left-handed" or counterclockwise spiral rotation. Departures from the ideal geometry, as expected, are primarily an absence of the sharp central point and, as a result, the production of a somewhat triangular rather than rectangular, rotating free surface.

FIGURE 6
SPIRAL BLAST CONFIGURATION, HEAD-ON VIEW

FIGURE 7
SPIRAL BLAST CONFIGURATION, HEAD-ON VIEW

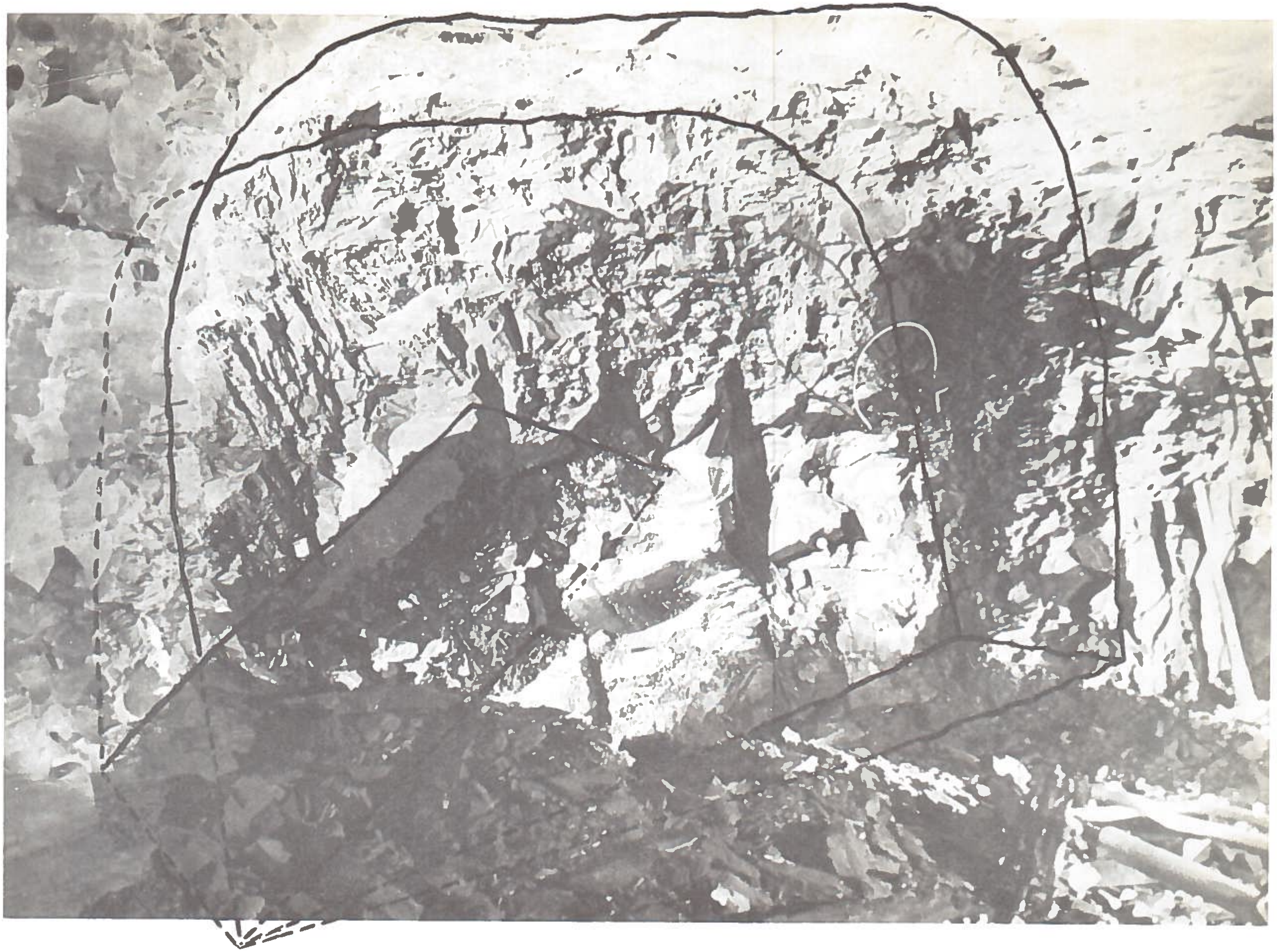


FIGURE 8
SPIRAL BLAST CONFIGURATION, LEFT QUARTERING VIEW
SHOWING "IDEAL" GEOMETRY

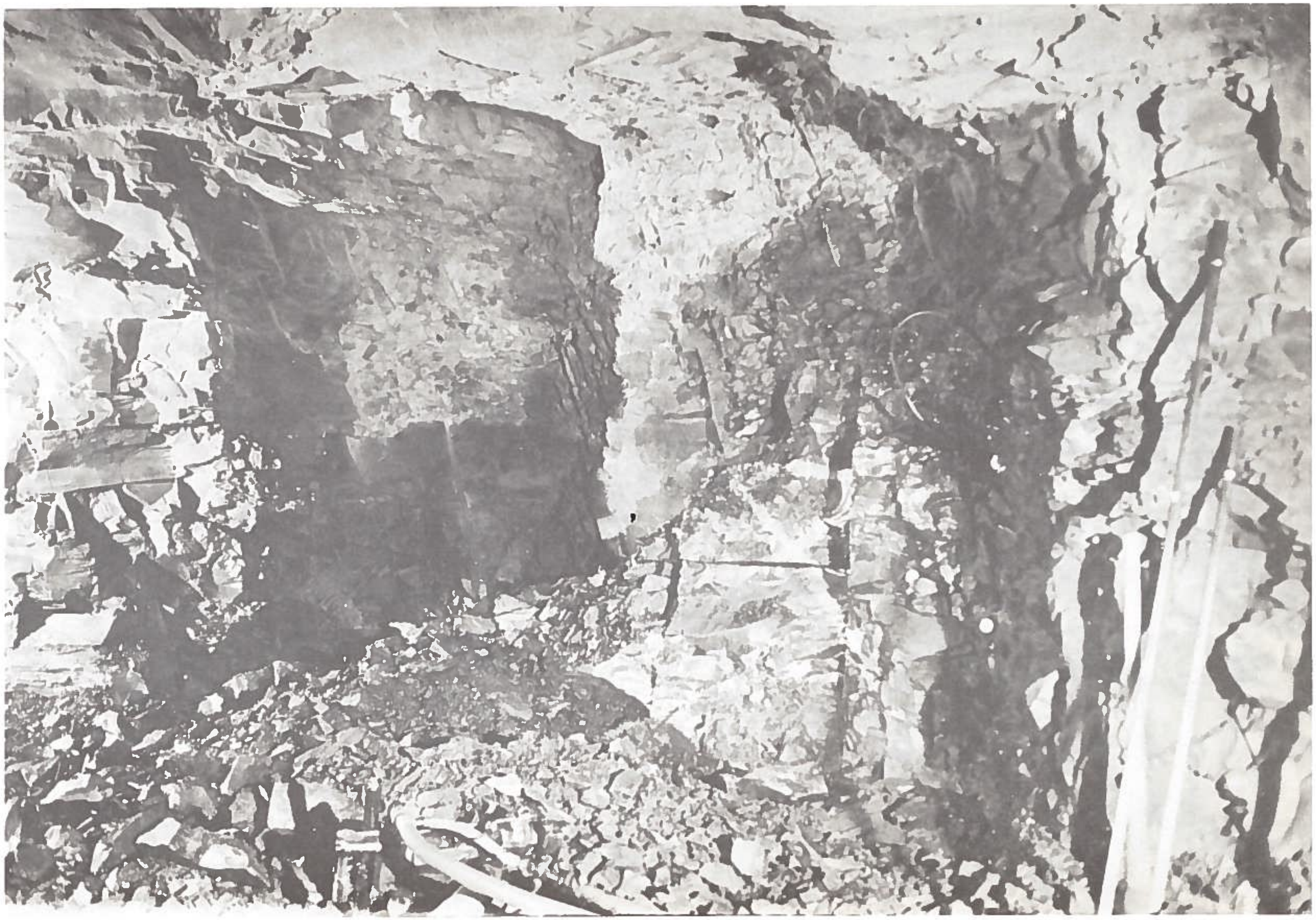


FIGURE 9
SPIRAL BLAST CONFIGURATION, RIGHT QUARTERING VIEW

Figure 6 is a typical "before" picture, taken for record purposes just before a blast. The "pie-shaped" segment to be shot is outlined in white. The edge of the free surface is here at the 9:00 o'clock position, with the intended new position, (after blasting) indicated by the line at about 7:30. Six loaded blast holes can be seen in the segment.

Figure 6 is a view looking straight into the tunnel with a light source at the camera. As a result, no shadows are present to distinguish the three-dimensional shape of the spiral face. However, it does illustrate the nature of the muck pile, in this case from two previous segment blasts.

Figure 7 is of the same configuration, with the same camera location, but with an additional angular light source. A shadow cast on the spiral tunnel face from the horizontal surface at 9:00 o'clock is clearly visible, along with a small shadow from the slight rock projection at the center of the tunnel.

Figure 8 is an "after" picture, taken immediately following the blast loaded in Figures 6 and 7. It is a quartering view taken from the left rib with an auxilliary light source to the right. The plane free surface at the 7:30 position is clearly visible, covered with a slight quantity of muck. Most muck has been thrown slightly rearward into the foreground of the picture.

An overlay is provided to indicate what the ideal geometry would look like from this vantage point. Note the decay of the central rock projection. More importantly, some impression of the spiral regression of the tunnel face can be seen in this figure.

Figure 9 is of the same configuration as Figure 8, but taken from the right rib, looking into the left front corner of the spiral heading. The left rib is seen as a surprisingly smooth wall, and the receding spiral face can be seen plunging deeply into a sharp corner.

These figures show the quite variable nature of the rock at the test site. While the entire area is horizontally bedded, the upper half of the heading was rather finely bedded while the lower half is better described as blocky. With some practice, fragmentation was satisfactory everywhere, although small, evenly distributed fragments were always more easily formed in the upper formation.

Note the prominent vertical faults in the lower formation most clearly visible in Figure 8: one near the center of the tunnel and the other about halfway over to the right rib (its lateral position is best seen in Figure 6). The blast segment following that shown in these photos was intended to break to the painted vertical centerline visible in Figure 6. Actually, it pulled all the way to the vertical plane of the second fault. Still, no difficulty was encountered in maintaining the desired spiral progression. This ability to handle variable rock properties and to adjust as results vary from shot to shot is considered a virtue of the spiral blast concept. However, optimum progression, taking full advantage of observed breaking behavior, does require the judgement of an experienced miner or tunneler. Thus it would be unwise, at least for the present, to attempt development of a fully automated spiral blast machine.

3.2 Choice of Explosive

For convenience, all of the early experimental work was done with RXL 254, a "60 extra" stick explosive manufactured by Atlas Powder

Company. Although mechanized loading of stick powder is possible (9), it is felt that the spiral blast concept will require a bulk loaded (either pumped or blown) explosive. However, since much of the precision blasting done at White Pine is done with RXL 254, this explosive was selected for early spiral work.

Upon observation of the ease of establishing the desired spiral advance it became clear that, at least from the rock behavior point of view, explosive selection would not be a critical matter. Explosives experts stated that any of a wide variety of explosives would be suitable, with final choice dictated by handling requirements, not by fragmentation requirements. Thus, without extensive machine design considerations, the present experimental work did not require or permit a meaningful examination of explosive properties.

The most commonly used, and most economical, explosive is a mixture of ammonium nitrate and fuel oil (ANFO). Table III gives a comparison of the cost of stick powder, ANFO, and few other explosives that might be suitable for spiral blasting (10):

TABLE III. EXPLOSIVES COST

Explosive	Price/cwt
Power Primer	$30.
Gelodyn 1	27.
RXL 254	27.
Aquagel	31.
ANFO	7.

ANFO would make a suitable bulk loaded explosive for spiral blasting although, because it is not cap sensitive, it may complicate the initiation requirements and there was some thought that ANFO may not be sufficiently energetic for this application. Because of its low cost and very common usage, it was decided to test ANFO as an example of a bulk loaded, perhaps less energetic, candidate explosive.

ANFO was loaded with one (8 inch) stick of power primer. On the basis of limited testing its performance seems better than that of the RXL 254, giving better fragmentation with no greater throw. Better performance can be attributed to better explosive coupling to the rock and the use of more explosive, simply because the hole was filled with ANFO while it was not filled with RXL 254, The increased powder factor, by about 1.5, is of course more than offset by the decreased cost indicated in Table III.

For automated loading and initiation it will be most desirable to utilize collar, rather than hole-bottom, initiation. Accordingly, ANFO was also tried with collar initiation. There was no discernable difference between the two. Even with collar initiation, ANFO pulled to within an inch of the hole bottom.

Near the conclusion of the present experimental blasting work a non-technical explosives problem arose, stemming from the current energy crisis. It seems that ANFO, and many other explosives for that matter, is coming into increasingly short supply owing to the use of natural gas in the manufacture of ammonium nitrate. The spiral blast system just might offer a unique solution to the problem, both for mining and for tunneling applications.

A variety of liquid oxygen explosives is available which would avoid dependence upon natural gas products. These explosives consist simply of one of a variety of "absorbants" (fuel) soaked in liquid oxygen. One of particular interest, LOX and sawdust, has been in routine use in an underground mine for 30 years in France and, suprisingly, in that application it is competitive in cost with ANFO.

LOX explosives have not seen extensive underground use in this country, but they have seen commercial surface use (11). A primary reason for the lack of underground use is the "temporary" nature of the explosive: if left too long in the borehole before detonation the LOX explosive will be weak, and it may produce excessive carbon monoxide. The French application is geared to a maximum time lapse of 10 minutes between loading and shooting, whereas typical U. S. mining practice takes more than an hour to load the face after which delays of several hours before shooting are common. Clearly, the automated spiral blast system would avoid excessive delay between loading and shooting.

Reference 11, discussing only various forms of carbon as the absorbant, summarizes the advantages of LOX explosives as follows:

> "1. Since cartridges are soaked only to meet immediate requirements, there is a minimum of handling, transportation, and storage of high explosives. Dry cartridges and liquid oxygen held in storage separately are nonexplosive.
>
> 2. The temporary nature of the explosives permits misfires to be drilled or scraped out without hazard, provided enough time has elapsed to render the cartridge nonexplosive. For the same reason there is no hazard from live explosives in the blasted material.
>
> 3. Unused or excess cartridges may be safely and conveniently rendered nonexplosive and recovered for future use by merely permitting the oxygen to evaporate and returning the inert cartridge for resaturation.
>
> 4. The troublesome physiological effect of certain fixed explosives, which causes severe headaches among susceptible individuals, does not occur with liquid-oxygen explosive."

To this list of advantages we can now add availability of constituents.

Problems associated with LOX explosives are listed as follows:

> "1. Liquid-oxygen explosives are flammable, and the flow of gaseous oxygen emanating from a cartridge will cause ignition sources such as smoldering material, glowing coals, and cigarette stubs to burst into flames. If accidentally ignited, the cartridge may burn or detonate, depending upon both the degree of confinement and the burning behavior of the ingredients. Tests have shown that the safer types of liquid-oxygen explosives in use today will not detonate if ignited without confinement.
>
> 2. The loss of oxygen by evaporation limits the time that can be taken for loading and shooting. This limits the number of drill holes that can be fired simultaneously by a single loading crew."

The second disadvantage, as mentioned, is of no consequence to spiral blasting. The first disadvantage, within reason, may actually turn out to be an advantage for automated loading and shooting. Reference 11 notes that LOX explosives confined in a typical "borehole" (9 1/2 x 1 1/4 inch charges in a 12 x 1 1/4 inch pipe) do undergo a transition to detonation upon ignition. (In comparative tests, 40% nitroglycerin dynamite and 60% ammonia dynamite do not detonate under these conditions.) Thus it <u>may</u> be possible to directly ignite in-place LOX explosives with a laser, thereby producing detonation without blasting caps or any other initiation element. At the very least, LOX explosives <u>are</u> cap sensitive, a distinct advantage in comparison to ANFO which requires an energetic booster to reach detonation, and in conventional practice, a blasting cap to initiate the booster.

3.3 <u>Remote Initiation</u>

All experimental blasting to date has been with hand loaded explosives initiated by ordinary electric blasting caps (with ANFO using in addition a power primer). For automated, remote operation it would be highly desirable, if not mandatory, to eliminate wiring or any other connection to the explosive charge.

Remote initiation techniques have been studied by the Bureau of Mines (12) in conjunction with the first phase of the spiral blast work. That work tentatively concluded that projectile impact would be the best method for an automated loading and initiation system. Reasonably low projectile velocities (of the order of 1000 feet per second) are effective and perhaps even standard .22 caliber ammunition could be used. Gunpowder in some standard cartridge form represents an obvious projectile propellant system, but it is also believed that a satisfactory compressed air (or compressed hydraulic fluid for that matter) gun can be developed. The "module" type automated systems of references 5 and 6 also contemplate projectile impact initiation.

Unlike these module designs, the RAPIDEX spiral blast concept deliberately separates the drilling, loading and initiation components (thereby enhancing the survival rate of at least the first two). It is therefore inconvenient (but not impossible) to aim a projectile initiation system at the relatively small explosive charge with sufficient accuracy.

Laser beams present an obviously attractive alternate initiation means and recent work by the Bureau of Mines indicates that relatively low energy beams are quite suitable. It was found that ordinary fuse caps (blasting caps intended for ignition by safey fuse) could be ignited by a lower power unfocused laser beam, with an energy density as low as 0.019 joules/cm^2. The operational virtues of laser ignition are that it avoids the logistics and mechanical complexity of the projectile system and, while it must still be aimed, the operator can observe the beam impingement directly and make corrections necessary to strike the target. If blasting caps are used it may be desirable to equip each with a cheap plastic lens to effectively enlarge the "target" area. Of course, direct laser ignition of a LOX explosive, if possible, would be the simplest system.

Blasting caps are inexpensive, readily available, and, of course, familiar to tunneling contractors. However, a variety of light sensitive explosives is available and it is likely that some may prove more suitable than blasting caps for remote explosive initiation. For example, considerable work has been done at Southwest Research Institute (13, 14) on explosives initiated by the light from a Xenon flash tube. While the particular formulation developed would not be directly useful for spiral blast work (the explosive is desposited as a non-sensitive slurry and remains insensitive for too long a period until the carrier evaporates) there is little doubt that a suitable system could be derived from this technology. A pumpable initiation compound would of course be more easily handled than blasting caps, and it could be deposited to form a large target if desired.

It would not be difficult to remotely place a sensitive element (including an energetic primer) on top of a pumped explosive column if necessary. Explosive must be pumped into the blast hole through a tube extending into the hole to be withdrawn as the explosive enters the hole.

In one scheme, a pre-selected quantity of explosive would be pumped into the tube (and a flexible rearward extension thereform) ahead of a piston carrying the sensitive element(s).* The explosive would then be "pumped" into the blast hole by forcing the piston forward with a suitable inert fluid (water or nitrogen for example). The piston would be deposited on top of the explosive column and, in the process, leave behind an empty (safe) explosive loading tube.

Other initiation systems are possible including loading of pre-ignited cartridges of known (substantial) burning delay (15). However, at present, projective impact and laser (or other light) initiation seem the best candidates for remote initiation.

All of the "simple" remote initiation schemes require collar initiation of the explosive. The present work has shown this to be feasible in the spiral blast geometry, at least with ANFO.

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* The "Piston" could actually be the primer, molded in the desired shape from a rubber-like high explosive such as DuPont "Detraprime."

4. Machine Design Considerations

A preliminary machine design was produced in the Phase I study of the spiral blast concept (1). Nothing in the present work has necessitated any major change in that design concept. However, several refinements have been suggested by the Phase II experimental program and these will be discussed in this section. Blast shield design, perhaps the single most critical design consideration, has proceeded well beyond the preliminary stage and is discussed separately in Section 5.

Figure 10, repeated from reference (1), illustrates the general layout of the machine. It is a crawler mounted unit, carrying one or more rotating radial arms at the front which carry drilling, loading, and initiation equipment. A rotating shield, not shown in Figure 10, is also carried at the front as discussed in Section 5. A scoop pulls muck from the face area to an apron, thence up to a central conveyor which discharges at the rear of the machine.

Service lines, including air, hydraulic fluid, water and explosive(s), enter at the rear of the upper box-beam frame member. They are carried inside this member to the appropriate radial arm at the front of the machine. In this way, the lines are entirely enclosed and protected.

Note that, except for automated loading and initiation devices, standard, commercially available, components can be used throughout.

Rock drills, appropriate to the application are carried on a single radial arm as previously indicated. These may be percussive, rotary-percussive, or straight rotary, and of pneumatic, or, preferably, hydraulic actuation. For the successful drilling pattern of Figure 4, three drills would be carried on a single radial arm, mounted to drill

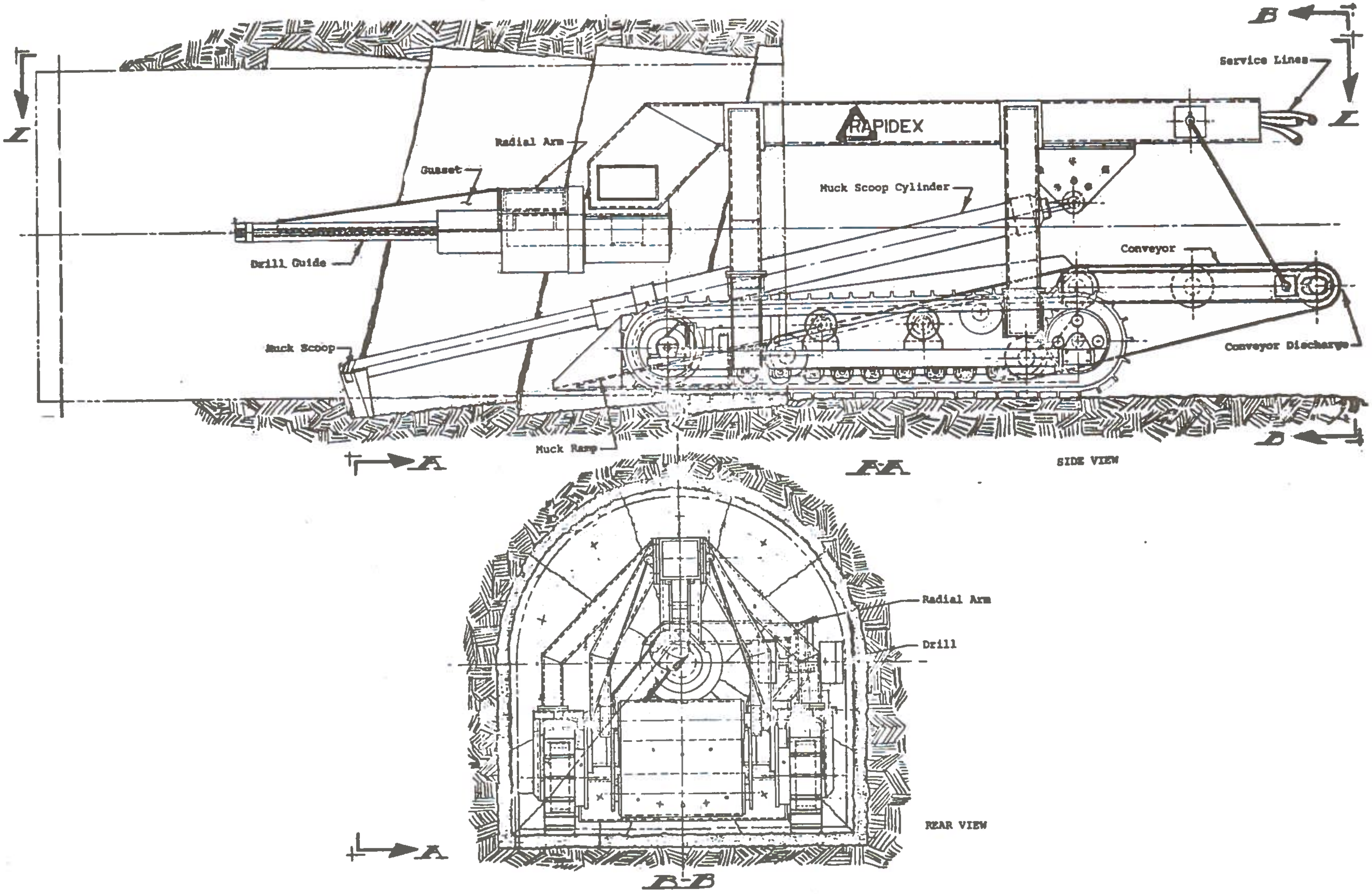

FIGURE 10
CONTINUOUS BLASTING MACHINE LAYOUT

simultaneously on a single spoke, with the inner drill working only half-time. Note that this represents a simplification of the original design.

Two necessary refinements were indicated during drilling for the experimental blast work. First, it is common practice to force the front of the drill guide, carrying a spiked shoe, against the rock face to stabilize the forward end of the guide. With multiple drills facing an irregular rock face from a single radial arm this would be inconvenient or impossible, but it would be a simple matter to hydraulically extend a ram forward from each fixed drill guide to achieve the same stabilization.

A second refinement is necessary to assure clean drilling sites when drilling near the tunnel floor. Without hand mucking capability, it is unlikely that all loose material can be cleaned from the corner at the junction between the tunnel floor and the spiral face. While it is relatively easy to drill through any loose material, it may be difficult or impossible at a later time to find and load a hole thus covered. It is believed that this problem can be avoided by equipping each drill guide, at its forward end, with a rather strong air jet. The jet would be used as necessary to blow material away from the immediate drilling site prior to drilling. It may also be necessary to equip the explosive loading system with a similar jet to remove any material which moves into the area between drilling and loading operations.

Automated explosive loading equipment has not been considered in detail, and indeed it cannot be until more definitive work is done on explosive selection and initiation techniques. Equipment is available for mechanized loading of stick explosives, pumpable explosives, and "blowable" explosives (ANFO was blow-loaded for the experimental blasting of the present program). Although it is unlikely that off-the-shelf equipment will be directly applicable to the spiral blast machine, no fundamental difficulties are foreseen in this area.

Remote explosive initiation is somewhat farther removed from off-the-shelf procurement although the initiation techniques recommended in Section 3.3 are certainly within the capabilities of available components. Clearly what is needed in this area is a test and development program, not simply a design effort.

Early thinking considered on-board operators housed in suitable protective cabs. However, it seems clear that closed circuit T.V. monitoring would be safer, more economical and, in all probability, more effective. That is, a shielded camera can be located to give better visibility than that afforded any reasonably placed on-board operator.

As part of the present program, T. V. monitoring equipment* was demonstrated at the White Pine test site. A routine pneumatic drilling operation was monitored under conditions that happened to result in considerable fog from the drill exhaust. With automatic aperture control, it was shown that modest lighting was sufficient, the spot from an ordinary miner's headlamp beam being sufficient to "burn out" the area upon which it fell. It was noted that television was somewhat better able to penetrate the fog and dust generated by drilling than was the naked eye. After observing a three-drill jumbo performing production drilling within the

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*Equipment and its operation provided by Mr. Edwin Johnsen, Manager Developmental Automation and Control Technology, Institute for Computer Sciences and Technology, National Bureau of Standards; and Mr. Richard Sales U. S. Army MERDC, Fort Belvoir, Virginia mine it is clear that the drilling operation will not unduly obstruct visibility.

Dust generated by blasting is much greater than that due to drilling as may be seen in high-speed motion pictures of the spiral blasting operation (see Section 5). However, it is felt that overall visibility can be maintained at acceptable levels by a reasonable ventilation system including blowing at the face and suction behind the machine. Furthermore, if necessary, high visibility "tunnels" can be produced along the viewing axis of monitoring cameras by suitably directed jets of clean ventilating air.

Suitable television monitoring equipment, including stereo equipment if necessary, is not excessively costly. Estimated cost for a stereo system, including camera, cable, viewing equipment, movable camera mount and controls, and lighting is about $3,000. Two such systems seem necessary although it is not obvious that both (or either) need to be stereo.

For the present, no change is contemplated in the scoop and ramp mucking system shown in Figure 10. Simple gathering arm type loaders have been used on rough blasted floors at White Pine, but after consideration, it is felt that such loaders could not reach forward sufficiently (or safely) to muck all the way to the spiral face as required. Long stroke (10 feet), non-rotating cylinders are commercially available for the muck scoop, but in all probability a more durable system could be fabricated by enclosing a conventional cylinder within a telescoping pair of heavy square mechanical tubes.

A refinement in scoop mounting and control is deemed desirable over that previously shown where two diagonal hydralic cylinders determined the lateral and vertical position of the muck scoop. The refinement provides independent lateral and vertical controls for the scoop axis (like a small "Gradall") so that, with lateral angle set, the operator can control scoop motion, forward and back, and up and down, simply with two levers. The former system would have required three levers (or a complex servo control) since vertical and lateral motions were not independent.

The entire vehicle is carried on a crawler-mounted chasis. A variety of crawler mountings is available depending upon anticipated gross vehicle weight. Total weight was estimated using, where possible, weights of commercial components from manufacturers including Ingersoll-Rand, Gardner-Denver, Chicago Pneumatic, Joy Manufacturing, Eimco, and others. The following is a list of major components and their approximate weights:

TABLE IV. MACHINE WEIGHT

Drills and drill feed, 3 @ 650 lbs.		1950
Radial arm		900
Rotary joint		1000
Shield		1000
Muck Ramp		300
Muck scoop and cylinder		1200
Conveyor components		600
Conveyor drive		400
Superstructure		2500
Muck on ramp and conveyor		1200
Crawlers and Frame		10000
	Total	21050 pounds

To this we must add considerable miscellaneous equipment such as hoses, various actuators, T. V. monitoring and lighting equipment and its shielding, and additional stationary shielding over various vital areas as necessary. It is believed that for a prototype unit of about 12 x 12 foot tunnel capability a crawler unit such as the Eimco Model 600 having a gross vehicle capacity of 30,000 pounds would be adequate. Distribution of the various component weights places the center of gravity acceptably within the crawler capabilities.

5. Blast Shield Design and Test

If the "continuous" spiral blast concept is to succeed, a suitable shield is necessary to permit reliable and prolonged operation with the entire machine at the face. Except for the fundamental question of spiral blast behavior per se, the survivability of the machine is perhaps the most critical aspect of successful performance.

The Phase II effort was originally proposed to explore only the problems of spiral blasting behavior. However, it soon became evident that the spiral pattern performed satisfactorily in a horizontal horseshoe entry. Indeed, after some practice, spiral advance was considered easy by those directly associated with the experimental blasting. Although much remains to be learned regarding the "optimum" blasting pattern and explosive combination(s), it is quite clear that economic (from the standpoint of powder factor and hole factor) patterns and explosives (including ANFO) will be available. Therefore, with the approval of the Department of Transportation, the contract effort was redirected to explore, in a preliminary way, the problems of blast shielding.

Unlike other "continuous" blasting concepts which require heavy shielding directly in front of the blast (5, 6, 15), the spiral pattern itself affords some shielding. This can be seen in Figure 11, a schematic of the shielding concept (for a left-hand spiral as tested at White Pine). Note that the shield is aligned axially and positioned so that major blast fragments are thrown away from it.

An attempt was made to film several blasts to learn a little of fragment velocities using a shielded, high speed (64 frames per second)

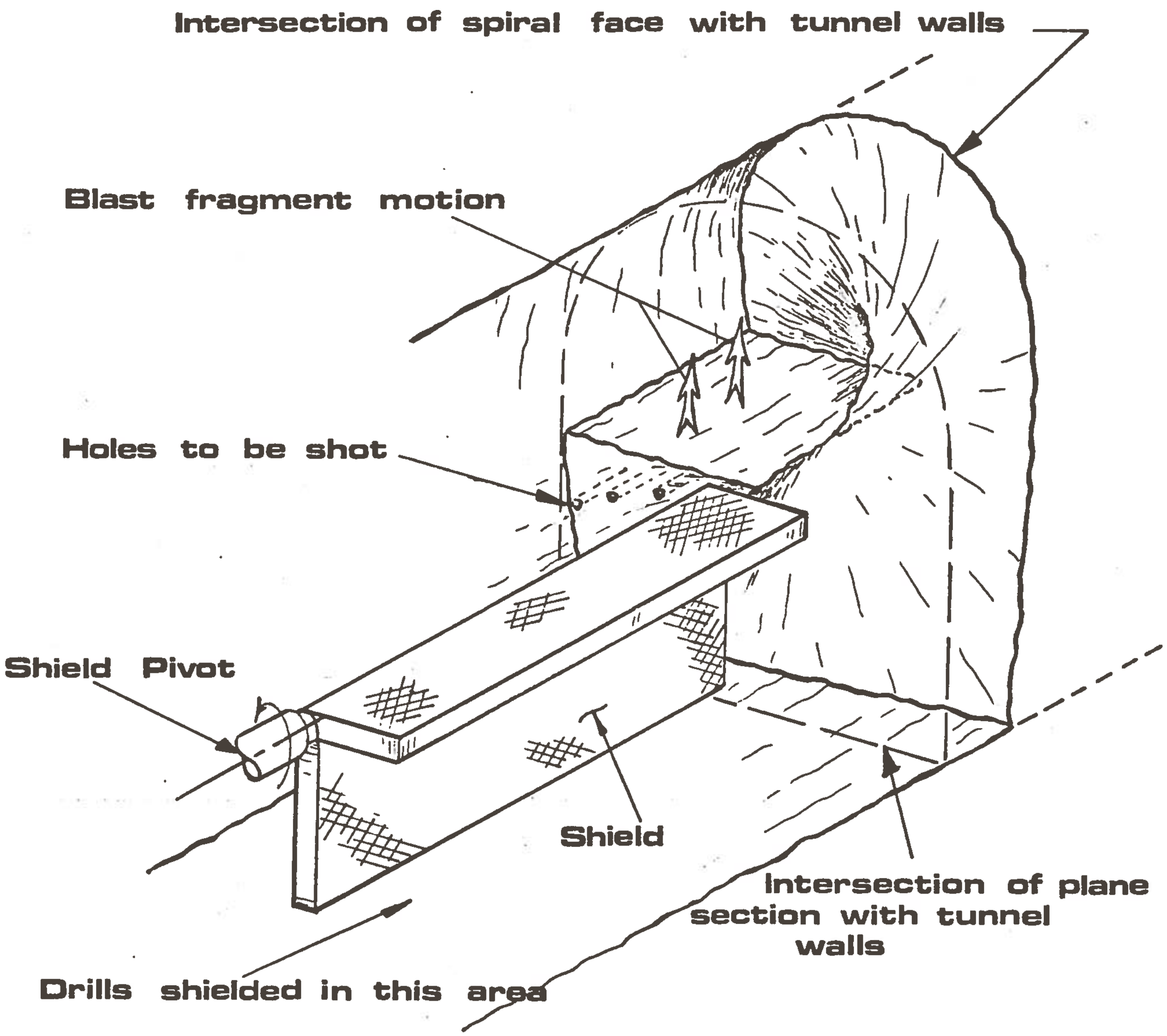

FIGURE 11
BLAST SHIELD CONCEPT

camera borrowed from the Bureau of Mines. It was felt that the shielding was insufficient to allow direct viewing of the blast. Therefore, a second spiral tunnel heading was started and, once a spiral face was established, the camera was positioned off to the side and aimed at right angles to the tunnel axis to view axial fragment trajectories. Thus the camera was "around a corner" out of direct sight of the blast, but with a very shallow heading, axial velocities could be observed within about ten feet of the face.

Figure 12 is a sequence of frames from a typical blast. In general only fragments in front of the light-colored blast dust cloud could be distinguished and, although some quantitative data could be obtained, it was deemed of little real value. In fact, with shield work accelerated to provide testing within the Phase II timespan, these film results were not used in design.

Qualitatively, the blast films show relatively small (three inches or less) fragments traveling directly from the blast while a larger number of fragments are seen tumbling along the floor. Most large (6 inches or greater) fragments fall very close to the face as may be seen in Figures 6 - 9. Time of each blast is relatively well indicated by a visible light flash. The first noticeable effect thereafter is the raising of dust from the floor in front of the tunnel caused by the impact of small (not visible on the film) fragments that appear to be thrown directly from the borehole. Appearing in the third frame after the light flash, and striking approximately 20 feet from the face, a velocity of about 420 feet per second is indicated. The next visible effect is a dust cloud

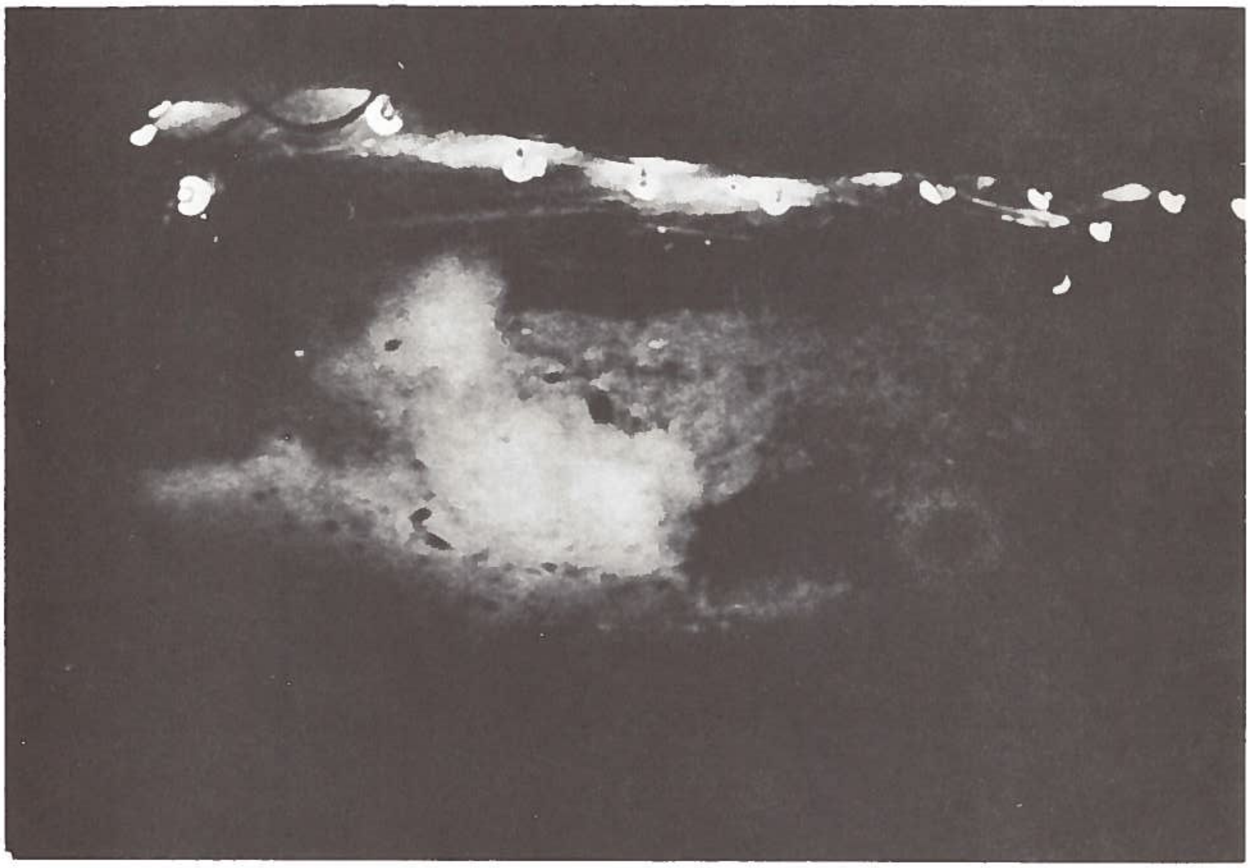

FIGURE 12
BLAST FRAGMENT FILM

issuing from the blast and thereafter individual fragments can be seen silhouetted against the dust. Figure 13 is a plot of fragment trajectories for a typical blast (the same as Figure 12). The fastest projectile was the first to be seen (as might be expected), and it was traveling about 70 feet per second. Only clearly discernable fragments visible in three or more sequential frames are shown in Figure 13 where circles indicate sequential fragment positions, and the numbers indicate velocities in feet per second. Langefors and Kihlstrom (16) also picture rock trajectories having velocities of about 50 feet per second so that, although Figure 13 represents only a small sampling, the velocities do seem reasonable.

The blast shield was designed around information supplied by Norman Junk of the Atlas Powder Company. Their research personnel had determined that a small blast, such as utilized in the spiral blast concept, would produce a pressure wave of 500 psi in the immediate vicinity of the blast, having a duration of one-tenth of a millisecond. The pressure wave would be followed by the fractured rock at velocities up to 200 feet per second. (The fact that no fragment velocities approaching this velocity were observed is probably not significant since the number of observations was not great and, except for rather large fragments, the film quality may not have been adequate to distinguish fragements at this velocity.) The Atlas data, together with the observation that spiral blast muck rarely exceeded six (6) inches in major dimensions,* led to the decision to design the shield for a static load of 5,000 pounds.

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*Larger fragments visible in the photos were generally slabbed off by drilling or mucking operations subsequent to blasting.

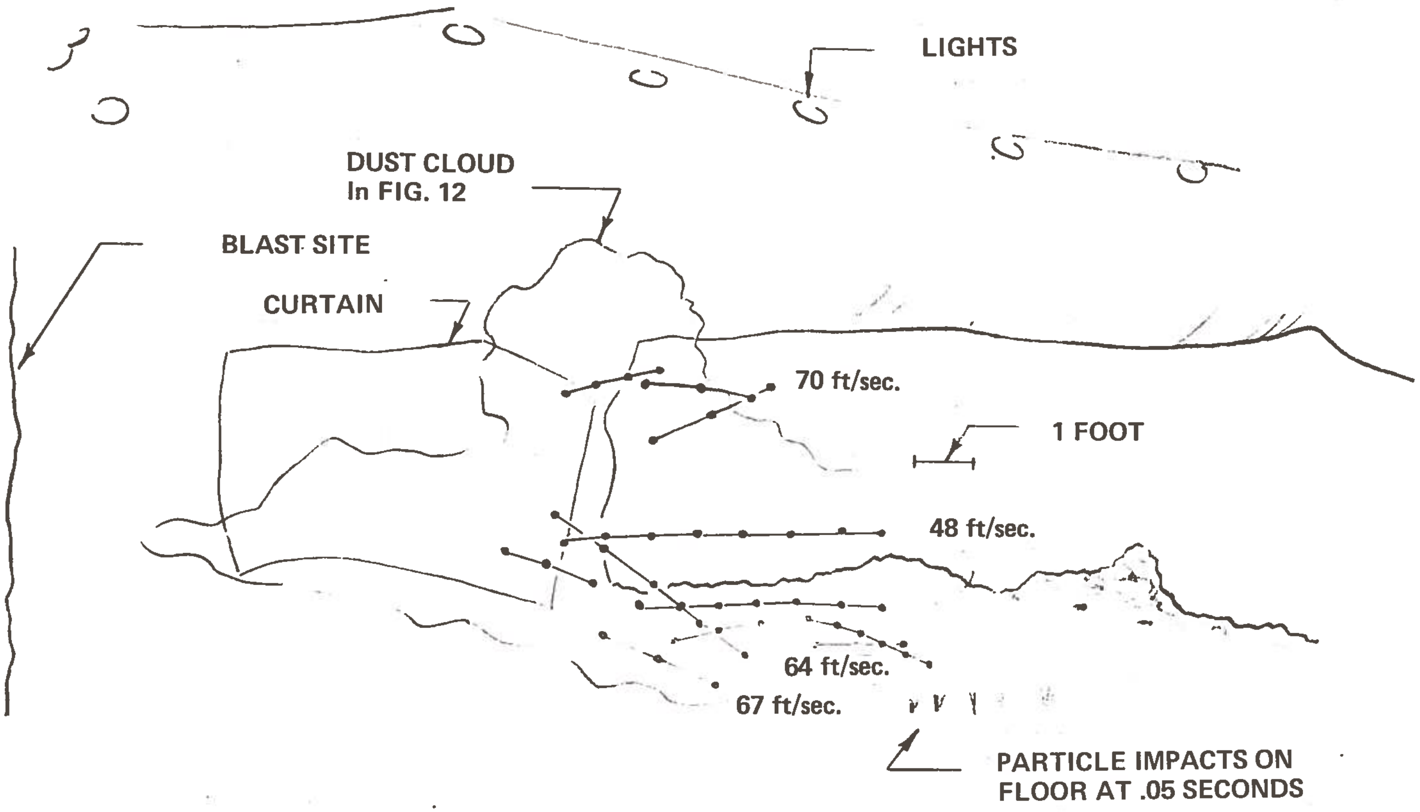


FIGURE 13
BLAST FRAGMENT TRAJECTORIES (REFER TO FIGURE 12)

The shielding concept, shown in Figure 11, anticipated a light-weight shield. At the outset it was clear that the shield would have to present minimum obstruction to passage of the pressure wave while resisting passage of solid fragments. The resultant design is shown in Figure 14. The shield is a 4 1/2 by 10 foot rectangle having a frame of pipe and axial stringers welded to evenly spaced bulkheads. This is covered by a wire mesh, of 1/4 inch wire having one-inch spacing on the blast side and two-inch spacing on the back side (to permit fragments passing through the first screen to fall out). It is felt that any fragments which penetrated the combination would inflict only superficial damage to shielded equipment. The mesh was welded in place diagonally, lending shear strength to fabrication in a "stressed skin" design for minimum weight. Complete shield weight was 1,200 pounds.

For testing the shield was rotably mounted on a temporary support shown in Figure 15. This support was skidded into place and filled with muck to act as ballast.

The shield was tested through one complete revolution of the spiral. The shield was essentially stationary for all but one blast, the fourth shot in the first spoke. This shot, having little burden and positioned nearly "broadside" to the shield, pivoted the shield and stand as a unit horizontally with the front of the shield pushed about three feet to the side. It was estimated, on the basis of the force necessary to drag the loaded shield and stand, that the maximum experienced loading of the shield was about 2,000 pounds.

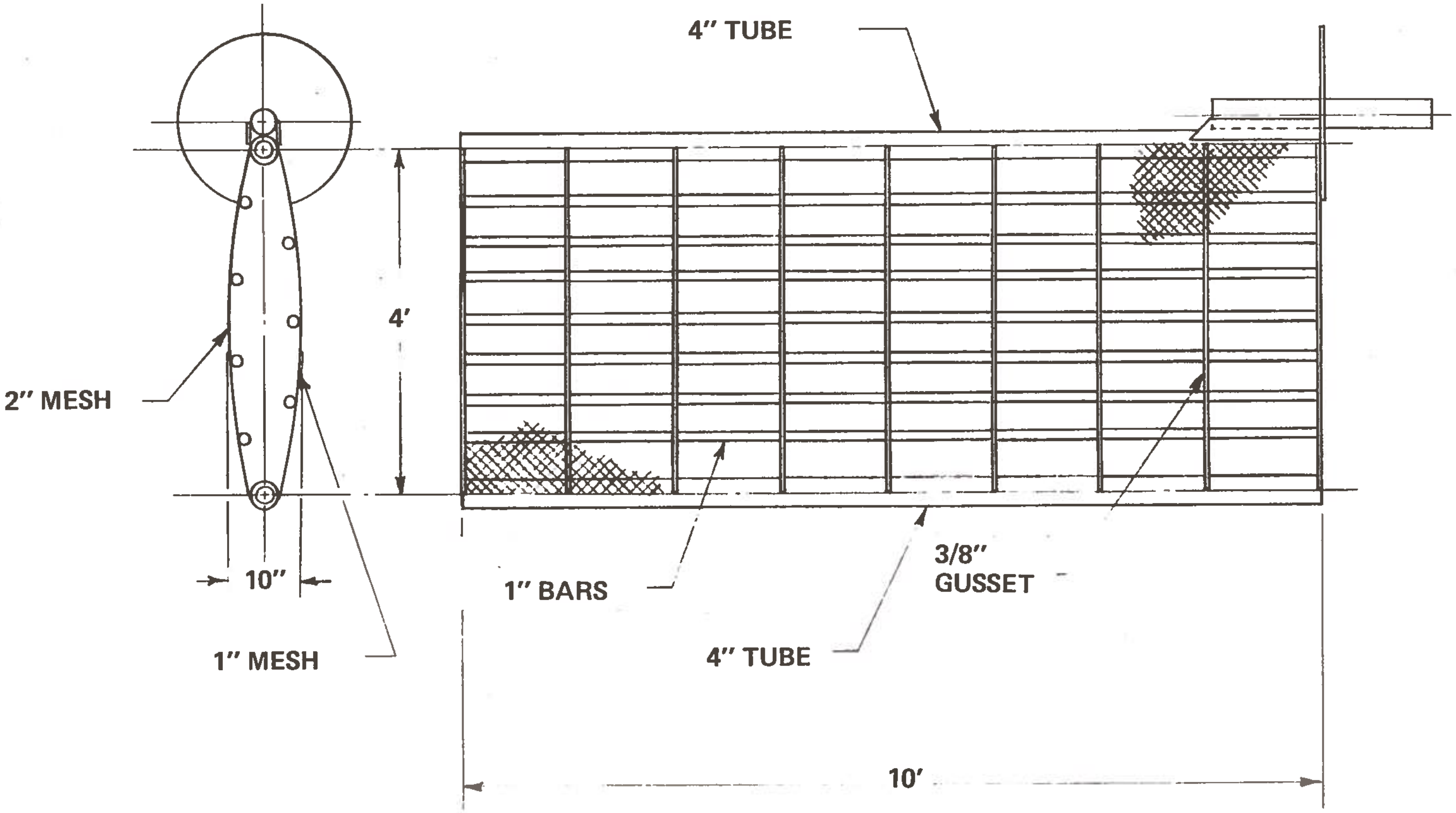
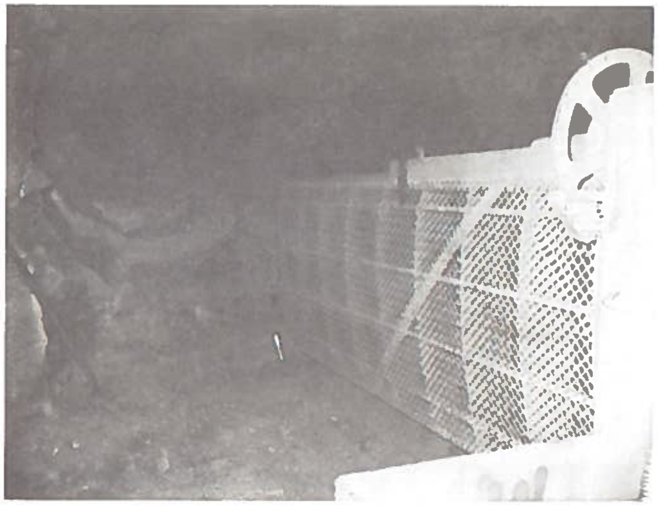


FIGURE 14
BLAST SHIELD DESIGN



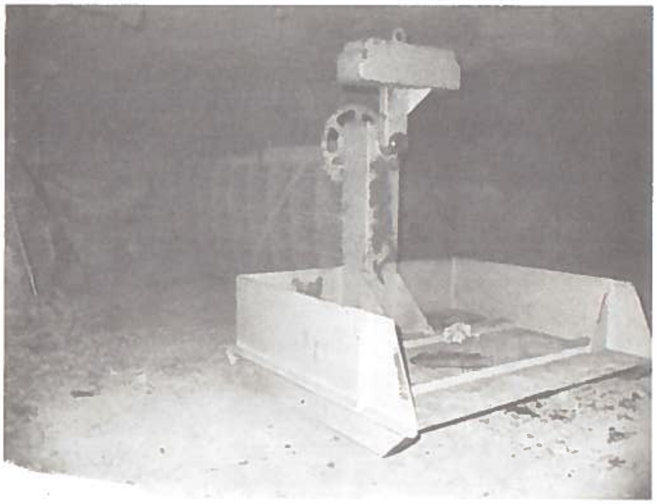


FIGURE 15
BLAST SHIELD ON TEMPORARY SUPPORT

The shield was essentially undamaged by the test. However, as seen in Figure 16, some of the welds between the wire mesh and the frame were cracked. This was attributed to the spring steel alloy used in the wire mesh which, although said to be weldable, proved to become brittle at the welds.

Objects placed behind the shield (an empty aerosol can and a cardboard box) received only minor dents and, in the case of the box, holes. There was no buildup of muck within the shield.

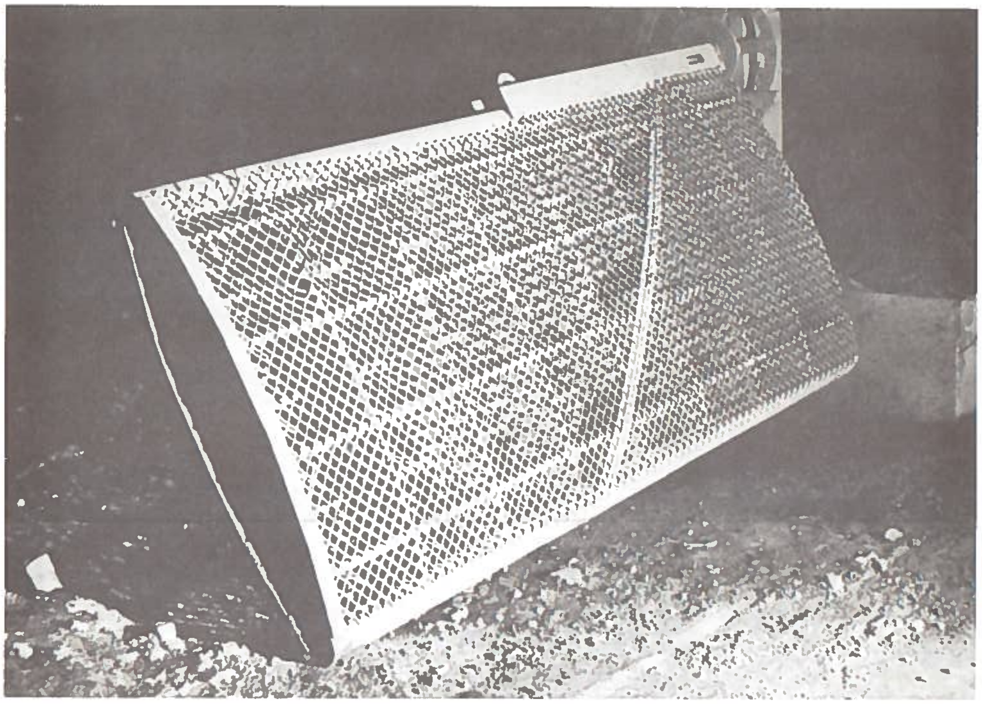
Although several modifications were suggested by the test, it is evident that the small blasts inherent to the spiral blast concept can be shielded effectively to allow the necessary excavation equipment to remain at the face during blasting.

Suggested design modifications are as follows:

1. Use a mild steel wire mesh to avoid brittle welds or, alternatively, do not weld the mesh to the shield frame. This alternative would permit simple, periodic replacement of mesh, but it does not provide the desired stressed skin design.

2. The front of the shield should be cut back at an angle to roughly match the depressed-center face shape, thus permitting the shield to move in closer to the face.

3. An "L" shaped shield, as shown schematically in Figure 11, may be needed to provide protection from ricocheting fragments.



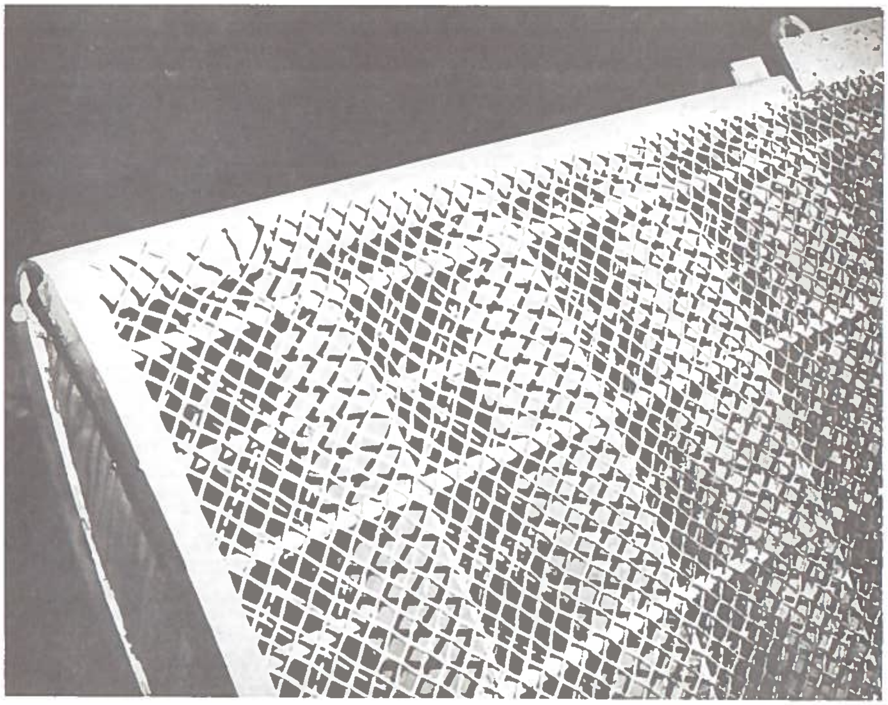


FIGURE 16
DAMAGE TO BLAST SHIELD

6. Economic Considerations

Implicit in the cost analysis of any new concept, and particularly for one offering substantial improvement, are two assumptions. The first is simply that the new concept will work in accordance with the claims made for it. This assumption is recognized, if not accepted, by all. The second, though not as often recognized, is just as important: that all improvements in peripheral equipment necessitated by the existence of the new concept will be available when and as required.

In the following it is recognized that a drill and blast tunneling system that advances at four or five times the conventional rate will require improvements in peripheral equipment, and it is further recognized that the required improvements are not trivial. However, in these times of increasing attention to underground excavation it is perhaps not unreasonable to assume that the improvements will be realized. Certainly it would be unwise to hold back on partial improvements, awaiting instead a concept which solved all problems.

For example, the increased demands on muck haulage necessitated by the anticipated spiral advance rate is perhaps the most obvious peripheral requirement. However, it may also be one of the more easily attained improvements for, just as the spiral blast concept promises high performance through uninterrupted use of relatively conventional components, so the muck haulage equipment can benefit from full-time useage.

A simple comparison has been made on the basis of the, new standard, work of Robert S. Mayo and Associates (17). Costs in this reference are for the period January - June, 1967. No attempt has been made to update these costs, our purpose being merely a comparison.

A tunneling operation requires a great variety of both personnel and equipment. For comparison, the personnel requirements, equipment costs, and consumable and other costs were extracted from pages 229, 230, and 39, respectively, of reference 17. A one mile, 18 x 18 foot tunnel in dry, stratified or schistose rock, in which Mayo estimates an advance rate of 36 feet per day for standard practice, was assumed for this example. Changes were made in personnel and equipment needs only in those instances specifically effected by the spiral blast concept. No doubt some changes would be required in other tasks and equipment, but no further substantial change in the total number of persons or the cost of equipment is anticipated. Specifically, no change in the muck hauling operation is made, it being assumed that full time operation of a modern haulage system will handle the increased (but steady) muck flow.

Performance of an 18 x 18 foot spiral blast machine is projected on the basis of the drilling pattern illustrated in Figure 17. This provides a hole spacing equal to or less than that successfully tested in a 10 foot heading. In an 18 foot heading, holes will be 9 feet deep.

The pattern contains 28 spokes, alternating between 3 and 4 holes per spoke. We will <u>assume</u> that the machine advance rate is drill-limited by today's drill performance. That is, we shall optimistically assume that automated loading and initiation equipment will be developed to load and fire holes as fast as they can now be drilled, but we shall

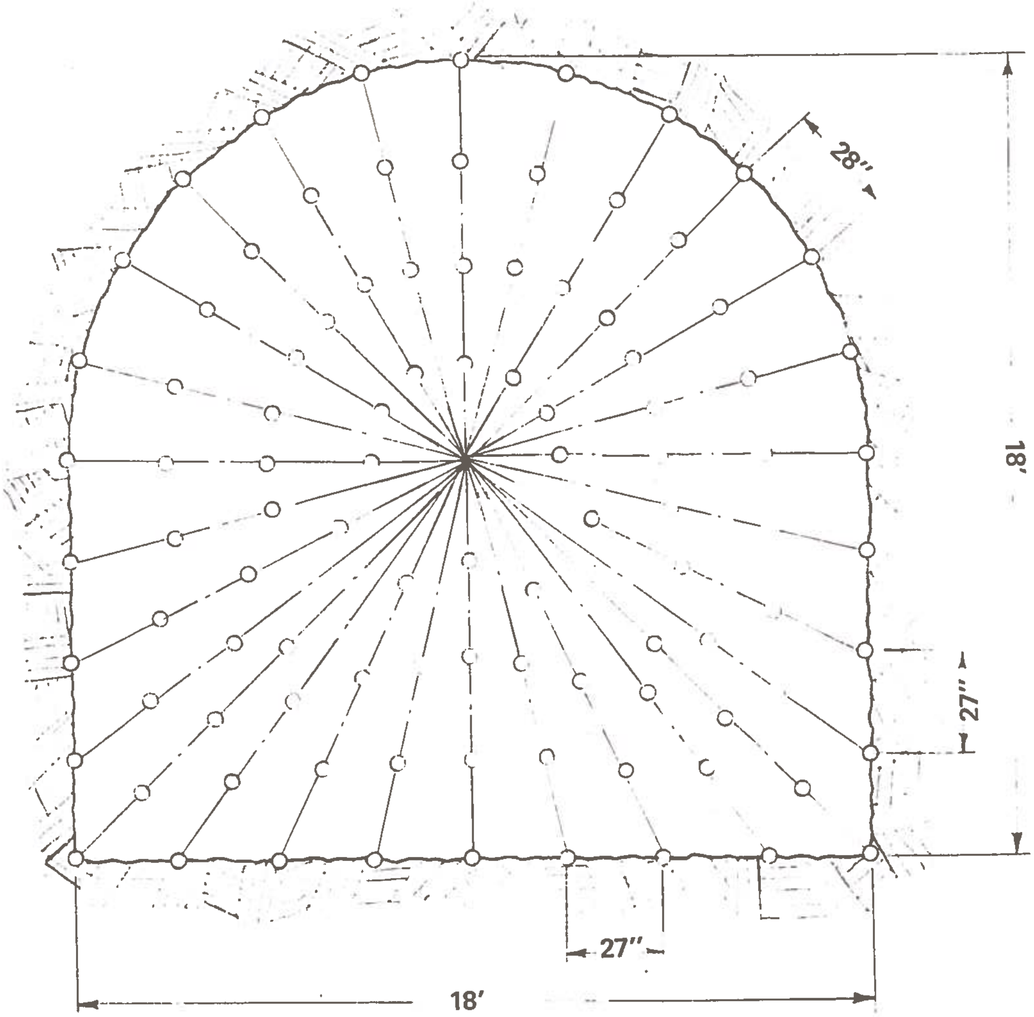


FIGURE 17
EIGHTEEN-FOOT BLAST PATTERN

pessimistically ignore improvements in drilling performance that will no doubt materialize over the same development period.

Drilling time, as with conventional practice, depends upon the number of drills used. If only four drills are used on a single radial arm, with the inner one idle on every other spoke, than 28 drilling cycles will be required per 9-foot (i.e., on spiral revolution) advance. Assuming a drilling rate of 4 feet per minute and a 45 second radial arm shift time, each cycle consumes 3 minutes. One revolution would take 84 minutes for an advance rate of 6.43 feet per hour or 154 feet per day (if used full time).

Alternatively, the radial arm could carry seven drills, not an unreasonable number for an 18-foot tunnel, and only 14 drill cycles per revolution would be required. Advance rate would then be double the above or about 300 feet per day.

Of course no machine can operate at maximum rate for 24 hours per day. With time out for shift changes and routine maintenance, perhaps half of these maximum performance figures can be attained.

It is expected that the spiral blast machine will be operated by four "miners:" one each operating the drills, the loading and initiation equipment, and the muck scoop, and one spare. In comparison to standard practice as presented in reference 17, these four men replace 9 miners, 9 chuck tenders, and one mucking machine operator.

The complete personnel requirements for standard and spiral tunneling are shown in Table V. Total per diem labor costs for personnel and wage rates shown are $7,435.88 and $5,443.88 for the standard and spiral systems, respectively. The labor cost per foot of tunnel advance is simply this total divided by the daily advance.

Equipment costs for the standard tunnel are listed in Table VI, made up from items listed on page 230 of reference 17, and totaling $98 per foot in a one-mile tunnel.

The modified RAPIDEX equipment costs are shown in Table VII. Standard drilling and muck loading equipment has been eliminated along with all but one compressor, it being assumed that hydraulic rock drills will be used with power supply cost included in the spiral blast machine cost. A high salvage value is shown since, unlike standard tunnel boring equipment, the spiral blast equipment can be reused in tunnels of different size and shape with little or no modification.

Total costs of excavation with standard and spiral methods are shown in Table VIII, modeled after Table 3-D-1 on page 39 of reference 17. The potential advantages of the spiral system, as plotted in Figure 18, are substantial even in the absence of any marked increase in advance rate. That is, as should be the case, the introduction of automated or semi-automated equipment has resulted in a significant reduction in labor cost. Specifically, nine miners, nine chuck tenders, a shifter and a mucking machine operator have been replaced by four spiral blast machine operators (listed in the personnel table as miners).

An apparent savings in equipment cost is also realized, but this may be somewhat artificial as it stems from the assumed salvage value of the spiral blast machine. This term is included to emphasize the flexibility of the concept. Presumably the standard equipment also has some salvage value which has not been shown on either standard or spiral costs.

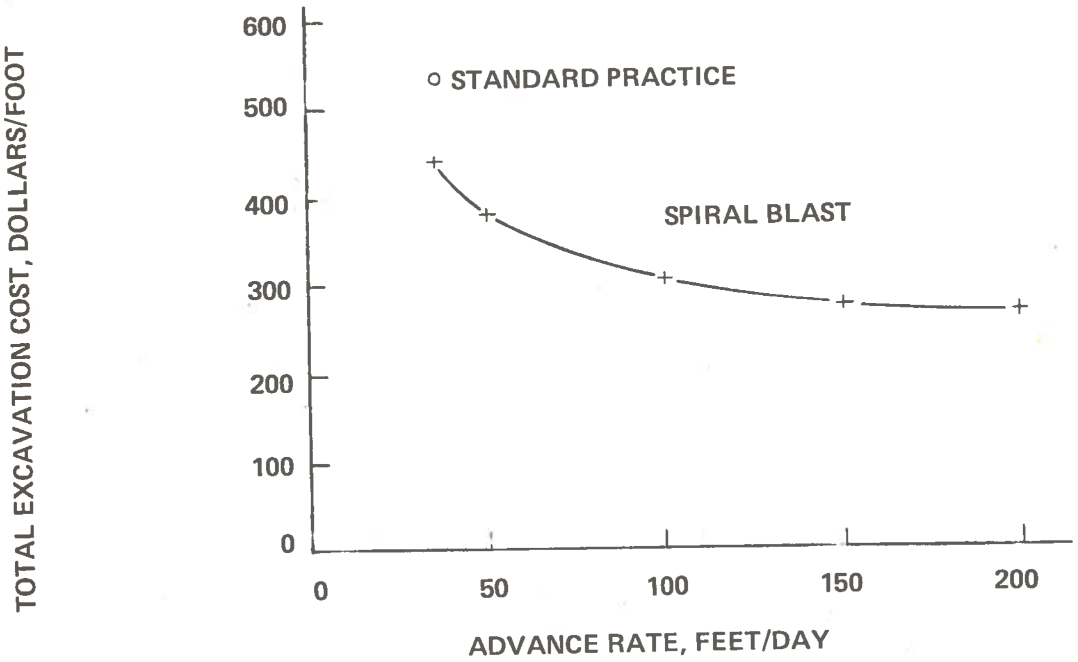


FIGURE 18
SPIRAL BLAST TOTAL EXCAVATION COST

However, even if the $38 per foot salvage value is not allowed for comparison, the spiral system is significantly ahead at the anticipated advance rates.

This comparison makes no direct accounting of the added value of the anticipated increase in advance rate. At the very least, an earlier completion date can provide a reduction in financing costs which may be of the order of $50 per foot in the standard case.

See next page

TABLE V. TUNNELING PERSONNEL

Hourly Wage Rates and Estimated Personnel Requirements of Tunnel Construction Crews in Southern California

(Prevailing Wages of January-June, 1967)

	Hourly Wage Rate	Number of Personnel Per Shift 15-24 ft. unlined diameter			
		Standard System		Spiral System	
		No. of Men*	No. of Shifts	No. of Men	No. of Shifts
Shifter	$ 5.65	1	3	0	0
Nipper	5.025	2	3	2	3
Mucking Mach. Oper.	6.25	1	3	0	0
Oiler (Hose Tender)	5.18	1	3	1	3
Motorman	5.48	4	3	4	3
Brakeman	4.925	4	3	4	3
Dumpman	4.925	2	3	2	3
Electrical Foreman	8.025	1	3	1	3
Electrician	7.475	2	3	2	3
Compressor Man	5.89	1	3	1	3
Warehouse Man	5.155	1	3	1	3
Warehouse Man Helper	5.03	1	3	1	3
Carpenter	5.935	2	1	2	1
Mechanic, Master	7.50	1	3	1	3
Mechanic, Heavy Duty	6.22	2	3	2	3
Blacksmith	6.22	1	1	1	1
Blacksmith Helper	5.48	1	1	1	1
Drill Doctor	6.22	1	1	1	1
Powder Man	5.025	1	3	1	3
Pipe Foreman	5.30	1	1	1	1
Pipe Fitter	5.175	2	1	2	1
Track Boss	5.30	1	3	1	3
Track Crew	4.925	4	3	4	3
Labor Crew	4.925	2	3	2	3
Truck Driver	5.125	1	3	1	3
Walker	6.875	1	3	1	3
Time Keeper	3.75	1	3	1	3
Office Men	3.75	3	1	3	1
Bookkeeper	3.875	2	1	2	1
Superintendent	10.00	1	1	1	1
Miner	5.175	9	3	4	3
Chucktender	5.025	9	3	0	0

*Average (See exact crews in Bulletin 78, App. C)

TABLE VI. STANDARD TUNNELING EQUIPMENT COSTS

Equipment Cost, Standard Practice

Conway 100-l loader	2 @ $64,650	$129,300
Gantry type drill		20,000
Rock Drills	18 @ $ 2,840	51,120
Hydraulic jibs	12 @ $ 2,790	33,480
8-ton locomotive	2 @ $30,500	61,000
Batteries		15,000
120 cfm compressors	3 @ $26,830	80,490
8 yard side dump muck cars	16 @ $ 3,300	52,800
Man cars	4 @ $ 2,830	11,320
Flat cars	4 @ $ 2,220	8,880
Powder cars	2 @ $ 3,330	6,660
Circuit chargers	4 @ $ 3,530	14,120
In-line ventilation fans 15hp	20 @ $ 1,575	31,500
		$515,670
Cost per foot in one (l) mile		$98.

TABLE VII. RAPIDEX TUNNELING EQUIPMENT COST

RAPIDEX Spiral System Equipment Costs

8-ton locomotive	2 @ $30,500	$ 61,000
Batteries		15,000
1200 cfm compressor		26,830
8-yard side dump muck cars	20 @ $ 3,330	66,600
Man cars	4 @ $ 2,830	11,320
Flat cars	4 @ $ 2,220	8,880
Powder cars	2 @ $ 3,300	6,660
Circuit Chargers	4 @ $ 3,530	14,120
In-line ventilation fans 15hp	20 @ $ 1,575	31,500
		$241,910
RAPIDEX Spiral Blast Machine		$400,000
Salvage Value		200,000
Total First Cost		$641,910
Net Cost		441,910
First cost per foot in 1 mile		$122
Salvage value per foot		38
Net cost per foot in 1 mile		$ 84

TABLE VIII. TOTAL EXCAVATION COST

Comparative Summary of Estimated Costs of Tunnel Excavation

(Price Levels of January, 1967)

		Standard	Spiral
I.	Equipment Cost/foot		
	First Cost	$ 98	$122
	Salvage	-	38
	Net Cost	$ 98	$ 84
II.	Consumables Cost/foot		
	Power	$ 5	$ 8
	Pipe, track etc.	25	25
	Explosives	19	19
	Drill bits and rods	3	3
	Sub total	$ 52	$ 55
III.	Rate dependent labor dollars/foot		
	Rate, ft/day 36	$206*	$151
	50	--	109
	100	--	54
	150	--	36
	200	--	27
IV.	15% Profit, 25% Contingencies (on sum of I, II, III)		
	Rate, ft/day 36	$142	$116
	50	--	99
	100	--	77
	150	--	67
	200	--	66
V.	Miscellaneous, cost/foot	$ 32	$ 32
VI.	Total Cost, dollars/foot		
	Rate, ft/day 36	$530	$438
	50	--	379
	100	--	302
	150	--	274
	200	--	264

Footnote:

*This cost and those related costs that follow are derived from the labor costs in Table V which apparently differ slightly from those of Table 3-D-1 of reference 17

7. Spiral Blast Applications

The spiral blast tunneling machine, as conceived here, is an "all-function" machine, as must be the case for any machine that remains at the face of an advancing tunnel. Indeed, the requirement might be looked upon as the problem that distinguishes tunneling from surface excavation, or even underground mining for that matter. In a tunnel there is only one work place, and if all functions cannot be performed there simultaneously then obviously, equipment and personnel for the separate functions cannot be employed full time.

The spiral blast system retains at least some of the flexibility of the conventional drill and blast method and, thus far at least, it seems to promise performance not attainable by that method. Thus, in comparison either to conventional practice or other "all-function" systems such as boring machines, the spiral blast system offers an unique combination of high performance, economy, and flexibility that suggests a very broad applicability. These features are virtues in any tunnel application whether the tunnel be intended for transportation, water, utility, sewer, mine development, or even mine production

If a single heading is sufficiently large, as for example a typical room and pillar mining entry, or an excavation for an underground station in a transportation tunnel, the "all-function" requirement might be relaxed somewhat, but automated loading and shooting capability in a single, shielded excavator would still be of great value. Figure 19 illustrates an application in a wide heading where such a machine would be of great value. Figure 19 illustrates an application in a wide

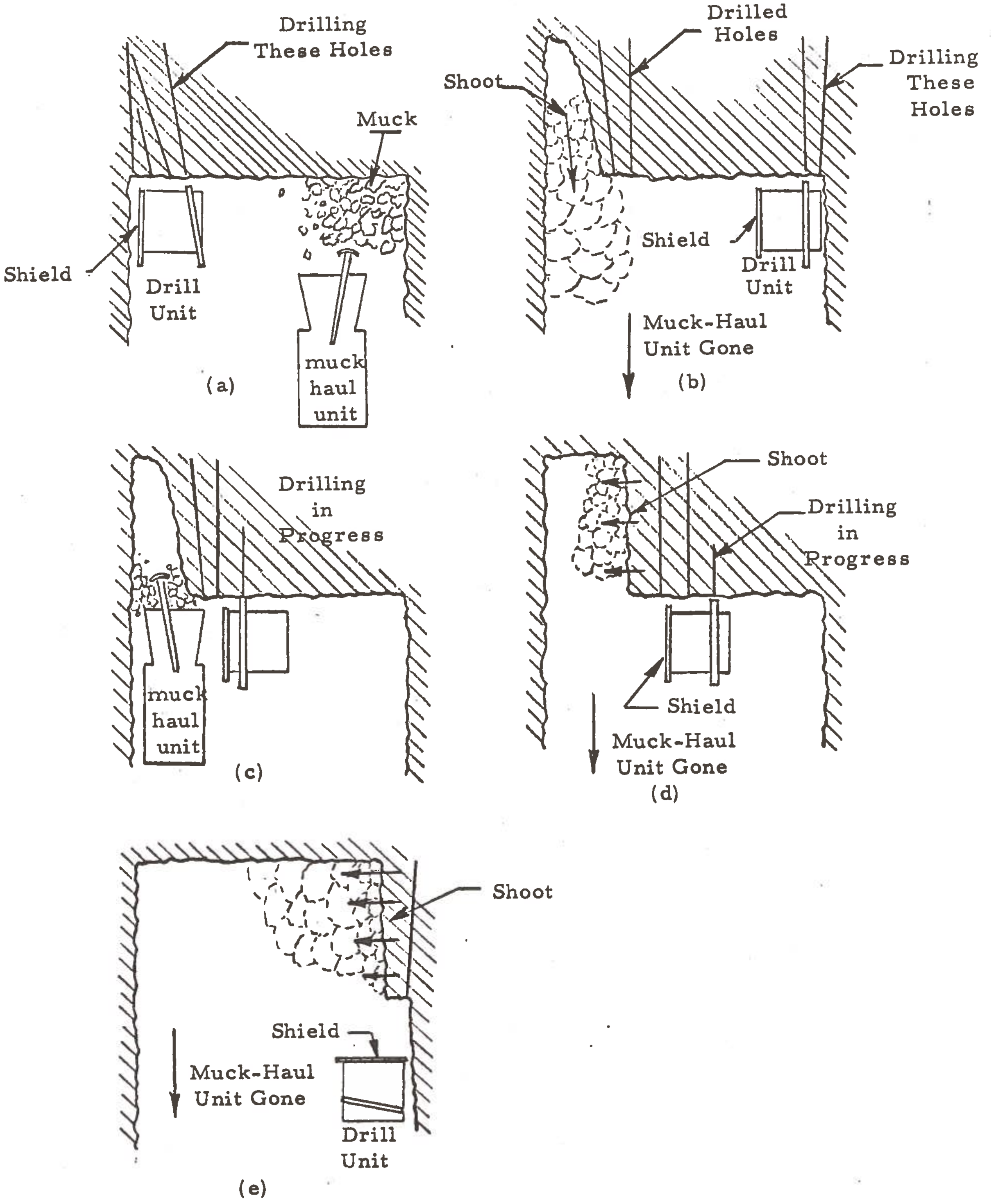


FIGURE 19
"CONTINUOUS" DRILL AND BLAST MINING

heading where such a machine would provide "continuous" drilling, loading and shooting, while mucking is handled by separate load-haul vehicles. With a T. V. monitored drill-load-shoot machine which stays at the face, and relatively conventional load-haul mucking vehicles (life support cabs would be necessary to provide a breathable atmosphere for the operator), this system would actually be easier to develop than the complete spiral blast machine. Note that in Figure 19 the blast timing is such that blast shielding of the mucking equipment and its operator is not needed. However, by simply arranging for the full-time utilization nearly conventional mucking equipment, this approach would permit a fourfold increase in the excavation rate in a single heading.

Clearly, the techniques of automated drilling, loading, and shooting necessary for the successful development of the spiral blast concept would be directly applicable to this new approach.

8. Conclusions and Recommendations

The spiral blast concept, with a shielded machine remaining at the face to carry out all tunneling functions, was conceived as a means to attain a "continuous" drill and blast tunneling capability. The virtues of this capability have long been recognized and, indeed, development of the capability is a specific goal of the recommended "Rapid Excavation" effort. The incredible benefits afforded by continuous application of even conventional excavation components is clearly shown in Section 6: a fourfold increase in advance rate at roughly half the cost of conventional drill and blast practice.

The RAPIDEX spiral blast work has progressed through a feasibility study and field testing of critical aspects. Specifically, in the present program, the spiral blast pattern in a horizontal entry has been proven workable and economical; it has been shown that explosive selection, insofar as rock fracture is concerned, is not critical; preliminary tests indicate that a durable, effective, light weight shield can be built; and design work indicates that, except for remote explosive loading and initiation equipment, today's state-of-the-art machine components will suffice.

At present no insurmountable technical problems are foreseen, although it would be premature to state with certainty that none will be discovered. One thing that <u>can</u> be said about remaining problems, presently foreseen or not, is that they will not be solved on paper. It is time to undertake fabrication and testing of a prototype. The performance projection for the continuous spiral drill and blast concept certainly justifies the not inconsiderable effort and expense of such a program.

Prototype development may be broken into three major tasks:

1. Development of the basic assembly, providing all necessary functions in a reliable, durable machine capable of remaining at the face during blasting.

2. Provision for monitoring and remote control of the above assembly.

3. Development of the required remote explosive loading and initiation system.

Without ranking these tasks as to relative importance (since *all* must be accomplished before any will be of value), it is recommended that the first item listed be the first undertaken.

Critical examination of drilling and other excavation components reveals that virtually all are "remote controlled" in the sense that the operator seldom, if ever, touches the component directly during operation. Instead, he operates valves and other control mechanisms to position the components, apply power, cause the desired motions (often requiring forces well beyond the operator's capacity), and so on. It will be a relatively easy task to provide for more distant remote control of such devices.

The problems in this first task will then be to provide all necessary functions, properly controlled, to assure simple and reliable operation. This will require selection of *simple*, rugged components, and careful shielding. While good engineering and design are clearly necessary, it seems just as clear that successful completion of this task will require considerable testing, modification, and retesting. The task is a *development* program in the broadest sense, not just a design and fabrication program.

Clearly the second task must follow the first, since it cannot be adequately defined prior to development of the overall machine. While "more distant" remote control may not be difficult, provision of adequate monitoring capability to provide sufficient information to a remote operator is not quite so simple. It will require careful consideration of television camera placement (and camera movement), proper lighting, adequate ventilation to maintain adequate visibility, and, on top of all this, careful shielding of relatively delicate equipment (both cameras and lighting) to assure survival under the harsh conditions expected at the face.

Development of remote explosive loading and initiation techniques, the third task,.can be undertaken independently, but such development cannot long remain independent of overall machine development. There can be little doubt that some loading and initiation technique can be developed: after all, semi-automated equipment is already available for loading stick powder, blow loading granular explosive, and pumping slurry explosives. The more difficult aspects of this particular application include provision of adequate control for a remote operator to get the explosive in the hole; to determine and deposit the proper quantity of explosive; to remotely "aim" the initiation device (if indeed it is aimed); to provide for safe storage and delivery of explosives; and, again to provide sufficient shielding to assure survivability. Thus, while some independent preliminary work can be carried out, say to test initiation behavior and to develop particular explosive combinations or loading mechanisims, this work must be done with very careful consideration of the final requirements, and the real testing of such equipment can only be done on the spiral blast machine itself.

Specifically, then it is recommended that the RAPIDEX spiral blast program be continued and accelerated to develop a prototype spiral blast machine. The first task of this program, Phase III of the ongoing effort, would be the development of a complete vehicle, stopping short of television monitoring and remote control. This vehicle should provide all functions, but each component would be controlled by an "on-board" operator. The machine should demonstrate the ability to stay at the face during blasting (but, obviously, the operator(s) would not).

The Phase III vehicle would be crawler mounted and should include; a drill mounted on a suitable radial arm (one drill would suffice for this effort); a rotating shield; a muck scoop and ramp; and a discharge conveyor. At least initially, explosives would be hand loaded and conventionally initiated with the test vehicle serving as a single boom drill jumbo to provide its own test site. On-board operation (with delay for ventilation after each single shot) will provide the opportunity for close observation of component behavior and serve as the basis for redesign as necessary. With careful dovetailing of design and procurement schedules this effort could be completed in one year.

Parallel effort(s) could be undertaken to develop explosive loading and initiation techniques as attractive combinations became evident, Such programs should all aim at preliminary field testing on the above spiral blast vehicle in the latter half of its development.

Upon successful operation of the basic vehicle, suitable monitoring equipment should be mounted and true remote operation capability developed.

The prototype could then serve at least as a demonstration unit, leading to production of a fully operational unit for application in an actual tunneling job.

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REPORT OF
INVENTIONS
APPENDIX

After a diligent review of the work performed under this contract, no new inventions, discovery, improvement or invention was made.