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EXPERIMENTAL STUDY OF THE
SELF-ADVANCING MINER FOR COAL (SAM)

FINAL TECHNICAL REPORT

This report represents work on a program that was originated by the Interior Department's Bureau of Mines and was transferred to the Department of Energy on .1 October 1977.

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U.S. DEPARTMENT OF ENERGY
Assistant Secretary for Fossil Energy
Office of Coal Mining

FOREWORD

This report was prepared by Rapidex, Inc., subsidiary of Foster-Miller Associates, Inc., Waltham, MA, under DOE Contract No. DE-AC01-77ET12568. The contract was administered under the technical direction of the Pittsburgh Mining Technology Center with Mr. Thomas A. Zemo acting as the Technical Project Officer. The Contracting Officer for DOE has been Mr. Eugene Callahan.

Prior to its transferral to DOE, this program was executed under USBM Contract No. HO272040. Acting as Technical Project Officer for the U.S. Bureau of Mines was Mr. Richard J. Wilson of the Twin Cities Mining Research Center, while Mr. David Askin was the Contracting Officer.

This program was awarded to Rapidex based on an unsolicited proposal submitted to USBM in 1977. Co-inventors of the Self-Advancing Miner (SAM) concept are Dr. Carl R. Peterson, Senior Consultant to Rapidex and Professor at MIT, and Mr. Allan T. Fisk, Program Manager of this project for Rapidex. Mr. Stephen B. Douglas has served as Project Engineer.

We would like to express our appreciation to Messrs. William Schmidt and Hamilton Reese, both of DOE. Without their continued support for this program, the field testing of the SAM concept would not have been possible.

We would also like to extend our thanks to Mr. Ed Moore, Mine Superintendent, and the entire staff at Kaiser Steel's York Canyon Mine in Raton, NM. During our field tests at the York Canyon strip mine, we received excellent cooperation at all times.

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ABSTRACT

The design, fabrication, and field testing of the Rapidex Self-Advancing Miner (SAM) are discussed in detail. The SAM concept utilizes a unique conical screw geometry to excavate coal by first slotting the face and then breaking free the weakened material between slots. Field tests proved that the technique works well in coal and that the SAM does self advance along the face. Using the experimental data obtained, full scale estimates are made for four mining applications. Longwall mining with SAM cutterheads appears the most feasible and offers many operational advantages, including improved dust control. Other key SAM features are increased cutting efficiency, improved face control to minimize slabbing, and low methane emission and risk of face ignitions.

1. EXECUTIVE SUMMARY

Productivity in the United States coal mining industry has been declining in recent years. It is generally felt that the lower productivity figures are a direct result of increased federal health and safety regulations. The decrease in productivity is not a reflection of inefficient coal winning equipment but rather a result of the required addition of manpower to perform tasks not directly associated with the coal production process. For example, surface mining productivity has been lowered due to stricter reclamation laws, while underground productivity has fallen off due to the strict dust regulations implemented in 1969.

Whatever the reasons for the drop in productivity, everyone involved with the industry is concerned about it, since profit drops when production drops. It is known, however, that the industry does not need a new coal excavation device capable of a higher excavation rate. Indeed, present devices, such as the continuous miner, are quite capable of instantaneous excavation rates well in excess of our present haulage and other backup capabilities. What is needed, however, is a mining system including excavator plus all necessary backup equipment that is capable of steady production and therefore higher daily tonnages. The point can be made that present equipment, particularly the continuous miner, is fundamentally unsuited to this task, and that the SAM has inherent advantages in this regard.

The U.S. Department of Energy (DOE) has funded a contract to design, fabricate and field test an innovative coal cutting concept called the Self Advancing Miner (SAM). This concept, proposed by Rapidex, Inc., uses the principle of kerfing and breaking coal from the face to continuously excavate it in a highly efficient manner. The SAM offers many advantages unique to its geometry and not found in any state-of-the-art mining system used today. It has the potential for high production and low generation of airborne dust at the coal face.

Because SAM is very suitable to slow continuous operation, unlike a continuous miner, it is possible to design a system such that:

- a. A high average production can be achieved without overloading the conveyor system.
- b. Ultimate operator safety can be achieved with totally automated operation, using a steady, slow advance rate.

Whereas the development of SAM has been based on the potential for an increase in production, the hidden benefit of low dust generation may ultimately prove to be the dominant advantage of the concept. The SAM geometry includes features which inherently lead to less dust production, such as the following:

- a. Cutting takes place at the bottom of a deep slot or kerf where dust can be controlled.
- b. Less than 20 percent of the excavated material is cut; the remainder is broken.
- c. All cutting is performed at a predetermined (optimum) constant depth of cut.
- d. The peripheral bit tip speed is kept low, thereby minimizing fanning of the fines into the air.

In addition to the more obvious safety and maintenance advantages of any system which uses less energy to extract a given quantity of coal from the face, SAM has the following additional safety features:

- a. The force required to advance the cutterhead through the coal is negligible.
- b. There is little change in the low haulage force even as cutter bits become increasingly worn due to the direction at which the SAM bits attack the coal.

1.1 Project Summary

The purpose of the present development program has been to determine if the SAM cutterhead could excavate coal and how it should be employed in the many possible mining applications. To evaluate the feasibility of the SAM geometry for use in a variety of applications, it was necessary to instrument the prototype for the field tests to acquire the proper data base.

The critical tasks in the program include the following:

- a. Literature and Industry Survey - With very little information available on excavation in slots, an extensive survey was required to establish design guidelines for the kerf-cutting SAM. Based primarily on industry experience with coal cutter bars, a specific energy value of 1200 lb/in.² was established for SAM kerf cutting. This value is four times the typical specific energy achieved by longwall and continuous mining machines in cutting from a free face but proved to be an accurate figure.

- b. Hardware Design - Based on an industry average 60-in. seam thickness, the prototype SAM was designed to be 25 in. in diameter while cutting a 1 in. wide kerf 9 in. deep. To ensure coal breakage between kerfs, a 6-in. lead was selected for the SAM screw cutterhead. A test trolley and track arrangement was designed to support the cutterhead, the diesel hydraulic unit, and the instrumentation package.
- c. Fabrication - Extreme care was required in fabricating the cutterhead and the custom carbide bits. It was critical that the conical, helical cutterhead track in the kerf to be cut without excessive frictional drag.
- d. Field Tests - Arrangements were made to conduct the testing at a western strip mine with an 8 ft coal seam. During the short test period the SAM demonstrated its excavation and self-advancing capability and potential for low dust production. All force and power measurements were recorded and found to be acceptable.
- e. Full Scale Estimates - Based on the field data, calculations were needed to estimate cutting loads for full size equipment. Applications that were evaluated include longwall, blind heading, strip, and auger mining. Although the concept is suited for any of these applications, it appears to be best adapted to the longwall mining application.

1.2 Conclusions

Using the data acquired in the field tests, we have made estimates of the full-scale mining hardware using the SAM concept for several mining applications. The system which seems best suited to the SAM geometry is longwall mining, and most of our analysis was therefore concentrated in this area. The major conclusions reached are the following:

- a. The overall specific energy of the SAM cutterhead is lower than state-of-the-art equipment, representing a higher cutting efficiency. The prototype SAM demonstrated a specific energy of 240 lb/in.², compared to typical continuous miner and shearer efficiencies of 240 to 340 lb/in.² as noted in Table 2, subsection 3.7.1, Field Testing. Because the production longwall SAM will incorporate a geometry with kerfs spaced wider than the prototype, a further reduction in the specific energy is expected because a smaller proportion of material will be cut in the kerf and consequently a larger proportion of coal will be broken out efficiently in large pieces.

- b. The SAM production capability, detailed in Appendix G, Longwall Production Analysis, is compatible with standard face haulage equipment and operating techniques. For a 54 in. seam, a double ranging arm longwall SAM configuration is proposed, as shown in Figure 1. This unit is equipped with 36 in. diam screw cutterheads. A production rate of 406 tons/hr is obtained with 177 cutting horsepower. The advance rate has been set at 25 ft/min along the face, and the "web" depth is 18 in.
- c. Operating loads are compatible with existing face hardware. The horizontal load generated during cutting operation is 8.3 tons. The haulage force required is merely the 9 tons required to overcome sliding friction to engage the screw cutterheads. Once engaged, the longwall SAM should pull itself along the face as long as the coal being excavated remains competent. This longwall configuration is investigated in Section 4, Full-Scale Estimates.
- d. Bit tip speeds are exceptionally low for the production rate developed. Rotational speed of the cutterheads has been set at 25 rpm, yielding tip speeds of 236 ft/min for the 36 in. SAM screws. This low speed eliminates the hazards of face ignitions and minimizes the fanning of coal fines into the mine ventilation air. Subsections 4.1.1.3 and 4.1.1.4 discuss this feature in more detail.
- e. The bit loading is constant as the cutterhead rotates, regardless of rotational speed. Because the depth that each bit penetrates is fixed during the design and fabrication of the SAM cutterhead, there is no variation possible during operation; it is always optimum. As the screw rotates, each bit takes a constant depth of cut around its arc of contact with the coal. Likewise, should the screw rotational speed slow down, the depth of cut remains constant and cannot be varied by the operator. Section 2, Concept Description, gives a detailed explanation of the SAM operation.
- f. Production rate is almost independent of bit condition and face haulage forces. As bits become worn, the normal cutting force increases dramatically and causes additional frictional drag. Unlike continuous miners and shearers, the normal cutting forces generated on the SAM cutterhead do not act to oppose the sump or haulage motion of the machine. Because the normal forces are perpendicular to the direction of travel,

LONGWALL SAM FOR 54-78 in. SEAMS

SCREW DIAMETER ~ 36 in. ϕ
 WEB DEPTH ~ 18 in.
 SCREW rpm ~ 25
 ADVANCE/HAULAGE RATE ~ 25 fpm
 TOTAL hp ~ 300 hp

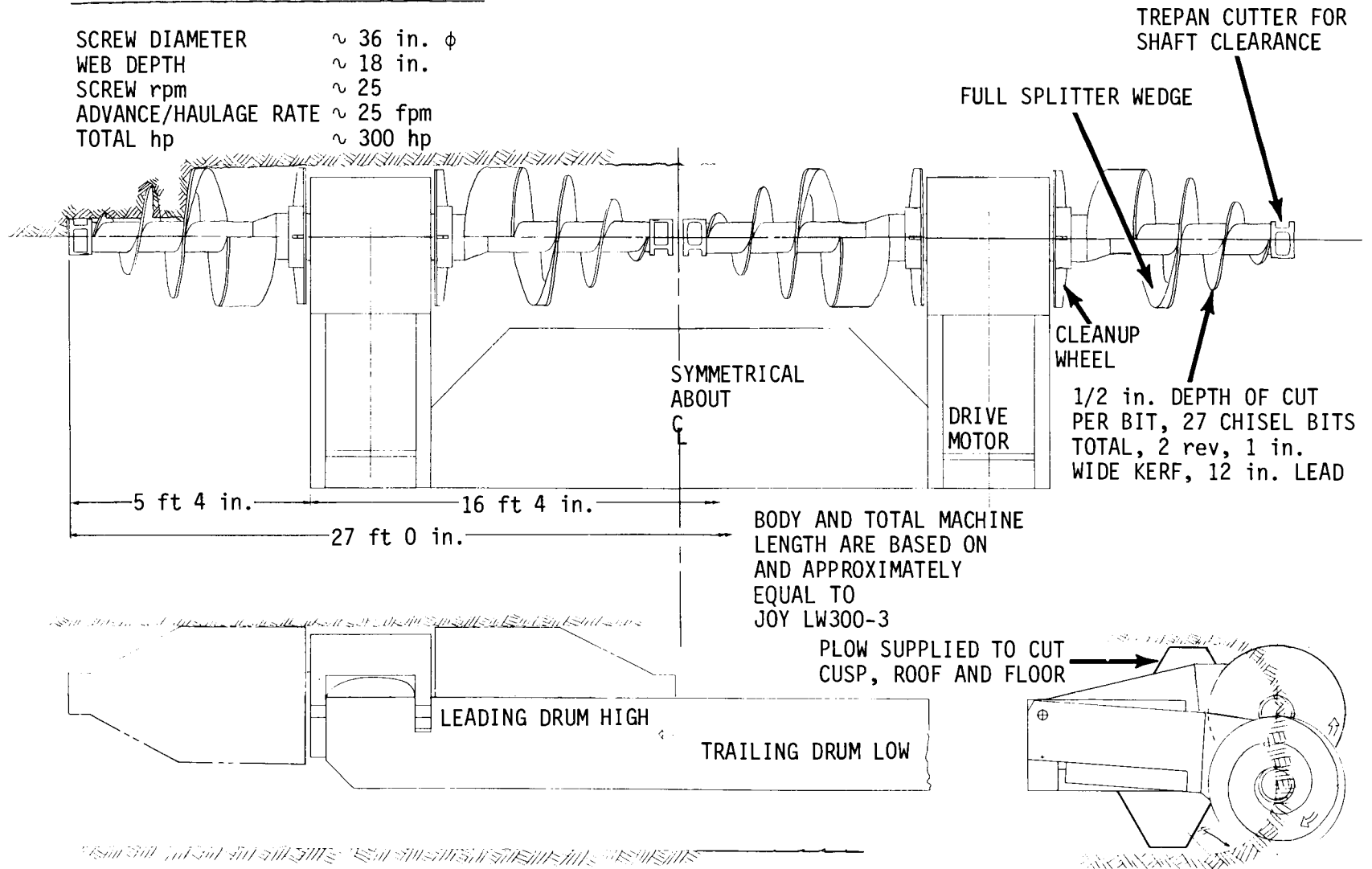


FIGURE 1. - Longwall SAM configuration.

machine performance does not degrade rapidly as the cutter bits become dull. In Appendix B we have detailed the operating characteristics unique to the SAM geometry.

- g. Dust generation will be low. For the reasons just stated, the fines generated by the bits in the kerf will be minimized. The fines produced will be contained deep within the kerf and can be controlled easily with water sprays. The fines swept out of the slot by the bits will not be thrown into the airstream because cutterhead rotational speeds are very low.
- h. The excavated material from the longwall SAM will contain a large proportion of sized coarse material. As detailed in Appendix E, Size Analysis, an analytical estimate of the product from the longwall SAM indicates a large proportion of coarse material. Fines are lower, and ultrafine material is slightly higher than typical mechanical cutting schemes, indicated in Table 1. The high proportion of coarse material is beneficial in terms of methane liberation, dust generation and power consumption.

Additional specific conclusions regarding the field testing are found in subsection 3.5, Field Observations.

TABLE 1. - Size consist comparison

Machine	Percentage		
	Coarse	Fine	Ultrafine
Conventional	88	11	1.3
Borer	63	33	4.1
Ripper	64	34	1.8
SAM, Production	81	17	2.1

1.3 Recommendations

We are of the opinion that the next major step forward in coal mining productivity, comparable to that provided by the shift to trackless equipment and the production of the continuous miner, will be the introduction of satisfactory remote controlled mining. Remote controlled mining entails a complete system, from excavator to haulage system, and including whatever roof support and ventilation equipment may be necessary, capable of traveling long, uninterrupted distances with no onboard operators.

In addition, we are also of the opinion that the continuous miner in its present form is basically unsuitable for remote controlled mining. It utilizes large high-speed excavation elements which must undergo a variety of motions in normal operation, all the while subject to considerable dynamic forces. Proper operation quite literally demands sensitive machine performance feedback to the operator.

It would seem, then, that while a coal excavator of greatly increased instantaneous productivity is not really needed, an excavator basically suited to remote operation in an ever tightening regulatory environment is needed. As an aside, it should be mentioned that such a machine must be simple, and we believe that the SAM is such a device. However, by whatever device (or devices) we firmly believe that the much needed major gain in productivity, compatible with adequate safety, can only be achieved when men are removed from the immediate coal production site.

We have determined that SAM does perform up to expectations and does have the potential to increase underground coal mine productivity in two distinct ways. These are:

- a. The coal excavation process itself is more efficient than state-of-the-art schemes. With less work required to perform the cutting function, there will be less wear on machine components, thereby promoting better availability. Since present shearers and continuous miners excavate for less than 3 hr/shift, any increase in availability (or decrease in conveyor downtime) will result in more productivity.
- b. By reducing the amount of airborne fines generated during the coal winning process, there will be less downtime associated with dust suppression and monitoring functions. With a larger size consist, methane liberation should also be less.

The strip mine at which the SAM prototype was tested also maintains a large longwall operation. The management was very enthusiastic about the prospects for the SAM to reduce dust generation on a longwall face and offered to assist us in any further development of the SAM concept.

Based on the successful field tests, the full scale estimates and the interest offered by a cooperating test mine, we recommend that the SAM concept development proceed into the next phase.

Due to the ease with which the geometry can be adapted to the longwall hardware and the compatibility of the SAM with longwall operating procedure, we recommend that the first application of SAM be to the longwall mining system. It is also true that the longwall system, plagued with inadequate dust control measures, would benefit greatly from the potential for decreased dust generation offered by the SAM concept.

To evaluate a full size longwall SAM, we would propose a surface test at a cooperating strip mine. The SAM cutterheads would be mounted to a modified shearer body with the proper ranging arm configuration. To minimize the risk at this point we recommend fabrication of only one ranging arm assembly, complete with a double ended (bidirectional) SAM cutterhead.

The SAM body would fit onto face conveyor hardware and be capable of moving along the face just as it would in an underground longwall operation. A standard haulage system would be utilized to facilitate testing and to engage the screw for each pass along the face. Once the force and power levels of the full size machine have been properly evaluated above ground, it would be a simple matter to add the second ranging arm at a later date. Because the longwall SAM would be sized to operate on standard longwall face hardware, it could be installed underground with little additional delay or risk.

2. CONCEPT DESCRIPTION

Like other Rapidex concepts, the SAM is based on the fairly obvious principle of balancing large excavation forces with equal and opposite large excavation forces. In this way, much of the nonproductive machinery, like the slipping crawlers of borer-type continuous miners or the massive (and occasionally slipping) wall jacks of tunnel borers, can be simply eliminated. The SAM, in its simplest form, excavates from the rib of an existing opening. It can be used singly in longwall mining applications or in balanced pairs to excavate from opposite ribs while widening an existing opening. It can also be designed to excavate a blind heading from solid material.

The basic excavating element of the SAM is simply a wood-screw-like spiral saw blade as shown in Figure 2. It could almost literally be made of a piece of screw conveyor. The screw is tapered or conical towards the front end, followed by a short cylindrical section at the rear. The central shaft of the screw is shown carried in bearings at its ends, and these, in turn, are carried in a frame that travels parallel to the rib. For example, in longwall mining the "rib" would be the longwall face itself, and the frame would travel along, and be supported by, the roof supports and face conveyor just like conventional longwall equipment.

Returning to Figure 2, a frame-mounted motor rotates the screw about its axis as it engages the adjacent rib along one side and travels forward, parallel to the screw axis and the rib, as shown. Upon engagement with the rib, teeth on the periphery of the screw cut a single spiral groove as the rotating cutter literally screws itself forward, advancing exactly one screw pitch per rotation. The single spiral groove is interrupted by the absence of material on one side, but all visible segments are portions of the same groove.

This self-advancing behavior has been hard for some to imagine. However, it is easily accepted if one simply imagines that SAM is a woodscrew, which, of course, does advance upon rotation exactly one pitch per turn. All we have done, for the rib cutting configuration shown, is to remove the "wood" on one side of the screw and provide a means (the frame) to maintain engagement with the wood on the other side.

Figure 3 is a photograph of an actual SAM demonstrator which "mines" Styrofoam in longwall fashion, and which clearly and emphatically demonstrates the simple screw-like geometry and self-advancing behavior of the SAM concept. As the photo shows, the SAM screw element is splined to a horizontal drive shaft so that it is free to slide axially along the shaft, but it must rotate with the shaft when the crank handle is turned.

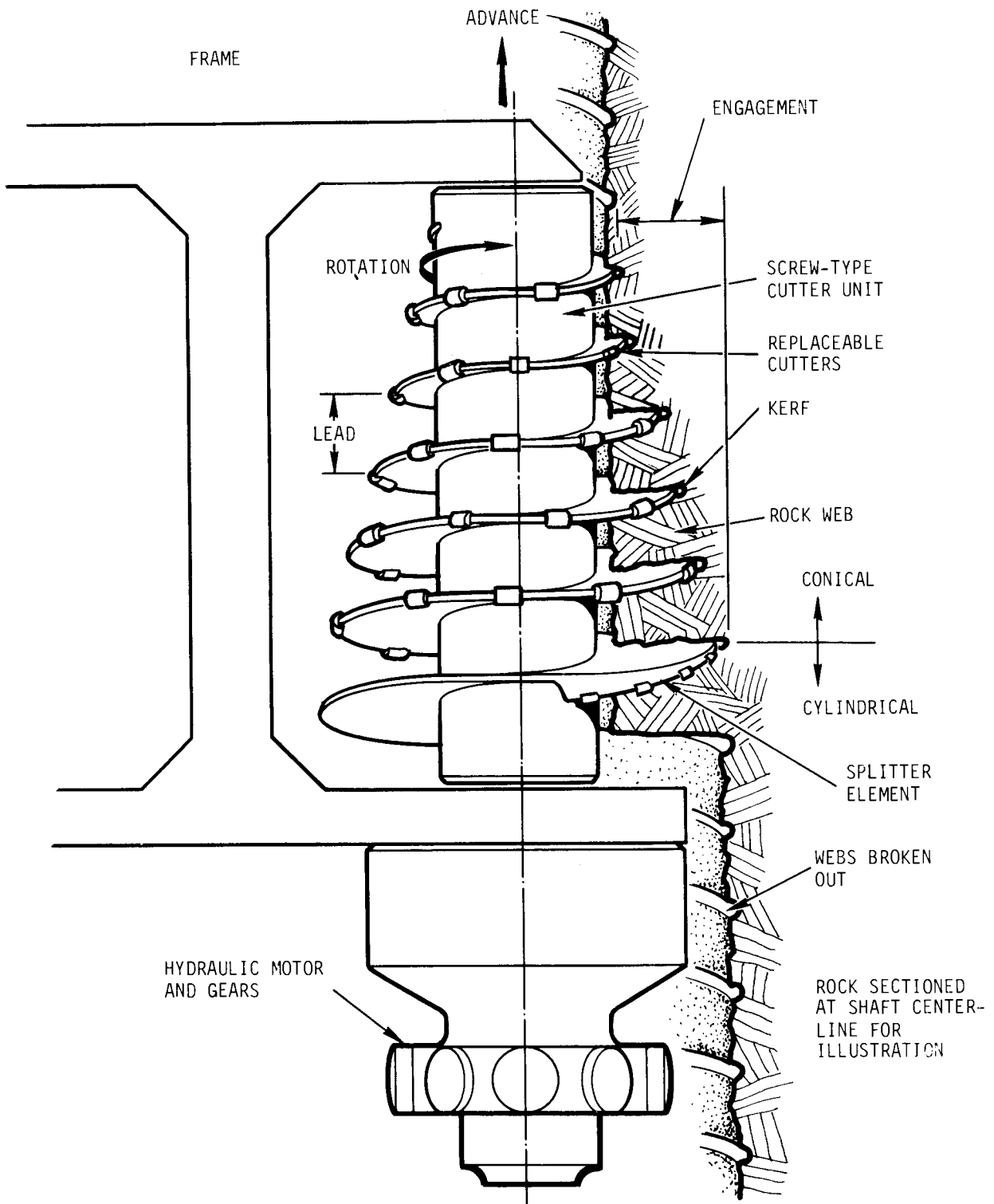


FIGURE 2. - Top view of SAM cutter element.

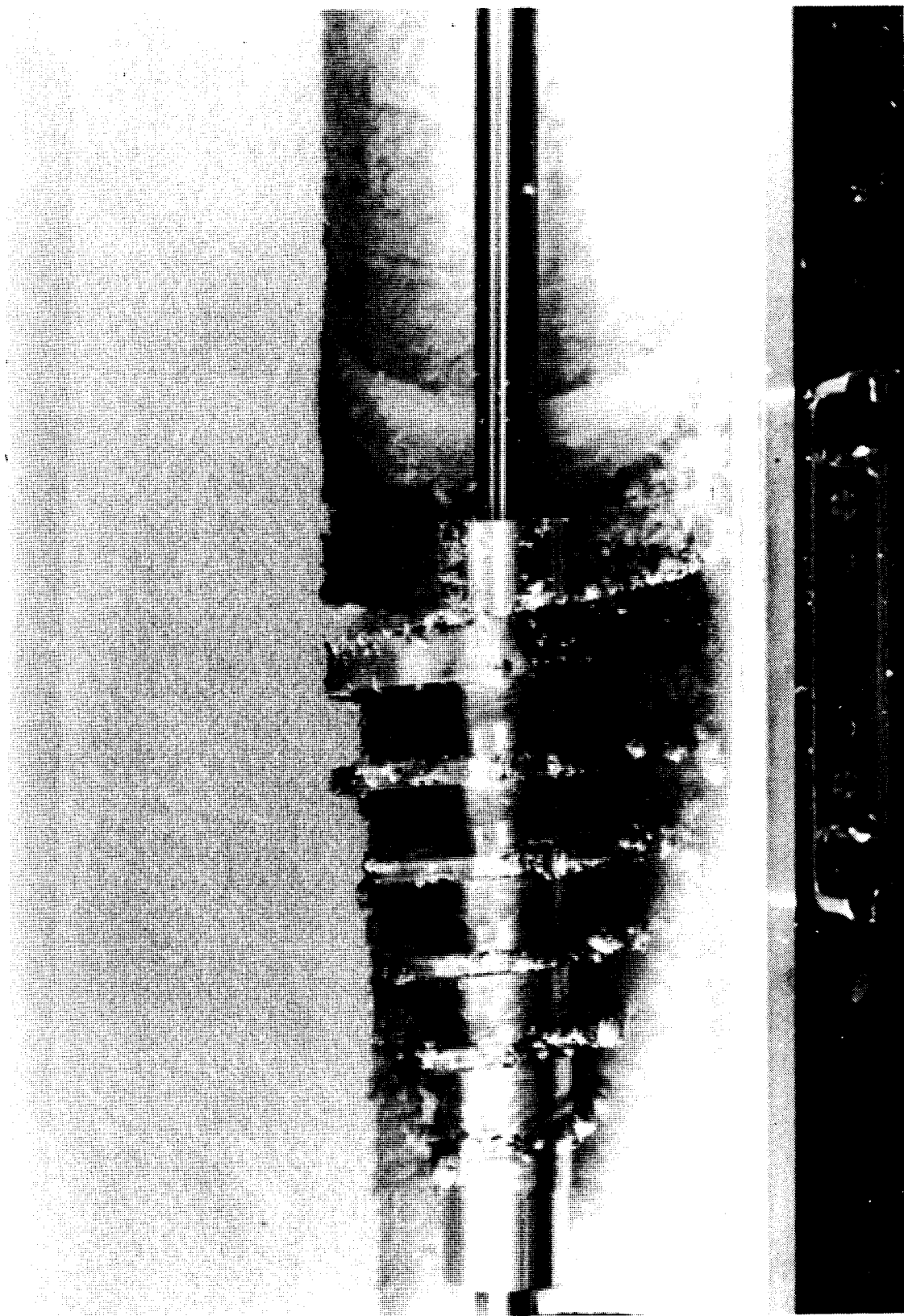


FIGURE 3. - Styrofoam SAM.

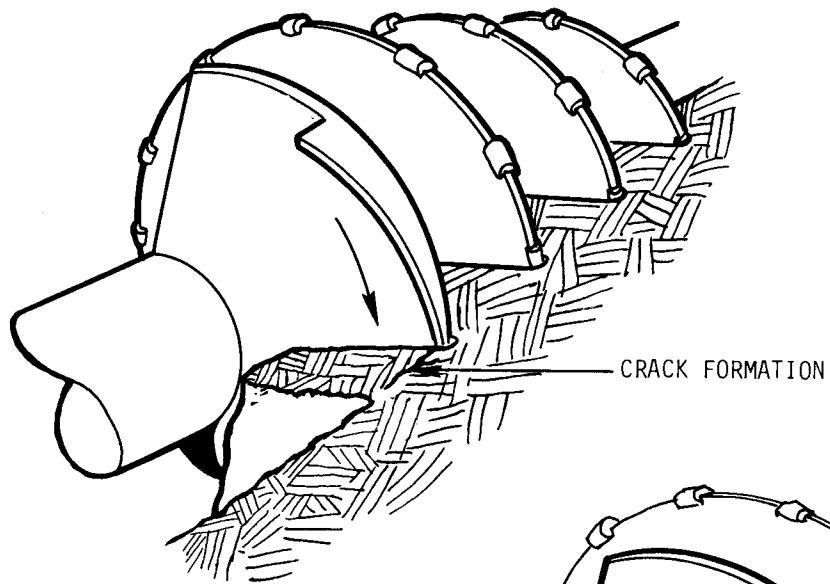
In operation, the nose or core of the SAM screw is placed in contact with the edge of the "coal", that is, the Styrofoam block, and upon rotation of the spline shaft the SAM screw cuts its spiral groove while pulling itself from right to left along the rotating shaft at the correct pitch. Appendix A contains additional details for the SAM model operation.

The increasing radii of successive teeth on the conical spiral flite cause each tooth to bite deeper than its predecessor, thereby deepening the groove, or kerf. Note that, except for a very short transition region as a tooth first engages the coal, the vast majority of cutting by each tooth is done at constant depth of penetration. This depth can be selected (it is simply the tooth-to-tooth change in radius) for maximum efficiency and minimum dust.

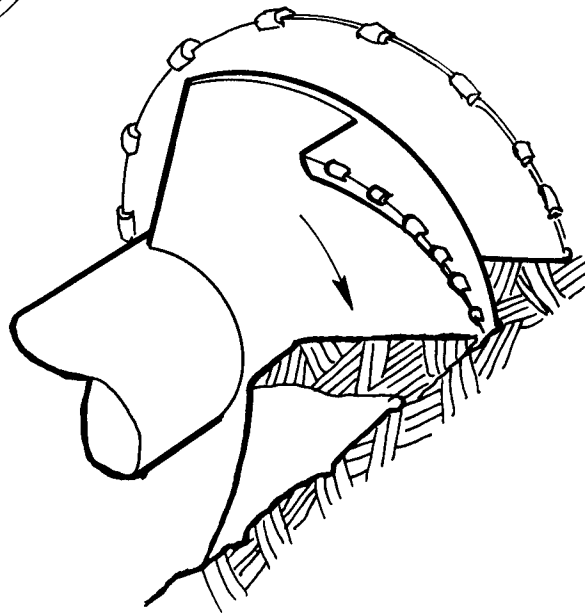
The sum of the tangential forces of the cutting teeth, times their radii, is the torque required of the drive motor. Since the teeth are all moving helically forward in the groove, their motion is resisted by a slight rearward force component. This force is reacted by rubbing the rearward flank of the tooth or tooth-support against the side of the groove just like that of a woodscrew thread flank as it drives the point of the woodscrew forward.

Maximum groove depth is reached at the large diameter end of the conical screw section. Thereafter, a "splitter" mounted on the cylindrical screw section enters the base of the groove and breaks out the "quarter-moon" shaped web of material left between grooves. Some of these moon-shaped webs may be seen in earlier photographs. In weak material like coal, this splitter could consist of simple circumferentially expanding wedge shapes, as sketched in Figure 4. Alternatively, it may consist of several cutter teeth to undercut the web slightly, followed by a wedge to finish the job. In the extreme, in strong material, it could even consist entirely of cutter teeth to completely saw out the web, but this may be an unnecessary waste of power (it was necessary in Styrofoam because the material is not brittle). In effect then, SAM not only isolates a block of coal by sawing kerfs around it (as do other tools); it actually reaches under the block (by sawing if necessary) to detach it from the solid, and it does all this in a continuous process.

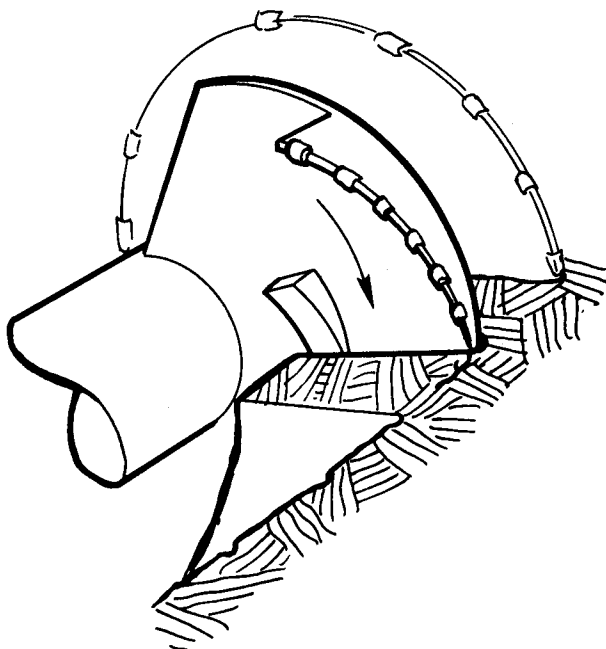
The helical flite of the SAM screw is ideally suited to carry cutter teeth. It is a continuous metal section, very strong in the helical direction and, in general, this is the direction of tooth loading. Thus, a relatively thin flite (1/2 in.), carrying cutters of about 1 in. width, can easily cut a kerf to a depth of 8 in. or more. From this we gain the major advantage of reduced power consumption (and reduced airborne dust), simply because less material need be ground to a fine powder in the kerf.



a) SIMPLE WEDGE AT
BASE OF KERF



b) SAW AND WEDGE AT
BASE OF KERF



c) SAW AT BASE OF KERF, WEDGE
AT TOP OF ROCK WEB

FIGURE 4. - Various splitter designs.

Unlike conventional equipment, very few rotations of the SAM cutterhead are required for it to advance through a given quantity of coal. A result of this phenomenon is that for the same production rate, the maximum cutter bit velocity is very low for SAM when compared to a machine with a high-speed drum. Low cutter velocity should lead to quiet operation, long cutter life, and relatively little airborne dust. In fact, with almost all cutting occurring deep within narrow grooves, it would be a simple matter to flood the cutters with relatively little water (or foam) to virtually eliminate airborne dust generated from the cutters themselves, and probably reduce face ignitions as well.

By elongating the SAM, the peripheral length of the screw flite may be made as long as desired to accommodate as many teeth as desired. In Figure 2, this length is greatly exaggerated to illustrate this possibility, but in coal a much shorter cone suffices (see Figure 5). Single cutter experiments by the U.S. Bureau of Mines (USBM) and others in coal, suggest advantages for fewer and deeper cutting teeth. In fact, experience even in rather hard rock has shown that deep tooth penetration, necessarily at low speeds, leads to better cutting efficiency. Teeth on the SAM enter and leave the cut gradually, without impact, in a short transition zone, and thereafter travel at quite low speed and at constant, controlled depth. Hence, it is possible to exploit this means to further reduce power consumption and reduce both the amount of material ground to very fine powder and the tendency to throw that material into the air.

In the foregoing, a "side-cutting" SAM has been illustrated; however, a "blind" SAM also has exciting applications. Two new problems arise in designing a blind SAM. The first and most obvious is that some means must be found to excavate material at the center of the blind hole since SAM is basically a side-cutting device.* The second is that, unlike the preceding single-sided designs in which teeth can deposit their cuttings into free space once per revolution, the blind SAM is completely immersed in coal and some other means must be found to clear cuttings from the bottom of the (continuous) kerf.

Figure 5 illustrates a blind SAM design concept. It includes an auger-like central cutter driven through a hollow SAM shaft. Cuttings from this central portion together with cuttings from the spiral kerf saw are continuously flushed to the rear through the groove and/or central bore clearance by water or an air-water mixture. This simple solution seems entirely feasible

*

In principle one might make a blind SAM that looked just like a woodscrew, with all kerf cuttings flushed back through the spiral. However, the center point would be forced directly into the coal with no cutting action whatsoever. This design might be closely approached, however, with a small central cutter and all-spiral flushing.

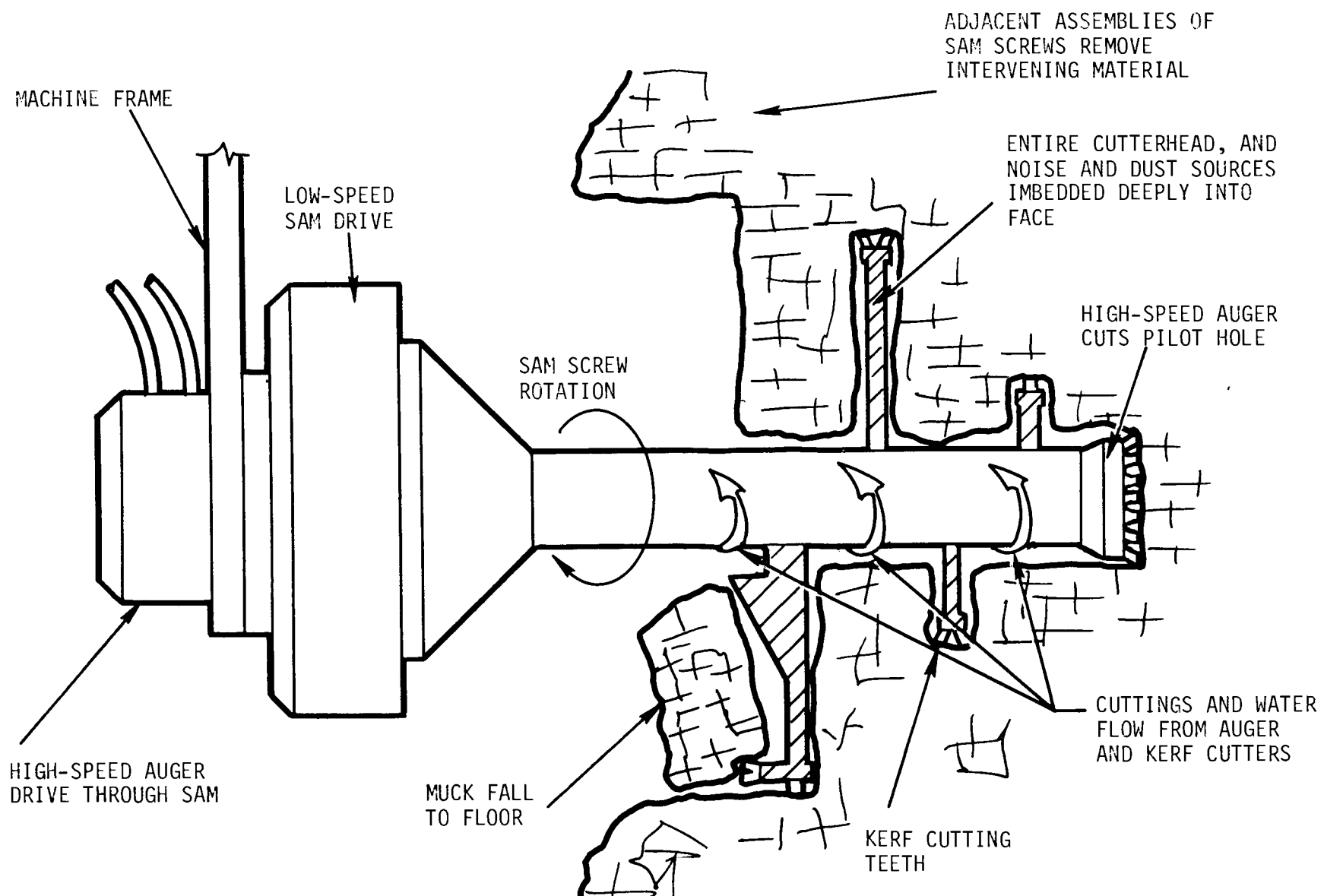


FIGURE 5. - SAM blind heading concept.

because of the unusually low velocities demanded of the SAM element. For example, one blind SAM application (which has drawn more interest than others from the coal industry) would be to drive a full-face or half-face heading with an assembly of such units spread over the face, screwing themselves forward simultaneously and pulling the mining machine forward.* Coal webs broken out by the screws and from between the screws simply fall from the face to a conveyor system on the floor. Many of the initial design fears that arise from this concept are greatly eased by the rather slow progress required of such a machine. For example, a 7×20 ft full-face machine would advance at 2 ft/min while producing 12 tons/min. These parameters are well within present capabilities for the central cutter or pilot hole device, and no problems should occur in flushing the groove with reasonable fluid velocities that are still high relative to cutter velocity.

The proper application of the SAM concept requires a comparison of its operating characteristics with those of conventional mining machines. We have included a detailed analysis of excavation techniques in Appendix B.

*Or, more likely, providing their own advancing force while the following machinery simply propels itself.

3. FIELD TESTS

To evaluate the SAM concept, the test hardware described in Appendix C was shipped to Kaiser Steel's York Canyon surface mine for actual coal excavation testing. A surface, rather than underground, mine was selected due to the fewer health and safety requirements in force. It was more difficult to find a corner of an underground operation where we could remain undisturbed for several months without disrupting production, the mine plan, and requiring MSHA approvals. The downtime and troubleshooting encountered in any test program are much more difficult obstacles in an underground test than at a surface facility.

Mine personnel at York Canyon found the SAM machine intriguing because of the problems they were having with dust control in their underground operations. The seam in which was tested it was the same as that being mined underground, and the coal was just as competent. There was no significant fracturing of the seam during the stripping operation, and the resident mining engineer felt that surface excavation would be more difficult than underground mining due to the lack of overburden pressure. The seam selected was prepared shortly before testing and therefore was not weathered.

Core tests performed previously on coal samples from the seam indicated a compressive strength of 1650 lb/in.². It was very obvious during the tests that the competency of the coal varied greatly through the seam. The upper and lower sections of the seam contained a significant amount of calcite and were friable; the center was very homogeneous and difficult to cut.

3.1 Test Plan

The field test program was originally designed as a thorough investigation of all the interrelationships among the SAM cutter-head variables. As budgetary and scheduling constraints became tighter, the field testing was reduced to the role of merely proving the SAM concept in coal. Correspondingly, the field test schedule was shortened from 16 to 3 weeks.

The test plan included in Appendix D lists in detail the plans for the field tests. We will discuss here the actual execution of the tests as took place in the field.

With the scope of the tests reduced to proving the concept, an exhaustive parametric test sequence was not required. Likewise, the quantity of data acquired is not voluminous, nor is the quality of the data exceptional. The best data taken was in the form of photographic documentation showing the screw cutting coal.

The excavation parameters varied during the field tests were the following:

- a. Depth of Kerf: 7 and 9 in.
- b. Bit depth of cut: 1/8, 1/4, 1/2, and 1 in.
- c. Number of bit lines: 1 and 3
- d. Bit skew angle: 0, 7, and 12 deg
- e. Flywheel: 0 and full
- f. Splitter design: None, full knife-edge wedge, half knife-edge wedge, and tee head bits
- g. Amount of screw engagement with the coal: 90 and 180 deg.

For each test the values of screw torque, speed, and bearing reactions were recorded. From these data, the concept was compared against the state of the art for cutting efficiency or specific energy.

3.2 Site Layout

The cooperating mine left behind an exposed three-sided block of coal in the surface mining operation. The block was available for our test purposes longer than we could afford to use it. For our cutting tests, the block was sculpted to dimensions of 30-ft long, 8-ft high, and approximately 30-ft deep.

The 45-ft long track system was aligned parallel to the face with the appropriate extension beyond each end so that the cutter-head could begin and end each test pass out of the coal. The trolley was designed so that at all times the 36-in. wide Bobcat loader could fit between the rail and the face for mucking duty.

The test site is shown in Figures 6 and 7.

3.3 Test Procedure

Prior to taking any cutting data, the face was sculpted into the cutting profile to be left by SAM. Since the screw cuts a crescent of coal as it passes down the face, a circular clean up disk, shown in Figure 8, was used to cut the semicircular contours in the face. Note that since we were working on an 8-ft thick coal panel, three passes vertically could be made with the 25-in. screw, leaving 7 in. between passes.

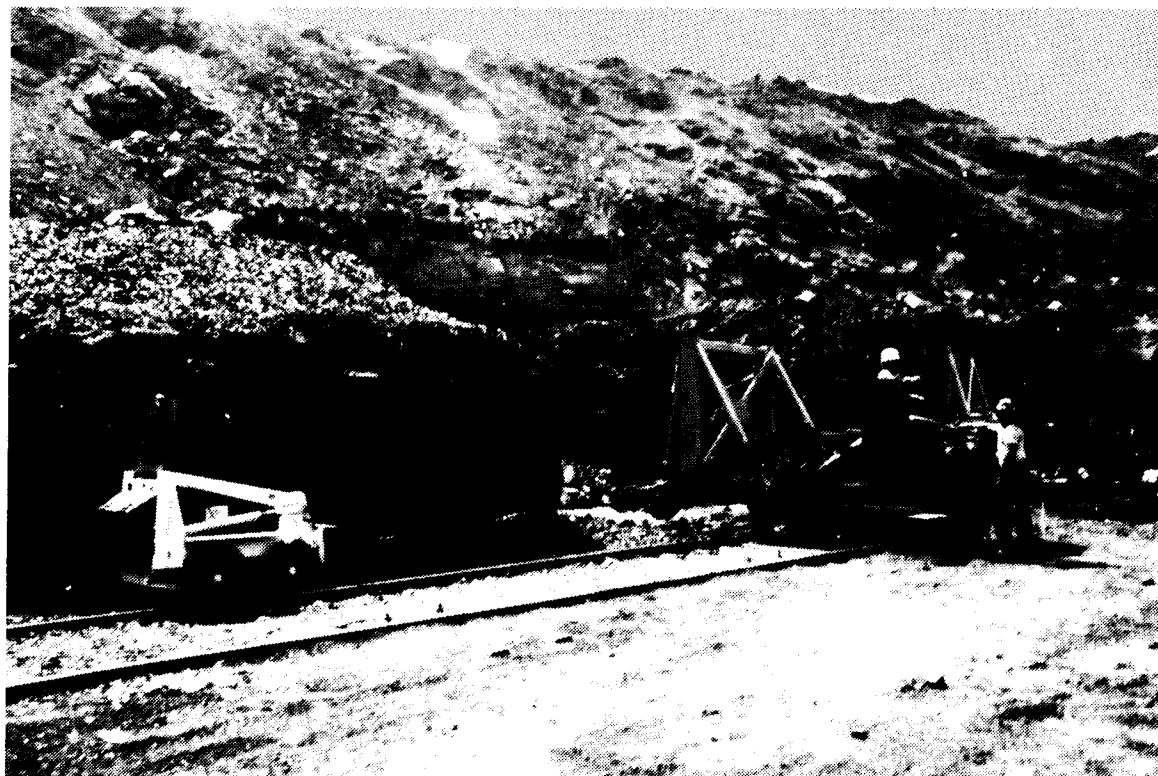


FIGURE 6. - Overall view of test site.



FIGURE 7. - Test panel.

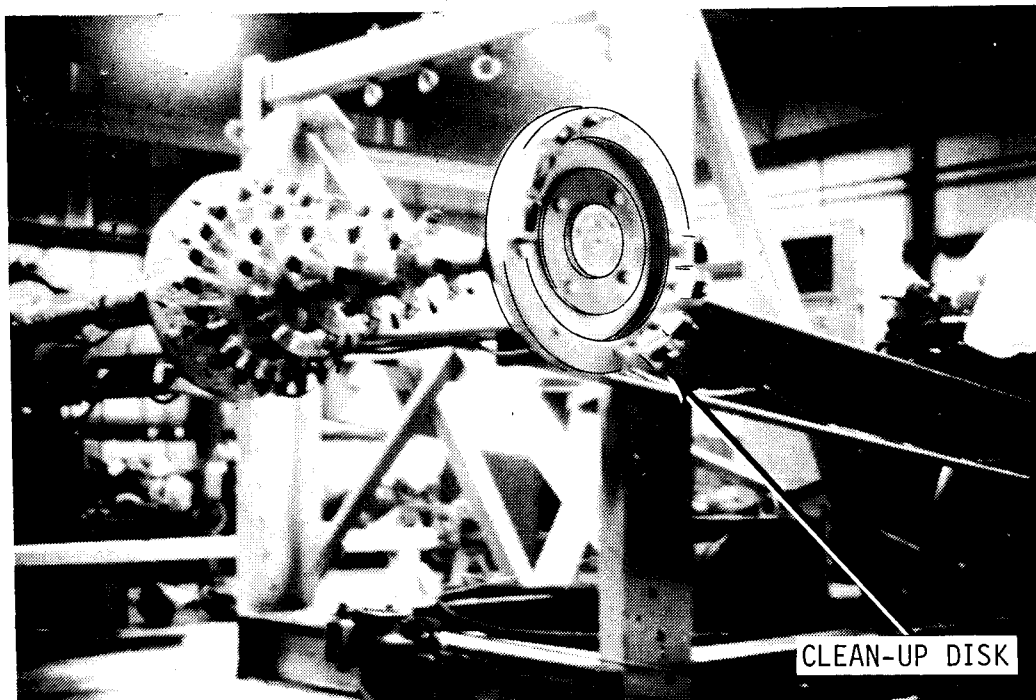


FIGURE 8. - Clean-up disk.

The screw was designed to cut 9-in. deep kerfs. We discovered immediately that:

- a. 7-in. deep kerfs would have to be excavated.
- b. The extremely hard band of coal in the center of the seam had to be avoided.
- c. The use of the flywheel was *not* optional.

Using the alternate bolt hole spacings on the trolley, these operating procedures were implemented for the duration of the test program.

Some of the preliminary tests were run using the hydraulic winch to compensate for the trolley friction as the screw excavated and advanced down the face. As noted in the Appendix D test plan, we were able in this way to center the screw in the kerf and record a slightly lower required cutting torque. Because the difference proved to be so slight and because this procedure added considerably to the test complexity, the use of the winch was abandoned early in the test program. For the bulk of the testing, the Bobcat loader was used to move the trolley

up and down the tracks. While excavating, the loader was required to restart the screw when it fell out of engagement with the face; normally, the screw pulled the trolley along with no assistance.

Because we required all of the drive train inertia that we could muster, the screw was run at maximum speed for all tests. At 25 rpm, the translational speed of the cutterhead was 12-1/2 ft/min; therefore, one pass along the face took only 2 to 3 min.

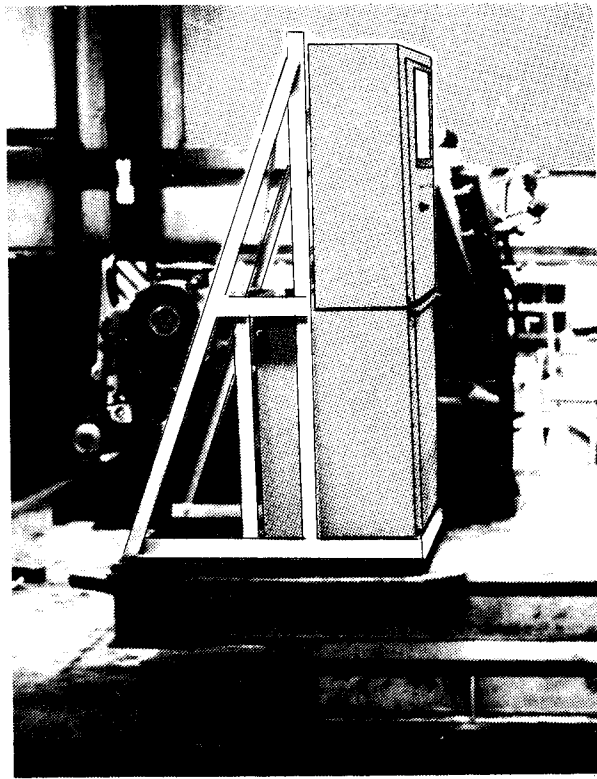
Depending on the hardware modifications required, two to three tests were normally run per day. Additional test site functions included changing bit lacing, varying the splitter design, advancing the top of the trolley, changing the trolley arm position, and taking slides, movies, and tape recordings of test progress.

3.4 Data Acquisition

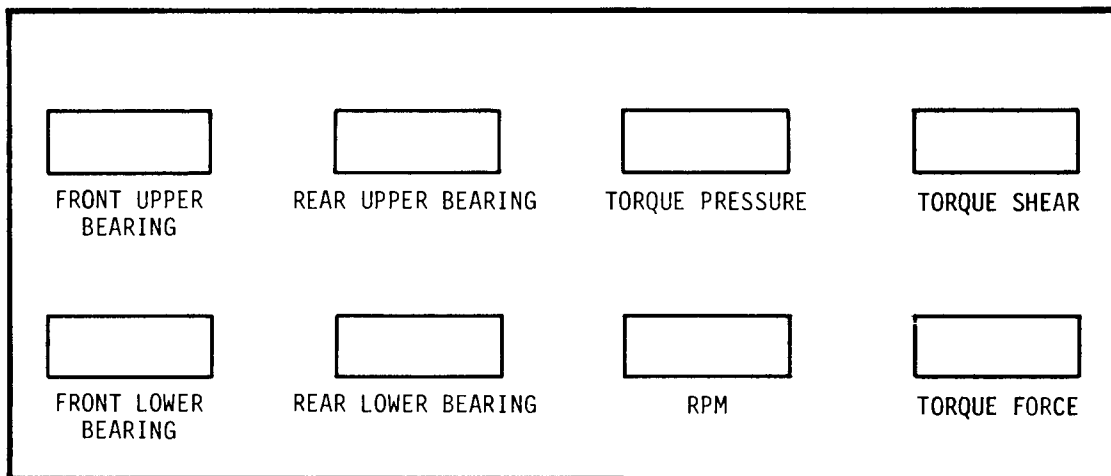
During cutting tests, all transducer readings were displayed on digital panel meters mounted in the instrumentation cabinet, shown in Figure 9. The signal conditioning was designed to take a reading simultaneously on all eight channels and display the values for an adjustable delay time, usually 15 sec, sufficient to permit verbal recording of all figures. A handheld tape recorder served as the recording means.

With all 65 bits mounted in the cutterhead and the screw rotating at 25 rpm, there were approximately 30 bits/sec entering the coal. To minimize the amount of averaging that was built into the force levels recorded, special care was taken to minimize the size of the "window" used to "see" the transducer voltage levels. The components selected required only 10 msec to receive and display a new voltage level; in this way, "instantaneous" readings were approximated as closely as possible.

Because we recorded digital information on a continuous process, there is no guarantee that the spike cutting loads were "caught" by the data acquisition system. The values recorded give an indication of the average loads on the system but do not accurately indicate the peak loads. This digitizing problem is accentuated by the fact that with only a verbal recording system, each of the eight channels was read once every 15 sec; therefore, in a 3-min test, only 12 readings of screw torque, for instance, could be taken. The system was designed and fabricated to accept an FM tape recorder for continuous data recording, but this option could not be implemented due to budgetary constraints on the program.



a) ENCLOSURE



b) DIGITAL READOUTS

FIGURE 9. - Instrumentation package.

3.5 Field Observations

Following seven passes along the face to debug our operating procedure and feel out the capabilities of the system, 14 cutting tests were run with different cutting parameters in each. Due to the limited time available, many options, rather than many replications of only a few options, were tested. The data therefore tend to be scattered but do give an overview of the SAM performance.

The conclusions reached during the field tests were the following:

- a. The SAM cutting concept is slightly more efficient than continuous miners and shearers.

The total cutting efficiency of the kerf/break concept turned out to be 240 lb/in.²; shearers and miners range from 250 to 350 lb/in.² specific energy.

- b. The screw does self-advance along the face.

Even with the test trolley cocking on the track system, it was pulled along by the screw. In the very weak, friable coal, the screw would occasionally fall out of engagement as the coal cores crumbled, requiring that the screw be "restarted" in the spiral kerf.

The strength of the core is dependent on the total circumferential length of screw/kerf engagement. In the field tests, the 25-in. diam screw was cutting a kerf 7 in. deep, not much engagement. A screw cutter-head designed to excavate a pass along the face equal in depth to half the screw diameter would have much more cutterhead periphery available to distribute the advancing load. The screw load bearing against the coal cores at the base of each kerf is correspondingly reduced and self-advancing would be more trouble-free.

- c. High drive train inertia was required to prevent the diesel prime mover from slowing down in the hard coal bands.

The diesel powered hydraulic supply could sustain 35 gal/min at 1500 lb/in.² continuously, equivalent to 29 hp at the screw shaft or 38 hp at the pump input shaft. Although the average cutting horsepower proved to be approximately 14 hp at the screw shaft, the peak power requirements were of such magnitude and duration that the diesel power output could not sustain cutting

operations. Even with the diesel stalled, intermittent cutting could be performed by selective use of the directional control valve and flywheel inertia.

- d. Skewing the cutter bit carbides had negligible effect on the self-advancing action.

The cutterhead self-advanced equally well for all combinations of cutting parameters. No correlation was noticed between skew angle and screw torque, as would be expected if bit skew angle did indeed reduce rubbing of the flight in the kerf.

- e. There was a slight decrease in power required at the larger depths of cut.

Most tests were conducted with a half-inch depth of cut.

- f. Chip clearance, even at 1-in. depth of cut, did not appear to be a problem.

Because kerf depth was only 7 in. for the 25-in. screw, the kerf length was not great and probably contributed to the ease with which chips would escape the slot. It was noticed that the inherent manufacturing inaccuracies of the screw geometry resulted in kerfs slightly wider than 1 in., further promoting chip clearance.

- g. Three line bit arrangements performed slightly better than single line.

The difference in power requirements is so slight as not to warrant the additional expense of a three line geometry in a production screw.

- h. All of the splitters broke the coal core between kerfs very efficiently.

The use of the splitters did not increase the required drive torque noticeably. When a splitter design was tested which did not wrap completely around the full circumference, as in the case of the tee head bits, there was a definite torque surge as the splitter entered the kerf.

The degree of cleanup by the splitters proved to be directly related to the height of the breakout wedge or bit. Most tests were performed with the knife-edge wedge, designed to shear 4 of the 5 in. of

core between kerfs. The knife-edge splitter is constructed from four quadrants, each increasing in height by 1 in. When excavation tests were run with only two quadrants installed, noticeable ridges were left where the 3 in. of core not sheared were left intact.

- i. The largest blocks of coal excavated were those that broke off the overhanging ledge between the nonoverlapping screw passes.

The core material left between kerfs tended to break up, frequently before it was attacked by the splitter. The material between the screws broke off intact and therefore in larger pieces.

It was noticed that the blocks of coal falling onto the screw would frequently lodge between the screw and supporting structure (see Figure 10), allowing the screw to slowly chew it into pieces that would reasonably be managed by a conveyor system.

- j. The direction that the screw rotates has a direct effect on the amount of overhang between nonoverlapping screw passes.



FIGURE 10. - Cutterhead handling oversize.

When the screw rotates as in Figure 11a, exiting bits cut into the overhang, putting it in tension, and pull or "pluck" it from the face. In this case, the face is continuously plucked, keeping oversize to a minimum. In Figure 11b, the entering bits continually push or "stuff" the coal into the face. This scheme of screw rotation promotes large overhangs and oversize. In a production arrangement, one screw only should suffice to provide adequate plucking to keep the face clean.

- k. The size consist of the cuttings was generally dominated by 3- to 6-in. lumps coated with a light dusting of the fines generated in the kerf.

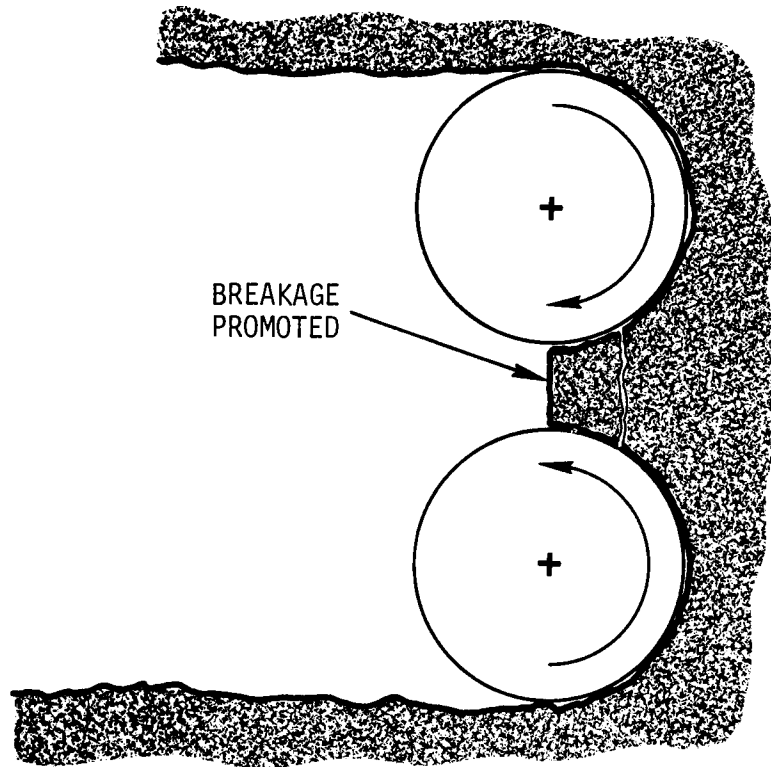
The surface field tests were performed dry and without high levels of airborne dust. When 1-in. depth of cut was tested on the kerf-cutting bits, the size consist was noticeably coarser for the kerf fraction and more uniform for the core fraction.

3.6 Data Analysis

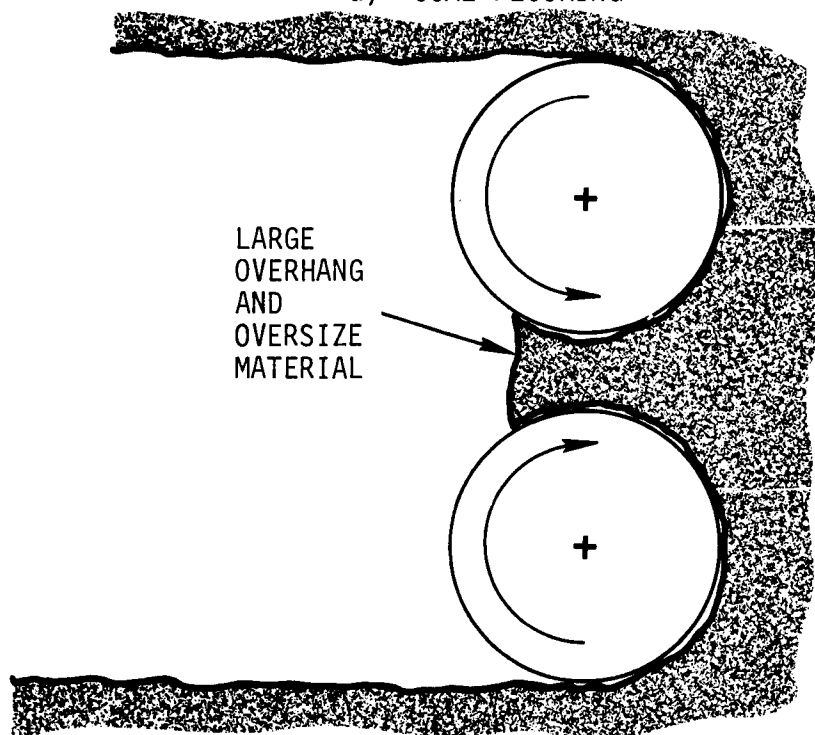
The full test program consisted of seven preliminary runs plus 14 controlled cutting tests; a total of 35 tons of coal was mined with SAM. For 11 of these tests, data were recorded throughout the duration of the pass. A summary of the test parameters varied for each test, the recorded data, and calculated power and efficiency is shown in Figure 12.

Before an examination of the SAM test summary is made, some explanation of Figure 12 is in order:

- a. In test No. 8, a three-line, 1-in. depth of cut bit lacing was tested. This cutting arrangement was achieved by using bits installed as shown in Figure 13.
- b. The tee head bit splitters tested in tests 12 and 14 are shown in Figure 14. The bits welded to the splitter flight were the standard 1/2-in. wide carbide style. This design splitter performed well, fracturing more of the core than the wedge style splitters.
- c. The support arm test positions were numbered 1 to 3 in quarter increments (see Figure 15). The original test positions were numbered 1, 2, and 3 and left 7 in. between each pass. Once into the test plan, it was decided to avoid the shale floor that we cut in position 1 and the hard coal band at position 3. Due to the limited number of tests, we attempted to cut coal of equal strength at all times to allow correlation of test results made with the arm at different positions.



a) COAL PLUCKING



b) COAL STUFFING

FIGURE 11. - Overhang breakage.

TEST	BIT DEPTH OF CUT (in.)	NO. OF BIT LINES	BIT SKEW ANGLE (deg)	STYLE OF SPLITTER	SUPPORT ARM TEST POSITION	SCREW SPEED (rpm)	DRIVE MOTOR AVERAGE PRESSURE (lb/in. ²)	AVERAGE SCREW TORQUE (ft-lb)	SCREW SHAFT HORSEPOWER (hp)	FRONT BEARING VERTICAL LOAD AVERAGE (lb)	FRONT BEARING HORIZONTAL LOAD AVERAGE (lb)	REAR BEARING VERTICAL LOAD AVERAGE (lb)	REAR BEARING HORIZONTAL LOAD AVERAGE (lb)	SCREW/ COAL ENGAGEMENT (%)	EXCAVATION SPECIFIC ENERGY (lb/in. ²)
1	1/4	3	0	FULL KNIFE- EDGE	1-1/4	23	789	2505	11.0	576	563	903	368	100	194
2	1/2	1	0	FULL KNIFE- EDGE	2-1/2	24.0	1269	4222	19.3	-	-	-	-	100	328
3	1/2	1	0	FULL KNIFE- EDGE	1-1/4	26	733	2326	11.5	179	255	620	797	100	181
4	1/2	1	0	HALF KNIFE- EDGE	1-1/4	25	754	2362	11.2	587	461	1316	600	100	183
5	1/2	3	0	HALF KNIFE- EDGE	2-3/4	25	857	2648	12.6	403	847	632	1323	100	206
6	1/2	3	12	HALF KNIFE- EDGE	2-3/4	21	976	3131	12.5	672	2074	676	2851	100	243
7	1/2	3	12	FULL KNIFE- EDGE	1-1/4	24	1022	3256	14.9	653	834	1442	828	100	253
8	1	3	7	NONE	1-1/4	24.0	986	3149	14.4	-	-	-	-	100	1467
9	1/8	1	7	FULL KNIFE- EDGE	1-1/4	24.0	1270	4222	19.3	-	-	-	-	100	328
12	1/4	3	7	TWO TEE BITS	2-1/2	25	750	2344	11.2	-	-	-	-	50	364
14	1/4	3	7	THREE TEE BITS	1-1/2	26	544	1753	8.7	-	-	-	-	50	272
AVERAGE, ALL 100% TESTS WITH SPLITTER						24.0	961.8	3091	14.1	511.7	839.0	931.5	1217.0	100	240
AVERAGE, ALL 1/2-in. DEPTH OF CUT						24.2	935.2	2991	13.8	498.8	894.2	937.2	1279.8	100	232

FIGURE 12. - Summary of SAM test data.

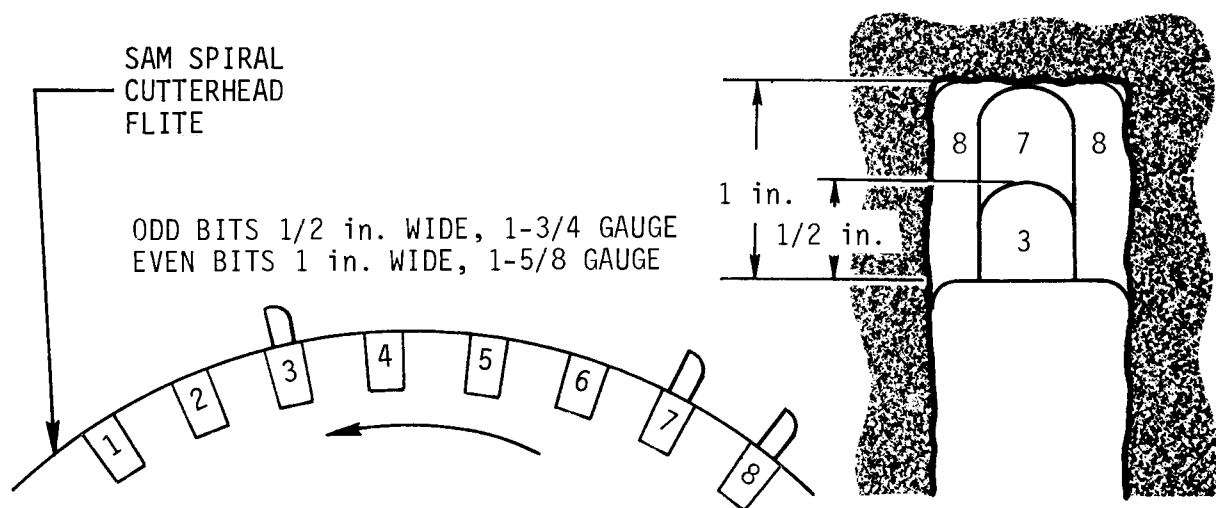


FIGURE 13. - Bit lacing pattern, 1-in. depth of cut, three-line.

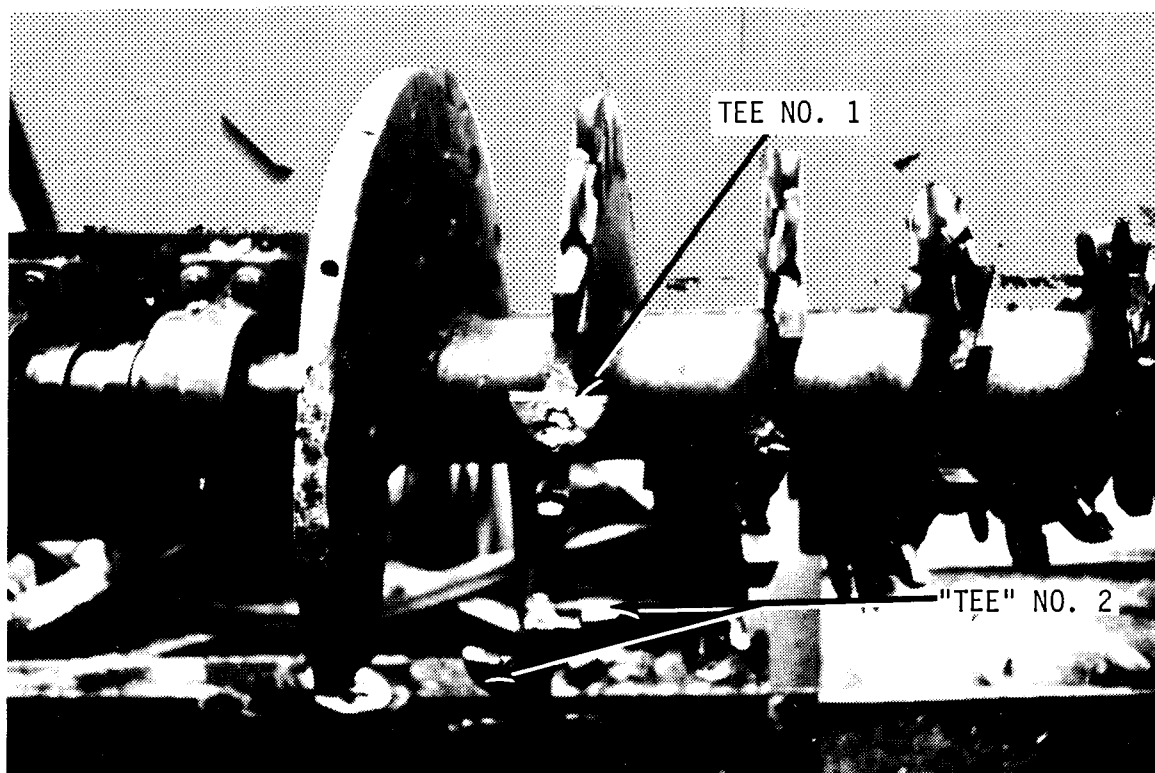


FIGURE 14. - Tee head splitter.

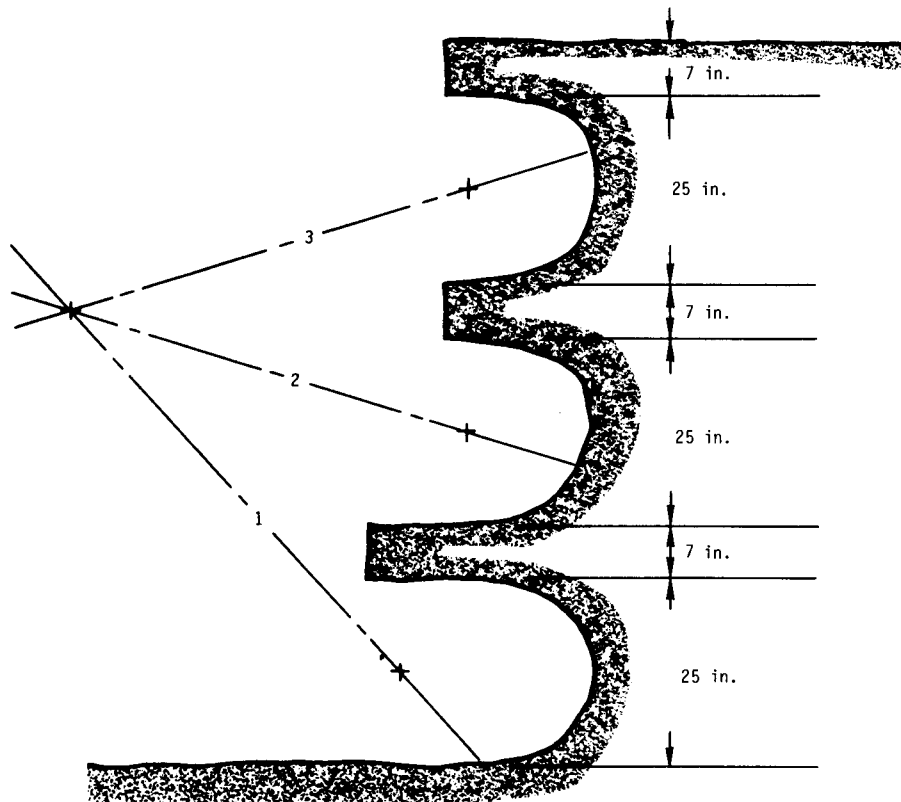


FIGURE 15. - Support arm test positions.

- d. Screw speeds listed as 24.0 rpm are calculated averages, not experimental.
- e. The average drive motor pressure is a differential pressure reading, accounting for flow losses in the return line from the motor.
- f. Bearing reactions have been adjusted for dead load and for support arm position. Direction of the bearing loads is as indicated in Figure 16.
- g. The percent of screw engagement is defined in Figure 17.

Inspection of the values listed in Figure 12 allows the following conclusions to be reached:

- a. Kerf cutting alone (test No. 8) is approximately six times more inefficient as kerfing and breaking. Since kerfing takes place in only one-sixth of the material excavated, the overall specific energy is very reasonable.

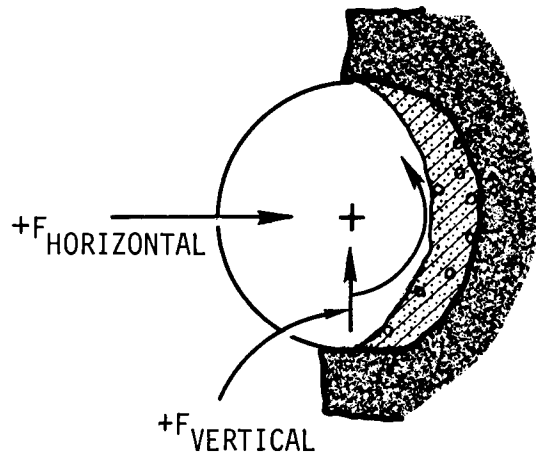


FIGURE 16. - Bearing reactions.

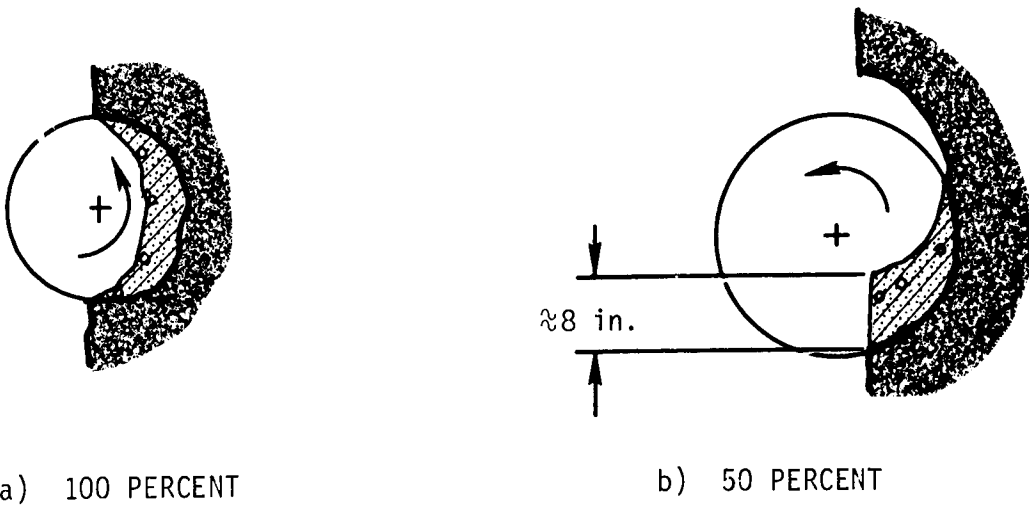


FIGURE 17. - Percentage of screw engagement.

- b. The increase in drive torque for operating with a splitter is negligible. Comparison of test No. 8 torque with the average values shows little difference. In other words, with the coal strength and 5-in. core width in which SAM was tested, most of the excavation work was done in the kerfs, not the cores. This imbalance suggests that a wider core is feasible, so that kerfing comprises a lower fraction of the total excavated material without increasing the drive torque due to large splitter forces.
- c. Bearing reactions are very reasonable. The calculated values for a 9-in. kerf depth of approximately 2000 lb vertical and horizontal, front and rear, correspond well with the measured values for a 7-in. kerf depth. The lower reactions seen in the field could be anticipated due to the lower normal cutting forces associated with new, sharp cutter bits.

The calculations of the tonnage rate of excavation of SAM are based on two field observations. They are:

- a. The excavation scheme left no cusp, floor or roof, due to the circular screw shape. As a result each pass along the face excavated 25 in. high (diam) and 7-in. deep (kerf depth).
- b. A measurement of the distance traveled by the cutter-head in 20 screw revolutions showed 117 in. advanced. Evidently the tolerances in the system or possibly kerfs slightly wider than 1 in. resulted in an advance rate that was not 100 percent efficient; a 6-in. lead screw should, of course, travel 120 in. in 20 revolutions.

The average rotational speed of the screw during tests was 24 rpm. The volumetric excavation rate was:

$$\begin{aligned}
 R &= D \text{ in.} \cdot K \text{ in.} \cdot \left(\frac{117 \text{ in.}}{120 \text{ in.}} \cdot L \right) \cdot N \text{ rpm} \quad (1) \\
 &= 25 \text{ in.} \cdot 7 \text{ in.} \cdot \left(\frac{117 \text{ in.}}{120 \text{ in.}} \cdot 6 \text{ in.} \right) \cdot 24 \text{ rpm} \\
 &= 24,570 \text{ in.}^3/\text{min} \\
 &= 14.2 \text{ ft}^3/\text{min}
 \end{aligned}$$

The resulting tonnage rate equals:

$$\begin{aligned}
 T &= R \frac{\text{ft}^3}{\text{min}} \left(\frac{82 \frac{\text{lb}}{\text{ft}^3}}{2000 \frac{\text{lb}}{\text{ton}}} \right) \left(60 \frac{\text{min}}{\text{hr}} \right) \\
 &= 14.2 \text{ ft}^3/\text{min} \left(\frac{82 \text{ lb/ft}^3}{2000 \text{ lb/ton}} \right) (60 \text{ min/hr}) \\
 &= 34.9 \text{ ton/hr} \\
 &= 0.58 \text{ ton/min}
 \end{aligned} \tag{2}$$

Given the average horsepower requirement indicated in Figure 12, the cutting specific energy equals:

$$E_1 = \frac{14.1 \text{ hp}}{34.9 \text{ ton/hr}} = 0.404 \frac{\text{hp/hr}}{\text{ton}} \tag{3}$$

An independent calculation of average specific energy can be made using the following relation:

$$\begin{aligned}
 E_2 &= \frac{(P \text{ hp}) \left(396,000 \frac{\text{in.-lb}}{\text{min-hp}} \right)}{R \frac{\text{in.}^3}{\text{min}}} \\
 &= \frac{(14.1 \text{ hp}) (396,000)}{24,570} \\
 &= 227 \frac{\text{in.-lb}}{\text{in.}^3} = 227 \text{ lb/in.}^2
 \end{aligned} \tag{4}$$

It is these values of specific energy that are tabulated in Figure 12.

Attempts have been made to correlate the cutting efficiency associated with the various combinations of cutting parameters with bit depth of cut and skew angle; graphs of each are shown in Figures 18 and 19. Due to the lack of replication of the tests,

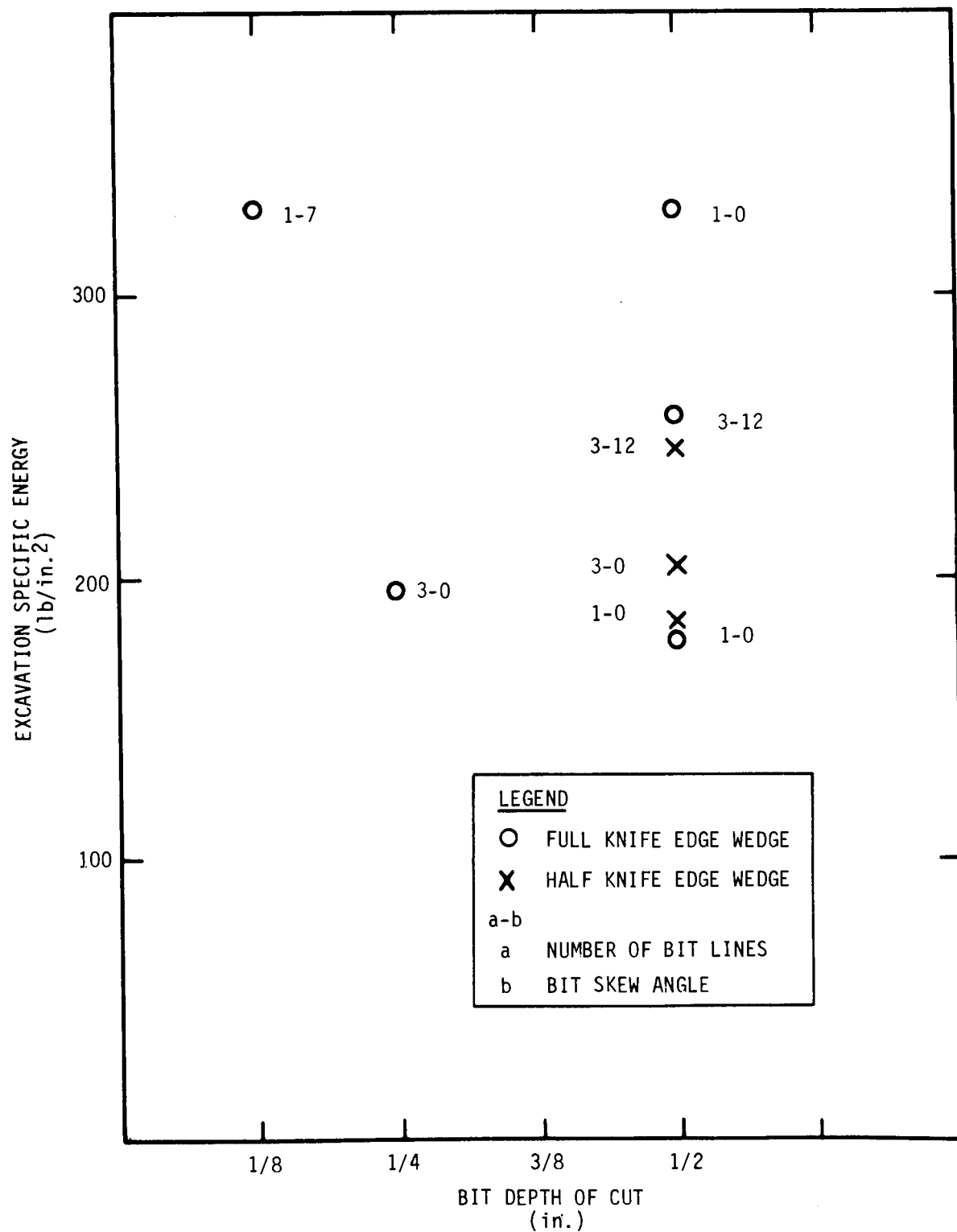


FIGURE 18. - Specific energy versus depth of cut.

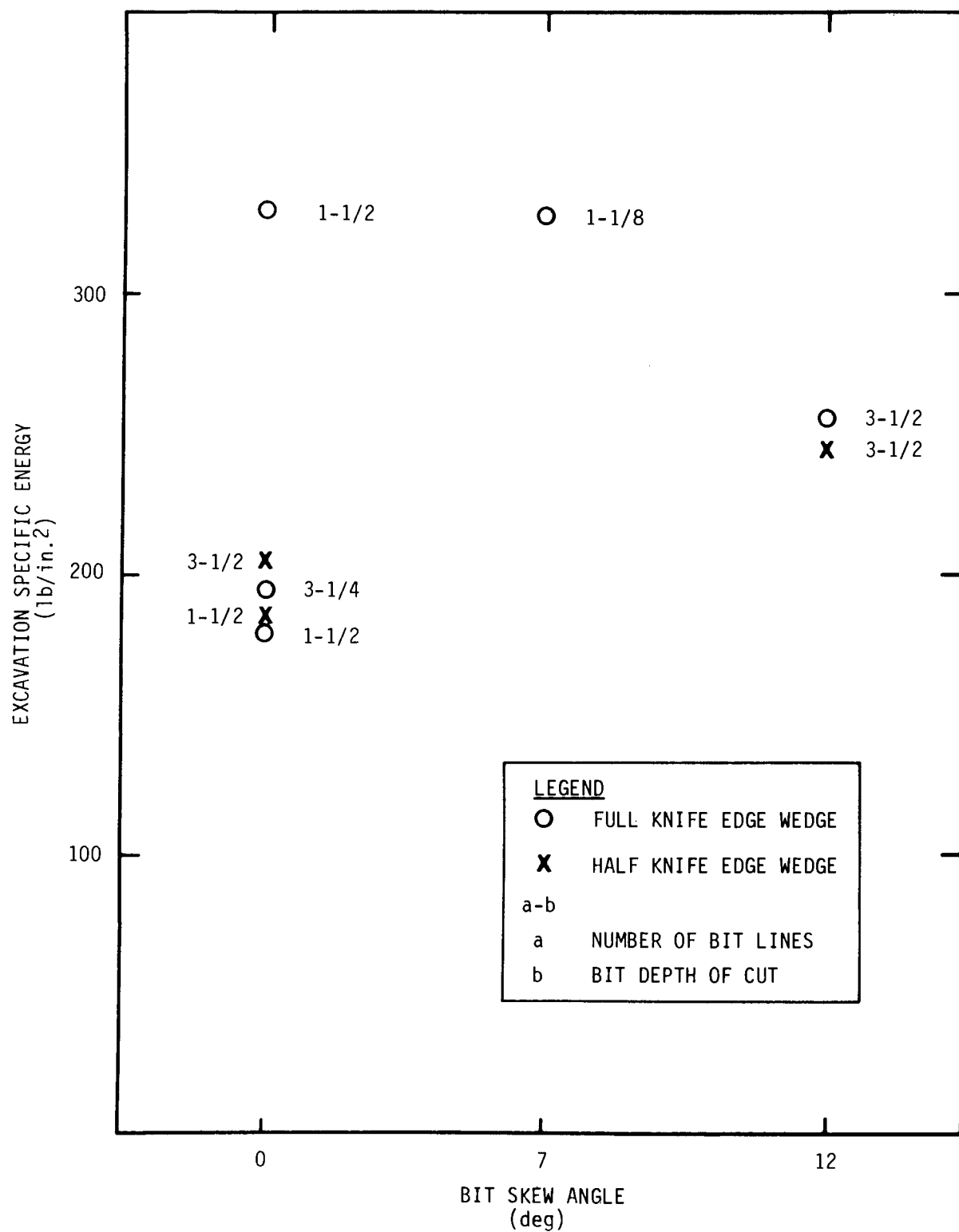


FIGURE 19. - Specific energy versus skew angle.

the data is inconsistent enough that no curves can be fitted to the data. Although no conclusions regarding the optimum selection of the depth of cut or skew angle can be made from the proof-of-concept data, the average values do represent approximately 10 different cutting combinations of the SAM geometry. It is these average values that were used for the full scale estimates.

3.7 Test Result Comparison

The data acquired during the field tests is by itself not very useful. Prior to using the data for full scale estimates, it is worthwhile to compare the SAM performance with the state-of-the-art; if no advantages can be noted in a quantitative comparison of SAM with other cutting techniques, no full scale estimates are justified. At this point, SAM performance will be compared with conventional equipment from the standpoint of cutting efficiency and cutting size analysis.

3.7.1 Cutting Efficiency

The single best comparison that can be made between competing excavation schemes is cutting efficiency or specific energy. For the same production rate, an efficient cutting machine offers the following advantages:

- a. Lower power consumption
- b. Lower force levels
- c. Higher availability
- d. Safer operation
- e. Healthier operation.

Numerous investigators have concluded that the lower the specific energy, the lower the level of airborne respirable dust.

Table 2 summarizes the efficiency of cutting for numerous mining applications. Although there is an expected wide scatter in the listed cutting efficiencies, it is fair to state that the calculated SAM specific energy of 240 lb/in.² is on the low end of the distribution.

TABLE 2. - Specific energy summary.

Type of Cutting	Investigator	Reference Specific Energy	Equivalent (lb/in. ²)
1 EDW 300L shearer	Eickhoff	273 $\frac{\text{W-hr}}{\text{ton}}$	201
2 Plow chisel bit	Evans & Pomeroy	700 $\frac{\text{ft-lb}}{\text{lb}}$	389
3 CM shear cut, -1 in. depth of cut	Ingersoll-Rand Research	325 $\frac{\text{W-hr}}{\text{ton}}$	240
4 CM sump cut, -1 in. depth of cut	Ingersoll-Rand Research	460 $\frac{\text{W-hr}}{\text{ton}}$	340
5 Plow chisel bit	Pomeroy	0.3 j/g	558
6 Plow chisel bit	Pomeroy	0.1 j/g	186
7 Longwall shearer	Pomeroy	250 to 400 $\frac{\text{W-hr}}{\text{ton}}$	240
8 Continuous miner	Roepke	$\frac{200 \text{ hp}}{6.6 \text{ ton/min}}$	278
9 Plumb bob, -1 in. depth of cut	Strebig	500 $\frac{\text{W-hr}}{\text{ton}}$	368
10 Industry Average	—	—	311
11 SAM	—	—	240

3.7.2 Size Consist of Cuttings

Because the cutting specific energy of SAM compares well with state-of-the-art equipment, it would be expected that the dust generation would be low also. However, because the cutting technique of kerf/break is fundamentally different than drum machines, an analysis of the cuttings generated is warranted.

Using detailed information available in the literature, we performed an analysis to predict the size consistency from a production SAM unit. The details of this analysis, included in Appendix E, are summarized in Table 3.

The versatility offered with the SAM geometry permits matching the kerf fraction to the individual seam conditions. The one-twelfth ratio selected as production proportions generates a size consist high in coarse, and with half as much fines and approximately 20 percent more ultrafine product as drum mining equipment. Note that the SAM coarse product is much more uniform and controllable than that from conventional mining. Because the SAM ultrafine material will be generated in a deep slot with a slow speed cutterhead, a much lower percentage of the ultrafine material should become airborne. While in the kerf, there is an excellent opportunity to administer dust suppression techniques. Overall the SAM concept holds excellent promise to reduce dust in underground coal mines.

TABLE 3. - Size consist comparison.

Machine	Percentage			
	Coarse	Fine	Ultrafine	Total
Conventional	88	11	1.3	100
Borer	63	33	4.1	100
Ripper	64	34	1.8	100
SAM, Production	81	17	2.1	100

4. FULL SCALE ESTIMATES

Using the data acquired from the field tests, conceptual designs have been proposed for four different mining systems:

- a. Longwall
- b. Blind heading
- c. Strip
- d. Auger.

Because the longwall mining application seems to be the area most suited to the SAM cutting geometry, most of our analysis has been for the longwall application. The existing longwall hardware can be used with no modification in most cases, and an accurate cost comparison can be made between a shearer system and a SAM arrangement. The utilization of SAM cutterheads for blind heading, strip, and auger mining, on the other hand, requires the development and analysis of totally new mining concepts. We will present concepts in each of these areas which show the SAM to be applicable, but the level of detail cannot match that of the longwall analysis because the longwall SAM is much closer to the present state of the art.

4.1 Longwall SAM

Longwall mining today is the safest and most productive method of underground mining. Due in part to the high production possible from a shearer drum, longwall is probably the least healthy method due to high dust generation and methane liberation. Because a plow face generates a larger product and advances into the panel at a more uniform rate, dust and methane can be more satisfactorily controlled. Unfortunately, due to seam height and overburden depth considerations, a plow does not perform properly in all applications.

If the primary limitations to longwall productivity were listed, the following items would be high on the list:

- a. Availability of all longwall equipment
- b. Capacity of the armored face conveyor
- c. Dust control.

Obviously, since total coal production is the product of the excavation rate and the excavation time, to obtain an increase in production requires a higher rate of cutting or more expenditure of time for the cutting function.

The shearer itself can normally produce coal at a rate greater than either the face conveyor or the ventilation system can handle. Although the conveyor and ventilation systems are not included in

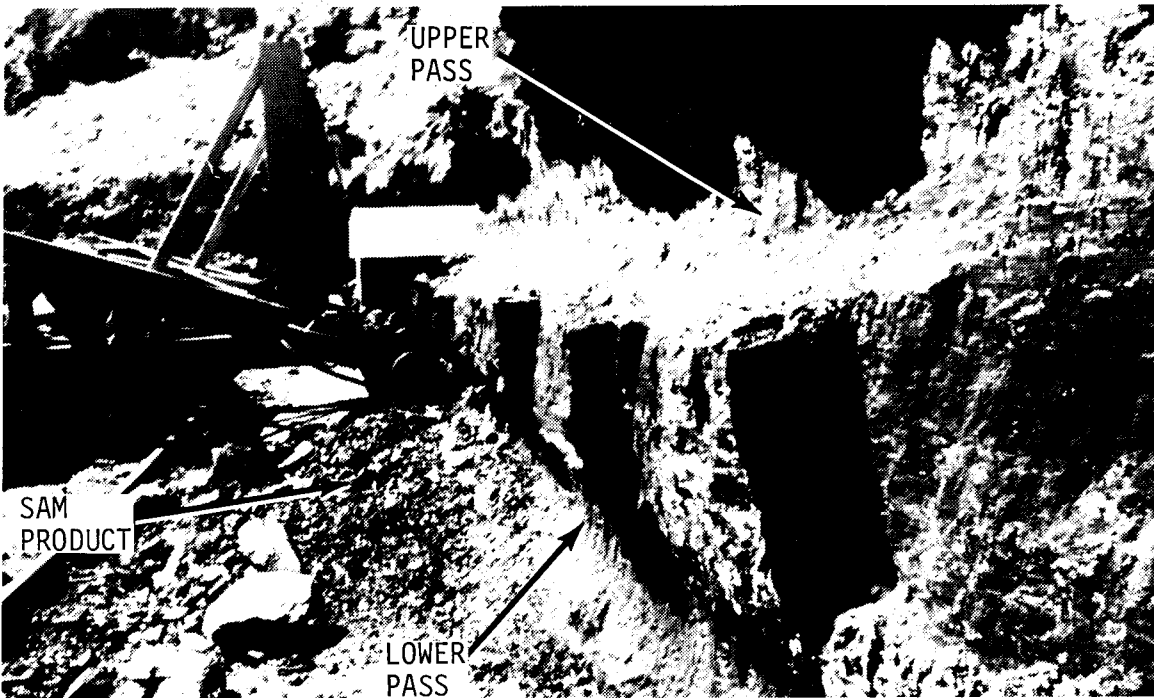
the SAM concept, it would be unresponsive to propose a cutting system that is incompatible with each. The SAM geometry appears to have excavation features that will benefit both systems.

Because a higher rate machine is not required or wanted, how can the cutting characteristics of any machine affect face conveyor performance? It is not only the quantity of material that determines performance, it is also the consistency and size of the product. A frequent cause of face downtime in certain mines is the blockage of oversize coal trying to pass beneath the shearer body. Central to this problem is the amount of "slabbing" that takes place ahead of the shearer as it advances down the face. The vertical wall left in the coal seam is particularly unsuited to resist the overburden pressure trying to pop it off the face; the vibration and general mechanical commotion of an approaching shearer is enough to cause occasional floor-to-roof slabs to fall onto the face conveyor and cause blockages.

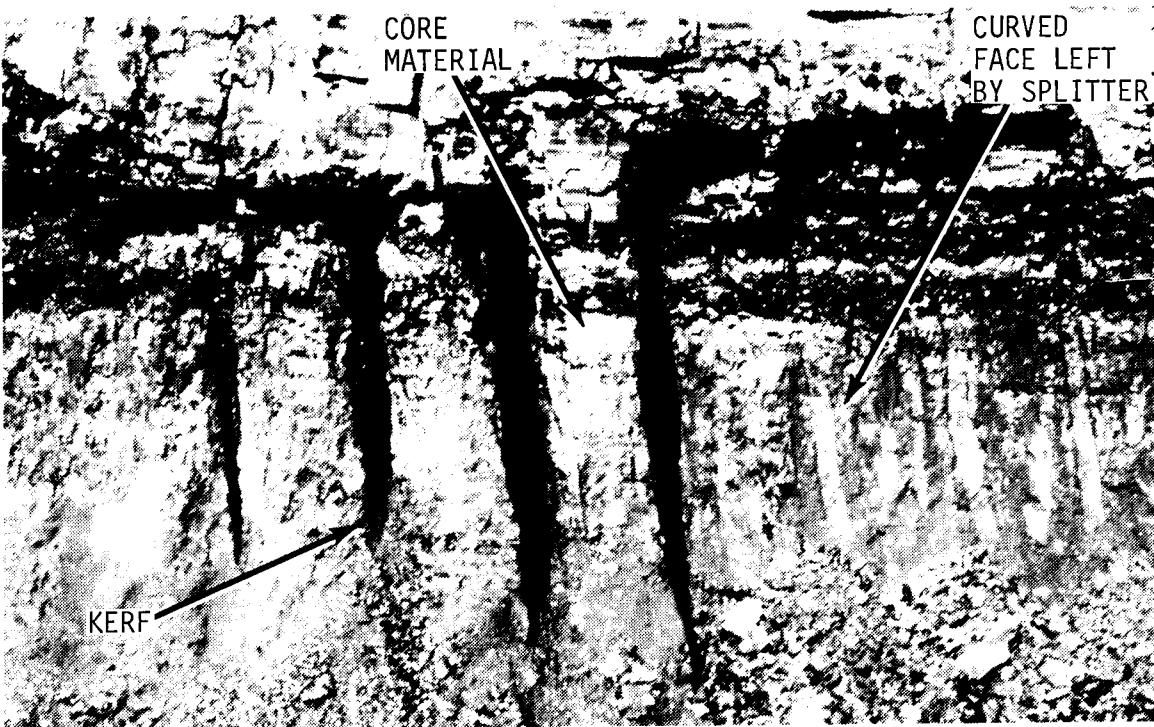
It is commonly acknowledged that a circular entry is inherently the strongest shape to resist roof loads. A primary advantage of twin borers was the arch effect of their rounded entries. The shape of the coal face formed by a longwall SAM, shown in Figure 20, includes arches top and bottom to minimize the high stresses at these points. In addition, the conical shape of the SAM screw allows it to enter the coal gradually, minimizing the rate at which the coal is attacked. The high normal forces generated during coal cutting with worn bits are directed into the face, tending to hold the coal in situ. The normal cutting forces of a shearer subject the coal ahead of the drum to bursting stresses which can be relieved only by popping coal from the face. The action of the screw kerfing cuts through blocky coal which otherwise might fall onto the conveyor intact; the selection of screw lead and splitter design can be made so that normal SAM coarse product can be handled by the conveyor system.

Cutting in slots has definite dust control advantages. The coal surface area exposed to the air is minimized, the volume of air exposed to the coal fines is very defined and controllable, and the quantity of water (or vacuum) available per surface area of coal excavated is maximized. If the increasingly popular method of bit tip flushing is employed, the kerf dust generation would be negligible; dust generation from the splitter breaking function should not be great. Phased water sprays should not prove a requirement; brattice cloth or a similar shield would prevent the water sprays not in the coal from deluging the face. Of course, the low bit speeds possible with SAM will keep dust generated from becoming airborne.

For a 12-in. lead screw to traverse a longwall face at 15 to 25 ft/min, rotational speed will be only 15 to 25 rpm. It



a) CURVED FACE



b) GRADUAL SCREW ENTRY

Figure 20. - SAM longwall face.

is expected that the availability on a longwall SAM face will be greater for the following reasons:

- a. Bit speeds are slower. Slower bit speeds mean less bit wear due to excessive rubbing and less bit breakage due to high impact loads.
- b. Bit loading is more uniform. It is agreed that bit loading in a kerf will be of higher magnitude than surface type drum cutting. Kerf cutting, however, is more uniform. There should be no side loads because the bits follow each other and track in the kerf. Due to the SAM geometry, each bit excavates with an exact, predetermined, constant depth of cut. Bits designed for the application should see service in uniform conditions, unlike drum bits which are subjected to varying depths of cut, side loads, and coal breakage patterns.
- c. Coal size excavated is more uniform. For the reasons previously cited, blockages of the face conveyor should be rare.
- d. Haulage forces are minimal. Due to the self-advancing feature, the haulage requirements of the longwall SAM should be comprised of getting the screw started and maintaining engagement along the face in weak coal. Use of existing haulage systems for the light-duty SAM requirements should result in exceptional availability of these components.

Due to the low-speed operation, the SAM drive train requires a robust high-torque construction. The actual drive inertia available should be equivalent to a comparably sized high-speed drum because most of the system inertia is in the motor itself.

A conventional longwall shearer utilizes ac cutter drive motor(s) and variable speed haulage motor. When the shearer encounters hard material that requires more power to excavate, the ac motor continues cutting operations while the dc motor slows the machine advance so that the drum can chew away at the coal at its leisure. This self-compensation prevents motor stall and allows continuous operation, but does promote cutting inefficiency and high dust generation due to small depths of cut.

A similar compensation arrangement is required on SAM to permit slowing the excavation operation when hard material is encountered without stalling. To accomplish this task, we propose using dc cutter drive motors and dc traction drive. Because the haulage speed is inherently synchronized with the rotational speed and excavation rate of the SAM screw, a variable speed cutter drive is required. By monitoring the amperage of the cutter motor and varying its speed accordingly, a constant

(maximum) horsepower utilization can be achieved. Because the SAM cutting characteristics do not vary with cutterhead speed, cutting efficiency remains constant at all times; the bit depth of cut is determined by the cutterhead geometry, not the advance rate.

4.1.1 Design Specifications

With a new machine design, you have all of the freedom of a blank piece of paper and all of the restrictions of the standard mining practice. In establishing the design specifications for a SAM longwall machine, we investigated the reasons for the design parameters that have found success in the present state of the art.

With a new concept, there are two definite stages which must be passed through prior to industry acceptance. First, as in the case of SAM, the innovation must be accepted by the industry by proving that it can perform the excavation function better than conventional equipment while adhering to conventional mining practices. Once accepted, then the new technology may be used to push the state of the art in mining practices. For instance, if the SAM concept is configured on a longwall shearer body such that it must traverse the longwall face at 60 ft/min to match shearer productivity, then it is unlikely that it will be accepted by industry. On the other hand, if the geometry functions as promised at 20 ft/min and can match productivity, then the possibility remains for a higher production machine that could perform at 60 ft/min, when the state of the art can be pushed to that point.

The following sections discuss the selection of key design parameters and the justification for each.

4.1.1.1 Haulage Speed

The typical longwall shearer operates at 15 to 25 ft/min, with higher speeds possible in the low seams. The state of West Virginia is in the process of limiting shearer haulage speeds, including flit, to 36 ft/min in seams under 60 in. and 40 to 45 ft/min in thicker seams; these limitations are being set for reasons of safety on the face.

In many cases the upper limit on shearer speed is determined by the rate at which roof supports can be advanced. It can be argued, though, that for an increase in production, more support operators are justified. As more semiautomatic support actuation systems become available, support movement should prove to be less of a restriction on shearer speed. It should

be noted that as shearer speeds get closer to the face conveyor speed, other materials handling considerations come into play.

To coincide with the state of the art we have set the design traverse rate at 25 ft/min. Only when excavation rates exceed conventional conveyor capacities have we considered slower speeds.

4.1.1.2 Cutterhead Diameter

On a shearer face, drum diameters are selected to maximize the percentage of coal taken by the leading drum and yet maximize the range of seams that can be excavated with one machine. The ratio of drum diameter to drum length also affects the efficiency of loading from the shearer drum scroll; larger drums are preferred.

The predominant style of shearer is double drum and bi-directional, with the drum diameters approximately two-thirds the seam height. This rule of thumb has proved the best compromise to the considerations mentioned above. To minimize dust generation and provide the best loading characteristics, the leading drum, rotating roof to floor, is high, and the trailing drum, rotating floor to roof, is low.

On a longwall shearer, the drum diameter and length are almost independent of each other; there are preferred ratios for drum scroll loading. The web depth is normally governed by roof support conditions; if the roof permits, it is preferable to take a deep web to minimize stress cycling of the roof. The average drum length and web depth found in United States longwall sections are 30 in. and 27 in., respectively.

There has been considerable discussion regarding the proper screw diameter for a longwall SAM. As demonstrated in the field tests, it is possible to leave a gap between the screws and win the overhanging coal for "free"; very little effort is required with judicious selection of screw rotation to "pluck" this coal out. For a given seam height, this scheme is the most efficient.

Given a maximum haulage rate and a particular seam height, production rate is maximized with a large web depth. With the SAM geometry, unlike a shearer, the "web depth" of the screw is tied to the cutterhead diameter. Maximization of web depth implies maximization of screw diameter; for that reason, maximum production from a given seam is obtained from large, overlapping screws.

To maximize the depth to which any screw can cut into the face, we have decided to mount a cutter on the front of the screw shaft to allow a given cutterhead to excavate a semi-circular "web" equal in depth to the radius of the screw. The prototype screw could only excavate to the shaft radius or 9 in. for the 25-in. screw.

An inconvenience associated with the crescent-shaped swath excavated by a SAM cutterhead is the roof and floor cusp left between consecutive overlapping passes along the face. For a given web depth, the cusp height is minimized with a large cutterhead diameter.

Realizing that different mine conditions may dictate different machine geometries, we tentatively set the screw diameter at two-thirds the seam height to correspond with the state of the art. As will be discussed later, there will be cases where the cutterhead diameter may be different.

4.1.1.3 Cutterhead Speed

The tip speed of *all* cutter bits on a shearer drum is typically between 500 and 800 ft/min. As discussed earlier, for incindive reasons it is desirable to stay below 300 ft/min. For dust control, tip speed should be kept as low as possible. On the SAM cutterhead, the maximum tip speed is attained by only *one* bit; due to the conical shape all others are traveling slower.

Just as important, on a shearer longwall face *all coal* is cut by bits traveling at maximum speed, and all of the floor and roof (potentially, sparking sandstone) is swept by high-speed bits. On a SAM face, only the deepest portion of the kerf is cut by a high-speed bit; all other bits are traveling slower. The splitter outside radius is moving fast but rubs against only a small proportion of the core material. Due to the cusps left on the floor and roof by the circular cutterhead, only a small proportion of a sandstone roof could be contacted by a SAM cutterhead.

For a given haulage rate, rotational speed is minimized when the screw lead is maximized. At the same time, large pitch leads correspond to low kerf fraction and low specific energy. Based on the breakage patterns observed in the field, a 12 in. screw lead appears feasible and is considered a given design parameter.

The relationship between cutterhead rotational speed and tip speed is plotted in Figure 21. Inspection of this graph shows how reasonable the tip speeds are at 25 rpm and less, in

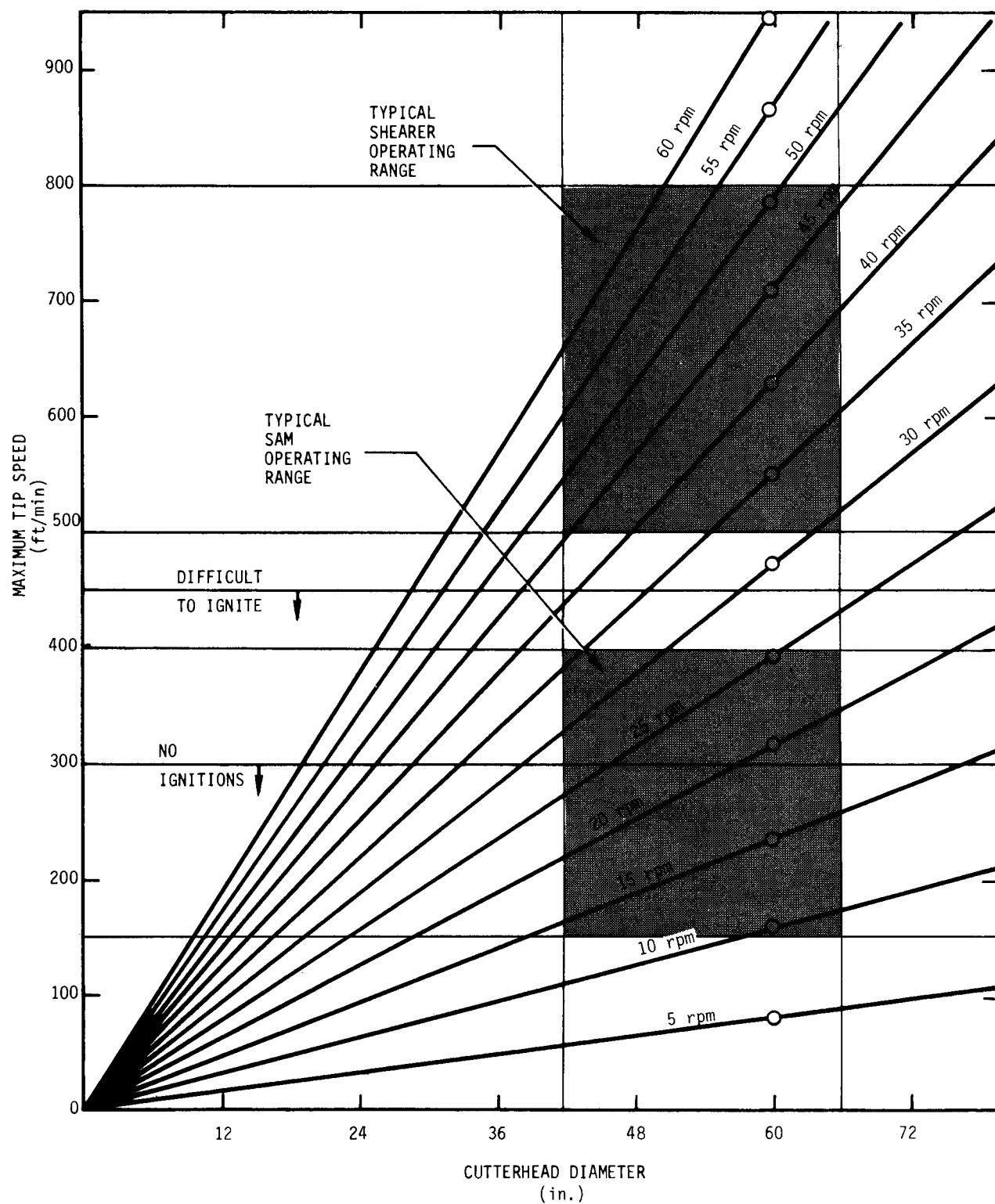


FIGURE 21. - Bit tip speeds.

relation to incendivity. Because bit tip speeds are acceptable at 25 rpm for typical cutterhead diameters and because 25 ft/min is a reasonable haulage rate, the design rotational speed of the SAM cutterhead has been set at 25 rpm; of course, lower speeds are acceptable if the conditions warrant. It is interesting to note that the trend in conventional drum cutting machinery is toward slower rotational speed to obtain a deep cut and less dust.

4.1.1.4 Production Rate

Due to the wide selection of design parameters for a SAM longwall, there is a corresponding range of resulting production rates. The graph in Figure 22 indicates the excavation rate of a longwall SAM with various screw diameters in different seam thicknesses. As expected, in any given seam, the larger the screw cutterhead diameter, the higher the production rate, because "web" depth is equal to half the screw diameter; in all cases, advance rate is 25 ft/min. Appendix G contains a tabulation of the data graphed in Figure 22 and includes figures for thicker seams. Also listed in the tabulation is the total cutting horsepower and torque per screw for each case.

So that suitable comparison can be made to state-of-the-art equipment, the following design production rate goals were set:

- a. Seams less than 60 in.: 800 tons/hr
- b. Seams between 60 and 96 in.: 1000 tons/hr
- c. Seams thicker than 96 in.: 1500 tons/hr.

Using the SAM screw diameter of two-thirds the seam thickness and the SAM "web" depth equal to one-half the screw diameter, the graph shown in Figure 23 was drawn up. The production rate of a shearer equals

$$X_s = S \times W \times A \quad (5)$$

where

X_s = shearer production rate, ft³/min

S = seam thickness, ft

W = web depth, ft

A = advance rate, ft/min

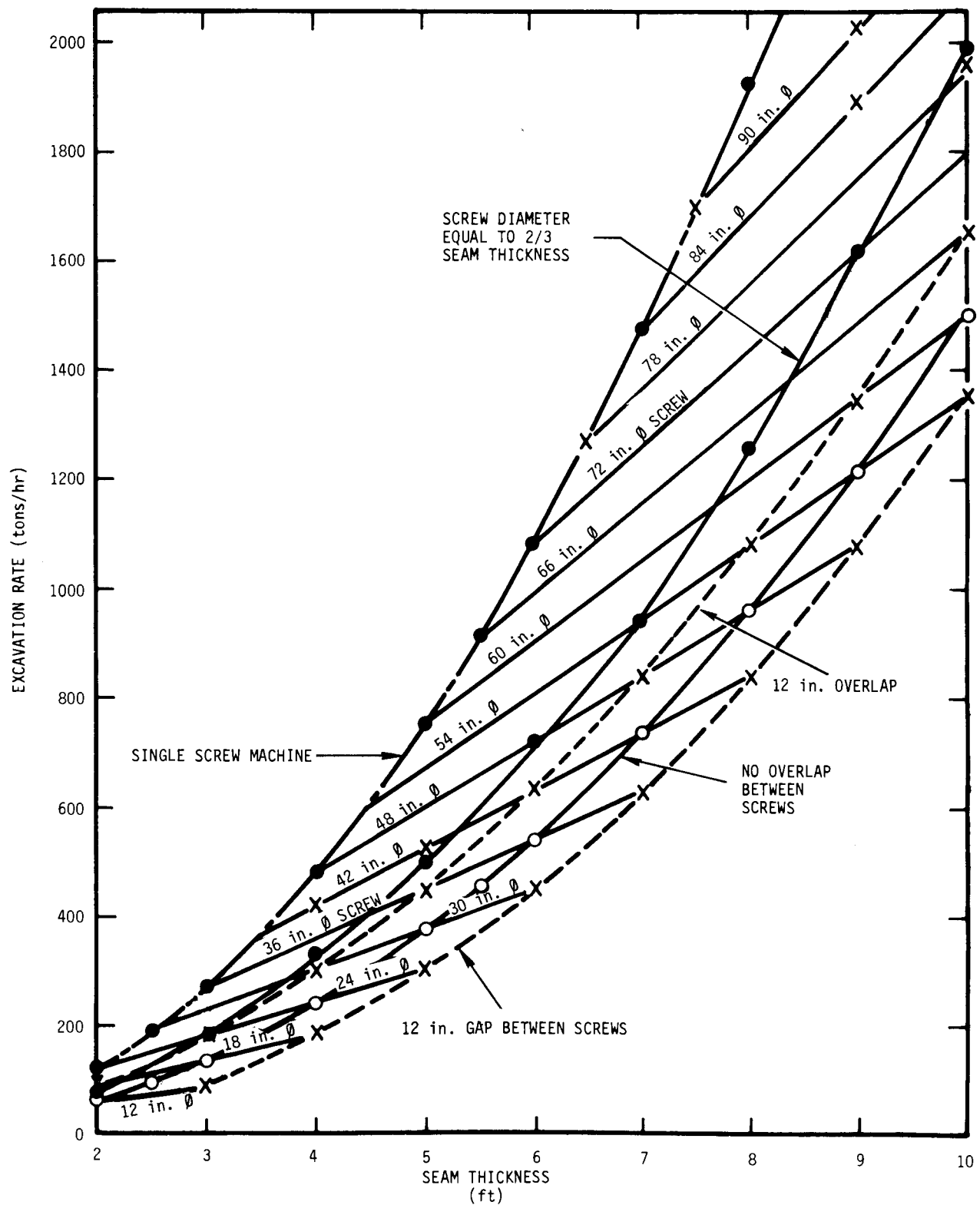


FIGURE 22. - SAM production versus seam and screw size.

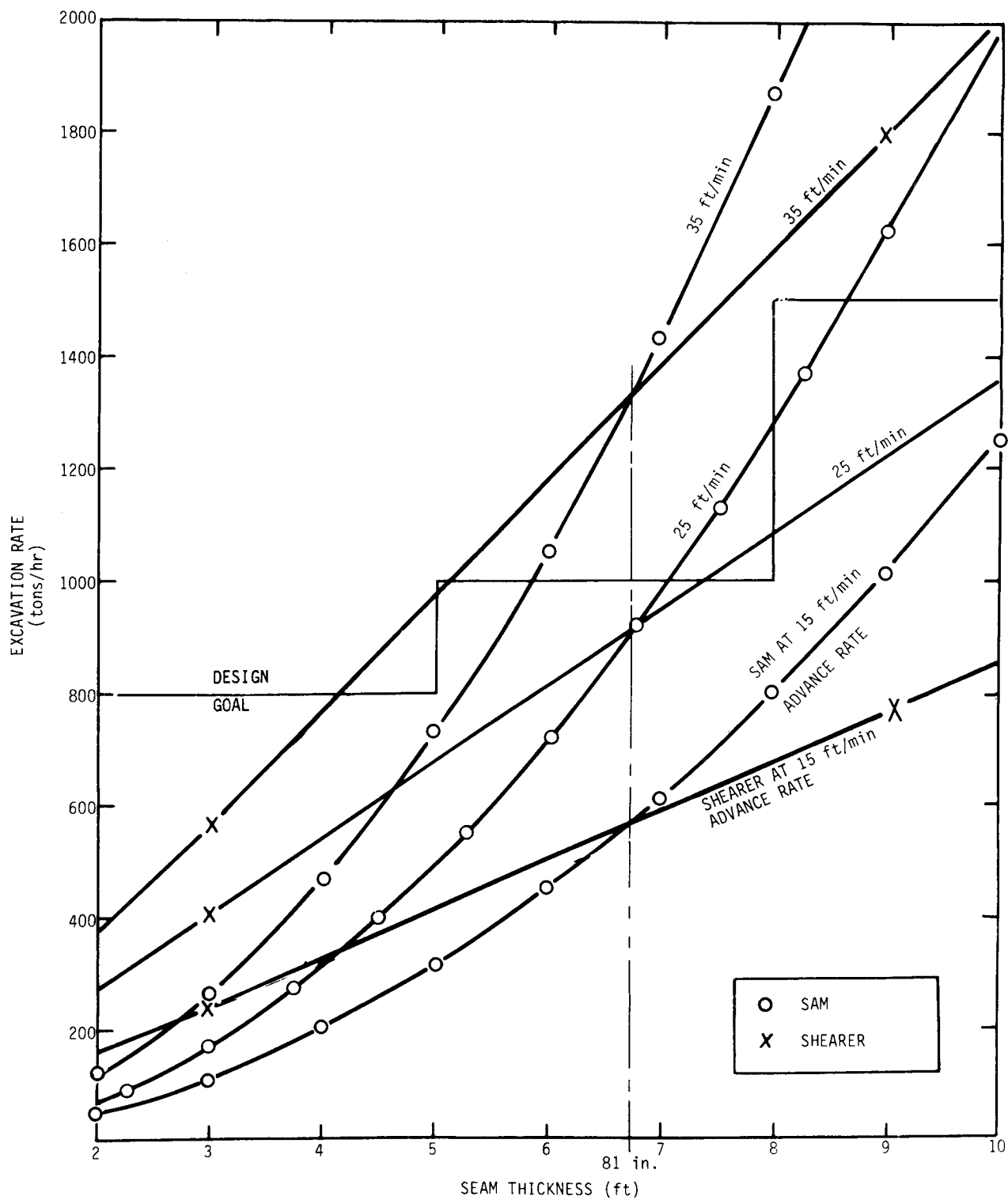


FIGURE 23. - SAM and shearer production versus advance rate.

The production rate of a SAM equals

$$X_{\text{SAM}} = S \times W_{\text{SAM}} \times A_{\text{SAM}} \quad (6)$$

where

$$X_{\text{SAM}} = \text{SAM production rate, ft}^3/\text{min}$$

$$W_{\text{SAM}} = \text{SAM "web" depth} = (1/2) \times (2/3 S) = 1/3 S, \text{ ft}$$

$$A_{\text{SAM}} = \text{advance rate, ft/min}$$

Since the typical shearer has a web depth equal to 27 in. or 2.25 ft, for the same advance rate ($A = A_{\text{SAM}}$), the shearer and SAM will have identical production rates when

$$(2.25)S = (1/3 S)S \quad (7)$$

or

$$S = 6.75 \text{ ft} = 81 \text{ in.} \quad (8)$$

As seen in Figure 23, the crossover point occurs at an 81-in. seam thickness for all advance rates. Since SAM has a higher production rate at thicker seams, it would seem that SAM is more suitable for thick seam applications.

In some mines, there is an upper limit to the bit tip speed that is acceptable on cutter drums to eliminate face ignitions. Let us assume a two start shearer drum that operates with a 2-in. depth of cut maximum for the cutter bits

$$\frac{(15 \text{ ft/min})(12 \text{ in./ft})}{(44 \text{ rpm})(2 \text{ bit/rev})} = 2.0 \text{ in./bit}$$

The rotational speed then equates to

$$N = \frac{(12 \text{ in./ft}) \times (A \text{ ft/min})}{(2 \text{ in./bit})(2 \text{ bit/rev})} = 3A \text{ rpm} \quad (9)$$

where

$$A = \text{advance rate, ft/min}$$

A SAM cutterhead in the same seam with the same diameter (two-third seam) and a 12-in. screw lead has a rotational speed of

$$N = \left(A \frac{\text{ft}}{\text{min}} \right) \left(1 \frac{\text{rev}}{\text{ft}} \text{ lead} \right) = A \text{ rpm} \quad (10)$$

For the same advance rate A , the average shearer will be rotating three times as fast as SAM. If bit tip speeds are set equal, then the SAM will advance along the face three times faster. If we alter the previous analysis of production rates accordingly, the shearer and SAM will have equal production when $X_s = X_{\text{SAM}}$ or

$$S \times (2.25) \times A = S \times (1/3S) (3A) \quad (11)$$

or

$$S = 2.25 \text{ ft} = 27 \text{ in.} \quad (12)$$

The production crossover point is 27 in.; in seams thicker than 27 in., SAM would outproduce a shearer *for the same bit tip speed*.

These relations can be generalized in the following manner. The production rate equals

$$X_{\frac{\text{ton}}{\text{hr}}} = (S \text{ ft}) (A \text{ ft/min}) (W \text{ ft}) \frac{\left(80 \frac{\text{lb}}{\text{ft}^3} \right) \left(60 \frac{\text{min}}{\text{hr}} \right)}{\left(2000 \frac{\text{lb}}{\text{ton}} \right)} \quad (13)$$

and the bit tip speed equals

$$V_{\frac{\text{ft}}{\text{min}}} = \pi (D \text{ ft}) \left(N_{\frac{\text{rev}}{\text{min}}} \right) \quad (14)$$

For a shearer, we know that $D = 2/3S$, $W = 2.25 \text{ ft}$, and from Equation 9, $N = 3A$; therefore

$$X_{\text{shearer}} = (S) \left[\frac{V}{\pi (2/3S) (3)} \right] (2.25) \left(\frac{80 \cdot 60}{2000} \right) \quad (15)$$

or

$$X_{\text{shearer}} = 0.859V \quad (16)$$

For SAM, $D = 2/3S$, $W = 1/3S$, and from Equation 10, $N = A$; therefore

$$X_{\text{SAM}} = (S) \left[\frac{V}{\pi (2/3S)} \right] (1/3S) \left(\frac{80 \cdot 60}{2000} \right) \quad (17)$$

or

$$X_{\text{SAM}} = 0.382 SV \quad (18)$$

These equations are graphed in Figure 24 and demonstrate the exceptional low-speed production potential of SAM cutterheads. It is safe to state that for those mines where incendivity is a consideration in the cutting machine selection, SAM offers significant production advantages.

A comparison of Equations 15 and 17 indicates that the SAM production advantage for a given bit speed is due in part to the fact that the SAM "web" depth W is dependent on cutterhead diameter and seam thickness. We realize that in some mines, roof conditions would not permit a web depth, even a strong semi-circular SAM "web" depth, equal to one-third the seam height. For that reason, the graph of Figure 24 indicates a constant production rate for seam thicknesses greater than 81 in.; in other words, a maximum web depth of 27 in. is included as a restriction on the SAM production rates graphed in Figure 24.

It is realized that longwall shearers excavate at rates higher than shown in the graph. These higher rates must be attained either with higher bit speeds, deeper depths of cut, or more starts on the cutting drum.

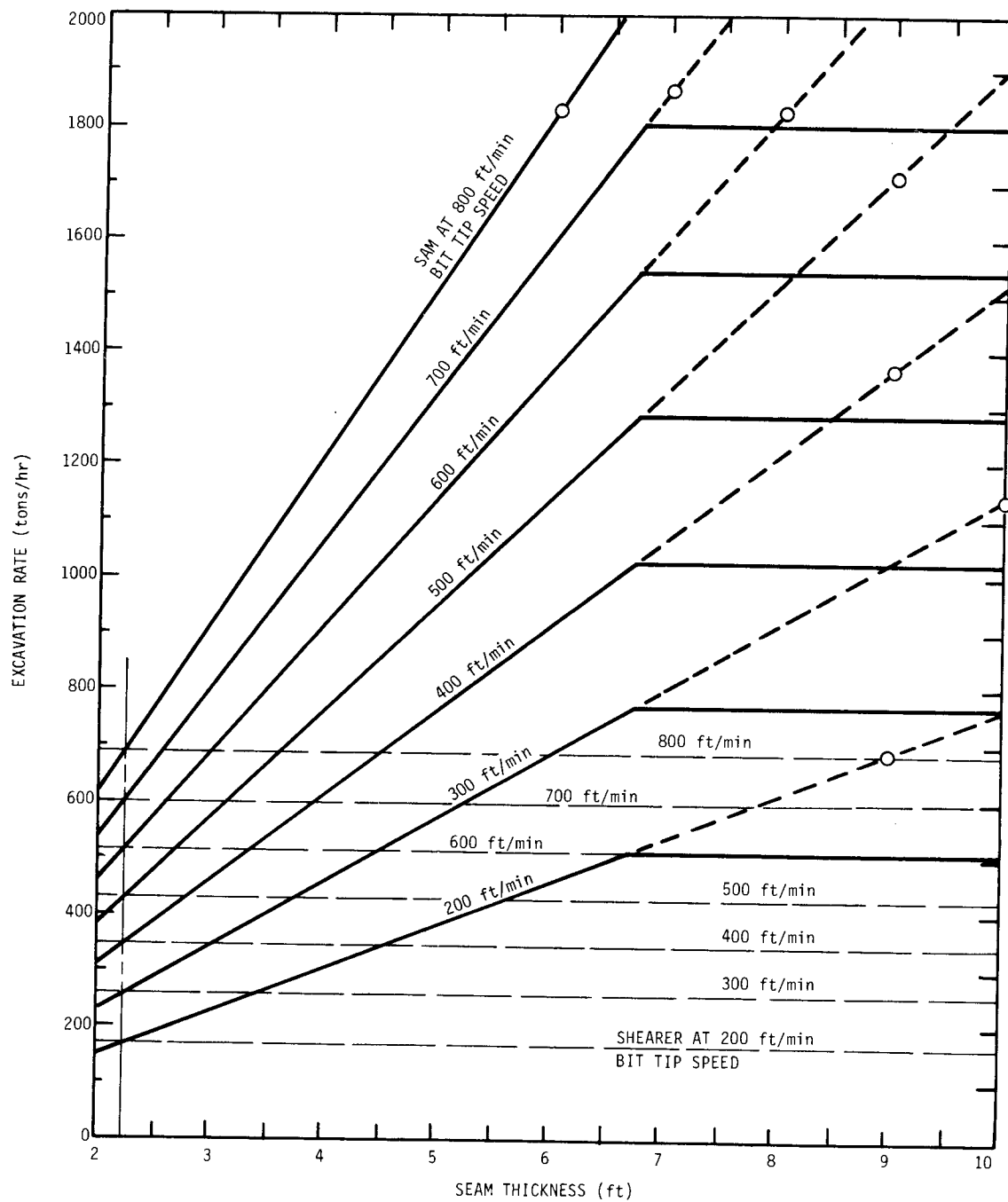


FIGURE 24. - SAM and shearer production versus bit tip speed.

4.1.2 Hardware Description

As the basis for comparison of the SAM longwall hardware to a conventional shearer, we have selected equipment suited for a 54-in. seam, considered to be the average seam thickness presently being worked in the United States. In Figure 25 we have depicted a conceptual design of a longwall SAM.

The body of the machine is based on the approximate dimensions of a typical Joy shearer; all conveyor furniture is identical. The Joy machine is a double ranging arm shearer that can be outfitted with drums with diameters from 24 to 42 in.

The longwall SAM includes two ranging arms, each complete with a 150 hp dc drive motor. The motor output shaft speed is reduced through a right angle speed reducer connected to the SAM cutterheads. Mounted on a common shaft on each ranging arm are two 36-in. diam SAM screw cutterheads. When cutting to the headgate, the two screws facing to the left are working; when cutting to the tailgate, the two right facing screws operate. To enable "web" depths equal to the cutterhead radius of 18 in., a coring cutter has been mounted to the front end of the cutterhead shaft. The overall length of the longwall SAM is the same as the commercial Joy double ended ranging drum shearer, but the weight of the SAM unit will be less because the SAM cutterheads themselves are lighter than the massive shearer drums they replace.

The longwall SAM geometry is similar in some respects to the trepanner. The axis of cutterhead rotation is parallel to the direction of travel for both machines. One important feature that has become associated with the trepanner is that it does an excellent job of sweeping material onto the face conveyor and keeping the floor clean. The longwall SAM will share this attribute. The direction of the upper screw rotation has been selected to maximize the capability of the SAM cutterhead to pull weakened coal chunks from the face, thereby minimizing slabbing. The lower, trailing cutterhead rotates in the same direction and sweeps material onto the conveyor. To maximize this effect, a paddle disk has been mounted on the cutterhead shaft behind each splitter.

The flow of material from the upper, leading cutterhead to the conveyor should pose no problem. In fact, the ranging arm itself serves as a plow to direct material in the proper direction. The natural flow of excavated material from the lower, trailing cutterhead is more troublesome. As seen in Figure 25, both the shearer body and the ranging arm have been profiled to maximize the cross section available for the material flow path.

LONGWALL SAM FOR 54-78 in. SEAMS

SCREW DIAMETER ~ 36 in. ϕ
 WEB DEPTH ~ 18 in.
 SCREW rpm ~ 25
 ADVANCE/HAULAGE RATE ~ 25 fpm
 TOTAL hp ~ 300 hp

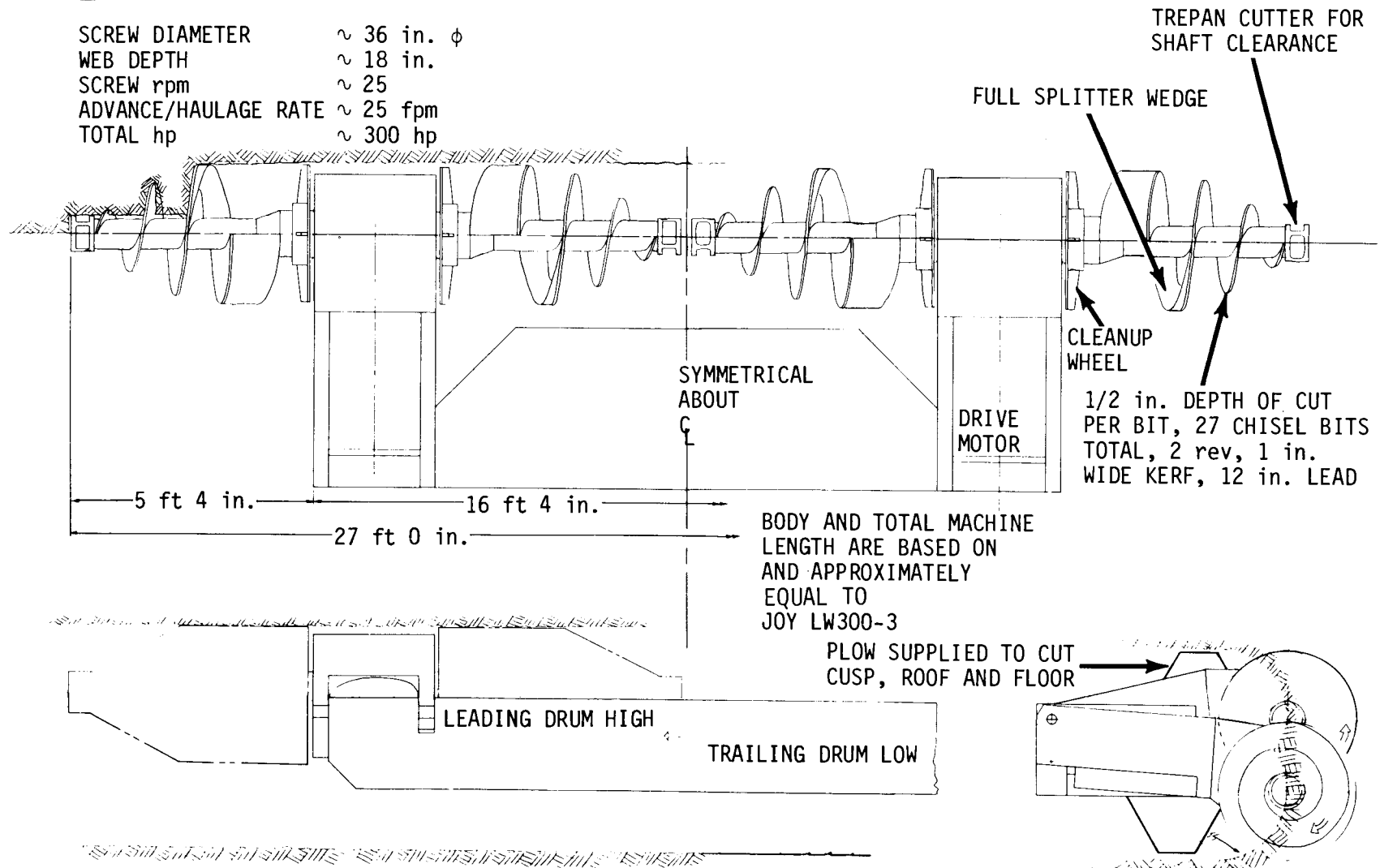


FIGURE 25. - Longwall SAM configuration.

Due to the crescent shaped cutout that the SAM makes with each pass along the face, cusps are left on both the floor and roof. For the example under discussion, the cusp height equals 2.41 in. ($0.134 \times$ cutterhead radius) and could prove bothersome on both the roof and floor. To eliminate the cusps, we have indicated that suitable plow style bits be mounted on the ranging arms. As the longwall SAM passes down the face the cusp plows will break off the offending cusps along the bedding planes.

4.1.3 Load Analysis

The external forces acting on the longwall SAM during cutting operations can be resolved into three components. We will briefly discuss the magnitude of these loads for the example longwall SAM for 54-in. seams.

4.1.3.1 Cutting Force

The vertical and horizontal cutting forces that act in the plane perpendicular to the direction of travel (or face conveyor) are proportional to the average number of bits that are cutting at any particular instant. Because the cutterbits are positioned on the screw with a uniform distance between them along the helical flights, the spiral that is seen when looking at the front of the screw is difficult to describe mathematically. As might be expected, there are many more bits mounted at the large radii than near the shaft centerline. Using layouts of the prototype 25-in. diam SAM, we were able to determine the percentage of bits engaged in the coal at any time as a function of the depth of the kerf, expressed as a percentage of the screw radius (see Table 4). Using these factors, we were able to get excellent correlation of the calculated bearing reactions with the measured field test values.

TABLE 4. - Bit engagement

$\frac{\text{Kerf depth}}{\text{Screw radius}} \times 100$ (percent)	$\frac{\text{Bits engaged}}{\text{Total bits}} \times 100$ (percent)
56	37
72	52
100	75

The calculated cutting force reactions for the 25-in. prototype SAM were 4000 lb, horizontal and vertical. The measured values noted in Figure 12 are approximately 70 percent lower than expected because only 70 percent as many bits are engaged when the kerf depth was 7 in. instead of the 9 in. that was originally planned. We also noted little variation in reactions as the bit depth of cut was varied. In other words, when we took a 1/4 in. depth of cut with each bit, half as many bits were engaged with the coal, but these bits experienced a loading condition twice as high. For the 1-in. wide kerf, a value of tangential and normal cutting force of 1400 lb per 1 in. depth of cut proved to be accurate.

To scale up the reaction force for the larger cutterhead a factor of 36/25 must be used because the total number of bits on the screw is proportional to its diameter. The proposed production longwall SAM will be cutting into the face a distance equal to the cutterhead radius. Because some of this material will be excavated by the more efficient core breaker on the leading end of the screw shaft, it is conservative to assume that it will all be cut inefficiently in the kerf. Whereas the prototype screw was designed to cut only 9 in., or 72 percent of its radius, the production version will cut 100 percent. The larger number of bits due to this factor is therefore 75/52, taken from Table 4. The total cutting force reaction for the 36 in. production screw should therefore be

$$F_V = F_H (36/25) (75/52) (4000 \text{ lb}) = 8308 \text{ lb} \quad (18)$$

vertically upward and horizontally away from the face. Although the calculated ratio of horizontal to vertical cutting reactions is 1:1 only for 72 percent advance, it is a reasonable approximation for other kerf depths also.

4.1.3.2 Haulage Force

The haulage force required for the longwall SAM will be due to three predominant factors:

- a. Frictional drag
- b. Plow forces to break the cusps
- c. Self-advancing tendency.

Note in Figure 25 that the direction of screw rotation has been selected so that the vertical cutting forces of each screw balance each other. The direction of rotation also helps to pry the roof and floor cusps free. For a 30-ton machine, then, we could expect the frictional drag to move the machine to be as high as 0.3×30 ton, or 9 tons.

The plow forces required to break up the cusp on the floor and roof should be minimal because the cusp will be isolated and free standing. Using the average plow specific energy values shown in Figure 12 and a travel speed of 25 ft/min, we calculate a haulage requirement of 10,032 lb to plow off each cusp entirely. Again this value is conservative because the freestanding cusp should be much weaker than the coal in the typical plow face.

The bit lacing of the 36-in. diam cutterhead requires a helical spiral of almost two revolutions when the depth of cut is set at 1/2 in. and a single line lacing is employed. If we assume that two revolutions are engaged with the coal for 180 deg on each of the two cutterheads, then there is a substantial shear plane available to provide a reaction for the self advancing force. Considering that the core width will be 11 in., the total shear area is equal to

$$\begin{aligned} A &= 2(\pi \times 15 \text{ in. average} + \pi \times 5 \text{ in. average}) \times 11 \text{ in.} \\ &= 1382 \text{ in.}^2 \end{aligned} \quad (19)$$

The total haulage force required is the sum

$$\begin{aligned} F &= 9 \text{ ton haulage} + 5 \text{ ton floor cusp} + 5 \text{ ton roof cusp} \\ &= 19 \text{ tons} \end{aligned} \quad (20)$$

The total shear stress in the core shear planes then equals

$$S = F/A = \frac{(19 \text{ ton})(2000 \text{ lb/ton})}{1382 \text{ in.}^2} = 27 \text{ lb/in.}^2 \quad (21)$$

If we assume that only the rear flight of one of the cutterheads is providing all of the self-advancing thrust, then

$$S = \frac{38,000 \text{ lb}}{\pi \times 15 \text{ in.} \times 11 \text{ in.}} = 73 \text{ lb/in.}^2 \quad (22)$$

Considering an average American coal with 50 lb/in.² tensile strength and 2000 lb/in.² compressive strength, the shear strength should be approximately 1000 lb/in.². Given the low shear stress levels at the root of the kerf, the factor of safety on self-advancing stresses is at least 10 (1000/73) and should ensure that the longwall SAM will be able to screw itself along the face in most cases. In any event, the haulage system will remain available to restart the SAM cutterheads should they fall out of engagement.

An interesting comparison can be made between the haulage horsepower requirement of the longwall SAM and shearer. A recent study* of several operating United States longwall sections revealed that the typical shearer used 50 percent of its 500 cutting horsepower for 50 percent of the time. The haulage horsepower requirement was normally 10 to 12 percent of the 250 hp utilized for cutting, or 25 to 30 hp. With the average shearer speed at 20 ft/min, the typical haulage force is then between 41,000 and 49,000 lb. This force represents the cutting resistance to the shearer drums and the frictional drag of sliding the shearer atop the conveyor pan line.

The SAM haulage force requirement of 38,000 lb results in a power requirement of 29 hp. These figures agree surprisingly well with the shearer values.

A key advantage with the longwall SAM is that the haulage power is provided by the large cutterhead motors. No high power haulage drive is necessary for continuous operation, and the improved availability of the total system should reflect this benefit.

4.1.3.3 Cutting Torque

Using principles based on the cutting specific energy, screw drive torque is calculated in Appendix G and summarized in Table G-1. For a 36-in. diam SAM cutterhead, the listed value is 25,000 ft-lb. Including the effect of side loads, an 8-in. diam AISI 4140 shaft would suit the service and is not unreasonable for mining duty.

The low speed, high torque operation inherent to the SAM concept will result in a very robust mounting structure and drive train. Although the initial cost of the machine could be higher than a standard shearer, the total long term system costs should be lower.

*Ludlow, J., "Field Test of Deep Cutting Double Arm Shearer," Final Report on USBM Contract No. J0199092, March 1981.

4.1.4 System Operations

The operation of a longwall face equipped with a self-advancing miner is very similar to a conventional longwall face. This similarity is due to the compatibility of the SAM geometry with the basic double-ended ranging arm shearer body and the ease with which the operating speeds can be varied on SAM without affecting performance.

From the standpoint of operations, the following similarities exist between conventional longwall and longwall SAM:

- a. Conventional longwall mining techniques can be used with SAM. For instance, the half face method is very suitable for SAM. Because there is excess space in the kerf for chip clearance, gradual snaking is possible without binding in the slot. The bidirectional ranging arm design functions the same for both systems.
- b. Conventional roof support and face haulage equipment can be used on a SAM longwall. No modifications in design or operation are foreseen for this equipment

The following are the advantages that a longwall SAM enjoys over conventional systems.

- a. The operator can adjust the traverse rate of the machine without a loss in cutting efficiency or increase in dust generation. As noted previously, a dc cutter motor is a requirement for SAM to prevent stalling in hard coal conditions. Although a trend may be anticipated toward dc cutter drives on conventional shearers, not all machines are yet equipped as such. When the SAM operator chooses to slow the machine advance, he automatically slows the cutterhead rotational speed. The screw geometry always ensures that the optimum depth of cut is maintained, dust generation remains low, and power efficiency stays uniformly high.
- b. Dust control is excellent. With constant depth of cut taking place at the base of a deep slot, conditions are optimum for controlling the escape of dust into the mine environment. The low rotational speed of the SAM cutterhead is also conducive to dust-free operation because fines are not fanned into the air. Although the predicted amount of fines generated by cutting coal in a kerf is higher than conventional systems, we contend that the control of those fines is much simpler.

- c. Control of slabbing at the face is much more positive with SAM hardware. First, the floor and roof inter-sections with the face are fully radiused to half the cutterhead diameter or one-third the seam height. Second, the conical cutterheads enter the coal gradually, not abruptly on a broad front. Third, normal cutting forces generated due to worn bits act directly into the face rather than along the face in front of an advancing shearer. The SAM normal forces tend to hold the coal intact rather than trying to pop it off the face. Fourth, the SAM helical geometry precisely determines what the maximum (conveyor-compatible) lump size will be, based on the screw flite spacing and splitter design. (Note that screw overlap prevents the large "free" blocks that were mined in the field tests when a gap was left between screw passes.)
- d. Methane liberation is minimized. Due to the large proportion of coarse material obtained with SAM, the methane liberation should be minimal.
- e. Housekeeping at the face is excellent. Besides the minimization of slabbing at the face, the use of paddles on the rear of the SAM cutterheads should provide excellent cleanup of material from the floor as it is swept onto the face conveyor.
- f. In thick seams, large "web" depths are feasible. The "natural" penetration of SAM kerfs into the face is approximately half the cutterhead diameter or one-third the seam thickness. In seams thicker than 100 in., the SAM has the potential for "webs" larger than conventional shearers and very high production rates are possible.

Of course, there are also some disadvantages of using a long-wall SAM, such as the following:

- a. In thin seams, it is not possible to obtain high production rates. Unless a complicated machine design is employed by ganging screws together horizontally, for practical reasons the "web" depth is limited to about half the cutterhead diameter. If traverse rate is limited to 25 ft/min, then production rate is also limited.
- b. Sumping is difficult, at best. The bit lacing on the helical screw flite is such that the cutterhead could be thrust sideways into the face. In this mode the screw would behave like a continuous miner drum, cutting away all of the material. The drive shaft end corer, the splitter, and the paddle arrangement can all be

outfitted with bits to be sumped into the face. However, the face end of the ranging arm cannot easily excavate a path for itself without adding an additional degree of complexity.

- c. Cusp cutting compromises the simplicity, efficiency, self-advancing tendency, and low dust generation features of the SAM longwall. Although the SAM concept has many advantages, the requirement that the roof and floor cusps be removed detracts from the simplicity and elegance of the cutting characteristics.

As the above listing indicates, the longwall SAM has many advantages which warrant further investigation.

4.1.5 Economic Feasibility

Although a quantitative analysis has not been completed for the longwall SAM, we have compared costs with the conventional shearer system. The analysis was divided into the following categories:

- a. Equipment
- b. Operations
- c. Coal processing.

We will discuss each area briefly in the following sections.

4.1.5.1 Equipment Costs

Because the operating loads and horsepower are nearly identical to the double-ended ranging arm shearer, the total SAM machine design has been based on a commercial shearer. The SAM cutter-heads should weigh less than the shearer drums, but the drive torque will be higher so that the drive train gearing will have to be more robust. Overall, the SAM machine should cost the same as the conventional longwall shearer.

The face conveyor and roof supports will be identical to the conventional longwall system. Costs will therefore be equal.

The haulage system used in the conventional longwall will still be necessary on the SAM face. The bulk of the haulage forces will be generated by the cutterhead drive as the screws self-advance. When the screws start each pass or fall out of engagement due to very fractured coal along the face, the haulage system will be required to engage the screw. The magnitude of the haulage force is similar to that in the conventional longwall system.

Because the haulage system will be utilized only on an intermittent basis, rather than continuous, we expect a higher availability for this subsystem. The initial equipment cost will be the same as that in the conventional longwall system.

4.1.5.2 Operating Costs

The greatest economic benefits derived from the longwall SAM are in operating costs. Each of the advantages listed in subsection 4.1.4 results in a savings to the mine. The primary cost savings are due to the following:

- a. Increased equipment availability
- b. Improved dust control
- c. Less downtime on the face.

The basic cutting machine should not demonstrate a significantly improved availability, with the exception of the cutter bits themselves. Although the loading on the bits in the kerf is higher than those acting on a shearer free face, we predict a higher bit life for the following reasons:

- a. To mine the same amount of coal, each bit travels less than half the distance as on a shearer.
- b. Bit loading is very uniform due to the constant depth of cut taken by SAM bits.
- c. Bits are not subjected to erratic breakage patterns and side loads because they are cutting at the base of a deep groove.
- d. Only the outermost bit can possibly contact the rock in the roof or floor because the splitter will prevent significant excursion out of the seam.

The availability of the haulage system should be higher, as discussed earlier, because its duty cycle is much less demanding than on a conventional longwall section.

The lower costs that could be attributed to improved dust control are numerous. A partial listing follows:

- a. Miner health and morale is improved.
- b. Production rates may be increased without fear of operator safety or MSHA violation.

- c. Water sprays and their maintenance can be minimized.
- d. Safety on the face is improved with better visibility.
- e. Rock dusting requirements in the entries are reduced.

A longwall dust control system that would keep the face in compliance with MSHA regulations should eliminate the need for personal positive ventilation helmets that are now being promoted.

The SAM longwall section should benefit from less downtime on the face for three important reasons:

- a. Slabbing should be minimized, thereby ensuring trouble-free face conveyor operation.
- b. Methane liberation should be very low due to the coarse product produced, and compliance with MSHA regulations should prove no problem. The lower speed SAM cutter-head will eliminate the hazard of face ignitions entirely.
- c. All loose material will be swept onto the face conveyor, thereby minimizing any potential problems with advancing the roof supports for that reason.

4.1.5.3 Coal Processing Costs

Following the coal washing cost analysis performed under DOE Contract No. ET-75-C-01-8976, Coal Block Mining System, by Foster-Miller Associates, Inc., we have arrived at some approximate costs to process the SAM coal product. Due to the rapidly changing processing costs, the calculations should be considered only on a relative basis for comparison.

In this analysis we will use the size distributions developed in Appendix E. The size distribution and cost to clean each size category are listed in Table 5.

TABLE 5. - SAM and shearer size distribution

	Coarse	Fine	Ultrafine
SAM	81%	17%	2.1%
Shearer	64%	34%	1.8%
1977 Cleaning cost per ton	\$0.92	\$1.75	\$3.14

If we assume a 95 percent recovery factor, then for every 100 tons mined, 5 tons becomes refuse while 95 tons is washed and sold.

The total cost to clean the SAM product, taking into account the recovery factor, can be calculated as follows:

$$\begin{aligned}
 C_{\text{SAM}} &= \frac{(81 \text{ tons coarse})(\$0.92/\text{ton}) + (17 \text{ tons fine})(\$1.75/\text{ton}) + (2.1 \text{ tons ultrafine})(\$3.14/\text{ton})}{95 \text{ tons}} \\
 &= \$1.17/\text{ton}
 \end{aligned}
 \tag{23}$$

The same calculation for the shearer product is as follows:

$$\begin{aligned}
 C_{\text{SHEARER}} &= \frac{(64 \text{ tons coarse})(\$0.92/\text{ton}) + (34 \text{ tons fine})(\$1.75/\text{ton}) + (1.8 \text{ tons ultrafine})(\$3.14/\text{ton})}{95 \text{ tons}} \\
 &= \$1.31/\text{ton}
 \end{aligned}
 \tag{24}$$

Although the SAM coal washing costs are calculated to be 89 percent of the standard shearer product, we consider that this advantage will only compensate for the fact that the SAM product may require an additional crushing operation outside the mine. The coarse SAM product is well suited to handling underground (low dust and methane) but will probably require sizing to be processed at a surface facility. In conclusion, we feel that the processing costs of SAM and shearer product are very similar.

4.1.5.4 Conclusion

The primary economic advantage foreseen for the SAM concept is in the area of operations on a longwall face. The equipment costs and coal processing expenditures for the SAM system should be very similar to a conventional shearer face. Because the operational costs are very dependent on specific mine conditions, no attempt was made to quantify the operational cost advantage that could be derived on a SAM longwall.

4.2 SAM Blind Heading System

Figure 26 illustrates the basic SAM concept for blind headings--a central, relatively high speed rotating cutter surrounded by a low speed SAM screw. This combination could quite literally be screwed into a coal seam. Therein lies the concept for an appropriate blind heading machine.

Characteristically, coal producing people are most interested in new machines that make the least change in the rest of their mining system. Hence, a SAM that produces a conventional room and pillar geometry is of interest. While there is no fundamental reason to assume that geometry is inherently correct forever, the reasoning behind "progress without change" has some virtue, and furthermore, for any mining system, a rapid development blind heading machine will be needed. Hence the blind heading SAM is in fact of major interest.

In general, the SAM cutting geometry is inherently unsuited for those applications which are intermittent in nature, such as the continuous miner duty cycle in the room and pillar mining scheme. Once the SAM cutterhead is engaged in the slots that it is excavating, it wants to stay there. In fact, reversal of the cutterhead through partially fractured coal may prove troublesome.

In a continuous miner type of cutting cycle, the duration of cutting or forward advance possible is minimized due to roof bolting and ventilation brattice regulations. A continuous miner outfitted with SAM cutterheads would be required to frequently back out of its kerfs and then rethread itself for the next cutting cycle. Although a machine design could be conceived for this application, we feel that the underground operations would be unworkable.

A blind heading SAM complete with onboard roof bolting hardware, on the other hand, could stay engaged with the face and continually develop a blind heading. The basic machine geometry would be similar to a conventional twin borer. Instead of two massive cutterheads, though, the SAM header would include an array of blind SAM screws, like that of Figure 26, spread over the face but not covering the entire face. These screws would pull the mining machine forward (or at least they would not have to be pushed forward) while producing spaced apart holes in the face. Material between holes would be left to fall to the floor, with trimmer bars (similar to that on borer type miners) and perhaps other mechanical assistance as necessary.

Individual screws would be driven via shafts long enough to provide that drive motors need not penetrate (and plug) the holes.

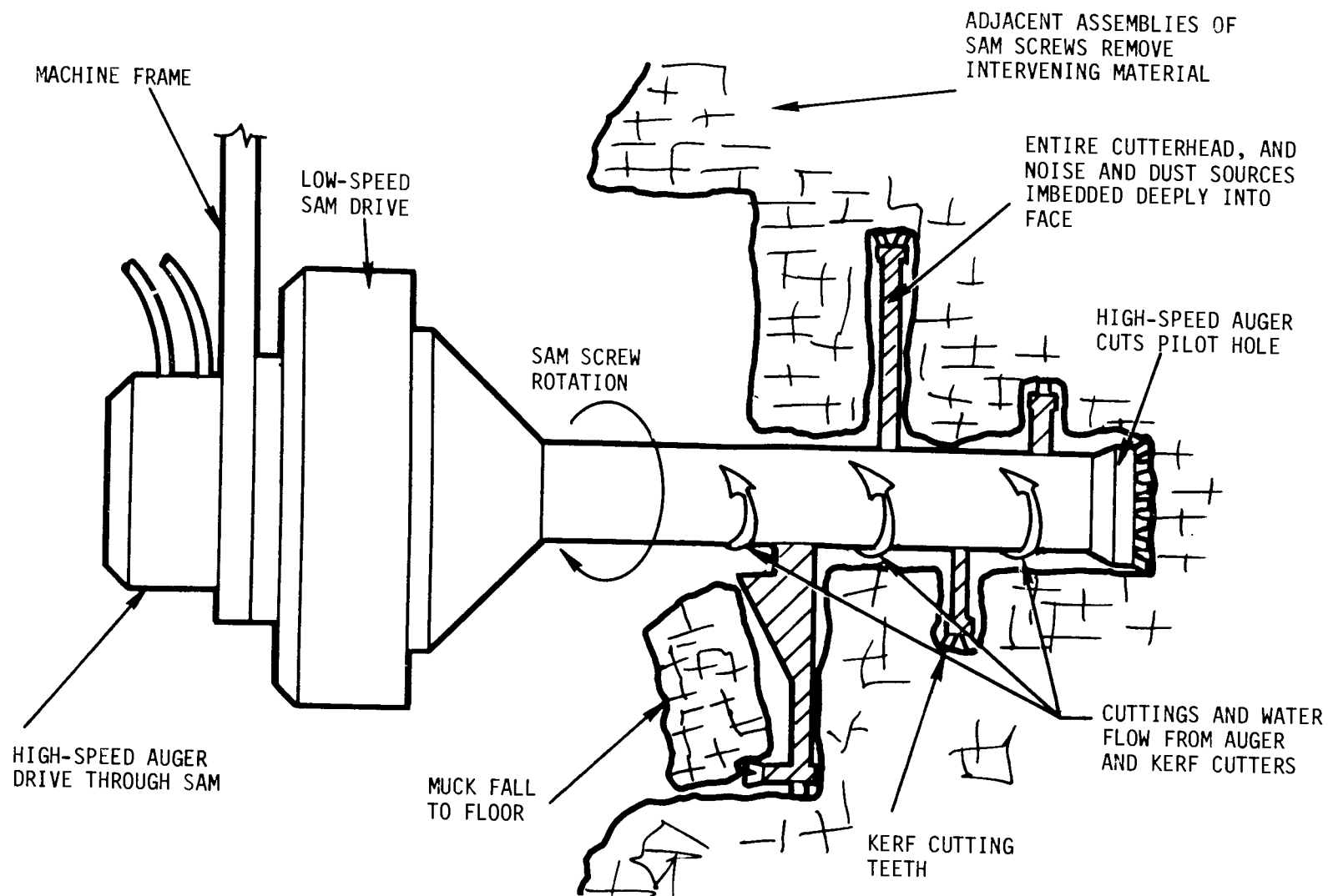


FIGURE 26. - SAM blind heading concept.

Practically all of the cutting action would be essentially buried in the face, producing minimum dust and noise. Coal would be gathered and conveyed continuously at the floor.

The concept of the face simply falling quietly to the floor to be conveyed away sounds preposterous at first glance, but upon closer examination it may be quite reasonable. For an example, suppose we wish to mine a 7-ft seam to a width of 20 ft in a single pass while producing coal at a rate of 12 tons/min. To produce 12 tons/min on such a face requires an advance rate of only 2 ft/min. SAM screws having a 6-in. pitch would rotate at only 4 rpm, and if of 18 in. diam (for this application they should be kept small) the maximum tooth velocity would be only 19 ft/min. At that advance rate it would not be difficult to take whatever additional action was necessary to assure that material between holes was broken free, nor would it be difficult to gather the material at an adequate rate across the face. Finally, it is believed that the region immediately behind the face would be sufficiently open to allow roof bolting (by automated means) very close to the face.

Each cutterhead in the array would be excavating 300 lb of coal per minute while using less than 4 hp each. Due to the low rotational speed, the drive torque of each screw would be 58,300 in. lb, requiring an AISI 4140 shaft at least 3-in. diam. Due to the high speed pilot bit required at the free end of the screw shaft, a larger hollow shaft would be required for the cutterhead shaft. The drive reducer used in the prototype SAM tests has the required torque capability for this blind heading application and measures only 14-in. in diameter, enabling any spacing of 18-in. screw cutterheads that is necessary.

The arrangement of cutterheads might be as shown in Figure 27 for the 7 × 20 ft entry. The screws are aligned so that half of them rotate clockwise while the remainder rotate counterclockwise. Note that the screws drive several trim chains which eliminate the cusps along the periphery of the entry. The direction of the chains is such that they tend to pull excavated material into the chain flite load-out conveyor. At this point the cutterhead and trim chain geometry is very preliminary, and field tests may prove that a different variation is superior.

By its very nature this blind SAM concept seems inherently better suited to remote or automated control. It is essentially locked to the face, employs no high speed elements, and experiences little or no dynamic loading: hence the "feel" necessary to operate a conventional continuous miner is simply not necessary. One mining engineer put it nicely when he noted that such a machine would "commit no violence at the face," and commented further that this may even improve roof behavior.

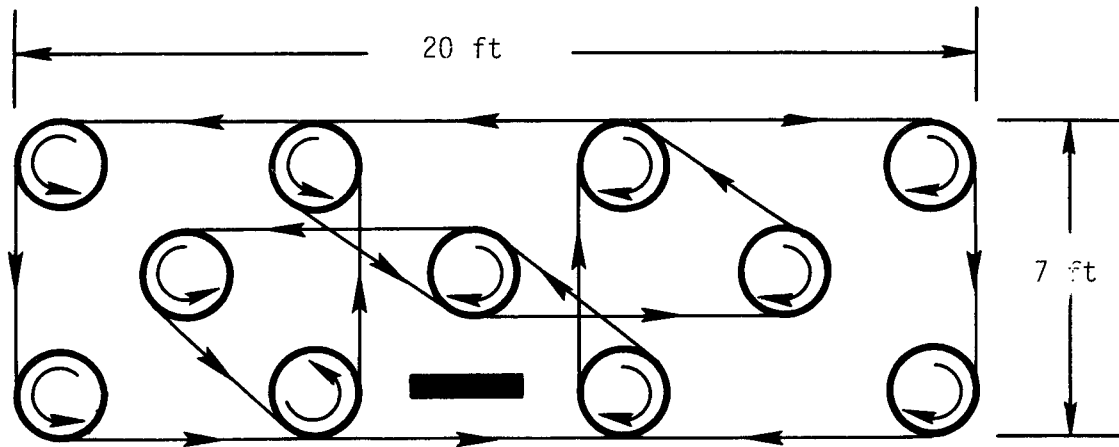


FIGURE 27. - Blind heading screw arrangement.

Because the SAM cutting elements tend to pull the machine into the face, the advance rate is not dependent upon the tractive capability of the machine. Hence, the machine need not be nearly as massive as the twin borers which required excessive bulk to obtain tractive force because they attacked a high percentage of the face at one time. Since the SAM cutter bits are mounted so that the normal cutting force acts perpendicular to the direction of travel, as the bits become worn there is no increase in traction required from the machine itself. As bits become worn on the twin borer, though, the reaction force required to hold the machine against the face becomes excessive.

The machine design of the SAM blind header will fill the entry during operations because excavation is taking place over the entire area. The SAM machine will not be nearly as heavy, though, and the maneuverability should therefore be improved. Because the machine will be lighter, it should be less expensive also.

The device would be easily steerable by relative speed control of appropriate screws, although very short radius turns do not seem possible for a full face machine. A very simple remote or

automatic guidance system in the vertical direction does seem possible. Presumably screws along the top or bottom of the machine would behave differently when contacting rock, for example, sharp pressure variations that could be "heard" in the hydraulic system would probably occur. Upon receipt of such a signal it would be possible to take corrective action, steering the assembly away from the rock content.

4.3 SAM Strip Mining System

An assembly of SAM screws excavating on the exposed face of a coal seam provides a simple, compact, high productivity strip mining machine. In fact, the compact mining geometry suggests a new mining plan.

Figure 28 illustrates the SAM strip mining vehicle. Multiple screws are arranged to excavate on the sloped face of an exposed coal seam. The horizontal offset from screw to screw, with all screws rotating in the same direction as shown, provides the necessary horizontal force to crowd the vehicle against the face, while the weight of the machinery holds it down. The self-advancing screws of course require no force in the traverse direction, although traverse would be controlled by ordinary traction means via the support vehicles at the top and bottom of the screw assembly.

The force and power levels associated with the SAM strip miner can be extracted from the data tabulated in Appendix G. Note also that the data in Figure 12 indicates that the horsepower and drive torque for tests 12 and 14 were approximately two-thirds the values of the 100 percent engagement tests. The 50 percent engagement tests, representing the 90 deg contact of the trip mining cutterheads, also show an average specific energy 30 percent higher than the other tests.

For an example 20-ft strip mine seam, the strip mine SAM might utilize four screw cutterheads each 10 ft in diameter. Each cutterhead will produce half of its capacity due to the overlap between screws. To be competitive with other mobile strip mining excavators, let us assume that we require a production rate of 2000 tons/hr. From Table G-1, the production capability of one 10-ft diam SAM, traveling 25 ft/min and cutting kerfs 5 ft deep, is 3000 tons/hr.

To be conservative we will derate the cutterhead and cut kerfs 2.5 ft deep, lowering the production capability to 1500 tons/hr. Since cutterhead engagement is approximately 90 deg instead of 180 deg, the actual tonnage rate should be 750 tons/hr per SAM screw. Now to determine what the advance rate must be to obtain 2000 tons/hr from the four screw arrangement, the following equation must be solved for advance rate, A (ft/min):

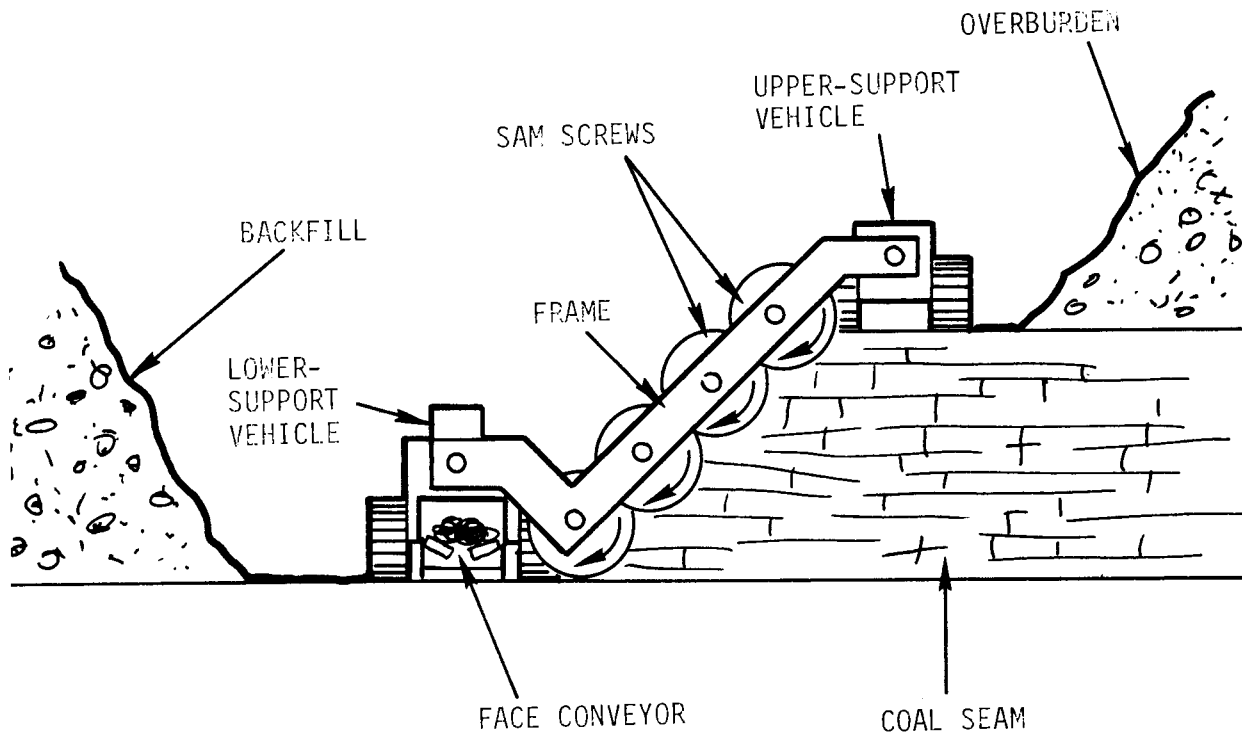


FIGURE 28. - SAM strip mining concept.

$$\left(\frac{A}{25}\right) (4 \times 750) = 2000 \text{ tons/hr} \quad (25)$$

or

$$A = 17 \text{ ft/min} \quad (26)$$

This speed is reasonable for a vehicle of this size.

Total cutting horsepower for an excavation rate of 2000 tons/hr should be 1134 hp. This figure, evenly distributed between the four drives, represents a specific energy 30 percent higher than the longwall values. Although the drive shaft torque requirements are high, there is ample room for very large shaft diameters.

As seen in Figure 29, each screw is mounted to the rear of the one immediately below in the assembly. This permits identical screw elements (that is, all of the same "hand") to rotate in the same direction without clashing, and it also permits cuttings from each screw to fall freely down the face without interfering with the lower screw elements.

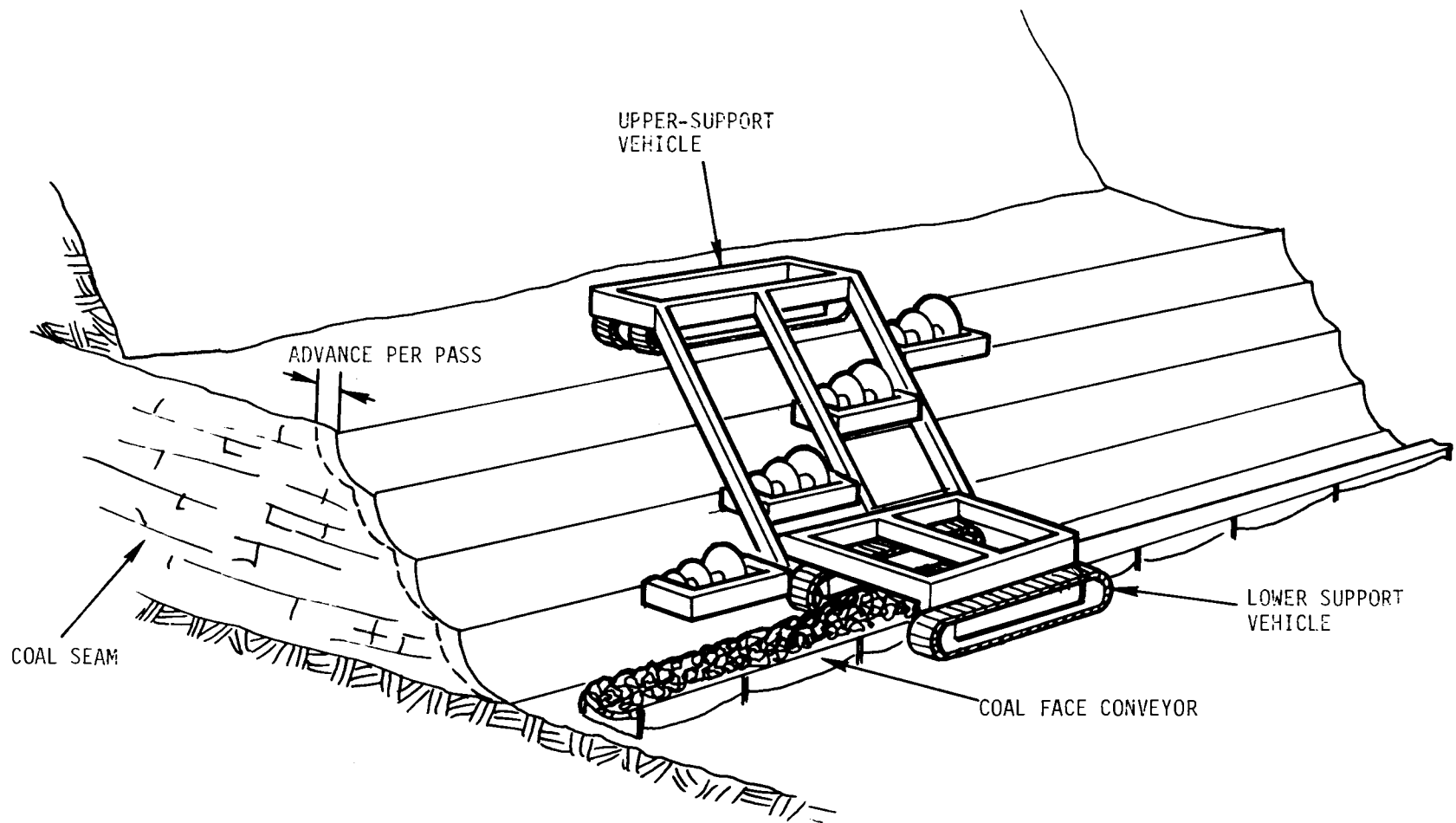


FIGURE 29. - SAM strip mining vehicle.

Obviously seams of widely varying thicknesses can be accommodated by varying the number of screws in an assembly while retaining the convenience and economy of a single standardized screw element design. Variations in seam thickness along the length of a single pit are easily accommodated by simply allowing the angle of the face slope to vary as necessary. Note also that, within reason, curved pit plans would present no problems.

A conveyor extends the length of the pit along the base of the coal face. Coal either falls onto or is directed onto this conveyor, thence out to the end of the pit to another conveyor that delivers coal from the pit. The face conveyor is moved laterally as the face recedes, just as in longwall mining. In fact, with proper conveyor design, it would be possible to have the SAM vehicle itself jog the conveyor sideways as it traverses the face.

Clearly this arrangement permits an extremely narrow pit floor. The minimum possible floor width would be that required by the lower SAM support vehicle, but it would be advisable to leave a slightly wider floor to permit access by maintenance vehicles alongside the conveyor.

This very narrow mining geometry suggests several cross-pit overburden handling schemes that provide fully mechanized materials handling and, at the same time, permit very direct restoration methods. Figure 30 illustrates a cross-pit bridge conveying scheme that provides for overburden deposition in its original sequence of layers.

A series of excavation machines is shown (SAMs are shown but others may be more suited to different materials), each handling a "lift" height suitable for cross-pit conveying. Material within each lift is, of course, mixed as it is deposited behind the mining operation, but the separate lifts are deposited in the same order excavated. Lifts that should not be mixed with others, but which are too thin to justify an independent cross-pit conveyor, for example, the topsoil layer illustrated, can be carried on separate small belts discharging to different levels from a common cross-pit structure.

Each cross-pit structure is carried on a suitable vehicle (probably crawler-mounted) at each end. Roadways for these vehicles are an integral part of the excavation and deposition plan, and they also serve to stop loose material from falling to the pit floor. On the deposition side these vehicles serve to compact the soil.

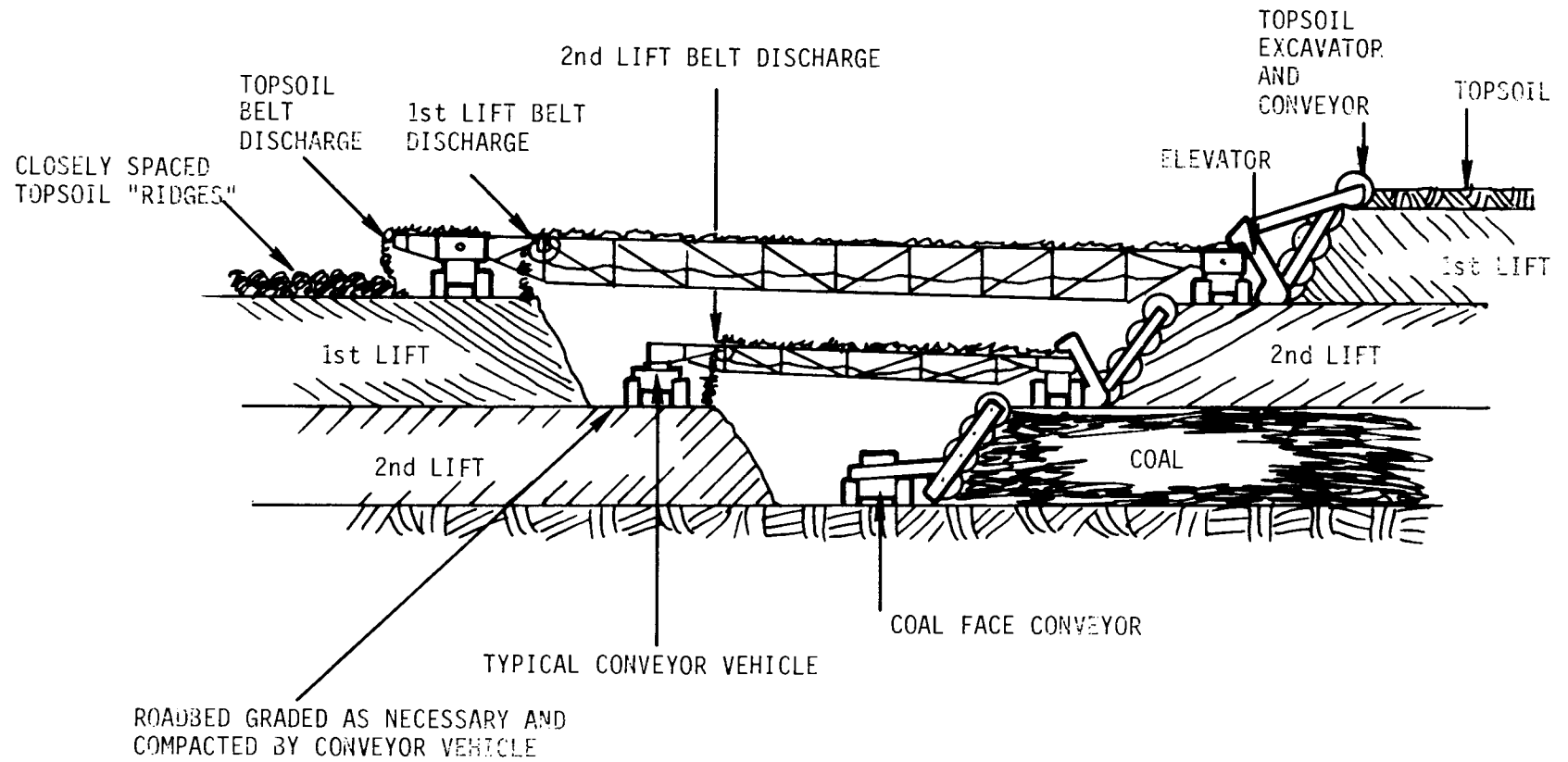


FIGURE 30. - Cross-pit conveying system, SAM strip miner.

As mining progresses the entire excavation sequence moves forward in relatively small steps, say 1 to 3 ft per pass. Thus material is deposited in many closely spaced small ridges, much like a plowed field. This would of course be very easily graded in comparison to the conventional series of large ridges.

If the direct cross-pit conveyor structures are considered too expensive, other conveying paths are possible. For example, a series of face conveyors, one on each bench, could be used to convey material to the end of the pit, across the pit on a suitable roadway, and back along the pit on the deposition side. Traveling excavators would deposit material on these belts, just as the SAM deposits coal on the pit floor conveyor, while traveling belt dumps would distribute the discharged material along the length of the pit. This arrangement could be used with the Low Wall Conveyor system presently being developed under another DOE contract.

In another alternative, excavated material might be conveyed down the excavation side of the pit, across the pit at its narrowest, and up the deposition face to the proper dump position. This would use traveling short conveyors rather than the very long cross-pit structures, but it would create more intricate and interdependent traffic problems. The high angle conveyor system being funded by DOE would fit into this type of conveyor scheme.

4.4 SAM Auger Miner

Auger mining is practiced both above ground and below ground. In either application a single blind SAM element could be used in place of a standard auger to excavate a similar round hole in the coal seam. However, if that were the only intent, it would be hard to justify replacement of the simple auger with the newly designed SAM.

A more significant SAM application follows from the observation that round holes are really not a very effective mining geometry. Indeed, work is presently underway to develop square hole "auger" miners. The SAM could be used to mine laterally extending slots which would be at least as effective as square holes in terms of extraction ratio, and a great deal easier to accomplish.

A counter-rotating pair of SAM screws, shown in Figure 31, could excavate on opposite sides of a pre-augered hole to widen the initial round opening to a slot. The slot could be opened further to whatever width roof conditions permit, either in multiple passes of a single SAM pair (indexed outward between passes) or in a single pass with multiple pairs of SAM screws. The use of pairs of screws provides for balance of

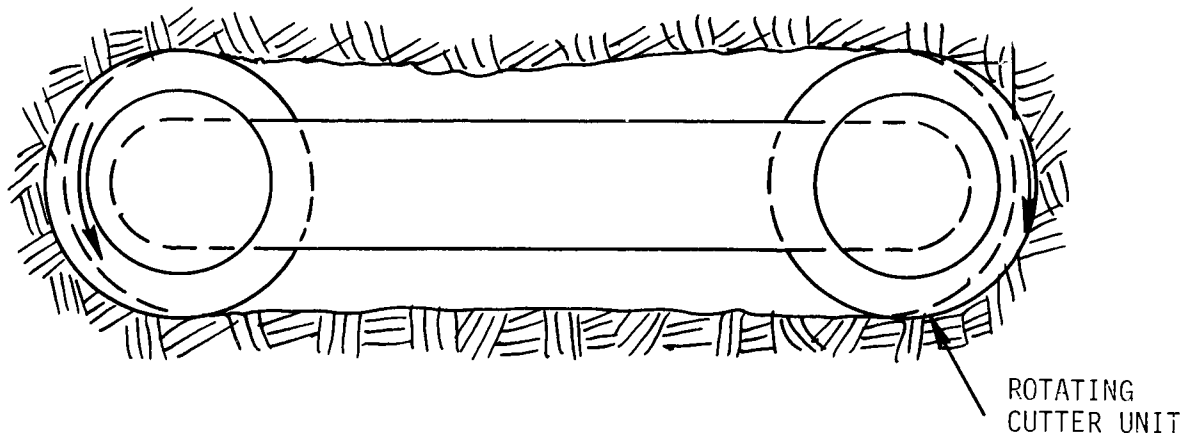


FIGURE 31. - Two-screw SAM auger miner.

horizontal excavation forces while counter rotation of the two elements balances torque on the assembly. The initial auger (or single SAM screw for that matter) would move ahead of the SAM operation drilling "pilot holes" on an appropriately wide spacing.

For any given seam thickness, the production rate can be extracted from Table G-1. For instance, for two 40-in. diam SAM augers to widen a 40-in. diam hole, the production rate would total 666 tons/hr, requiring 290 hp, and the drive torque on each shaft would be 31,000 ft/lb. All of these specifications are reasonable for the application.

It should be noted that the helical SAM geometry mates naturally to auger screw conveyor fluting. Conveyance of excavated material could be accomplished with screw flite attached to the rear of the SAM, just as it is presently attached to the rear of the auger cutterhead. To account for the material swell factor, the screw conveyor flite lead would have to be longer than the lead of the SAM cutterhead.

Interestingly, the auger, like the twin borer, is one of the few mining machines in use today using the kerf/break principle. But like the twin borer, and unlike SAM, normal cutting forces act to retard cutterhead advance and promote inefficient cutting and fines generation. In the case of the auger, high thrust forces also cause a lack of control of the auger and tend to limit the depth to which augers can mine before they leave the coal seam. With the SAM geometry, high thrust forces would not exist and longer depth holes could be feasible.

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APPENDIX A

SAM MODEL IN STYROFOAM

In this section we have collected a series of photographs which depict the operation of a suitcase-size SAM designed to demonstrate the concept by excavating a styrofoam material. Although the system is very simple and styrofoam does not behave like coal, the model has proved to be an effective means of explaining the SAM geometry.

Figure A-1 is a closeup of the SAM making a first pass from right to left, across a flat face on its spline drive shaft. The spiral saw flites of the SAM screw can be seen cutting an ever deepening kerf in the face. Also visible is a crescent of "muck" split from the face and beginning to fall away. For styrofoam, the "splitter," clearly visible at the aft end of the SAM, is 100 percent saw, due to the high tensile, ductile behavior of the material. In coal, the splitter requires little or no sawing action. The second pass of the SAM, shown in Figure A-2, allows one to see more clearly the developing kerf, the resultant intervening webs of coal, and the full crescents of muck being left in the wake of the traversing SAM. Figure A-3 shows the approaching SAM traveling down the longwall face after several passes. In the background the crank handle which is used to turn the spline shaft can be seen.

Figure A-4 is a rear view at the "tailgate" end after the SAM has begun a pass and is fully engaged.

The first web (crescent) of coal is beginning to be split (sawed) away. In Figure A-5, a fraction of a revolution later, the SAM has the first crescent fully freed of the face and beginning to fall, while the next crescent is visible and about to be sawed. Figure A-6, after one additional revolution, shows the SAM advanced one more pitch and the second crescent falling away while the first is still visible. The SAM continues in this fashion as the spline shaft is turned. It is self-advancing; no traversing force is applied, and the SAM pulls itself along the splined drive shaft. After multiple passes at two elevations, the continuing face geometry of Figure A-7 is developed. In coal, the central overhanging ledge regularly breaks and falls, or it can be nonexistent if the two pass elevations (or two counter-rotating screws) are overlapped.

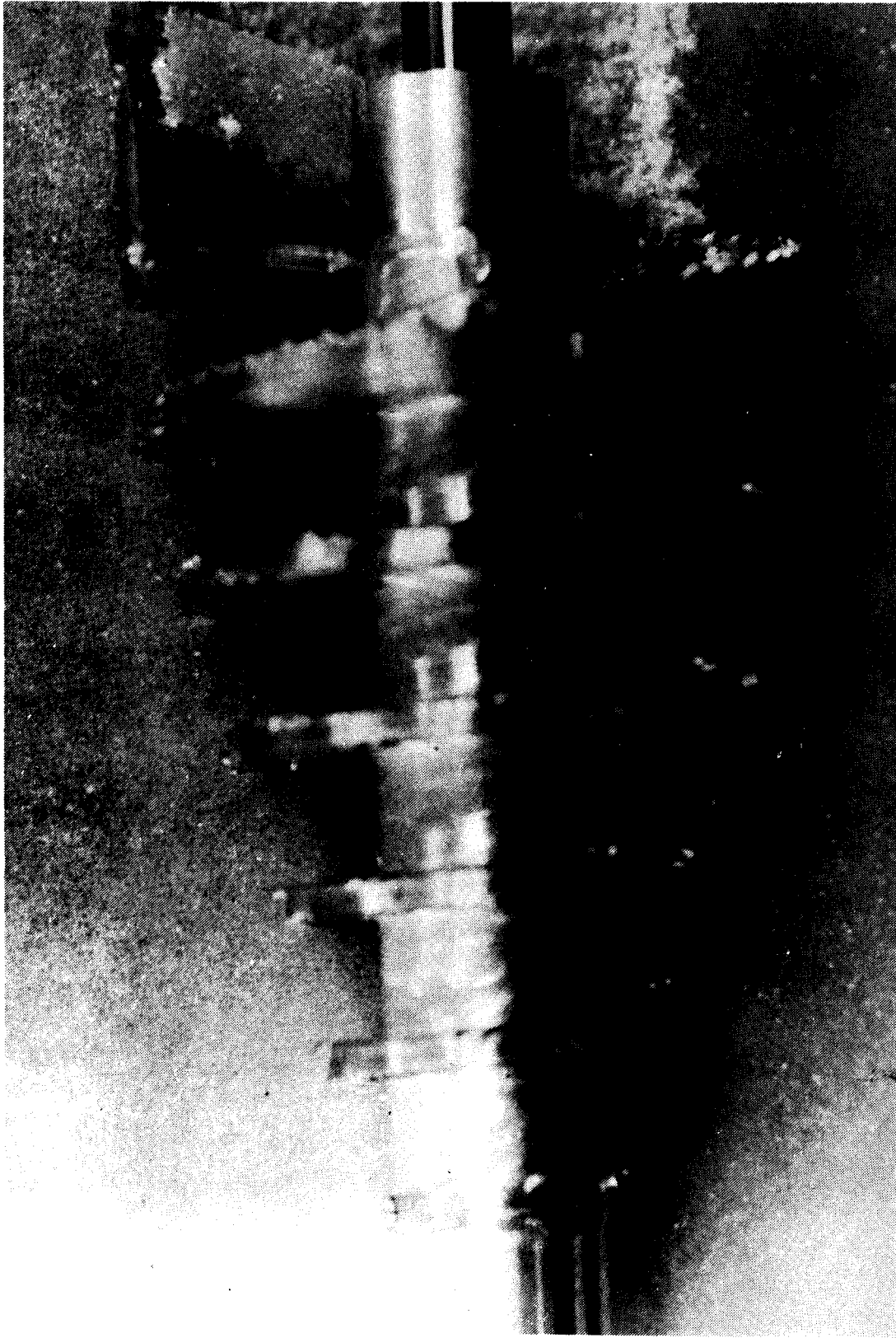


FIGURE A-1. - First SAM pass on a flat face.



FIGURE A-2. - Second SAM pass showing crescent of "coal."

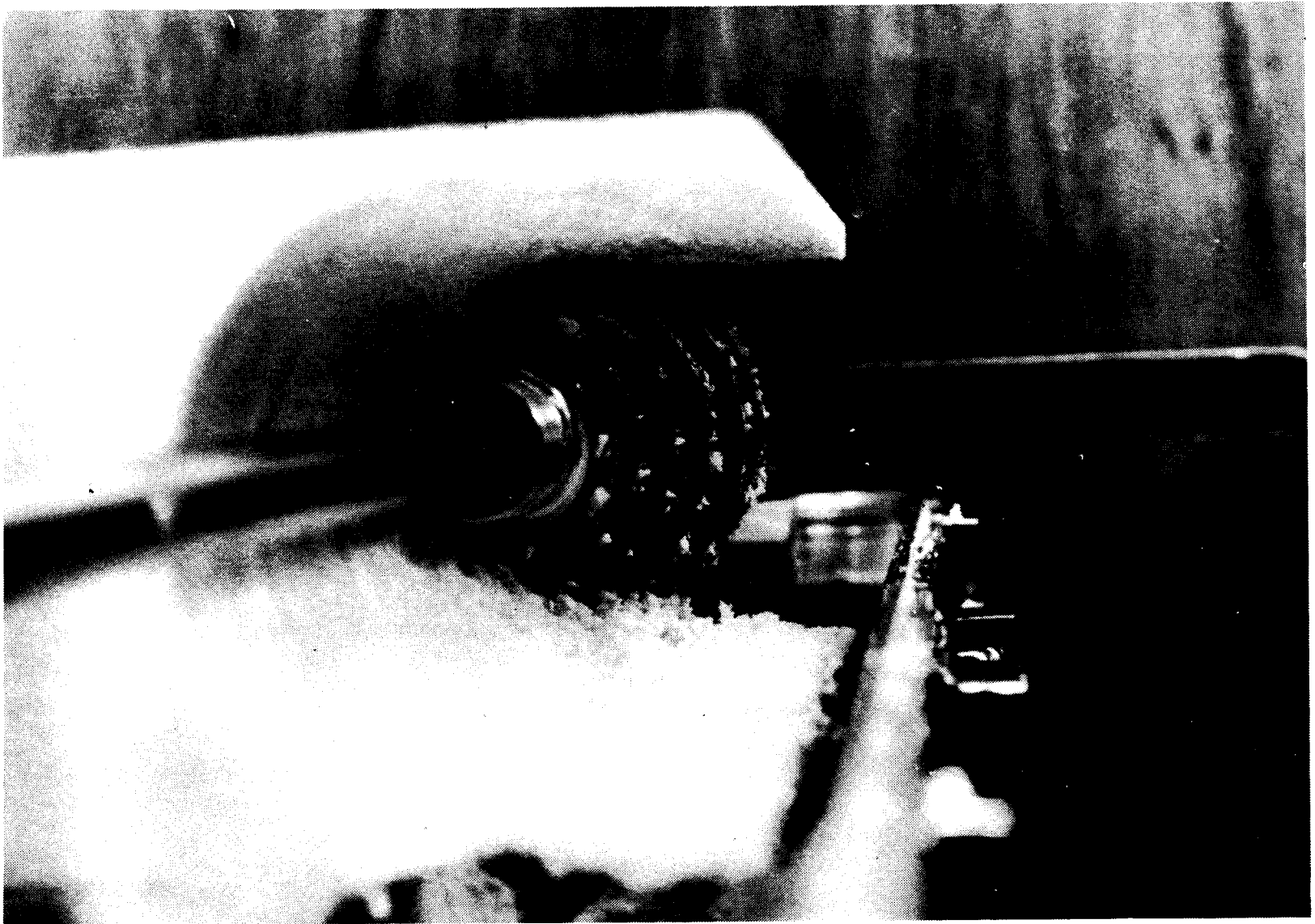


FIGURE A-3. - SAM cutterhead shown approaching along face.

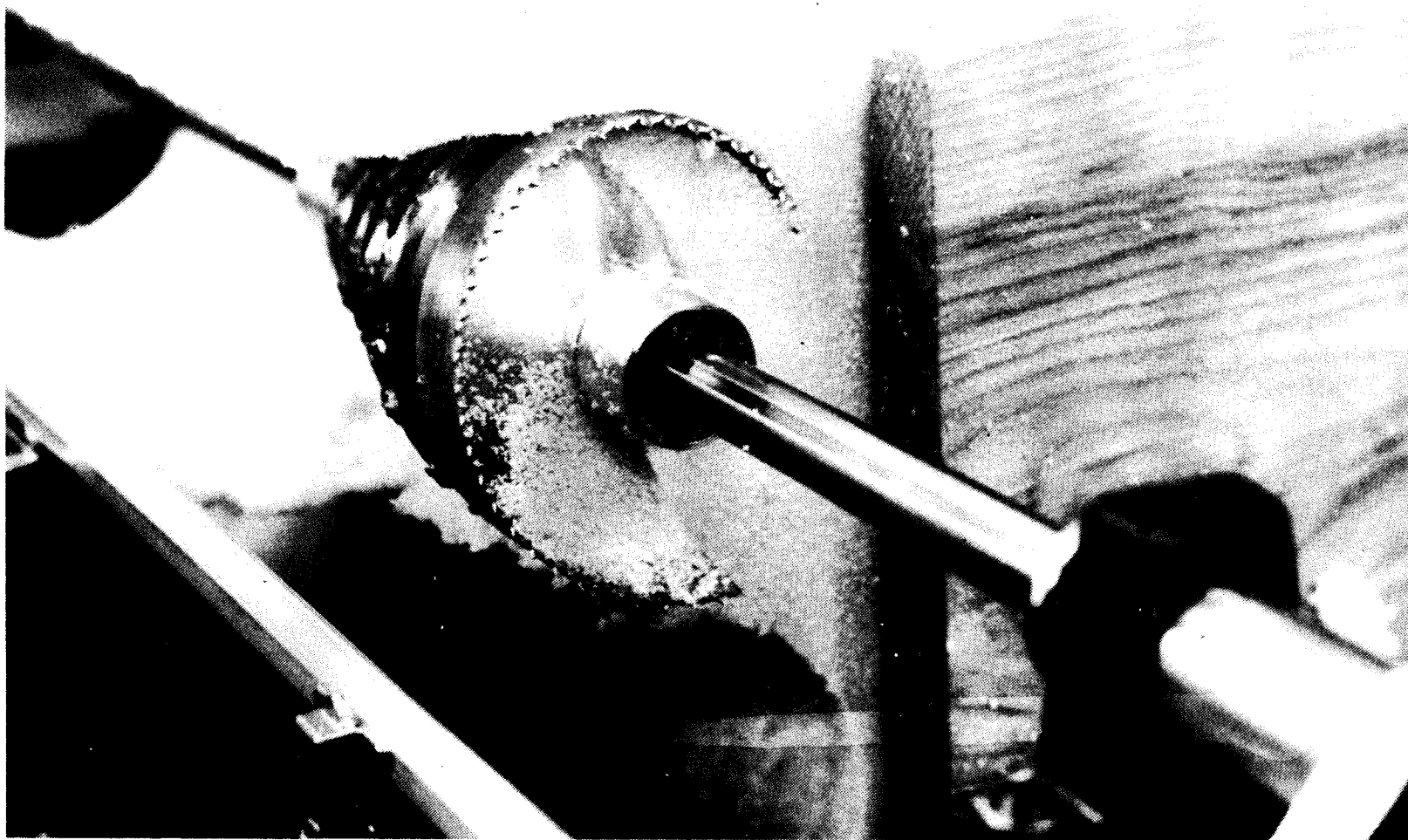


FIGURE A-4. - SAM fully engaged, first crescent being cut.

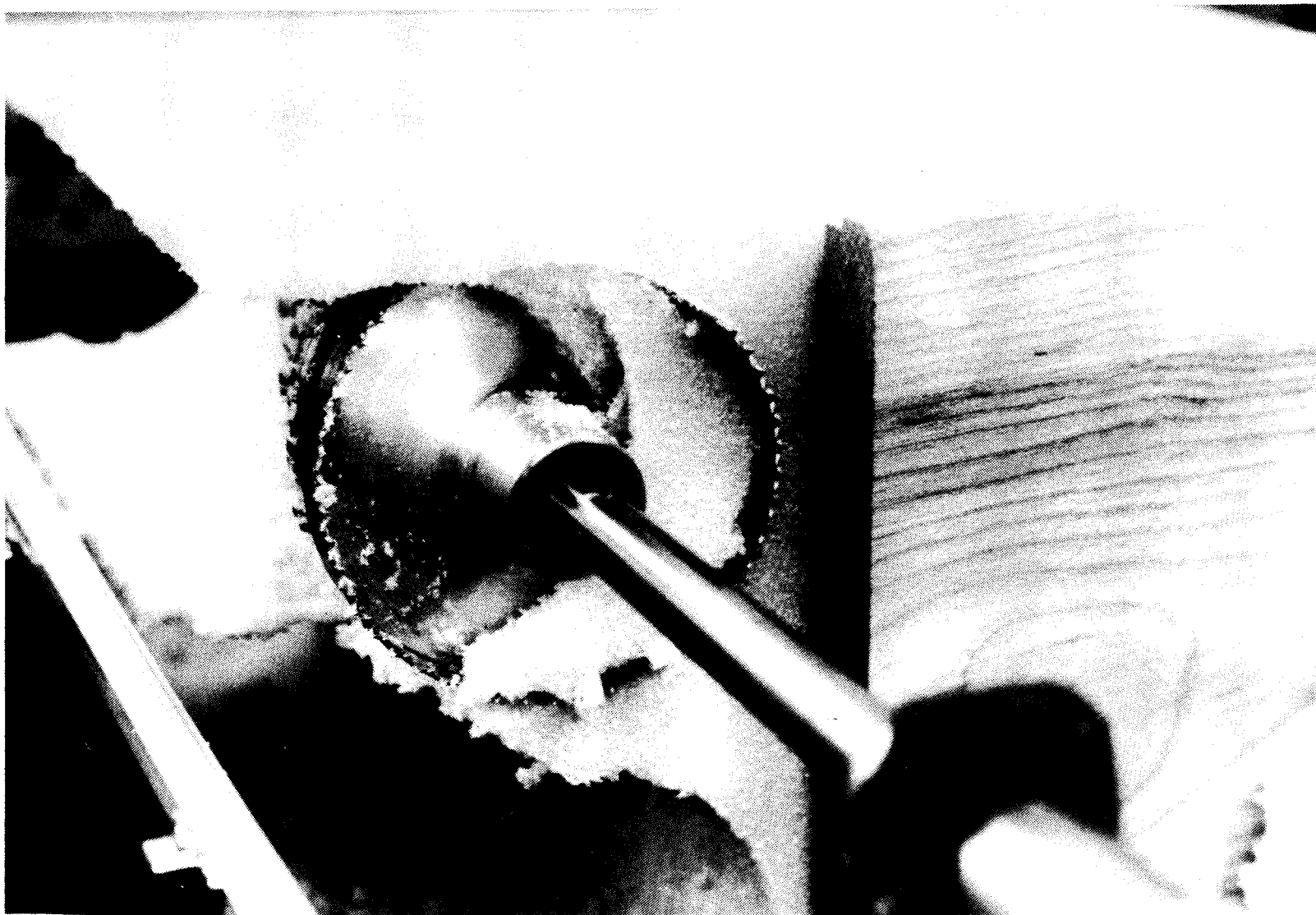


FIGURE A-5. - First crescent cut free of face as SAM advances.

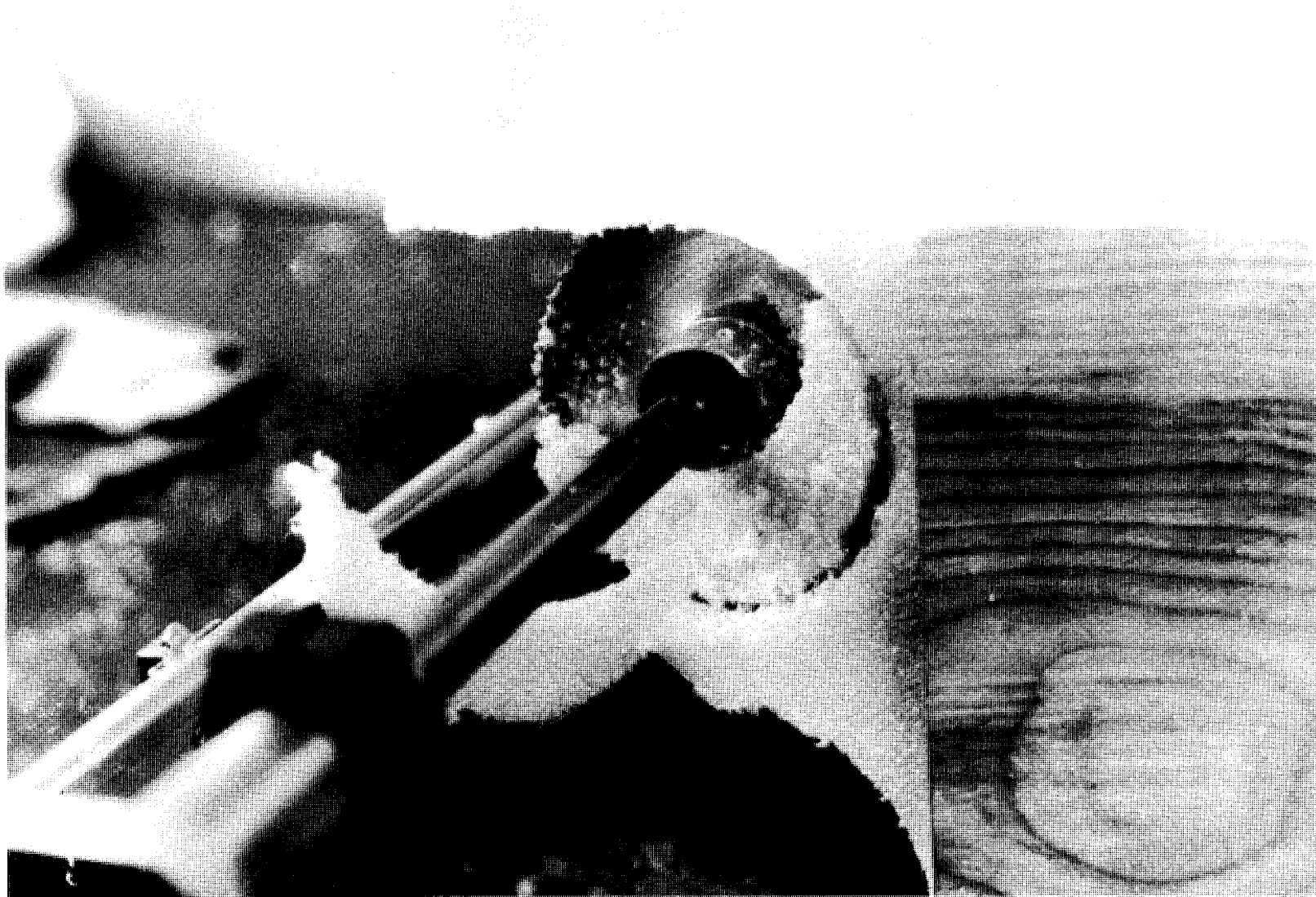


FIGURE A-6. - Second crescent cut free, falling after first crescent.



FIGURE A-7. - Typical twin SAM longwall face geometry.

APPENDIX B

COMPARISON OF SAM WITH OTHER CUTTING TECHNIQUES

Any excavation process can be categorized based on its pre-dominant operating characteristics according to the following areas of design:

- a. Characteristics of the material to be excavated
- b. Fracture and extraction process
- c. Bit design
- d. Cutterhead geometry.

Each of these items will be discussed briefly to delineate the differences between SAM and the state of the art.

It should be noted that the key to the SAM is its cutterhead geometry, and the limitations of the concept are due primarily to the interrelationships between the categories listed above. It is not possible, for instance, to compare the SAM concept to water jet cutting techniques; one is a geometry while the other is a "bit" design. SAM could be compared to another cutterhead geometry, such as a high speed cutter drum, just as water jets can be compared to tungsten carbide point attack bits. On the other hand, the SAM geometry can be used with various bit designs.

B.1 Excavated Material

The characteristics of a material which might affect its suitability for excavation by SAM include the following:

- a. Strength
- b. Abrasiveness
- c. Adhesiveness
- d. Incendivity
- e. Frictional properties
- f. Miscellaneous.

Although the application under discussion is coal mining, brief mention will be made of other materials besides coal and overburden.

B.1.1 Material Strength

Because SAM cuts slots in the material to weaken it prior to breaking between slots, it is preferable to keep the proportion of the material in the slots small in comparison to the total. Compact cutter bits are therefore preferred, such as drag bits or water jets, and we feel that roller cutters are unsuitable for SAM due to their bulk.

Because numerous splitter designs are available, the material strength has minimal effect on the suitability of SAM for breaking between slots. In strong or woody materials, it might prove advantageous to saw all material out between kerfs rather than break it, thereby lowering the overall efficiency slightly. Whenever feasible, breaking between kerfs is more efficient than sawing or cutting because less material surface area (equating to required power) is produced.

In conclusion, SAM is feasible whenever the material strength allows a slot to be cut that is small in proportion to the space between slots. "Smallness" is determined by the acceptable specific energy to excavate the material. Materials that require compressive failure, as with roller cutter applications, are considered unworkable.

On the other hand, materials that are brittle and fracture easily are particularly suited to any "breaking" method which does not cut all material into small pieces. Coal is such a material.

B.1.2 Abrasiveness

Depending on how SAM is deployed, the material abrasiveness may affect its successful application:

- a. The self-advancing force is generated primarily from the sides of the screw or bit blocks rubbing against the kerfed material. With a suitably controlled haulage system, this friction can be minimized.
- b. The screw flights must occupy the kerf alongside the cuttings that are exiting the slot. The tight quarters and relative motion may cause flight wear. This should

pose no problem in coal, and water flushing would alleviate the problem in more abrasive formations.

- c. The wedge splitter would probably prove a high-maintenance item under abrasive conditions due to the high frictional forces. Cutter bit-style splitters would prove superior.

As with any drag bit cutterhead, the abrasiveness of the excavated material affects the life attainable from the bits.

B.1.3 Adhesiveness

The suitability of the SAM geometry for any material depends on the ease with which the cuttings can leave the kerf once they have been cut by the bits. A sticky overburden such as clay would probably not be excavated easily with a kerf/break process. Once kerfed, a saw-type splitter would be required. Because this splitter design must necessarily get "behind" the weak, slotted material, a sticky material is apt to remain captured in the splitter.

B.1.4 Incendivity

Tests* have shown that cutterhead design has a definite influence on the likelihood of ignition in a coal dust-air-methane mixture.

- a. Sandstone is the most incendiary rock that is likely to be encountered.
- b. The typical bit and block material C4130 steel is rather incendive.
- c. Tungsten carbide is less incendive than steel.
- d. Mixtures with as little as 1 percent methane can be ignited if coal dust is present.
- e. Frictional heating, not sparking, is the primary cause of ignition.
- f. At 450 ft/min, ignitions were difficult to produce, while at 300 ft/min, none occurred.

*Kelley, John E. and Robert Blickensderfer, "Slower Speed, New Pick Metals May Reduce Ignition Hazards," Coal Age, November 1977, p. 83.

As mentioned previously, there may be frictional heating of the screw flight in the slot.

During underground coal mine operations, it is unlikely that kerfing would continue into the roof to such an extent that more than the carbide itself, not the screw flight, bore against sandstone.

The primary advantage of SAM in this regard is the low peripheral speeds required to obtain adequate production rates. At no time do we anticipate rotational speeds higher than 25 rpm, corresponding to 300 ft/min at 46 in. diam and 450 ft/min at 69 in. diam. Only those bits at the outside radius are traveling at these speeds due to the conically shaped screw geometry. On the other hand, *all* bits on a continuous miner drum are traveling at maximum speed.

B.1.5 Frictional Properties

Materials such as coal which have low coefficients of friction are particularly suited to the SAM, which will rub against the excavated material.

A material whose properties might change significantly with frictional heat could cause problems, for instance, ice, permafrost, or frozen ground. Permafrost has been noted* in the past as a likely material for the application of the kerf/break process. Frictional heating from SAM may or may not aid the excavation process.

B.1.6 Miscellaneous Properties

An overburden which contained sporadic large boulders could stall out a SAM cutterhead that tried to cut through or dislodge a firmly entrenched boulder. The more homogeneous the material, the easier it is for any cutter system to excavate. The cutterhead design can be more closely matched to the conditions to be encountered.

Very soft deposits, such as peat, are particularly suited to a SAM with a continuous spiral knife edge around its periphery. The cutting action is therefore very gradual, keeping turbidity to a minimum in underwater peat deposits, and thereby maximizing recovery.

In deposits such as salt, the use of water for dust suppression is not encouraged because salt can be dissolved and lost

*Foster-Miller Associates, Inc., "Fundamental Concepts for the Rapid Disengagement of Frozen Soil," CRREL Technical Reports 233 and 234, May 1973.

in solution. A kerf/break scheme such as SAM allows close control of the airborne dust because all cutting takes place at the base of a deep slot. Low bit speeds on SAM also keep fanning to a minimum. Of course, any dusty material, such as coal, benefits from an excavation scheme that minimizes dust generation.

In any material where machine traction is a serious detriment to excavation performance, the self-advancing characteristics of SAM are important. Overburden removal in wet or steeply pitched areas, peat harvesting, and underground coal mining on wet floor are examples where the tractive capability of SAM would complement the excavation capability.

B.2 Excavation Process

The most common methods of excavation include the following:

- a. Ripping - dragline, shovel, dozer, loader, longwall plow
- b. Rotary cutting - continuous miner, longwall shearer, bucketwheel excavator, dredge
- c. Kerf/break - auger, trepanner, borer, conventional mining, SAM
- d. Compressive fracture - tunnel boring, tricone drilling, conical reamer
- e. Blasting - overburden removal, conventional mining, hard rock tunneling.

In general, the amount of power required* (and the dust generated) is directly proportional to the total surface area of material excavated. The processes which produce large product, notably ripping and blasting, are generally the most efficient. The strongest rocks require the use of excavation techniques that produce small chips, and therefore compressive fracture is not very efficient.

Rotary cutting is suitable for materials such as coal where a 1/2- to 3-in. depth of bit penetration is compatible with acceptable force and power levels for a dependable machine design. Although rotary cutting is a continuous process, it suffers from a basic problem inherent in its geometry that, as installed on a shearer or continuous miner, the depth of cut of each bit is not

*Warner, E.M., "Machine and Cutting Element Design," Mining Congress Journal, August 1970, pp. 35-42.

constant.* This prevents the bit lacing from being optimized so that coarse product can be uniformly generated because the space-to-depth ratio is continually varying around the circumference.

Kerf/break techniques have been employed in those cases where large product is desired or where the excavation of the material is particularly troublesome. The kerf/break scheme requires cutting a slot, which is very energy-inefficient, followed by breaking the large product from between the slots, very energy-efficient. The result is material consisting of both a large proportion of fines and coarse. The overall efficiency of the scheme is dependent on the ratio of each portion of the total excavation process.

B.3 Bit Design

Because rotary drum machines excavate all of the material before them as they advance, there is little restriction on suitable bit styles. In general, the bit gauge must be sufficiently large as to be able to store as many chips as are produced during sump operations.

On the other hand, as discussed earlier, the bit selection for SAM favors those designs that are compact, thereby minimizing the required kerf width to contain the bits and blocks. Small bits also allow space for chips to flow from the kerf. On the prototype SAM, custom 1-in. wide carbide chisel bits were used.

Point attack bits are possible with SAM but would require wider kerfs, even with the Minibob, than can be achieved with chisel bits. A 1-in. wide kerf was successfully used in the SAM field tests; the use of conical bits would require a kerf width closer to 2 in. wide.

The use of high-pressure water jets for a SAM is a good possibility. The water jet is an excellent slot cutting device, requiring little space for structure around it. Some thought would be required for a splitter arrangement for a wet-head SAM.

* Roepke, Wallace W., David R. Lindroth, and Theodore A. Myren, "Reduction of Dust and Energy During Coal Cutting Using Point-Attack Bits, with an Analysis of Rotary Cutting and Development of a New Cutting Concept," RI 8185, USBM, 1976.

B.4 Cutterhead Geometry

B.4.1 State of the Art

Mellor* has classified machine cutting geometries into three broad categories, depicted in Figure B-1. Most coal is mined with shearers and continuous miners which are categorized as "transverse rotation" machines. The features of this type of excavation are noted below:

a. Advantages:

1. Continuous process
2. Relatively smooth removal of cuttings
3. Minimal shock loads because bits enter material at zero depth of cut
4. Ease of placement of bits to optimize both number of bits sharing the load and the bit lacing pattern

b. Disadvantages:

1. Depth of cut is continuously varying, thereby preventing the ultimate optimization of spacing to depth ratio of bit lacing
2. During sump operations, significant regrind takes place
3. Typical high-speed operation fans dust into the air.

The inefficiency associated with the varying depth of cut has been analyzed by Roepke** who noted that, during 60 percent of the time that any particular bit is engaged in the coal, only 10 percent of its total excavated volume is extracted. This finding has been the basis for the development*** of several

* Mellor, Malcolm, "Mechanics of Cutting and Boring; Part 1: Kinematics of Transverse Rotation Machines," CRREL Special Report 226, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, May 1975.

** Roepke, Wallace W., David R. Lindroth, and Theodore A. Myren, "Reduction of Dust and Energy During Coal Cutting Using Point-Attack Bits, with an Analysis of Rotary Cutting and Development of a New Cutting Concept," RI 8185, USBM, 1976.

***FMC Corporation, "Constant-Depth Linear Cutting Head for Continuous Mining Machines: Engineering and Economic Feasibility Study"; USBM Contract JO265010, March 1977.

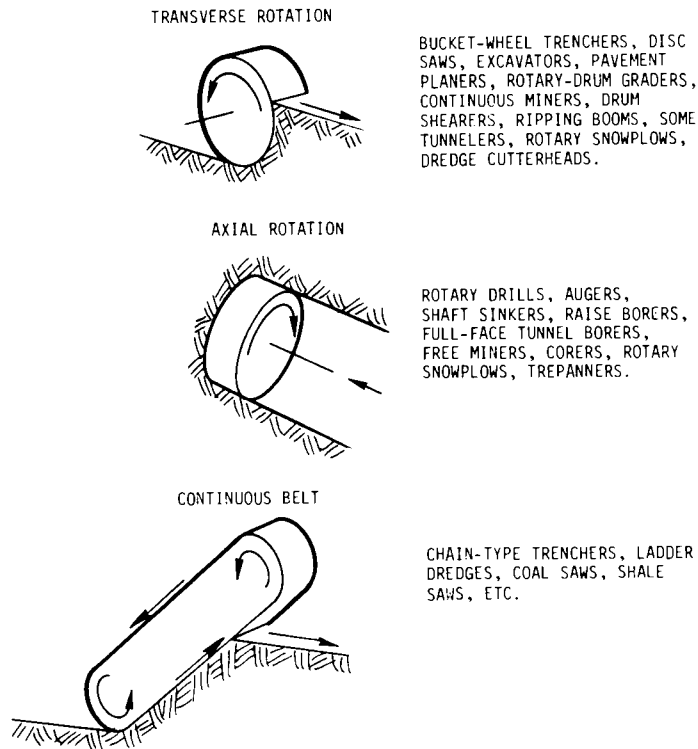


FIGURE B-1. - Classification of excavating machines.

linear cutting devices which provide constant depth of cut, just as in a longwall plow. The shortcoming of any linear cutting mechanism is that it is discontinuous, tends to generate high shock loads, and will therefore take much mechanical abuse in service.

The longwall plow is an extremely simple excavating device. It employs a static cutting element and takes 300- to 600-ft long, constant depth cuts along a coal face. Unfortunately, due to the simple design, it has difficulty cutting through hard material or material without significant overburden pressure on it to aid in the cutting process.* Inherent in the static cutting element design, the depth of cut (and "web" depth) is approximately 3 to 6 in. to keep haulage forces to acceptable values. For production rates to equal those of longwall shearers, typically five or more passes are made along the face at linear speeds from 75 to 100 ft/min between each advance of the roof supports. In other words to obtain the same amount of material

*Hittman Associates, Inc., "Underground Coal Mining: An Assessment of Technology," Electric Power Research Institute Final Report AF-219, Contract 284-1, July 1976, p. 5.68.

per unit time, a plow must travel five times as far as a shearer at five times the haulage rate. As expected, these speeds and distances compromise some of the benefits of the simple mechanical design.

At the same time it should be noted that the shallow "web" depth of the plow and the coarser product excavated promotes a more uniform generation of dust and methane along the face.* This factor has occasionally determined the selection of longwall style in dusty or gassy mines where the methane liberation rate from a shearer production would overpower the mine ventilation system.

All of the mobile surface mining equipment designed for continuous production is based on rotary cutting elements. Road planing style machines (CMI and Huron Manufacturing) and small bucketwheel machines (Barber-Greene, Unit-Rig, and FMA prototype) are classified as "transverse rotation" and have the same advantages and disadvantages noted previously for this style of cutterhead. Although dust generation is less of a concern in surface operations, power consumption on a diesel engine machine is a concern to anyone these days.

Large bucketwheel excavators are the most productive excavation machines available today. The high production rates can be attributed to the following:

- a. Continuous operation
- b. Large scale
- c. Use solely in soft to medium hard materials, uniform in composition.

To a lesser extent, these machines are efficient because of their method of excavating. Since excavation takes place predominantly during the slewing operation, the bucketwheel is classified as an "axial rotation" cutterhead with an approximately constant, large depth of cut on the side-cutting edge of each bucket.

A coal auger is an axial rotation, kerf/break excavating device. As is typical of axial rotation machines, for a given translational and rotational speed, the depth of cut is constant. Due to power and traction restrictions, as cutting becomes harder, the rate of advance, the depth of cut, and consequently the cutting efficiency all decrease. The variable depth of cut and

**Ibid*, p. 5.68.

kerfing operation of the cutterhead contribute to a large proportion of fines. The trepanner and boring machine, similarly designed, share the same characteristics.

The breaking arrangement in each of these machines utilizes cantilever bending of the cores. Because the cutterhead is continually advancing toward the core, any material that does not break forms a barrier to further advancement; this problem arises occasionally on boring machines. The kerfing bits must be mounted on supports that extend forward from the cutterhead; these arms are limited in length for structural reasons and therefore the amount of bending that can be applied to break the cores is also limited.

B.4.2 SAM Geometry

The SAM cutterhead geometry does not fit conveniently into the machine cutting categories defined in Figure B-1. Because the direction of advance is parallel to the axis of the cutterhead rotational centerline, SAM should be classified as an axial rotation machine. However, unlike all other excavation schemes, the direction of cutting is perpendicular to the advance direction. This feature is one of the keys to the unique SAM cutting characteristics.

As the screw rotates, each bit in turn cuts deeper than the previous bit by a predetermined amount based on the welded screw construction. This constant depth of cut is optimized for maximum efficiency in the difficult cutting required inside the kerf. Unlike transverse rotation machines (CM's, etc.), all axial motion machines (borers, etc.) have the potential for constant depth of cut operation. Because the advance rate, typically dependent on tramping, is variable, constant depth of cut has been unattainable.

Because the depth of cut of all bits on the SAM is dependent on its construction only, it is the only excavation cutterhead geometry to date that maintains a constant depth of cut during continuous cutting operations.

Because the SAM bits cut material perpendicular to the direction of advance, another important advantage is gained in actual operation when bits become worn. When a shearer, borer, auger, trepanner, continuous miner, bucketwheel excavator, or dragline operates with worn bits or teeth, the normal component of cutting becomes larger in proportion to the tangential cutting force; the tangential cutting force itself remains relatively constant. The strength of the material being excavated determines

what the maximum normal/tangential ratio can become. Typical values are 0.4 for clay overburden, 0.7 for coal,* and 0.55 for sandstone. The increase in the advance force serves to slow down the advance rate due to higher power requirements, and the depth of cut and cutting efficiency then decrease while dust levels increase.

In certain cases, the high advance force causes inefficiencies due to poor traction. A mobile bucketwheel machine is dependent on its tractive effort requirement being less than the traction available for its performance. When haulage forces are high, a longwall shearer risks damage to components and, especially in the case of a chain-type haulage system, injury to personnel. In the operation of a typical continuous miner, the operator sumps in the cutting head as far as possible before the caterpillar tracks slip on the ground. At this point, the shear cycle is begun. The sharpness of bits, normal force generated, and depth of sump possible all contribute to govern the production rate from the continuous miner.

The longwall plow and SAM share the attribute that, as bits become worn, the increased normal force does not directly oppose the direction of travel. When the normal force increases, the unbalanced force tending to thrust the machine out of the face pushes the machine harder against the roof supports. The required haulage force then is increased due to higher frictional losses, possibly 30 percent of the normal force. Therefore, due to the mounting orientation of bits on SAM, worn bits have a negligible effect on cutting efficiency.

The average helix angle of all bits on the SAM screw cutterhead is approximately 10 deg (for a 12-in. lead). Due to this helix angle, the sum of all cutting forces of SAM bits resists forward advancement of the cutterhead along a face. With a 10 deg helix, the retarding force is approximately 18 percent of the total cutting force. On a shearer or continuous miner, the cutting forces balance out; there is no net effect on advance force when the full diameter is cutting. On a longwall plow, 100 percent of the cutting force resists the haulage.

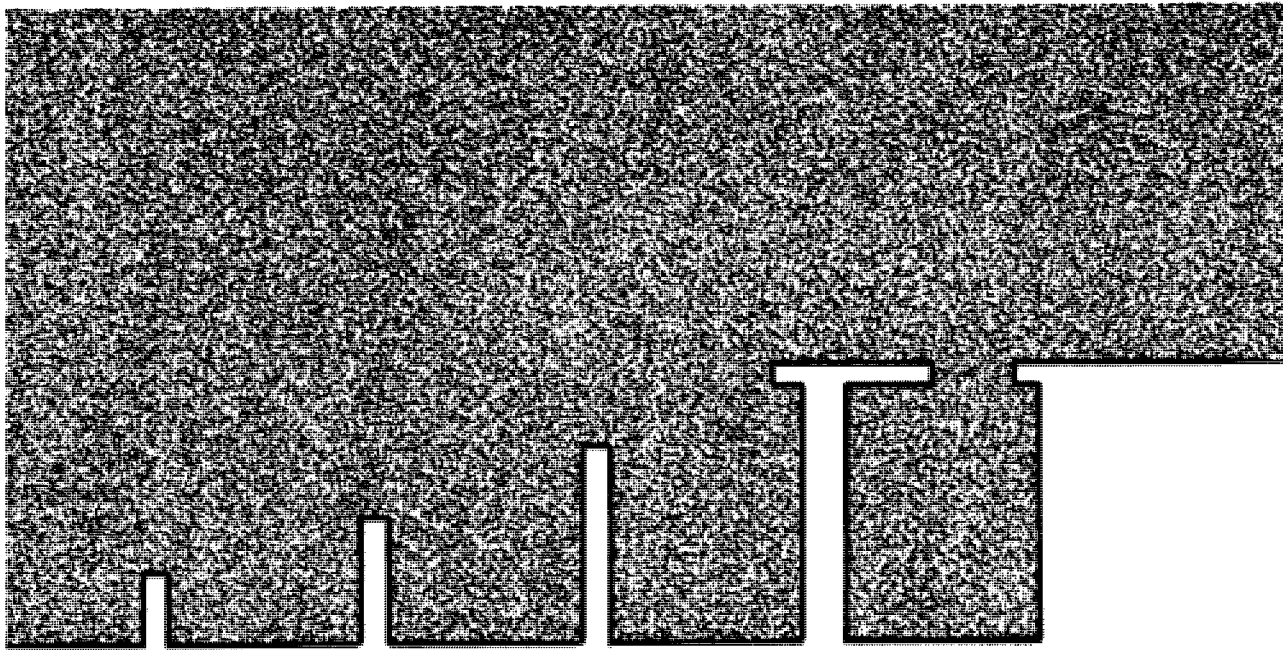
SAM is, of course, also a self-advancing machine. Demonstrated in a styrofoam model and verified in field tests in coal, the kerf cutting screw does indeed pull itself along a longwall type face. The strength of the coal cores proved sufficient to resist the slight thrust required to advance the

*Evans, I. and C.D. Pomeroy, Strength, Fracture and Workability of Coal, Pergamon Press, Oxford, England, 1966, p. 267.

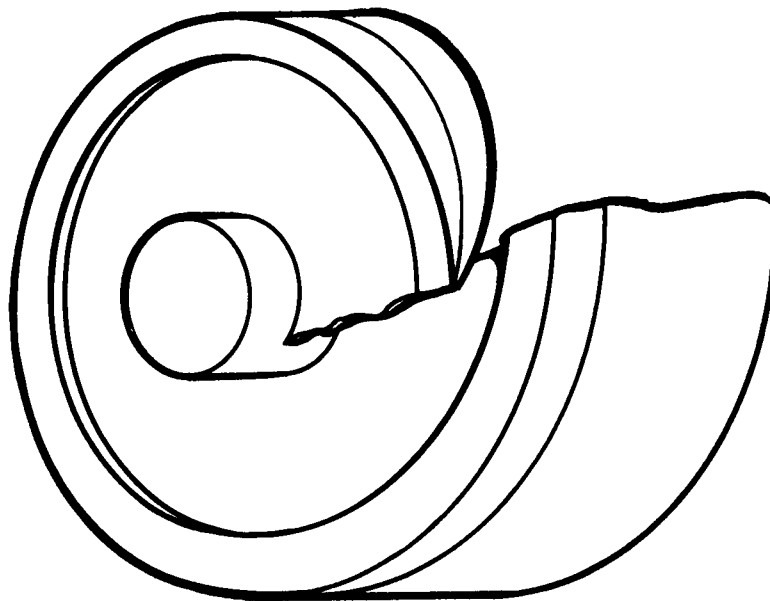
machine. In addition to the screw flights themselves, forward thrust is provided by the splitter as core material is broken to the rear.

Unlike borers, augers, and trepanners, there are several alternatives to breaking the core other than cantilever bending. The splitter options shown in Figure 4 - saw, bending wedge, and shear wedge - allow customizing the splitter scheme to individual seam conditions. In hard coal, it is intended that some of the breaking armament be mounted on the front of the splitter flight (see Figure B-2). In this way, some prenotching of the core can precede the final breaking out executed by wedges on the back side of the splitter flight. Not only is this arrangement beneficial because it promotes core breakage by causing stress concentration at the notch, it relieves stresses in the screw flight itself by balancing forward and rearward splitting reactions.

Another splitter design that has not been evaluated is one presently in favor with one of the borer manufacturers. Simply using longwall bits to rip out the weak cored material between kerfs can be energy-efficient. Note that this approach imposes high shock loads on the system, but does not tend to bend the splitter flight frontward or rearward. No advancing force is generated with this arrangement.



a) GOOD PRENOTCHING BY SPLITTER



b) PRENOTCHING SPLITTER

FIGURE B-2. - Balanced splitter design.

APPENDIX C

TEST HARDWARE

Given the ultimate program goal of determining the feasibility of mining coal with a SAM, a test program was developed to attempt to excavate with a prototype SAM cutterhead. The purpose of the field test was to

- a. Determine *if* SAM could excavate coal
- b. Obtain measurements of the cutting force and power tools.

With these data, a technical and economic feasibility analysis could be performed to determine if the geometry could be incorporated into a mining system.

C.1 Design Specifications

Contract specifications called for testing a full-sized cutterhead so that various mining machine designs could readily be evaluated. The four mining systems considered as possibilities for SAM cutterheads were the following:

- a. Longwall
- b. Blind heading
- c. Auger
- d. Strip mining.

Obviously, the dimensions of a strip mining screw are not the same as a longwall design. Due to the broader range of application, the decision was made to test a cutterhead sized for longwall, continuous miner, and small auger applications.

For design purposes, a longwall section in a 54- to 60- in. seam was used to size the cutterhead. With the apparent freedom to select the optimum combination of translational speed (or the number of screws) required to obtain the production rate typical of the industry, web depth was not originally considered a governing criterion for screw diameter determination. To suit the medium seam heights, two 25-in. diam screws, mounted vertically above each other, were chosen. The intent was to leave a 4- to 10-in. gap between the screws and recover the overhanging material "for free" as it fell to the floor (see Figure C-1). In the side-cutting longwall design, the 25-in. screw cuts a 9-in. deep kerf, leaving an allowance of 1 in. for clearance of the coal with the 5-in. diam shaft.

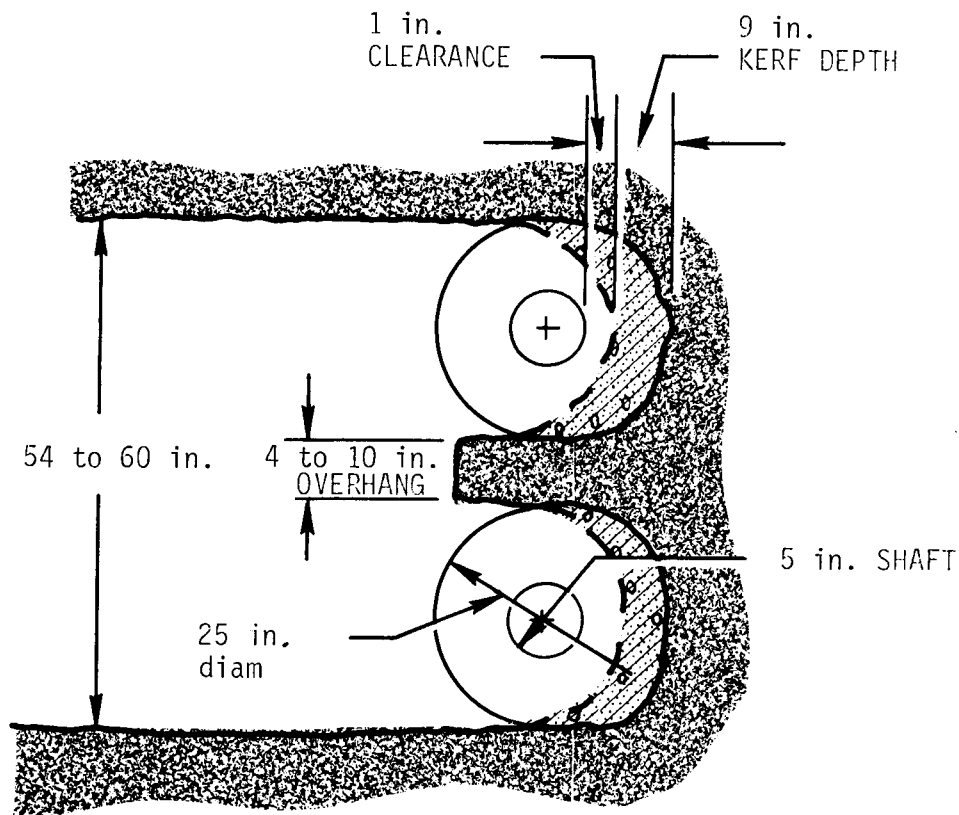


FIGURE C-1. - Test screw selection.

To minimize the percentage of coal that is cut in the kerf, a 1-in. wide kerf dimension was selected. This decision was based on the smallest bit design and screw flight thickness compatible with a competent structural design. To ensure that the core material left between kerfs could indeed be broken out, the screw lead was limited to 6 in. This combination meant that one-sixth of the coal would be cut inefficiently in the kerf; the rest would be broken out.

The screw rotational speeds to be tested were selected to match those expected in the ultimate areas of application. It was decided that the production screws would probably be double flight, 12-in. lead, still delivering one 1-in. kerf every 6 in. With the cutterhead capable of advancing 1 ft/revolution, rotational speeds of 25 rpm for longwall and 2 rpm for blind heading were estimated. The screw drive train was designed to accommodate this speed range.

C.2 Hardware Description

The test equipment was designed primarily as a data-gathering machine. Since the test goal was to acquire information on the SAM cutting process, the data acquisition system

comprises the central unit which all other subsystems must support. In addition, the test bed must allow adequate freedom of motion to permit testing the cutterhead in all configurations of interest.

The following items make up the SAM test hardware, shown in Figure C-2.

- a. Instrumentation package
- b. Screw cutterhead
- c. Drive train
- d. Trolley
- e. Track system
- f. Winch system
- g. Hydraulic supply
- h. Mucking system.

Basically, the instrumented, hydraulically-driven screw is mounted on a wheeled trolley which is pulled on tracks along the coal face during cutting tests. The following subsections briefly describe the test equipment. Arrangement drawings of key assemblies are shown in Appendix F.

C.2.1 Instrumentation Package

The phenomena measured and the means available for measurement are listed in Table C-1.

Because SAM was tested in an 8-ft thick coal seam, the screw was mounted on an arm which could pivot to allow testing at three different elevations in the seam. Commercial strain-gaged clevis pins (shown in Figure C-3) supported the screw shaft bearings from the arm; therefore, the reactions measured by the clevis pins were resolved into horizontal and vertical components by accounting for the inclination of the arm and clevis pins. Note also that the cutting reactions parallel and perpendicular to the support arm were not measured directly by the clevis pins but were calculated through sums and differences.

The force parallel to the direction of travel could be measured in three independent ways. A wire rope winch, shown in Figure C-4, was mounted on the test trolley to assist or retard screw translation. The 3/8-in. rope was reeved from the winch,



FIGURE C-2. - SAM test equipment.

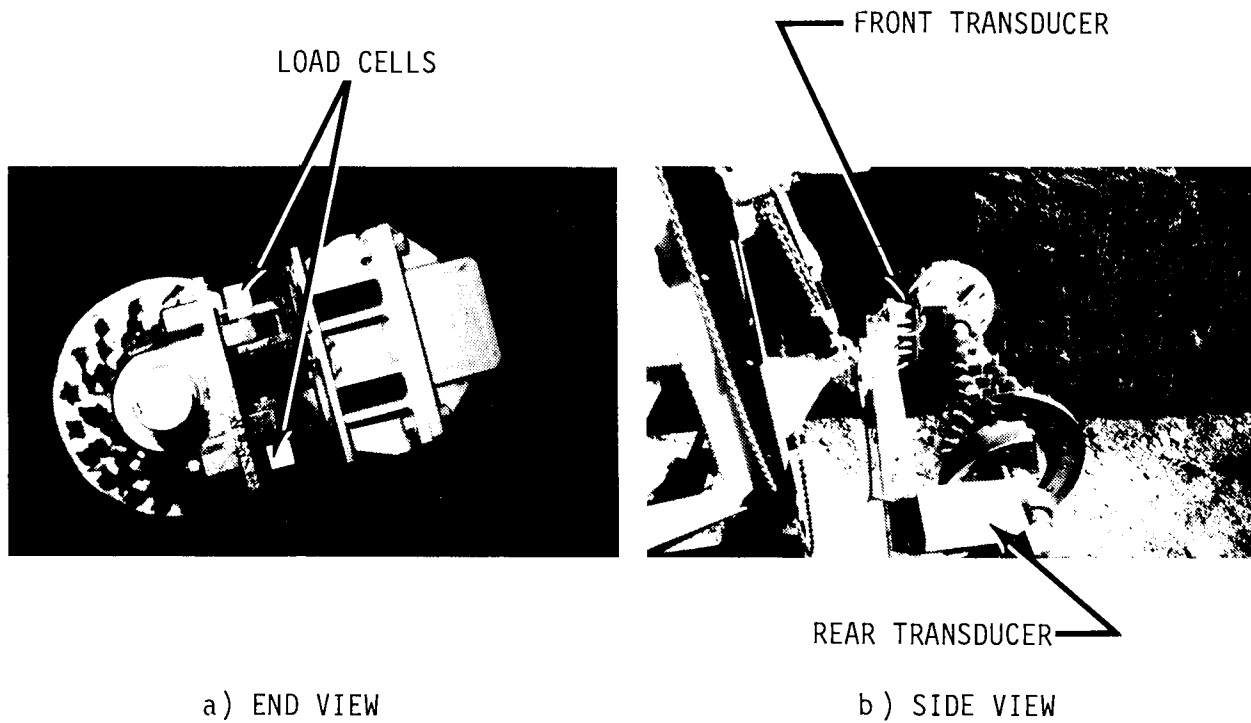


FIGURE C-3. - Bearing reaction transducers.

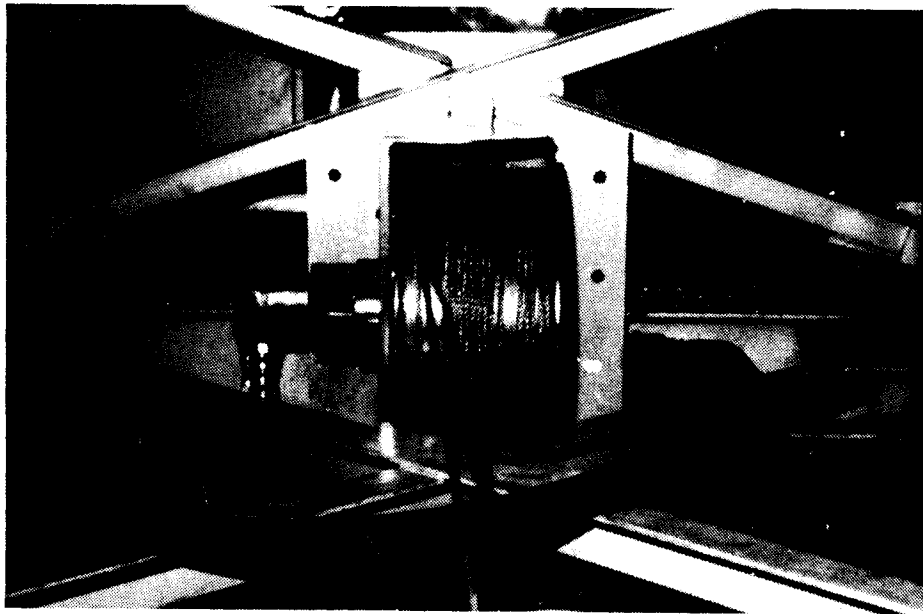


FIGURE C-4. - Haulage winch.

TABLE C-1. - Data measurement

Measured value	Quantity	Measurement scheme	
		Primary	Backup
1. Screw bearing reactions	4	Strain-gaged clevis pins	
2. Drive torque	1	Strain-gaged clevis pin	Pressure gauge
	1	Pressure transducer	
3. Tugger force	1	Strain-gaged stud	Pressure gauge, Strain gaged clevis pins
4. Screw speed	1	Noncontact digital tachometer	Stopwatch, Tape recorder
5. Advance distance	1	Microswitch (counting revolutions)	Tape measure
6. Coal excavated		Collect and weigh	
7. Size analysis		Screen	

around a sheave mounted at the end of the tracks, and back to the trolley where it was anchored with the use of a strain-gaged stud. Sheaves were available for both ends of the track system, so that the winch could either assist or retard the self-advancing effort of the SAM screw. Tugger force could be monitored by the following:

- a. A strain-gaged stud was available to be connected to a digital panel meter.
- b. The winch motor hydraulic pressure indicated pull force because the drum was sized to hold all required rope on one wrap; therefore, with constant radius, pressure was proportional to force.

- c. By rotating the strain-gaged clevis pins that support the screw 90 deg to their normal direction, they could be used to measure forces parallel, not perpendicular, to the face. With the trolley in motion, these readings indicate friction in the trolley/track system. With the trolley stalled, these readings are a check on the winch pull figures. Each of these clevis pins was connected to a digital panel meter.

The torque required to rotate the screw during cutting operations was measured in two separate ways (see Figure C-5). A differential pressure transducer installed in the lines to the hydraulic drive motor indicated hydraulic power required; instantaneous pressure spikes could be seen on a digital panel meter and on pressure gauges in the system. The drive train for the SAM cutterhead included a speed reducer to bring the hydraulic motor shaft speed down to the screw shaft speed of 2 to 25 rpm. The torque reaction of this reducer was transmitted to the structure through a strain-gaged clevis pin, thereby providing another indication of drive torque.

The difference in the torque determined from the hydraulic pressures and that calculated from the torque reaction clevis pin was due to the drive train inertia. The hydraulic motor was selected partly on the basis that it could be equipped with a through shaft to allow mounting a flywheel on it. When the screw encountered a hard spot, the rotary inertia and kinetic energy of the flywheel augmented the hydraulic horsepower available; in this way the peak load requirements on the power supply were reduced. The flywheel shown in Figure C-5 was designed in a two-piece construction, so that the effect of the inertia - zero, half, or full - on pressure spikes in the fluid lines might be investigated. When the complete flywheel was installed and the screw rpm set at 25 rpm, the drive rotary inertia was equal to that of an electric motor drive, high in inertia, that would probably be utilized in a production SAM. Although it was realized that a more expensive FM tape or strip chart recorder data recording system would have provided better design data, we were optimistic that we would still be able to discern a difference in pressure spike amplitude and frequency with the digital panel meter arrangement.

Because the SAM cutterhead is a constant pitch rigid screw, there is a simple relationship between screw rotation and translation: for every revolution, the screw advances 6 in. along the face. A noncontact proximity type of tachometer was aligned to sense screw rotation off a shaft-mounted 60-tooth gear. (See Figure C-6). At the same time, a microswitch was arranged to trip once every revolution. The microswitch was connected to an electrical counter which not only indicated position along the face,

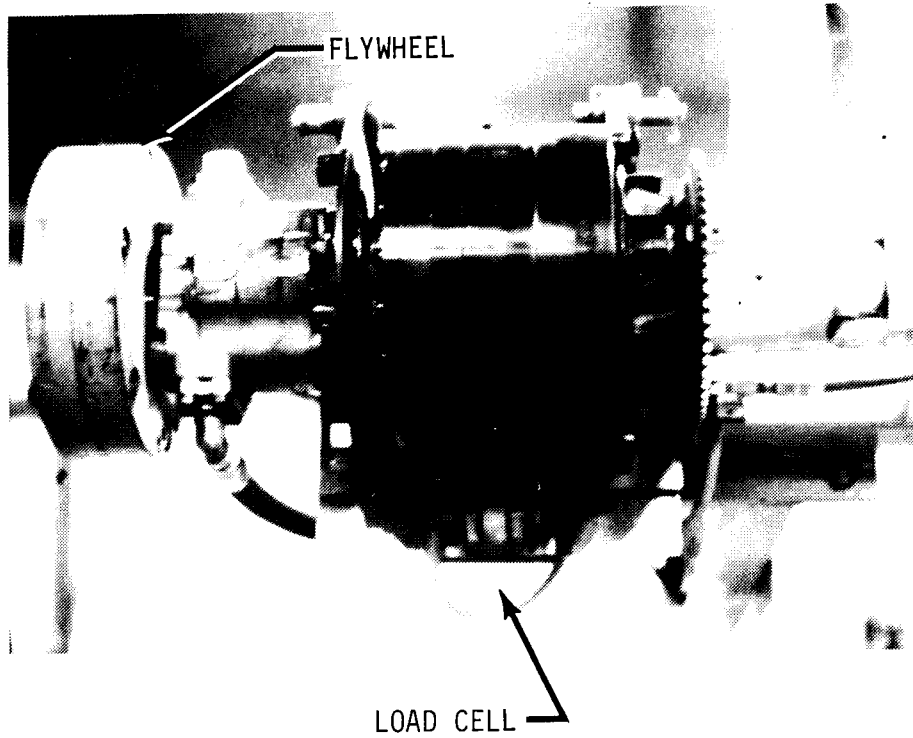


FIGURE C-5. - Instrumented drive train.

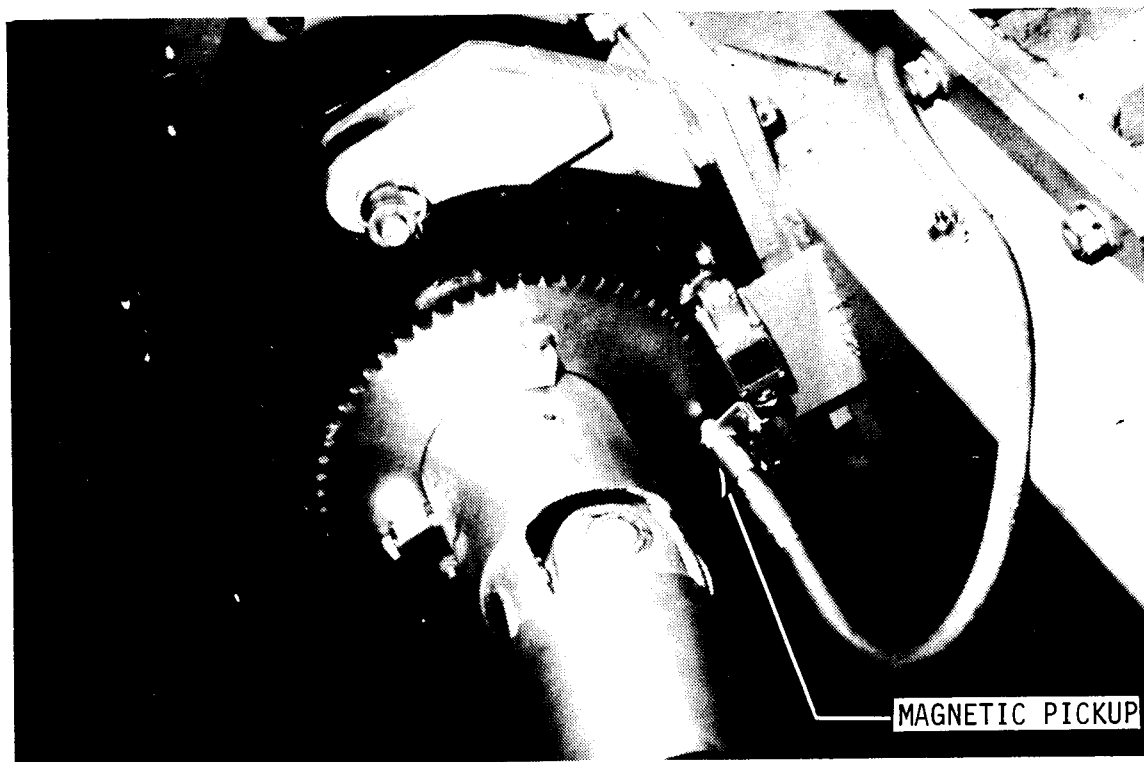


FIGURE C-6. - Speed measurement.

but, when used in conjunction with a stopwatch, served as a check on the tachometer. The data displayed on the digital panel meters were recorded verbally on a hand-held tape recorder. This recorder also recorded a buzzer that was actuated by the microswitch once per revolution. Timing the beeps on the cassette tapes has also been used as a speed indicator.

The cooperating mine offered to perform a size analysis of the cuttings generated during the cutting tests. Due to scheduling constraints on the program, size analysis was not performed.

C.2.2 Screw Cutterhead

The SAM screw has been designed to simulate a full-scale longwall screw, with two primary differences:

- a. The production screw will have two 12-in. lead flights whereas the test screw has one 6-in. lead flight.
- b. The production screw will have many fewer bits than the test screw which must provide versatility in bit mounting for proper investigation.

The test screw is tapered, starting with a 7-in. diam and building up to 25 in. The 9-in. deep kerf was cut with 65 bits nominally set at a radius $1/8$ in. greater than the preceding bit; the first several bits take $3/8$ - and $1/4$ -in. bits, principally to shorten the screw. The screw shaft is 5 in. in diameter, leaving 1 in. between the bottom of the kerf and the shaft.

The SAM screw was configured so that each bit in sequence took a predetermined $1/8$ in. cut of coal; by removing every other bit, this depth of cut could be increased to $1/4$ in. Similarly $3/8$ -in. and $1/2$ -in. cuts could be made; the carbide tip itself is $5/8$ in. high. By varying the depth of cut, the optimum value of specific energy was investigated. By increasing the cut as large as possible and still being able to purge the chips from the slot, production could be maximized while dust was minimized.

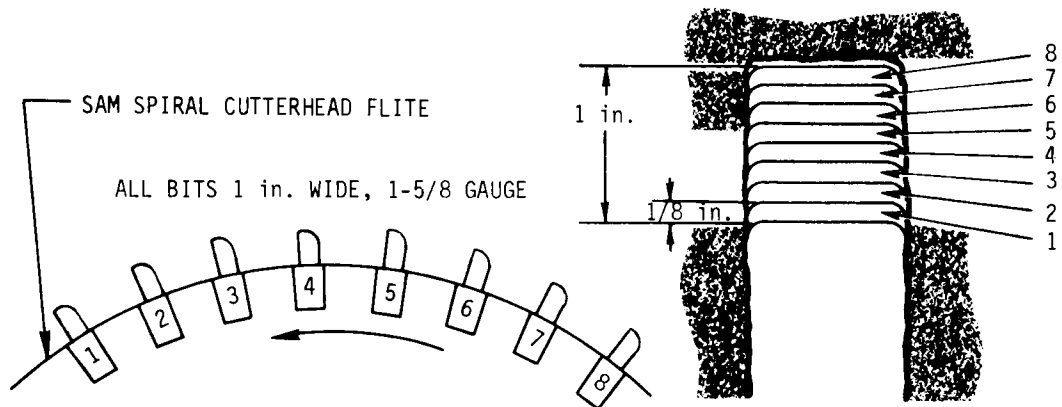
The kerf width was 1 in., formed by custom carbide bits. Bit blocks were $7/8$ -in. wide with $1/2 \times 1$ in. oblong holes for bit shanks; $3/8$ diam roll pins retained the bits. The bit blocks were machined to $1/2$ -in. width where possible and spaced around the periphery of the helix to provide a path for chips to flow from the space between bits back along the flight toward the shaft. The block positions also took into account the torque fluctuation due to uneven numbers of bits cutting at different times.

On a typical boom-type coal cutting machine used in the conventional mining system, a 6-in. wide kerf might be cut by 13 bit locations equally spaced across the kerf width; this arrangement would be designated as "13 line." Provisions were made to test the cutting of the 1-in. wide SAM spiral kerf with both a one and three line configuration. With all installed bits 1-in. wide, a single line arrangement was formed. Installation of narrower 1/2-in. wide bits in alternate bit blocks simulated a three line configuration because the 1-in. wide bits cut out both corners of the deepening slot simultaneously while the 1/2-in. bits cut out the center. Cutting both corners with the same carbide served to minimize the number of required bit blocks and to reduce side loads on the bits and thin-walled bit blocks. It was anticipated that the three line configuration would prove the most efficient due to the free faces formed at the base of the kerf during cutting operations. As shown in Figure C-7, the gage of the 1-in. bits was 1-5/8 in. whereas the 1/2-in. wide bits available to alternate with the wide ones had 1-3/4 in. gage. This difference allowed a 1/2-in. bit to cut clearance to a certain depth of kerf so that the following 1-in. bit (with its shoulder at a 1/8-in. greater radius) cut to the same depth as its tip.

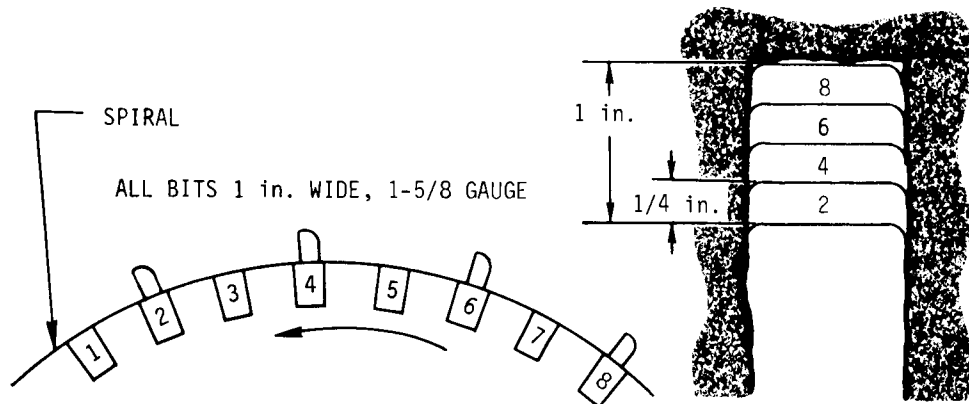
Three sets of 1-in. wide bits were fabricated, each with a different skew (or side rake) angle - 0 deg, 7 deg, 12 deg. It was anticipated that the larger the skew angle, the more the self-advancing tendency. The average helix angle for all 65 bits on the screw is 7 deg; keeping in mind the 5 deg clearance angle on each side of the chisel bit, 12 deg was considered to be the maximum skew angle to retain a competent edge on the tungsten carbide insert. Calculations indicated that due to friction between the coal and the bit carbide, the skewed cutting reaction itself could not entirely provide the forward self-advancing force; therefore, bearing of the screw flights against the coal, the splitter reaction, or an external tugger force had to provide some of the advancing tendency.

The 5-1/2 revolutions of screw that hold bit blocks were formed from 1/2-in. mild steel; the last of the 6-1/2 screw turns was constructed of 7/8-in. plate. The greater strength was required to support the splitters which mount to the last revolution to break out the weakened coal between kerfs.

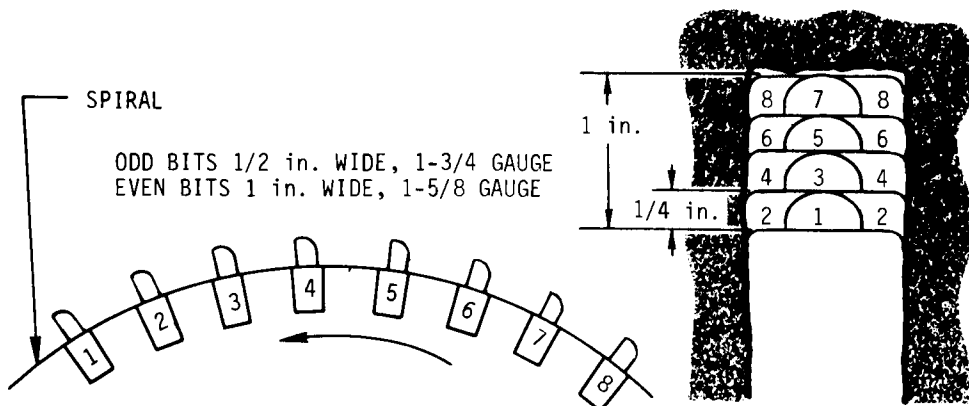
Two arrangements of splitter, shown in Figure C-8, were designed for this purpose. The knife-edge wedge attached to the last revolution of the screw and formed a knife-like interference wedge at the base of the kerf, forcing a shear fracture of the coal rearward while propelling the screw forward. The blunt wedge was designed to enter the kerf near the screw shaft, putting the weakened coal cantilever into bending, rather than shear. A third splitter arrangement, utilizing cutter bits to saw out the



a) SINGLE LINE, 1/8 in. DEPTH OF CUT

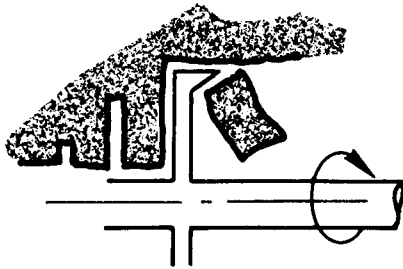


b) SINGLE LINE, 1/4 in. DEPTH OF CUT

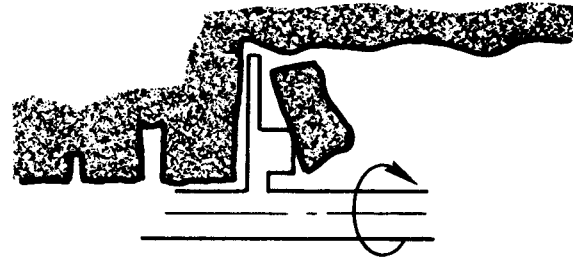


c) THREE LINE, 1/4 in. DEPTH OF CUT

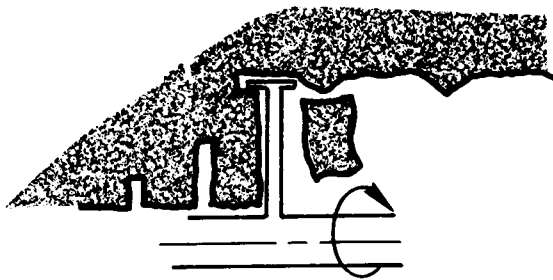
FIGURE C-7. - Bit lacing patterns, 1 and 3 line.



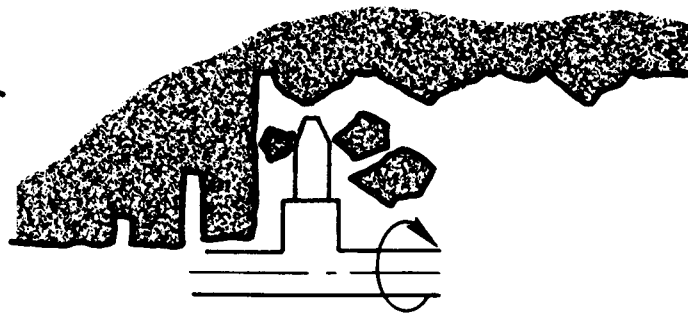
a) KNIFE EDGE WEDGE
DESIGNED, FABRICATED
AND TESTED



b) BLUNT WEDGE DESIGNED AND
FABRICATED ONLY



c) TEE HEAD BITS FABRICATED
AND TESTED



d) LONGWALL BITS DESIGNED
ONLY

FIGURE C-8. - Optional splitter designs.

coal between kerfs, was welded to the splitter flight in the field and tested. The longwall bit splitter was not pursued due to time and money considerations.

The variety of splitter options available also allowed mixing designs as necessary to obtain the optimum performance. Of particular interest is the use of the tee head cutter bits to prenotch the cored material so that a wedge splitter can easily break it off. Note that the four splitters shown in Figure C-8 cover shearing, bending, sawing and busting the core.

C.2.3 Drive Train

The screw shaft was coupled to the speed reducer and hydraulic motor through a heavy duty, low speed universal joint. The driveline offset, provided by this arrangement shown in Figure C-9, allowed running cutting tests without a splitter mounted on the screw, so that the behavior of the kerf cutting bits could be investigated independently from the splitter.

The speed reducer was a compact Fairfield Torque Hub* with a 45:1 ratio used primarily in low-speed vehicular wheel drives. The small diameter minimized the universal joint angle and shaft length required to obtain the driveline offset.

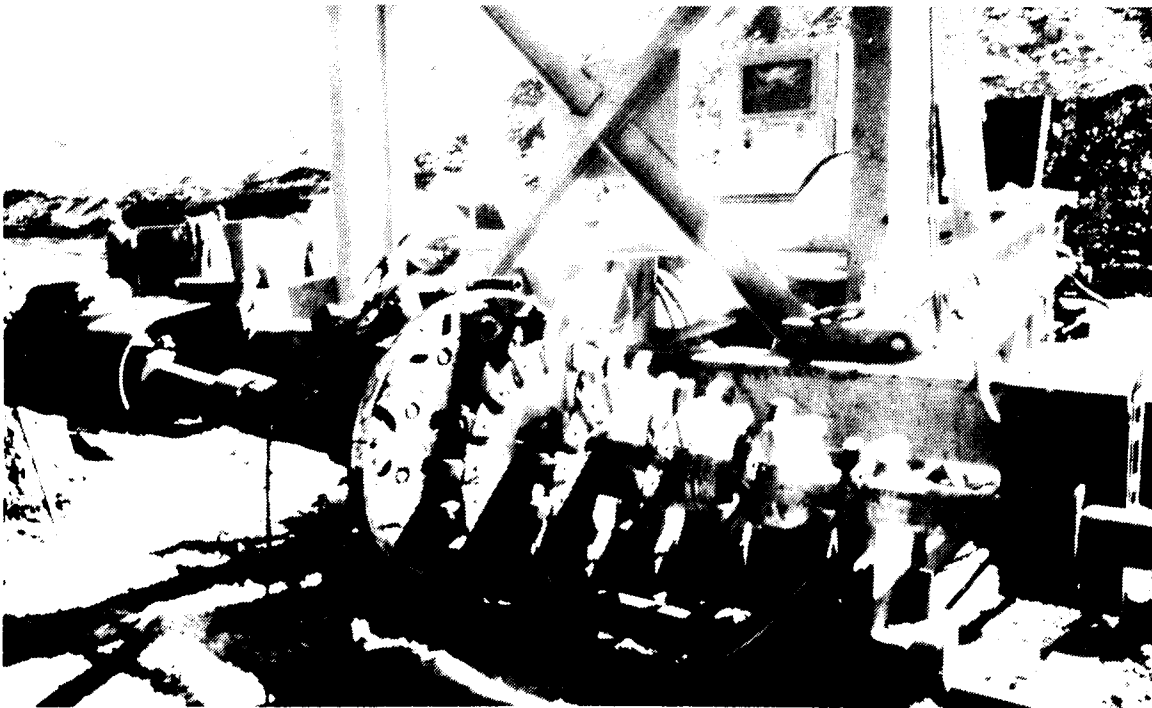


FIGURE C-9. - Drive train.

*The use of trade names is not intended as an endorsement of the product.

Mounted to the reducer was a rugged gerotor style hydraulic motor manufactured by HPI.* A 14-in. solid steel flywheel was mounted to the through-shaft of the motor with the use of a Dodge Taperlock Hub.*

C.2.4 Test Trolley

The support trolley, shown in Figure C-10, was designed to facilitate field testing wherever possible. The screw and drive train were mounted on an arm that could be bolted into alignment in three vertical locations, enabling the full seam height to be used for testing. If desired, intermediate positions were also available.

The trolley is comprised of an upper and lower section bolted together. The upper section could slide forward 36 in., allowing five tests spaced at 9 in. horizontally to be made without moving the tracks. An additional bolting alignment was provided to allow six tests with 7-in. kerfs, should the need have arisen to decrease kerf depth due to unexpectedly high power requirements. The hydraulic unit was located to the rear of the trolley to counterbalance the screw cutting forces; if additional weight proved necessary, space was provided for two ballastable 55-gal drums next to the power unit.

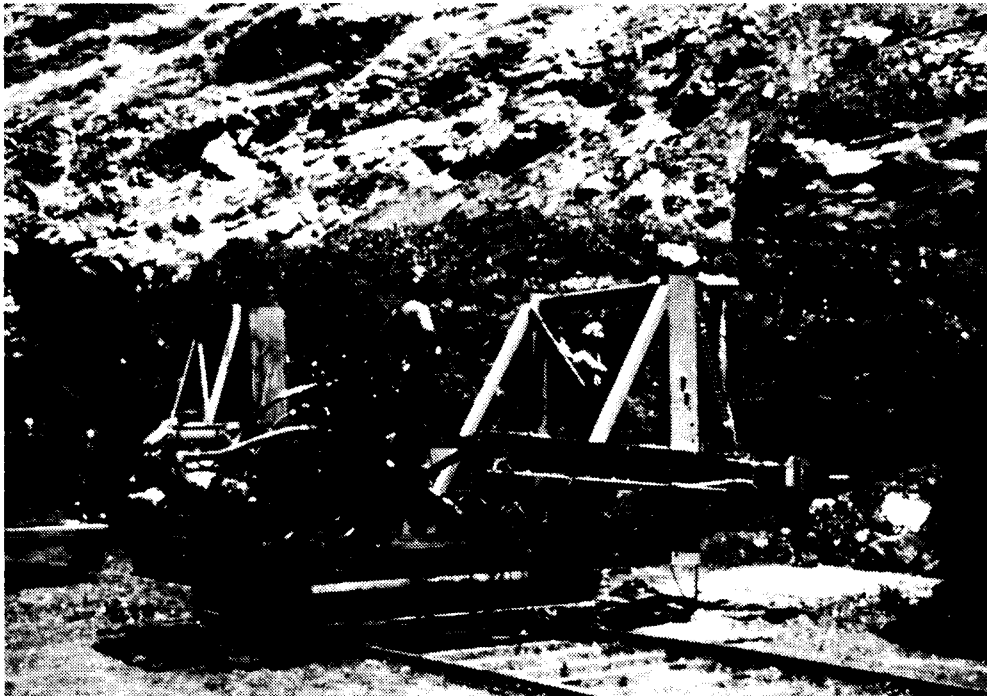


FIGURE C-10. - Test trolley.

*The use of trade names is not intended as an endorsement of the product.

The trolley was outfitted with wheels on each corner to guide the unit down the tracks during tests; each corner had a 5-in. wheel for vertical loads, a 3-in. wheel for horizontal loads, and a 1-7/8-in. wheel to prevent uplift.

C.2.5 Track System

The 45-ft long track system was composed of three 15-ft sections of 60-lb crane rail on steel ties; the 6-ft track gauge provided a wide, stable stance to resist operating loads. The ties were designed to be supported on 3-in. wooden wedges to allow leveling on uneven test site terrain. Tracks were secured with twelve 1-1/4-in. diam resin bolts, each 5 ft long; considerable tolerance to horizontal misalignment of the resin bolt pattern was designed into the hold-down scheme. Two sets of resin bolt holes were made in the ties to permit sliding the tracks forward without drilling a new set of resin bolt holes with a rock drill.

C.2.6 Winch System

A hydraulic winch was mounted on the trolley to provide the tugger force to move the unit along the tracks. The large diameter drum held 100 ft of 3/8-in. diam wire rope, so that hydraulic pressure remained at all times proportional to pull force. The Charlynn* motor provided 1000 lb of pull at 1500 lb/in.²; reeving the rope around a sheave at either end of the track system doubled the effective pull to 2000 lb.

The screw cutterhead itself applied a self-advancing force to the trolley but, because it is off-center, also cocked the trolley on the tracks. Because the trolley arrangement could not be expected to simulate the operating drag of the various support vehicles, as yet undesignated, we chose to cancel out the friction inherent in the trolley system. In this way, the screw forces, without the peculiar effects of the test trolley, could be added to whatever production arrangement was conceived. By reeving the wire rope so that the winch pulled the trolley, cocking of the trolley was eliminated; a higher pull force would then serve to center the screw flights in the kerf providing determination of advancing force generated by the screw and the minimum value of screw torque. By reeving the wire rope so that the winch retarded trolley travel, the structural strength of the screw and coal and mechanical aspects of the drive system could be investigated.

C.2.7 Hydraulic Power Supply

A diesel powered hydraulic supply, shown in Figure C-11, was mounted on the trolley to provide power to the screw cutterhead

*The use of trade names is not intended as an endorsement of the product.

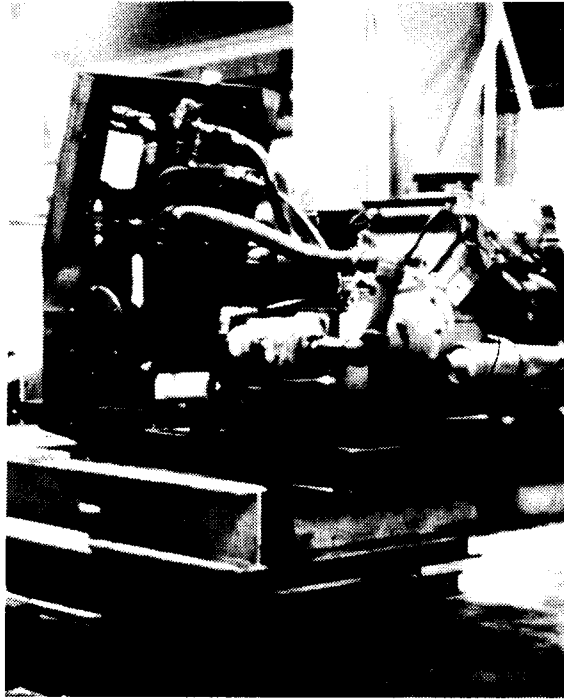


FIGURE C-11. - Diesel powered hydraulic power supply.

and the winch. Selection of a diesel engine as the prime mover allowed us to eliminate our reliance on the test mine for electrical power requirements. The engine was a 40-hp Bernard* diesel, derated slightly due to the 7000-ft elevation at the test site; the calculated power required for SAM was 20 hp.

The hydraulic power system was designed to permit variation of the screw rotational speed from 2 to 25 rpm. The ability of the SAM screw to excavate coal is dependent on speed because the chip clearance capability may vary with centrifugal force and the rotational kinetic energy increases with speed.

A "piggyback" pump arrangement supplied 35 gal/min to the screw drive motor and 4 gal/min to the winch motor. The Tyrone* gear pumps were rated at 3000 lb/in.² continuous while operating pressures were 1400 and 300 lb/in.², for the screw and winch, respectively. Bleed-off flow control, although it provided less accurate speed control, was selected for two important reasons:

- a. The pumps operated at only the pressure required to overcome their loads, minimizing the horsepower required from the prime mover and the heat generated in the hydraulic system during tests with slow screw rotational speed.

- b. The pressure relief valves in the system could be set at *double* the operating load to enable the hydraulic system to supply the cutterhead with peak power requirements during hard cutting conditions of short duration.

Because the cutting tests were all short, the 75 gal reservoir provided adequate oil cooling under all operating conditions.

C.2.8 Mucking System

Provisions were made in the test set up to enable mucking the excavated coal away from the test panel. The trolley and track system was positioned to allow a Melroe Bobcat 310 loader to fit between the tracks and coal face to clean out broken coal that accumulated there (see Figure C-12). The Bobcat was also available to perform numerous jobsite tasks, such as positioning the trolley for each cut.

C.3 Fabrication

The uniqueness of the SAM geometry required that special fabrication techniques be used for the prototype cutterhead and bits. Because the processes may be of interest, they will be

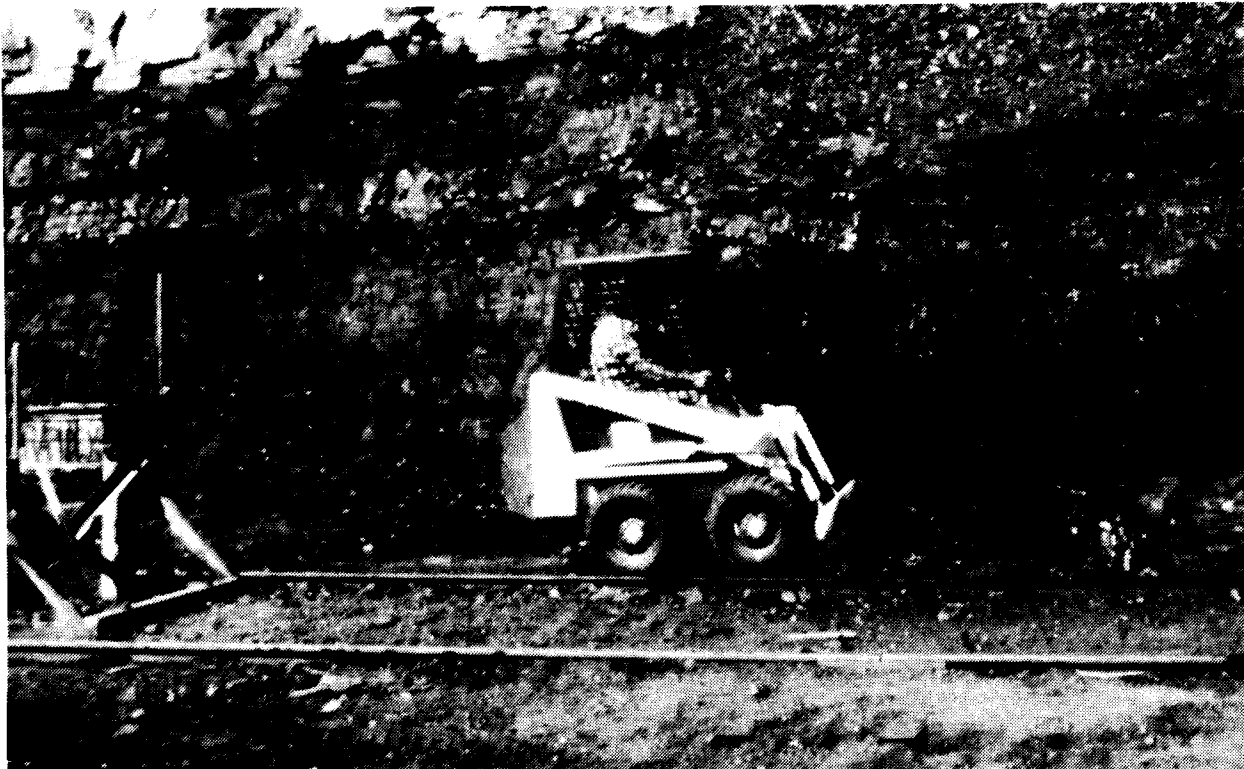


FIGURE C-12. - Bobcat mucker.

discussed briefly below. It should be remembered that the problems encountered in fabrication of the prototype would be handled in a much more efficient fashion in a production setup.

C.3.1 Cutterhead

The tapered screw presented several problems in its manufacture. The critical specifications included the following:

- a. The lead of the helix had to be kept accurate throughout the length and throughout the full diameter of the screw. In particular, the splitter flite was constructed of 7/8-in. plate and had to travel inside the 1-in. kerf without excessive frictional losses.
- b. Each bit block had to be set at a radius 1/8 in. larger than the preceding one. Because the blocks were set at an equal circumferential distance behind the preceding one, the screw is *not* truly conical.
- c. Each bit block had to be set in the flite so that the carbide bit tip would lie on the true helix, the block would be perpendicular to the shaft centerline, the mounting would provide correct bit rake angle, and the bit face would be perpendicular to the helix angle which is different for each different cutting radius. The inaccuracy of single-bit mountings would have caused premature bit wear and biased the data recorded.

The extra care taken in fabricating the prototype was justified because of the totally unproven concept and the data that would be taken with the apparatus. We did not want to needlessly compromise the possible success of the concept through sloppy workmanship. Nor did we want to bias the data unknowingly due to differences between the true geometry and that tested.

Due to the excessive cost of other methods, a welded construction was selected. To ensure the accuracy of the helical flight, a groove was accurately milled into the shaft outside diameter. The screw flite was then wound onto the 4130 shaft and welded in place. The bit block location was then milled in the periphery of the helix, automatically forming the taper. Bit blocks were then carefully positioned with a fixture and welded in position. A typical detail of one screw revolution is shown in Figure C-13. The screw was checked with a template in the shop and selectively straightened where required.

C.3.2 Bits and Blocks

The bits and blocks were designed with the intent of making them as similar to state-of-the-art hardware as possible. Due to the 1-in. wide carbide it was known from the outset that the design would be custom.

The bit design detailed in Figure C-14 is very similar to a commercial chisel bit with $1/2 \times 1$ in. shank. The bit has a 1-in. carbide, $5/8$ in. long, with 5 deg of side clearance, 7 deg top clearance, and a +10 deg rake angle. Bits were made with side-skew angles on the cutting surface of 0, 7, and 12 deg.

The block shown in Figure C-15 incorporates an oblong hole to accept the rounded bit shank. The generous end radius was provided to minimize the stress concentration which was so important to prevent breaking out to the side of the narrow bit block. We expected some side load on the bits when the cutting face was skewed. Where possible, the sides of the block were milled thin to maximize the space for chip passage away from the screw periphery.

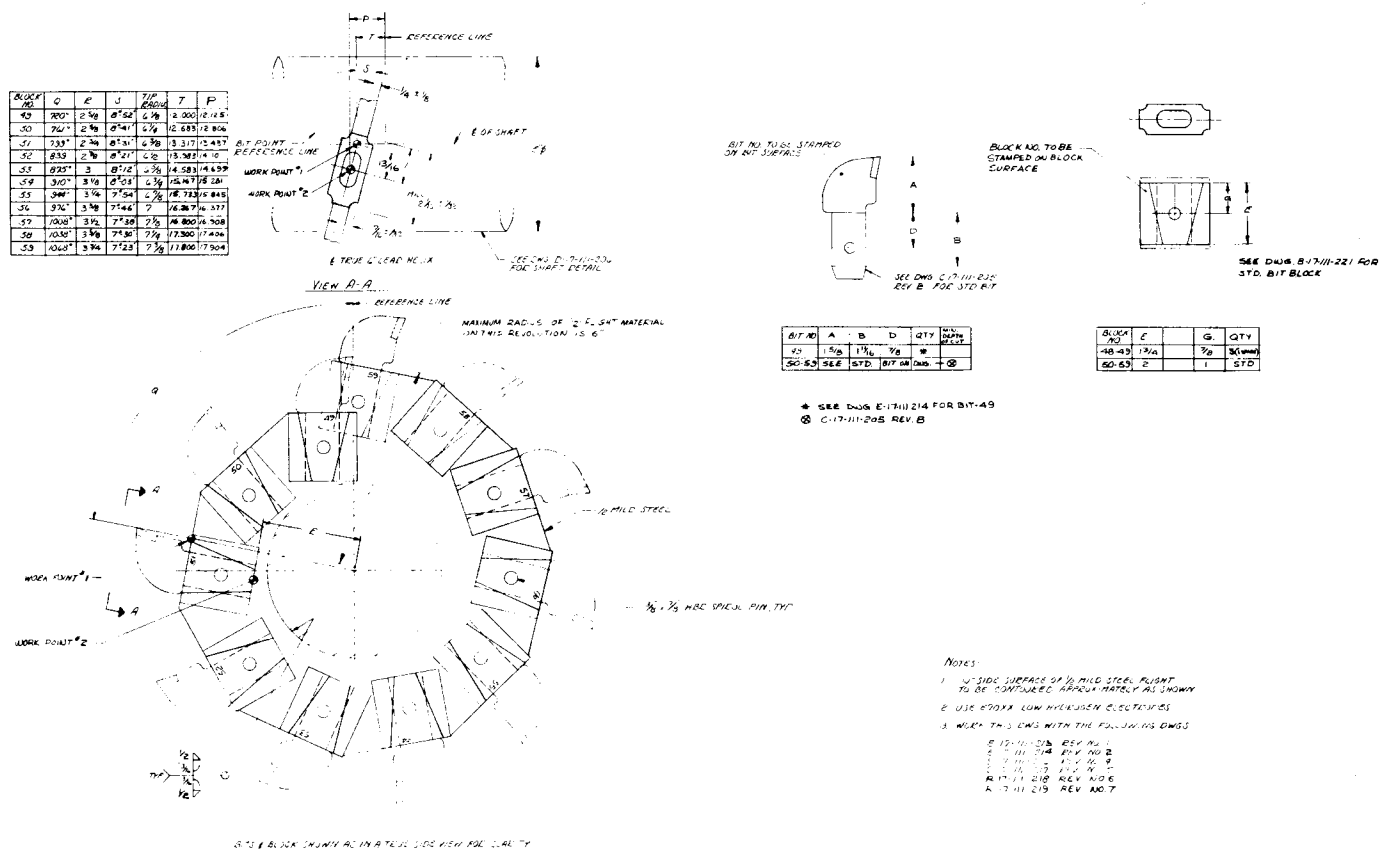


FIGURE C-13. - Typical screw flight detail.

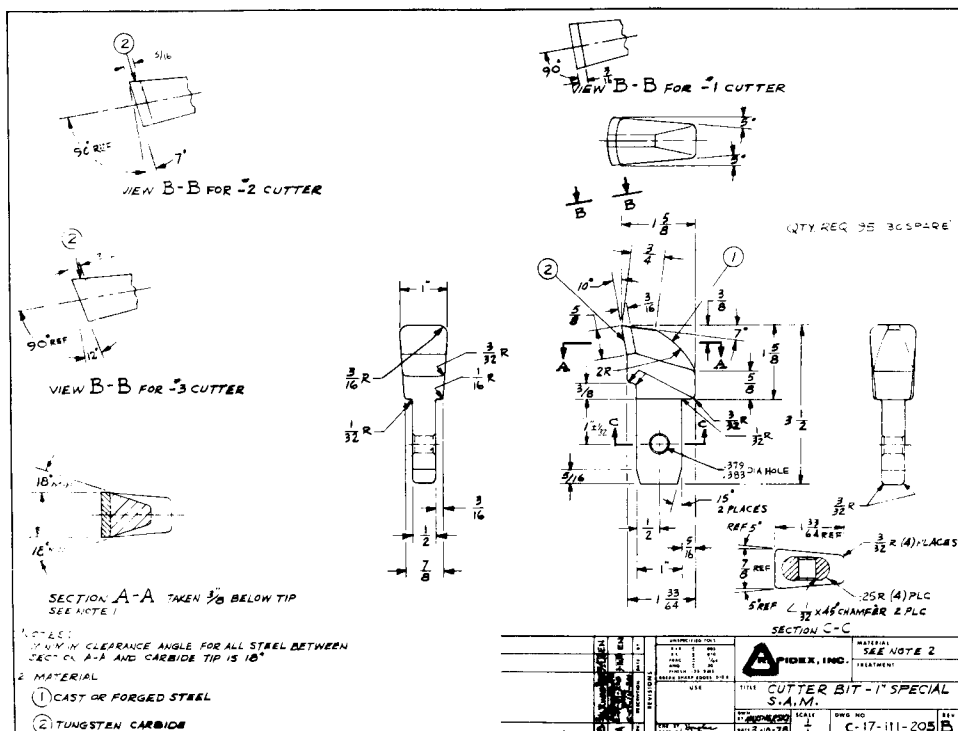


FIGURE C-14. - Bit detail.

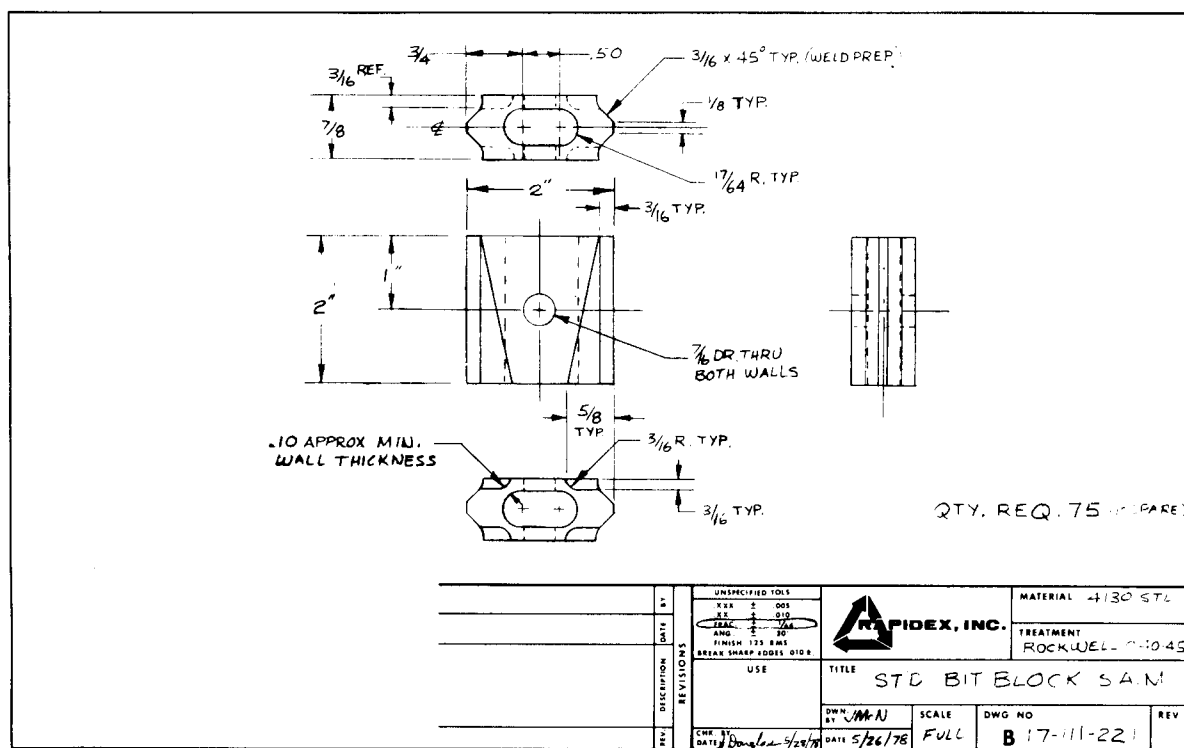


FIGURE C-15. - Block detail.

APPENDIX D

SELF-ADVANCING MINER TEST PLAN

Purpose

The primary purpose of the field tests is to determine if the SAM screw cutterhead concept can indeed excavate coal. By varying the many cutting parameters on the device, any difficulties in the mining process will be minimized. Any additional recommendations for a more successful concept will be noted.

Once it has been determined that the screw cutterhead does indeed function, the test instrumentation will be used to determine what forces and energy requirements are necessary for the SAM concept to mine coal. The intent is to acquire sufficient data to permit the evaluation of the technical and economic feasibility of various mining systems using the SAM geometry. To this end, several parameters peculiar to the SAM concept will be varied to determine which combination provides the most efficient mining arrangement. Although the optimization process will in no way be exhaustive, efforts will be made to give the SAM concept every opportunity to be a success.

Test Parameters

The parameters shown in Table D-1 will be varied throughout the test sequence to optimize the cutting operation. Although a true parametric test sequence is beyond the scope of this contract, the best combination of the options listed above will be sought during the limited number of tests.

Excavation Aids

Should the SAM screw fail to operate or perform up to expectations, there are several secondary variations in the excavation scheme that can be employed:

- a. By changing the direction of screw rotation, clearance of chips from the kerf may be improved.
- b. Reducing the depth of the kerf will provide greater clearance between the split coal of the previous pass and the screw shaft. Chip clearance would be improved and cutting torque would be less also.
- c. A two-piece flywheel will be employed to check the dependence of cutting efficiency on drive train inertia. At 25 rpm the drive inertia with flywheel is equal to that possible with an electric motor prime mover.

- d. If required, additional bits can be installed to widen the kerf, improving chip clearance.

Test Procedure

For each combination of test variables, several measurements will be made, as follows, to investigate the complex behavior of the SAM screw:

- a. The force required to pull the screw into the end of the coal face during the beginning of a pass to allow the screw to engage itself to the face will be measured. Depending on the skew angle of the cutter bits mounted in the screw, a different starting force is required and must be provided by an external source in a production machine.
- b. The buildup of screw rotational drive torque as the screw enters the end of the coal face will be monitored to learn more about the screw cutting process in general.

TABLE D-1. - Variation of test parameters

Parameter	Variation
1. Cutter bit depth of cut	1/8 in., 1/4 in., 3/8 in., 1/2 in.
2. Cutter bit skew angle	0 deg, 7 deg, 12 deg
3. Cutting lines	1, 3
4. Splitter scheme	Knife edge, blunt, cutter bits
5. Screw speed	2 to 25 rpm

- c. During kerf cutting tests without a splitter, the trolley will be pulled forward by the winch to center the screw flite in the kerf. This will minimize the frictional rubbing torque between the flite and the coal, and the pull force so measured, adjusted for the frictional rolling resistance between the trolley and rails, will represent the self-advancing force normally provided by the screw itself. The torque value will permit calculation of the optimum drive horsepower for a production screw.
- d. During kerf cutting tests without a splitter, disconnecting the winch entirely and enabling the screw to pull the trolley along the face will prove the self-advancing concept.
- e. During kerf cutting tests without a splitter, using the winch to pull back on the trolley will permit investigation of the screw cutting behavior when subjected to high support vehicle drag forces. Correlation of drive torque with pullback force will enable us to determine which cutter bit arrangement (and splitter design, when installed) provides the best self-advancing feature. Retarding the advance of the screw will also serve to test the strength of the coal in which we are cutting to determine its ability to resist the advancing forces satisfactorily without fracturing prematurely between kerfs.
- f. The cutter bit combinations that look promising will be duplicated with the different splitter designs to optimize their performance. A full parametric test involving all splitters with all bit arrangements is not possible in this program.

The primary parameters that will be monitored in the field for optimization of design features will be drive torque and pull force. The rotational speed and bearing reactions will be recorded for further analysis following data reduction. The effects of rotary speed and flywheel inertia will be investigated in conjunction with the above tests should time permit.

Test Series

To minimize the inefficient setup time involved in drilling holes and installing rock bolts, we will attempt to perform all of our tests from one hole pattern, usable for two track setups. Assuming an 8-ft coal seam and utilizing the upper portion of the trolley sliding on the bottom, a total of 23 tests can be run with an identical crescent of coal cut out for each test. An additional six passes are available, without an accurate crescent, for debugging purposes. If the coal seam available is not 8 ft high, the available number of test passes is reduced to 15.

The proposed tests include variations in all of the pertinent cutting parameters. To maximize the probability of proving the SAM concept in a very short test program, the order in which the tests are to be conducted has been determined so that those most likely to succeed are performed first. The test series is defined in Table D-2.

Due to the chip relief provided by the center bit for the corner cutting bit in the three line lacing pattern, it is considered "the most likely to succeed" and will be tested first.

In all of the tests the screw rotational speed and the amount of flywheel inertia used will be varied as required to obtain smooth performance. A depth of cut of 1/2 in. may be investigated should it look promising.

Test Schedule

Following the 1-week preparation of the coal face by the cooperating mine, we will require approximately 1 week to align and fix the track system in position. The auxiliary test equipment, rented and purchased, will be acquired and setup.

The test period is scheduled for 1 to 6 weeks' duration. Considering the time required to reposition the trolley, make a cleanup pass along the unsplit but kerfed face, mucking, and instrumentation setup, we anticipate making one test pass per day. Should the tests run smoothly, we may be able to get two tests per day. One test pass itself will take from 2 to 25 min, assuming a 25-ft long face and a screw speed varying from 2 to 25 rpm.

Following the cutter tests, 1 week has been allotted for cleanup and repacking for shipment.

Test Criteria

The data obtained from the field tests will be reduced for analysis of the cutting characteristics of the SAM screw. The following items will be of particular interest:

- a. Specific energy
- b. Cutting horsepower
- c. Bearing reactions
- d. Translational forces
- e. Cuttings size analysis.

TABLE D-2. - Test series

Test No.	Depth of cut	Number of lines	Cutter bit skew angle	Splitter used?
1	1/4 in.	3	0 deg	No
2	1/4 in.	3	0 deg	Knife
3	1/8 in.	1	0 deg	No
4	1/4 in.	1	0 deg	No
5	1/4 in.	Best	7 deg	No
6	1/4 in.	Best	12 deg	No
7	3/8 in.	1	0 deg	No
8	3/8 in.	3	0 deg	No
9	Best	Best	Best	No
10	Best	Best	Best	Knife
11	Best	Best	Best	Blunt
12-23	Replicate as required			

The primary criterion that will be used to judge how efficiently SAM cuts coal in comparison to conventional schemes will be *specific energy*. By weighing the cuttings of particular tests to do and noting the time and horsepower required to excavate the coal, a simple calculation of horsepower per (ton per hour) will be made. Because the screw has been sized primarily on the long-wall application, shearer specific energies will provide the principal basis for comparison.

Cutting horsepower, bearing reactions, and translational forces will be reduced for use in designing full-scale machine concepts based on the SAM principle. Even if specific energy is reasonable, abnormally high reaction forces may compromise the benefits derivable from the cutting scheme.

The cooperating mine has offered to run a *size analysis* on selected cuttings from the SAM tests. In this way we hope to correlate the amount of fines generated with other cutting schemes to determine if airborne dust levels may be reduced with the SAM arrangement. Of particular interest will be the size distribution derived from the kerf-break principle in comparison to shearer or continuous miner cutting which breaks the coal into a finer, but more uniform, product.

APPENDIX E

SIZE ANALYSIS

As discussed earlier, no cuttings' analysis was actually performed in the field. Using data from the literature, though, we have made an attempt to estimate the size consist that can be expected from a SAM. Specifically, USBM Report of Investigations 7687, "A Comparison of Borer, Ripper, and Conventional Mining Products in Illinois No. 6 Seam Coal," contains a rather detailed size analysis of different mining systems. With the use of this report, the SAM cuttings distribution was estimated by making the following assumptions:

- a. The core material of both the borer and SAM consists of cuttings with a distribution similar to the conventional mining system.
- b. All of the kerf is cut into fines for both the borer and SAM.

Because there normally is considerable rubbing action associated with a borer splitter, the SAM core material should actually contain less fines than the borer.

For the purposes of this analysis, the size consist is divided into the following three classifications:

- a. Coarse - 3/8 in. or larger
- b. Fine - 1/4 in. to 28 mesh
- c. Ultrafine - less than 28 mesh.

Using this breakdown, the three systems analyzed in RI 7687 have the consist shown in Table E-1. Although airborne dust was not measured in the referenced study, the percentage of ultrafine material is an indication of the likelihood of airborne dust.

Let us analyze the SAM cutterhead that was field-tested. This screw cut a 1-in. wide kerf and had a 6-in. lead; therefore, the kerf fraction was one-sixth or 17 percent. The core fraction is 83 percent.

Based on the size distribution of the conventional product, the borer core product can be estimated. As shown in Table E-2, the underlined values have been calculated from simple proportions.

TABLE E-1. - RI 7687 size consist.

System	Percentage			
	Coarse	Fine	Ultrafine	Total
Conventional	88	11	1.3	100
Borer	63	33	4.1	100
Ripper	64	34	1.8	100

TABLE E-2. - Borer core size consist.

System		Percentage		
		Coarse	Fine	Total
Conventional		88	11	100
Borer		63	8	72

In a similar fashion, the SAM core product, 83 percent of the total, can be estimated as shown in Table E-3.

The remaining borer product is derived from the kerf fraction (Table E-4), and can be sized by subtracting the core breakdown from the total. Since we have assumed that the SAM kerf product consists of the same ratio material as the borer, its kerf material is calculated similarly as shown in Table E-5. The total estimated product analysis for the field tested cutterhead is then simply the sum of the core and kerf material (Table E-6).

This breakdown is an estimate only for SAM cutterheads (of any diameter) with a kerf fraction of 17 percent. Since we are in the process of selecting the proper kerf width to screw lead for production applications, it is of interest to generalize the size analysis. If we denote the kerf fraction as N and go through analysis identical to the one just described, the following equations are derived to describe the generalized SAM size consist as a function of kerf fraction:

$$\text{Coarse Fraction} = 88 - (88) \cdot N \quad (\text{E-1})$$

$$\text{Fine Fraction} = 11 + (78) \cdot N \quad (\text{E-2})$$

$$\text{Ultra Fine Fraction} = 1.3 + (10.1) \cdot N \quad (\text{E-3})$$

$$\text{Total} = 100 \quad (\text{E-4})$$

TABLE E-3. - SAM core size consist.

System	Percentage			
	Coarse	Fine	Ultrafine	Total
Borer	63	8	0.9	72
SAM	73	9	1.1	83

TABLE E-4. - Borer kerf size consist.

Borer	Percentage			
	Coarse	Fine	Ultrafine	Total
Core	63	8	0.9	72
Kerf	0	25	3.2	28
Total	63	33	4.1	100

TABLE E-5. - SAM kerf size consist.

System	Percentage			
	Coarse	Fine	Ultrafine	Total
Borer	0	25	3.2	28
SAM	0	15	1.9	17

TABLE E-6. - Prototype SAM size consist.

SAM	Percentage			
	Coarse	Fine	Ultrafine	Total
Core	73	9	1.1	83
Kerf	0	15	1.9	17
Total	73	24	3.0	100

Notice that when $N=0$, the size analysis correctly predicts the product of the conventional system, and when $N=0.28$ the borer size distribution is predicted. The results of these generalized relationships are graphed in Figure E-1.

As noted previously, very little torque was required to break out the 5-in. core left with the prototype screw. To optimize the production obtained for the power used, we expect that a production cutterhead will perform well with a 1-in. kerf and a 12-in. lead; the kerf fraction then becomes 8.3 percent. The size consist generated from this design can be taken from the Figure E-1 graph as indicated. A comparison of this production design with state-of-the-art equipment is summarized in Table E-7.

TABLE E-7. - Size consist comparison.

Machine	Percentage			
	Coarse	Fine	Ultrafine	Total
Conventional	88	11	1.3	100
Borer	63	33	4.1	100
Ripper	64	34	1.8	100
SAM, Production	81	17	2.1	100

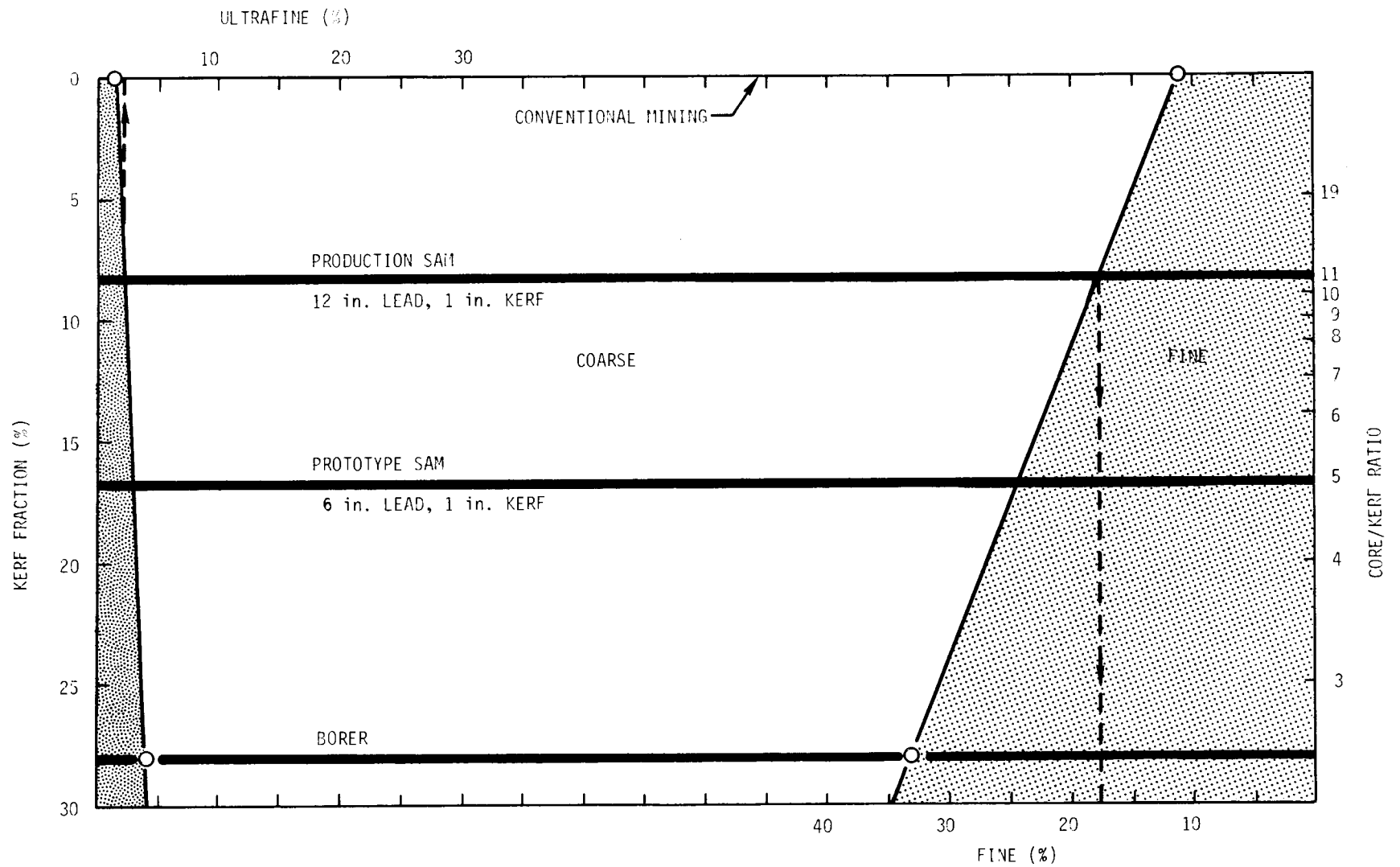
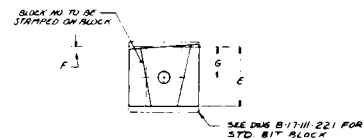
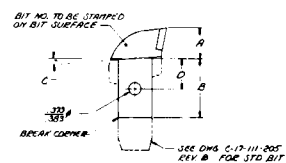
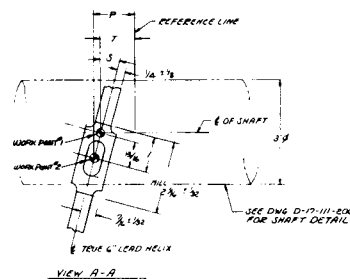


FIGURE E-1. - SAM size consist.

APPENDIX F
ARRANGEMENT DRAWINGS

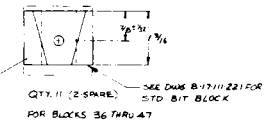
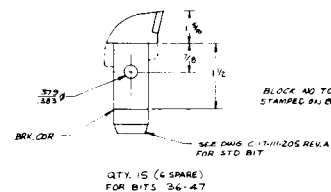
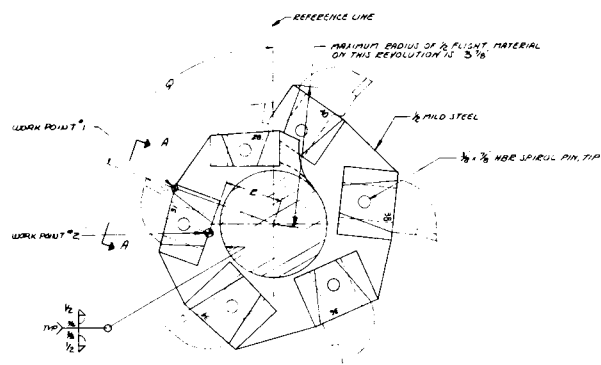
The figures which follow show key arrangement drawings and selected details of the SAM hardware.

FIGURE F-1. - SAM shaft.



BIT NO	A	B	C	D = $\frac{A+B+C}{3}$	QTY	WELL DEPTH IN FEET
28	$\frac{7}{8}$	$\frac{5}{8}$	$6 \times 10'$	$\frac{1}{2}$	2	0
31	$\frac{7}{8}$	$1 \frac{1}{8}$	$6 \times 10'$	$\frac{1}{2}$	3	$\frac{3}{8}$
34	$\frac{7}{8}$	$1 \frac{1}{8}$	$6 \times 10'$	$\frac{1}{2}$	3	$\frac{3}{8}$

BLOCK NO	E	F	G
28	1	4'10"	1/2
31	1 3/8	4'10"	1/2
34	1 3/8	4'10"	3/4



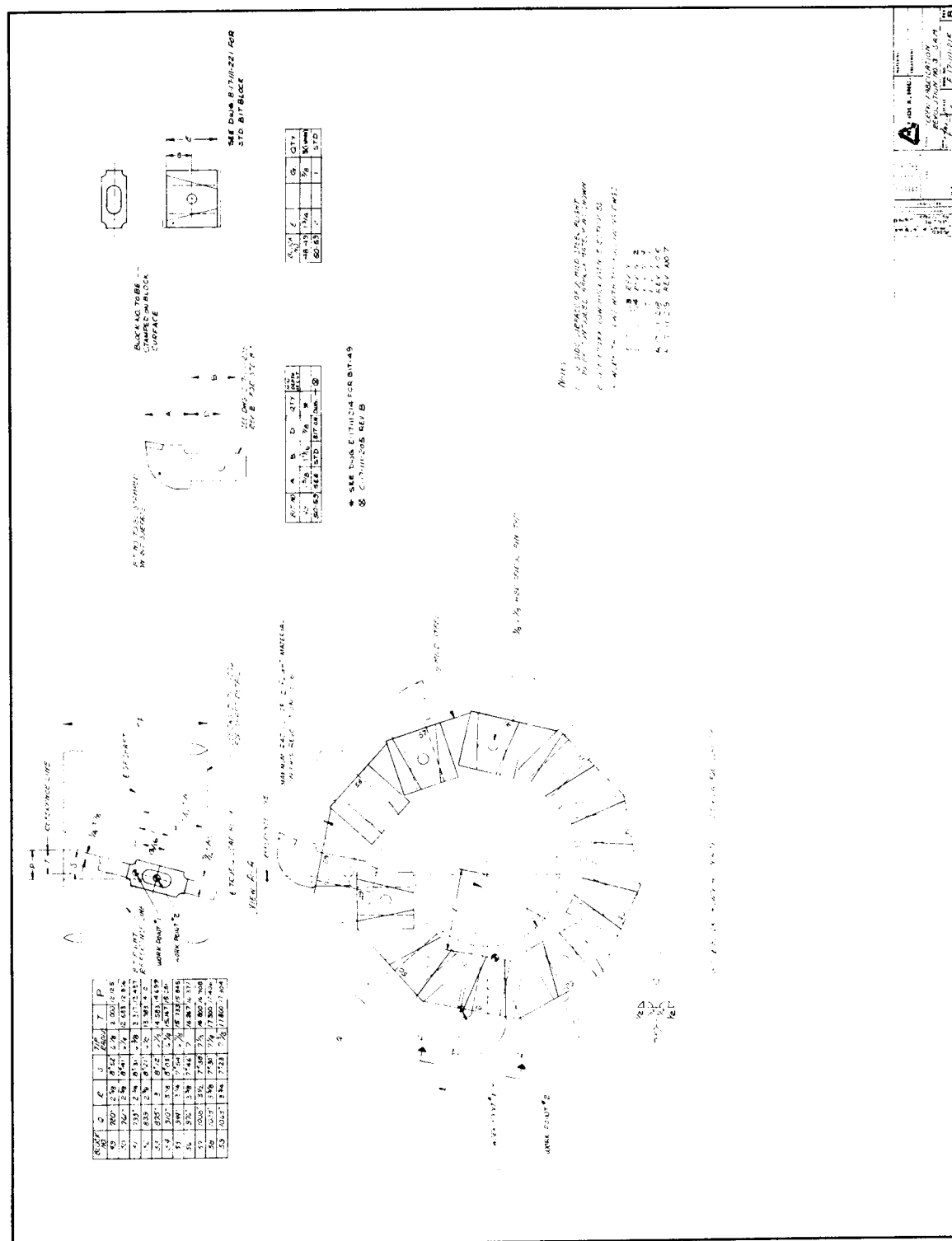
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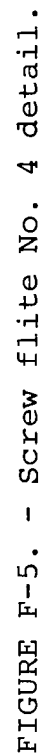
- 1 OUTSIDE SURFACE OF 1/2" MILD STEEL FLIGHT TO BE CONTOURED APPROXIMATELY AS SHOWN.
- 2 USE E70XX LOW HYDROGEN ELECTRODES
- 3 WORK THIS DWG WITH THE FOLLOWING DWGS:

E 17-111-213	REV. No 2
E 17-111-215	REV. No 3
E 17-111-216	REV. No 4
E 17-111-217	REV. No 5
R 17-111-218	REV. No 6
R 17-111-219	REV. No 7

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 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100 101 102 103 104 105 106 107 108 109 110 111 112 113 114 115 116 117 118 119 120 121 122 123 124 125 126 127 128 129 130 131 132 133 134 135 136 137 138 139 140 141 142 143 144 145 146 147 148 149 150 151 152 153 154 155 156 157 158 159 160 161 162 163 164 165 166 167 168 169 170 171 172 173 174 175 176 177 178 179 180 181 182 183 184 185 186 187 188 189 190 191 192 193 194 195 196 197 198 199 200 201 202 203 204 205 206 207 208 209 210 211 212 213 214 215 216 217 218 219 220 221 222 223 224 225 226 227 228 229 230 231 232 233 234 235 236 237 238 239 240 241 242 243 244 245 246 247 248 249 250 251 252 253 254 255 256 257 258 259 260 261 262 263 264 265 266 267 268 269 270 271 272 273 274 275 276 277 278 279 280 281 282 283 284 285 286 287 288 289 290 291 292 293 294 295 296 297 298 299 300 301 302 303 304 305 306 307 308 309 310 311 312 313 314 315 316 317 318 319 320 321 322 323 324 325 326 327 328 329 330 331 332 333 334 335 336 337 338 339 340 341 342 343 344 345 346 347 348 349 350 351 352 353 354 355 356 357 358 359 360 361 362 363 364 365 366 367 368 369 370 371 372 373 374 375 376 377 378 379 380 381 382 383 384 385 386 387 388 389 390 391 392 393 394 395 396 397 398 399 400 401 402 403 404 405 406 407 408 409 410 411 412 413 414 415 416 417 418 419 420 421 422 423 424 425 426 427 428 429 430 431 432 433 434 435 436 437 438 439 440 441 442 443 444 445 446 447 448 449 450 451 452 453 454 455 456 457 458 459 460 461 462 463 464 465 466 467 468 469 470 471 472 473 474 475 476 477 478 479 480 481 482 483 484 485 486 487 488 489 490 491 492 493 494 495 496 497 498 499 500 501 502 503 504 505 506 507 508 509 510 511 512 513 514 515 516 517 518 519 520 521 522 523 524 525 526 527 528 529 530 531 532 533 534 535 536 537 538 539 540 541 542 543 544 545 546 547 548 549 550 551 552 553 554 555 556 557 558 559 560 561 562 563 564 565 566 567 568 569 570 571 572 573 574 575 576 577 578 579 580 581 582 583 584 585 586 587 588 589 590 591 592 593 594 595 596 597 598 599 600 601 602 603 604 605 606 607 608 609 610 611 612 613 614 615 616 617 618 619 620 621 622 623 624 625 626 627 628 629 630 631 632 633 634 635 636 637 638 639 640 641 642 643 644 645 646 647 648 649 650 651 652 653 654 655 656 657 658 659 660 661 662 663 664 665 666 667 668 669 670 671 672 673 674 675 676 677 678 679 680 681 682 683 684 685 686 687 688 689 690 691 692 693 694 695 696 697 698 699 700 701 702 703 704 705 706 707 708 709 710 711 712 713 714 715 716 717 718 719 720 721 722 723 724 725 726 727 728 729 730 731 732 733 734 735 736 737 738 739 740 741 742 743 744 745 746 747 748 749 750 751 752 753 754 755 756 757 758 759 760 761 762 763 764 765 766 767 768 769 770 771 772 773 774 775 776 777 778 779 780 781 782 783 784 785 786 787 788 789 790 791 792 793 794 795 796 797 798 799 800 801 802 803 804 805 806 807 808 809 810 811 812 813 814 815 816 817 818 819 820 821 822 823 824 825 826 827 828 829 830 831 832 833 834 835 836
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FIGURE F-3. - Screw flite No. 2 detail.





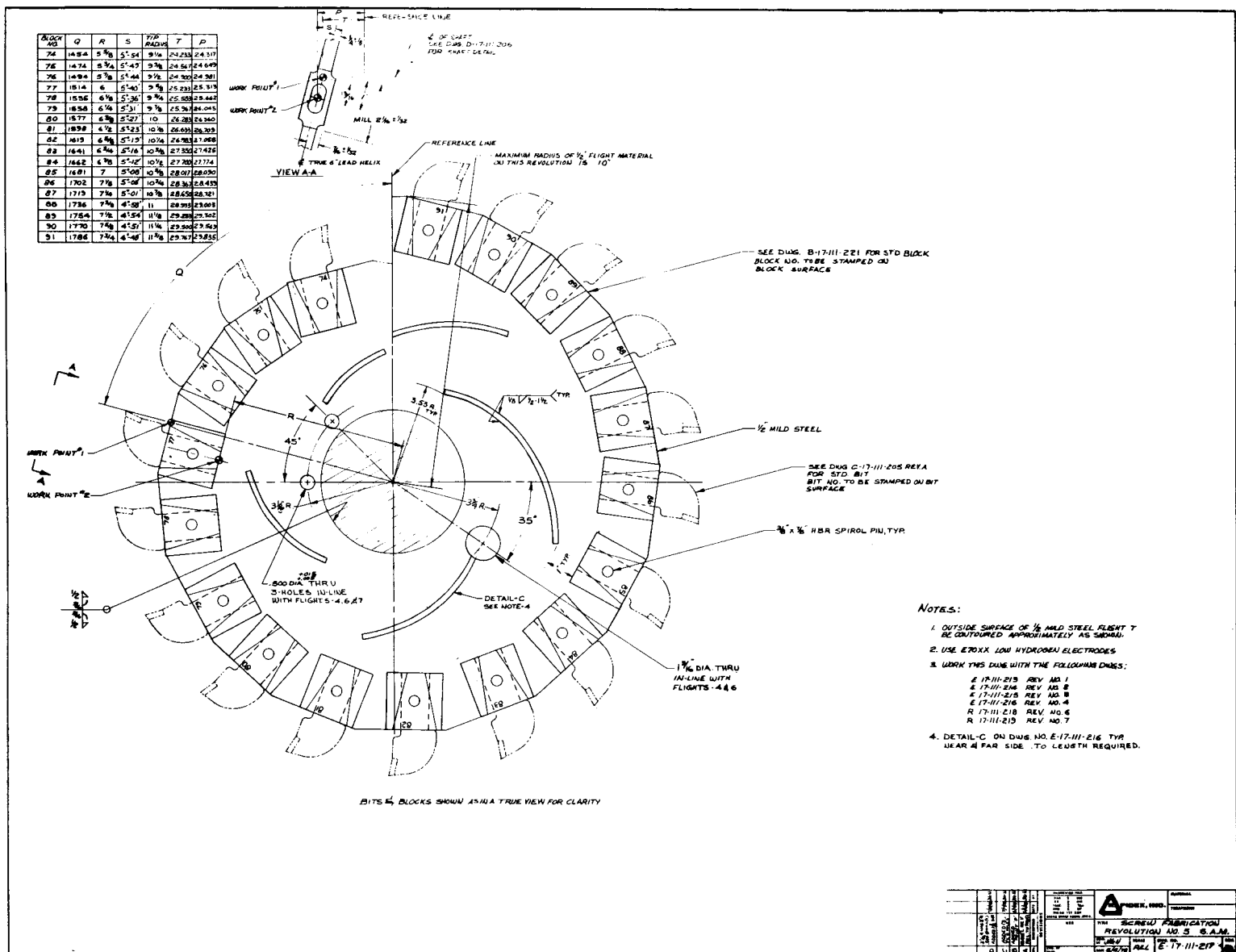


FIGURE F-6. - Screw flite No. 5 detail.

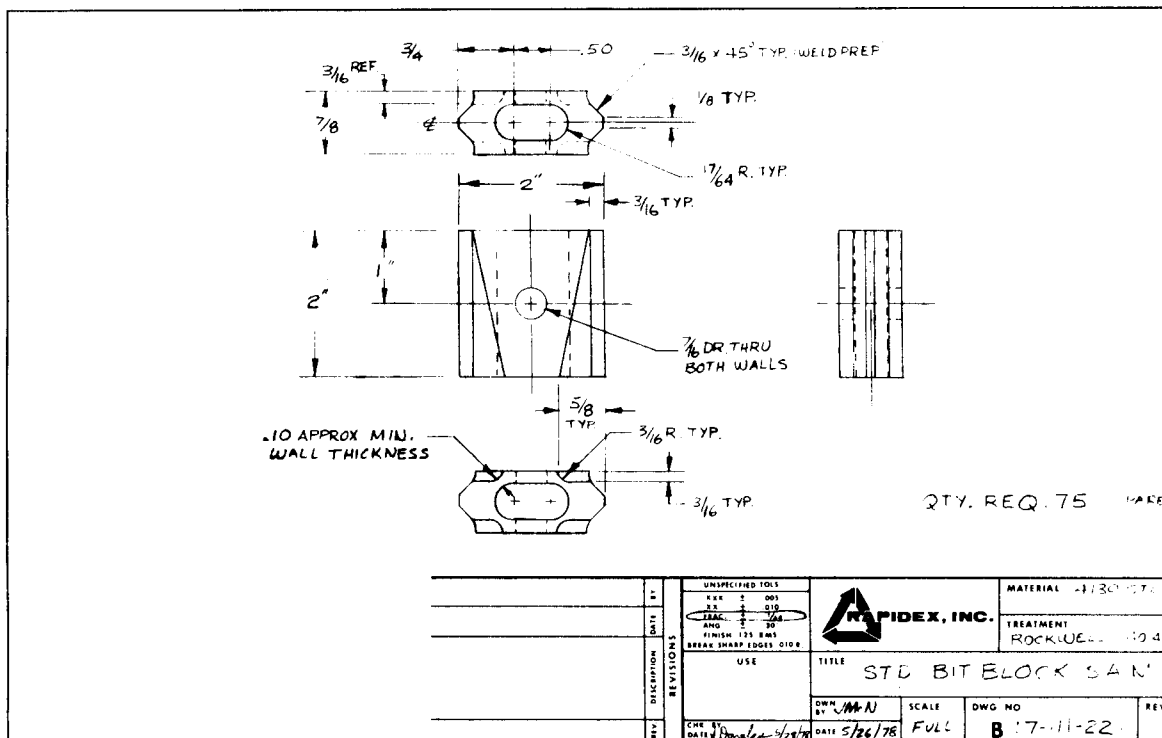


FIGURE F-7. - Bit block detail.

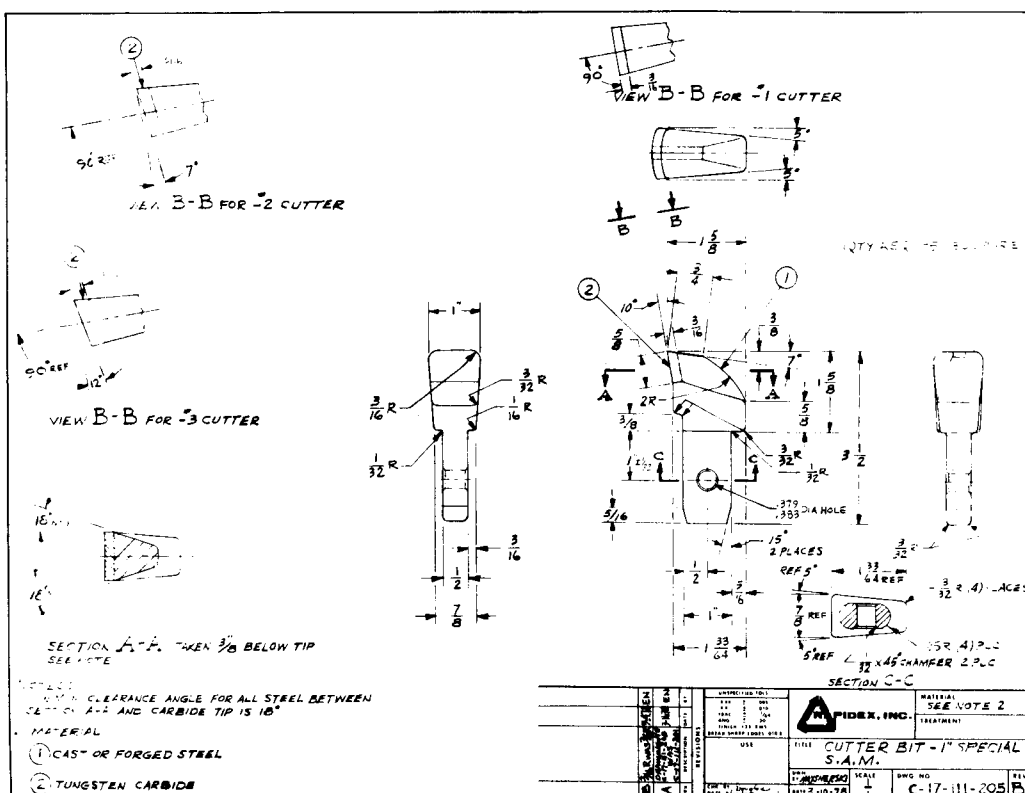


FIGURE F-8. - Custom 1-in. bit

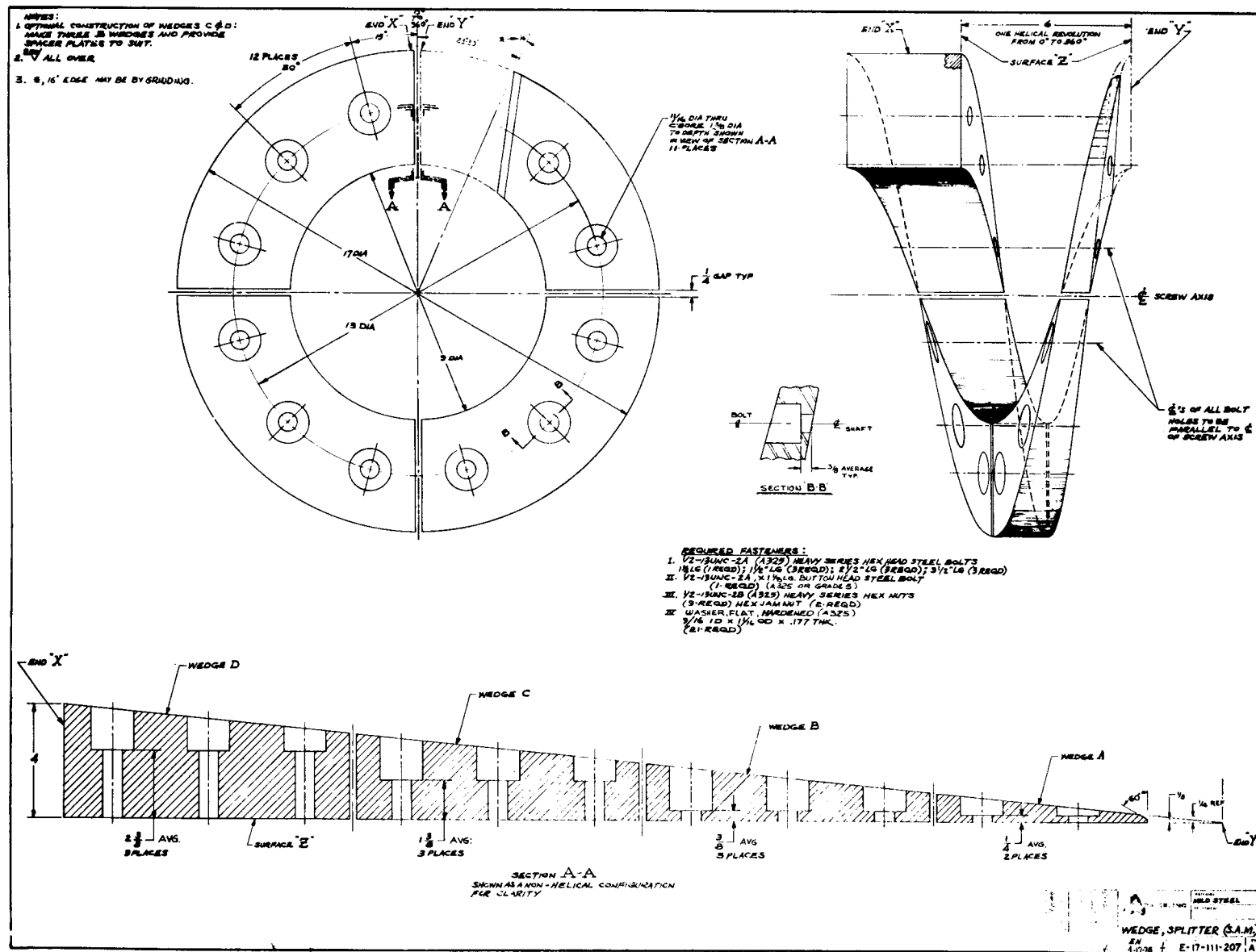


FIGURE F-9. - Blunt wedge splitter.

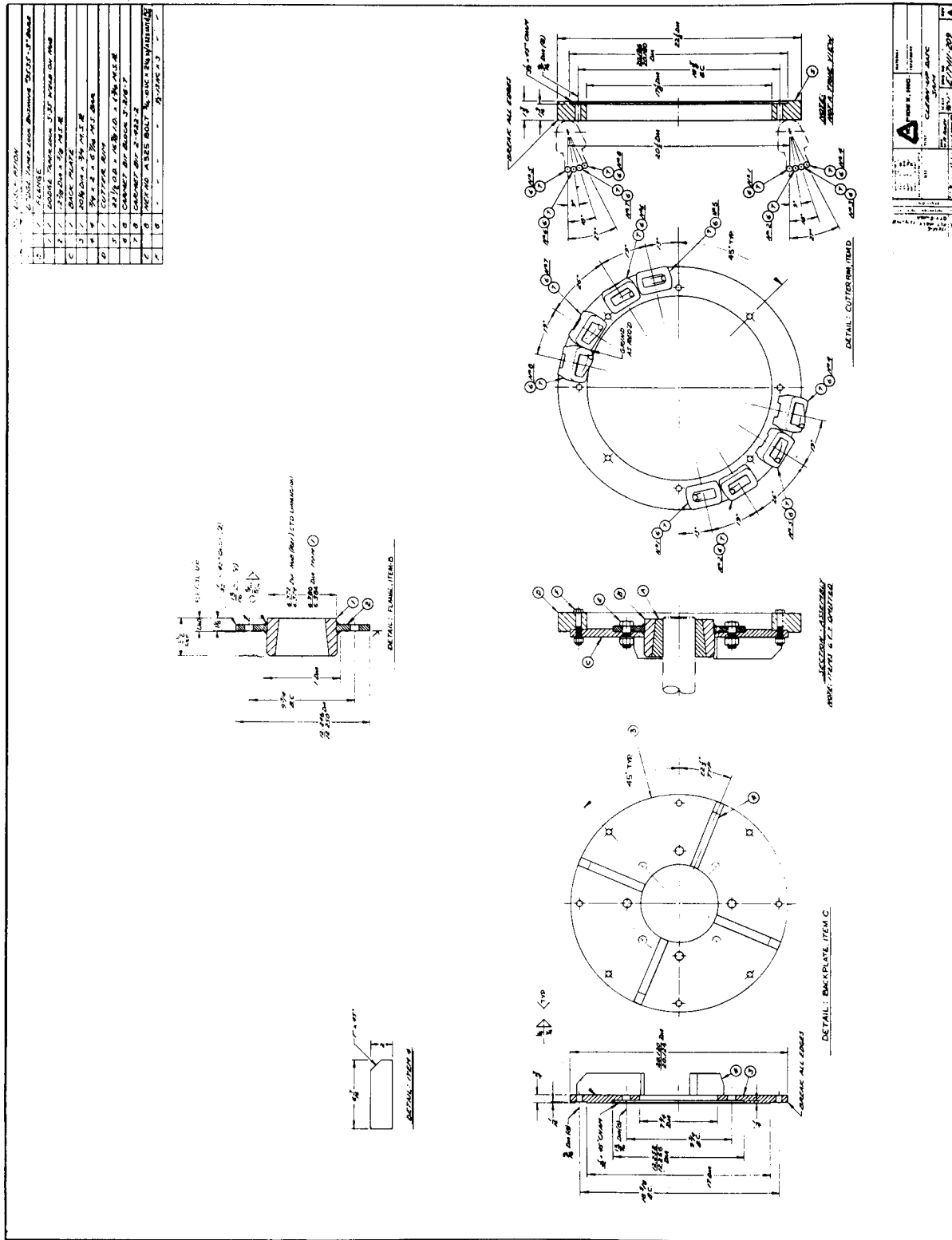


FIGURE F-10. - Clean-up disk.

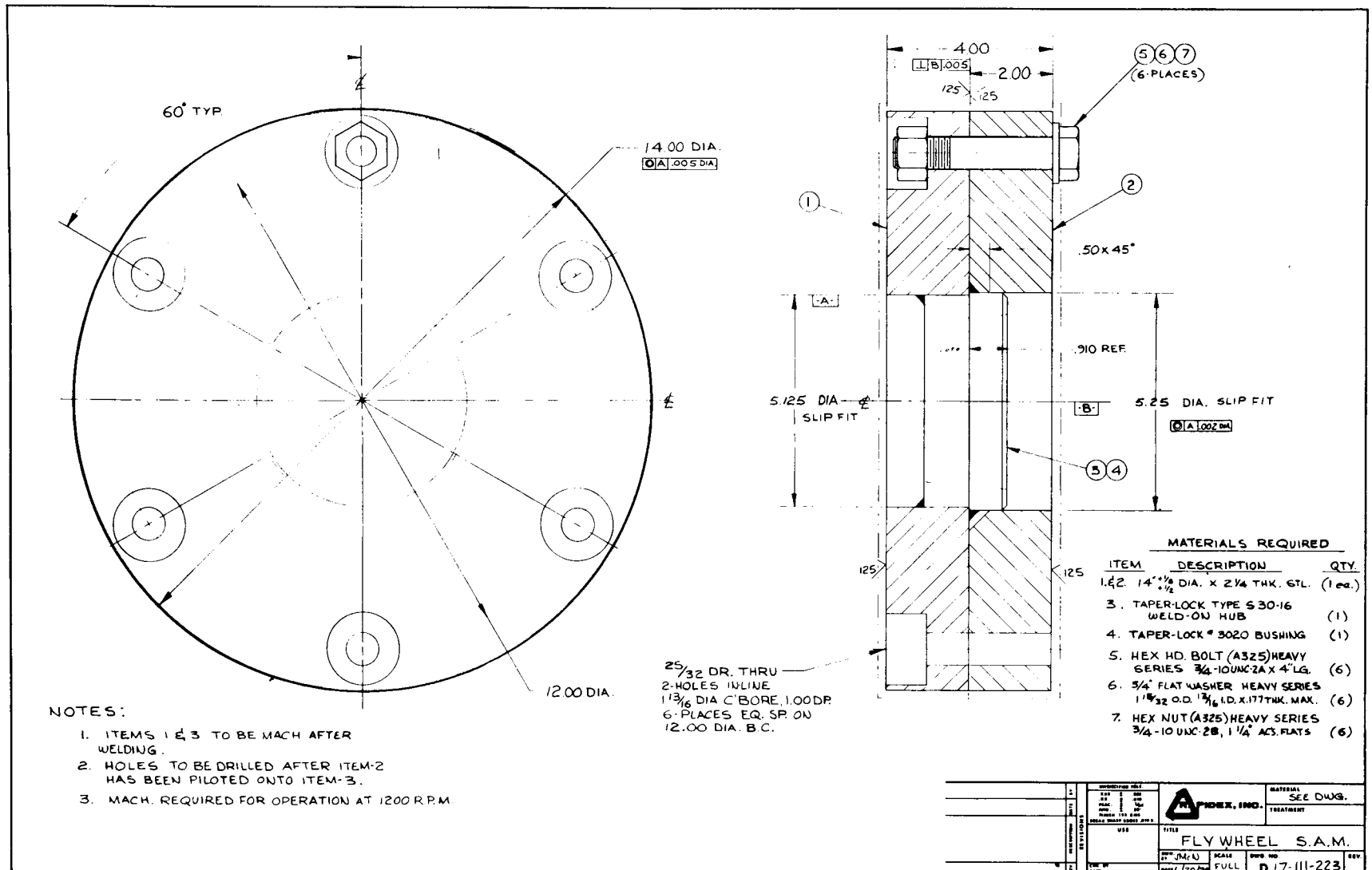


FIGURE F-11. - Flywheel.

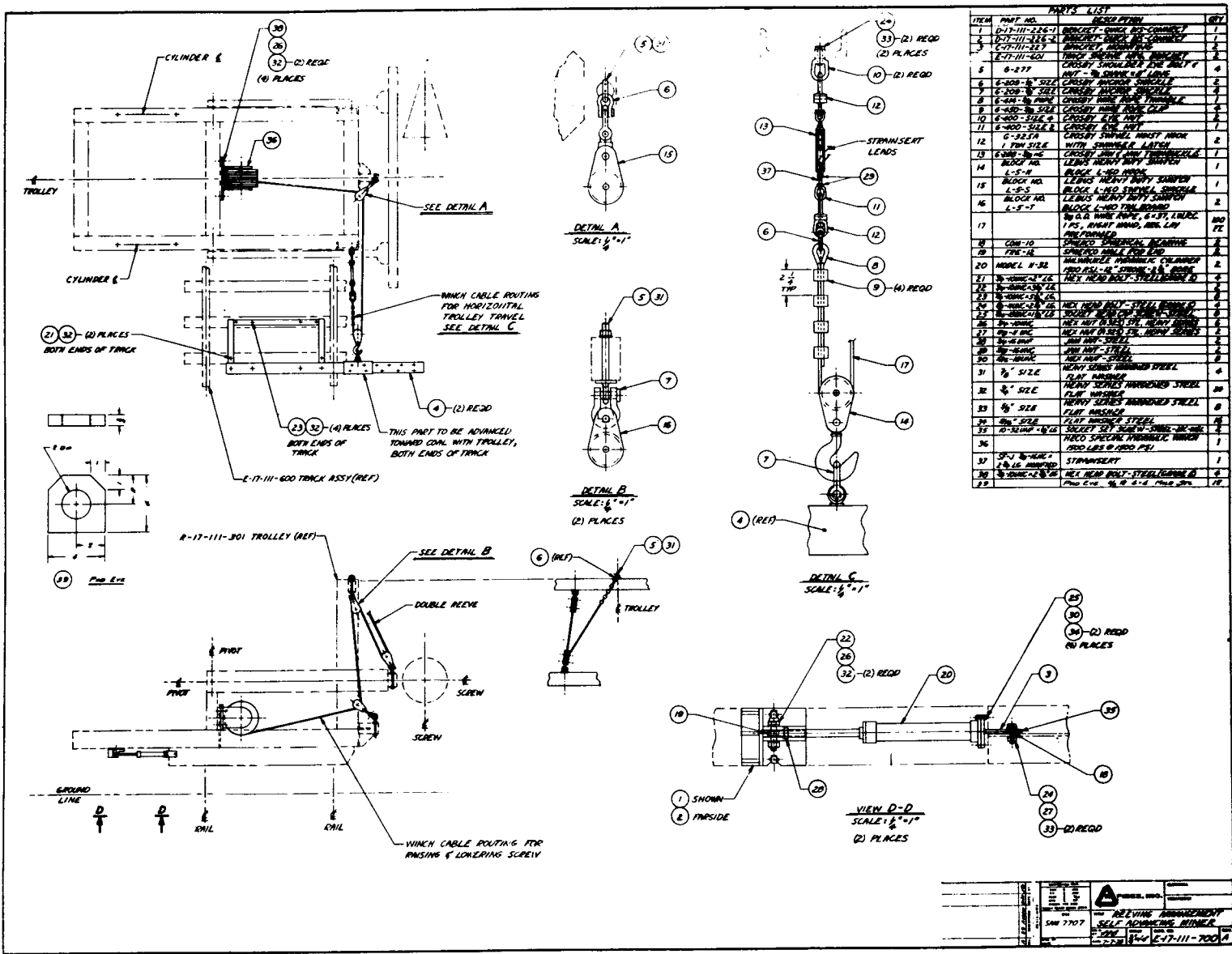


FIGURE F-12. - Reeving arrangement.

FIGURE F-13. - Track arrangement.

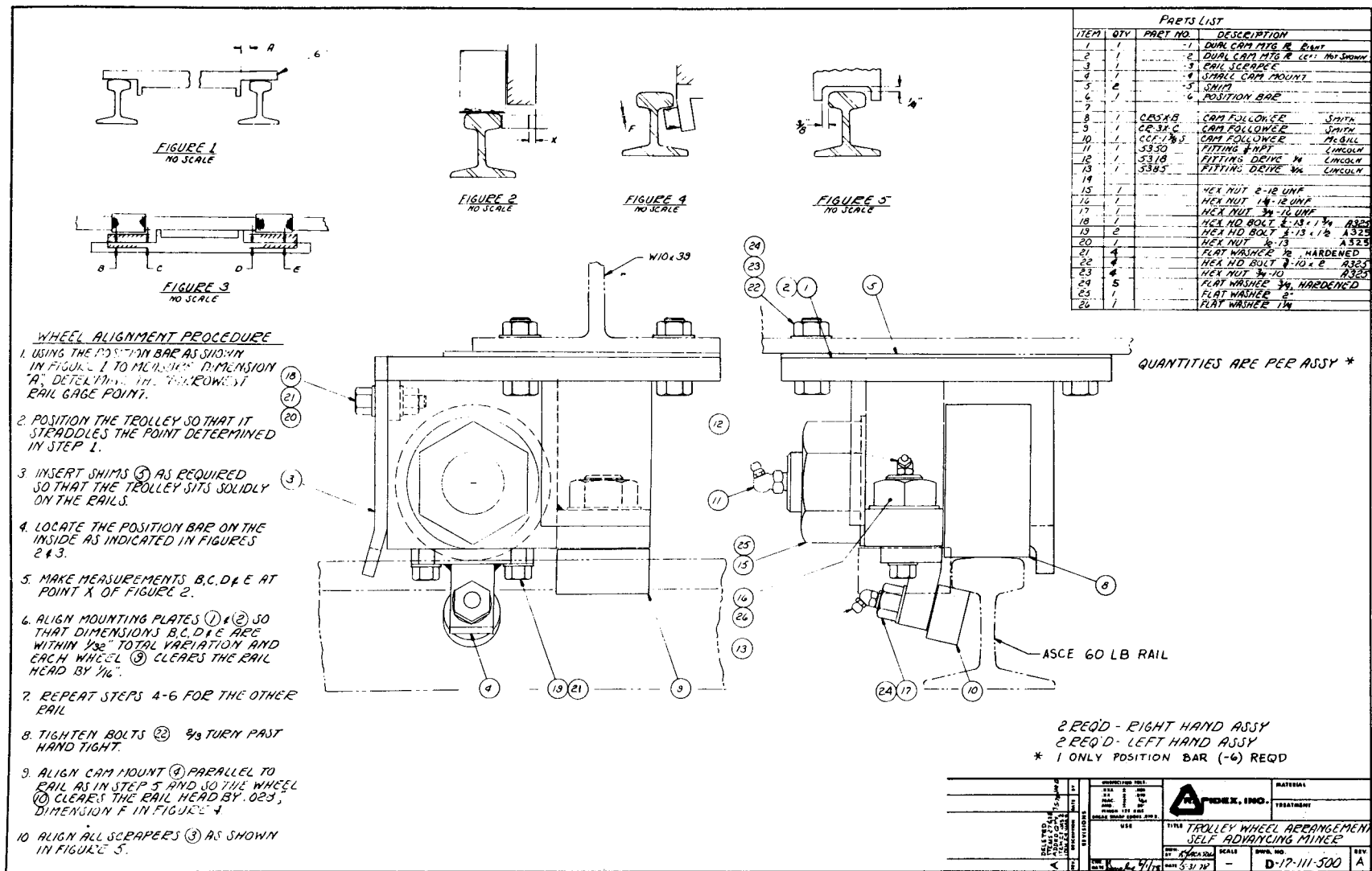


FIGURE F-14. - Trolley wheel assembly.

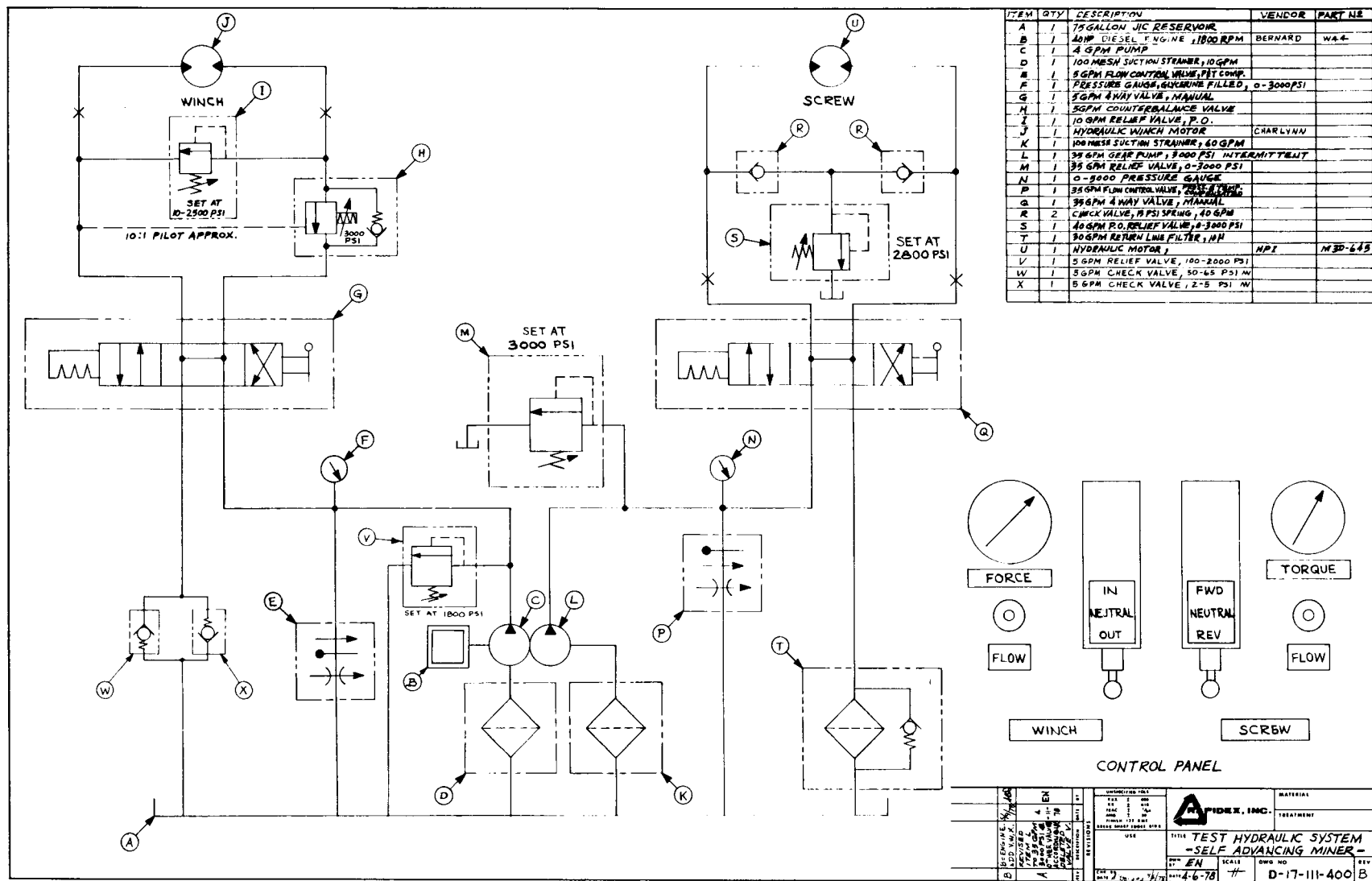


FIGURE F-15. - Hydraulic schematic.

APPENDIX G

LONGWALL PRODUCTION ANALYSIS

The tabulation that follows indicates the expected production rate, total cutting horsepower for two screw cutterheads, and the individual maximum screw drive torque for each cutterhead. In all cases, the advance rate is 25 ft/min, "web" depth is half the screw diameter, the roof and floor cusp volume is included, and the in situ coal density is taken as 80 lb/ft³. Note that a cutterhead overlap equal to the screw diameter represents the case of a single-screw machine.

Because these various cases are tabulated here, we do not mean to imply that every one is an appropriate combination for a longwall mining arrangement. The listing is so complete merely to permit an analysis of the SAM cutting performance. Particularly in the thick seams where the listed production rates are very large due to large diameter cutterheads (and correspondingly deep webs), the SAM rotational speed and advance rate would have to be reduced to remain compatible with state-of-the-art conveyor systems.

The equations used to calculate the listed values are as follows:

$$S = 2D + G \quad (G-1)$$

where

S = seam height, in.

D = cutterhead diameter, in.

G = gap between cutterheads, in.

Note that a positive value of G denotes a gap between screws, and a negative value of G indicates an overlap.

$$X = \frac{S \times W \times L \times N \times (80 \text{ lb/ft}^3) \times (60 \frac{\text{min}}{\text{hr}})}{\left(1728 \frac{\text{in.}^3}{\text{ft}^3}\right) \times \left(2000 \frac{\text{lb}}{\text{ton}}\right)} \quad (G-2)$$

where

X = excavation rate of machine, tons/hr

W = web depth, equal to D/2, in.

L = screw lead, equal to 12 in.

N = screw speed, equal to 25 rpm

Combining Equations D-1 and D-2,

$$X = 0.417 D^2 + 0.208 GD \quad (G-3)$$

This relation holds for both positive and negative values of G.

$$P_{+G} = \frac{2 \times E \times D \times W \times L \times N}{396,000 \frac{\text{in.} \times \text{lb}}{\text{min} \times \text{hp}}} \quad (G-4)$$

where

P_{+G} = total cutting power for positive values of G, hp

E = cutting specific energy, equal to 240 lb/in.²

substitution yields

$$P_{+G} = \frac{D^2}{5.5} \quad (G-5)$$

$$P_{-G} = \frac{E \times S \times W \times L \times N}{396,000 \frac{\text{in.} \times \text{lb}}{\text{min} \times \text{hp}}} \quad (G-6)$$

where

P_{-G} = total cutting power for negative values of G, hp.

Substitution yields

$$P_{-G} = \frac{D(2D + G)}{11} \quad (G-7)$$

The maximum individual screw torque is that experienced by the leading screw of a two-screw machine, whether there is an overlap or a gap between cutterheads.

$$T = \frac{E \times D \times W \times L}{2\pi \left(12 \frac{\text{in.}}{\text{ft}}\right) \left(1000 \frac{\text{lb}}{\text{kip}}\right)} \quad (\text{G-8})$$

where

T = cutterhead drive torque, ft $\times$ kip

kip = 1000 lb

substitution yields

$$T = \frac{D^2}{52.36} \quad (\text{G-9})$$

Table G-1 shows the calculated values of G , P , X , and T for given values of H and D .

The tabulated figures demonstrate the increased efficiency due to a gap between the two cutterheads. Let us compare the values shown in Table G-2.

Assume that we have a machine similar to that shown in Figure 25, with two 36-in. diam cutterheads. In a 36-in. high seam, 270 tons of coal are excavated per hour, requiring 118 hp. In thicker seams, the leading cutterhead is ranged upward until, at 72-in. seam height, there is no more overlap of the two cutterheads. As long as there is an overlap of the screws, the specific energy is constant at

$$\begin{aligned} E &= \frac{118 \text{ hp}}{270 \text{ tons/hr}} = \frac{157 \text{ hp}}{360 \text{ tons/hr}} = \frac{236 \text{ hp}}{540 \text{ tons/hr}} \\ &= 0.436 \frac{\text{hp} \times \text{hr}}{\text{ton}} \end{aligned} \quad (\text{G-10})$$

As the seam thickness increases from 72 to 84 in., no additional cutting power is required, but the excavation rate increases from 540 to 630 ton/hr. The specific energy then equals

$$E = \frac{236 \text{ hp}}{630 \text{ tons/hr}} = 0.375 \frac{\text{hp} \times \text{hr}}{\text{ton}} \quad (\text{G-11})$$

TABLE G-1. - Longwall SAM production

H	D	G	P	X	T
Seam height (in.)	Screw diameter (in.)	Gap (+) overlap (-) (in.)	Total cutting power (hp)	Total excavation rate (tons/hr)	Individual screw torque (ft × kip)
18	9	0	15	34	2
	12	- 6	20	45	3
	18	-18	29	68	6
24	12	0	26	60	3
	18	-12	39	90	6
	24	-24	52	120	11
30	12	6	26	75	3
	15	0	41	94	4
	18	- 6	49	113	6
	24	-18	65	150	11
	30	-30	82	188	17
36	12	12	26	90	3
	18	0	59	135	6
	24	-12	79	180	11
	30	-24	98	225	17
	36	-36	118	270	25
40	14	12	36	117	4
	20	0	73	167	8
	24	- 8	87	200	11
	30	-20	109	250	17
	36	-32	131	300	25
	40	-40	145	333	31
48	18	12	59	180	6
	24	0	105	240	11
	30	-12	131	300	17
	36	-24	157	360	25
	42	-36	183	420	34
	48	-48	209	480	44
60	24	12	105	300	11
	30	0	164	375	17
	36	-12	196	450	25
	40	-20	218	500	31
	42	-24	229	525	34
	48	-36	262	600	44
	54	-48	295	675	56
	60	-60	327	750	69

TABLE G-1. - Longwall SAM production (continued)

H	D	G	P	X	T
Seam height (in.)	Screw diameter (in.)	Gap (+) overlap (-) (in.)	Total cutting power (hp)	Total excavation rate (tons/hr)	Individual screw torque (ft × kip)
66	33	12	198	454	11
	36	- 6	216	495	25
	40	-14	240	550	31
	50	-34	300	688	48
	60	-54	360	825	69
	66	-66	396	908	83
72	30	12	164	450	17
	36	0	236	540	25
	42	-12	275	630	34
	48	-24	314	720	44
	54	-36	353	810	56
	60	-48	393	900	69
	66	-60	432	990	83
	72	-72	471	1,080	99
84	36	12	236	630	25
	42	0	321	735	34
	48	- 12	367	840	44
	60	- 36	458	1,050	69
	72	- 60	550	1,260	99
	84	- 84	641	1,470	135
96	42	12	321	840	34
	48	0	419	960	44
	54	- 12	471	1,080	56
	60	- 24	524	1,200	69
	72	- 48	628	1,440	99
	84	- 72	733	1,680	135
	96	- 96	838	1,920	176
108	48	12	419	1,080	44
	54	0	530	1,215	56
	60	- 12	589	1,350	69
	72	- 36	707	1,620	99
	84	- 60	825	1,890	135
	96	- 84	943	2,160	176
	108	-108	1,060	2,430	223
120	54	12	530	1,350	56
	60	0	655	1,500	69
	66	- 12	720	1,650	83
	72	- 24	785	1,800	99
	84	- 48	916	2,100	135
	96	- 72	1,047	2,400	176
	120	-120	1,309	3,000	275

TABLE G-1. - Longwall SAM production (continued)

H	D	G	P	X	T
Seam height (in.)	Screw diameter (in.)	Gap (+) overlap (-) (in.)	Total cutting power (hp)	Total excavation rate (tons/hr)	Individual screw torque (ft x kip)
132	60	12	655	1,650	69
	66	0	792	1,815	83
	72	-12	864	1,980	99
	84	-36	1,008	2,310	135
	96	-60	1,152	2,640	176
	132	-132	1,584	3,630	333
144	66	12	792	1,980	83
	72	0	943	2,160	99
	84	-24	1,100	2,520	135
	96	-48	1,257	2,880	176
	144	-144	1,855	4,320	396
156	72	12	943	2,340	99
	78	0	1,106	2,535	116
	84	-12	1,191	2,730	135
	96	-36	1,361	3,120	176
	156	-156	2,212	5,070	465
168	78	12	1,106	2,730	116
	84	0	1,283	2,940	135
	96	-24	1,466	3,360	176
	168	-168	2,566	5,880	539
180	84	12	1,283	3,150	135
	90	0	1,473	3,375	155
	96	-12	1,571	3,600	176
	180	-180	2,945	6,750	619
192	90	12	1,473	3,600	155
	96	0	1,676	3,840	176
	192	-192	3,351	7,680	704
204	96	12	1,676	4,080	176
	204	-204	3,783	8,670	795
240	240	-240	5,236	12,000	1,100
360	360	-360	11,782	27,000	2,475

TABLE G-2. - Longwall SAM overlap efficiencies

D	H	G	P	X
Screw diameter (in.)	Seam height (in.)	Gap (+) overlap (-) (in.)	Total cutting power (hp)	Total excavation rate (tons/hr)
36	36	-36	118	270
	48	-24	157	360
	72	0	236	540
	84	12	236	630

It should be noted that the calculated power requirements should be conservative because a specific energy of 240 lb/in.² was used in all cases. You will recall that this figure was measured in the field for the prototype screw which cut one-sixth of the product in the kerf. We expect that the production cutterhead will cut only one-twelfth of the product in the kerf. We realize that the specific energy will not be cut in half because there will be an increased torque requirement to break the larger core; however, the power to break the thicker core should be much less than that required to cut a kerf.

To demonstrate the practical use of the tabulation, let us consider an example. Suppose you are fortunate enough to have a 12-ft coal seam and are currently using a shearer equipped with 96-in. diam drums (two-thirds the seam height). Let us say that your armored face conveyor can handle 1000 tons/hr reliably. The tables indicate that a longwall SAM equipped with two 96-in. cutterheads on the face would excavate 2880 tons/hr and use 1257 hp. These values include a web depth of D/2 or 48 in. and an advance rate of 25 ft/min.

To lower the excavation rate to 1000 tons/hr, the web depth and advance rate may be reduced. By making the web depth only 30 in., the trepan cutter on the front of the screw shaft can be avoided. With the same advance rate, the excavation rate then becomes

$$\left(\frac{30 \text{ in.}}{48 \text{ in.}}\right) \times 2880 = 1800 \text{ tons/hr}$$

An additional reduction in the advance rate brings the excavation rate down to 1000 tons/hr:

$$\left(\frac{1000 \text{ tons/hr}}{1800 \text{ tons/hr}}\right) \times 25 \text{ ft/min} = 13.9 \text{ ft/min}$$

The power required is then

$$\frac{1000 \text{ tons/hr}}{2880 \text{ tons/hr}} \times 1257 \text{ hp} = 436 \text{ hp}$$

The low advance speed corresponds to a low cutterhead rotational speed of 13.9 rpm; bit tip speeds are approximately 350 ft/min.

A similar analysis can be performed to raise the tabulated excavation rates in low seam applications.

APPENDIX H

LIST OF INVENTIONS

In accordance with DOE regulations, we have included here the Summary Report of Inventions and Subcontracts. Included are the Kerf Bit Lacing and the Tee Head Splitter, both described in the body of this report.

Date 31 August 1981

The following report must be submitted in *triplicate* as part of the interim or final report as provided for by the REPORTS and/or PATENT ARTICLE in the grant or contract.

(Check appropriate boxes)

1. Type of Report:

☐ Interim From _____, 19____
To _____, 19____
☒ Final.

2. Interim Report Data:

A. Invention made ☐, not made ☐, during interval of (1).

B If invention(s) made, provide the following information:

☐ Previously fully disclosed in Invention Disclosures. Give dates submitted, and Contractor's docket numbers.

.....

☐ invention Disclosures attached herewith. Give Contractor's docket numbers.

[illegible]

3. Final Report Data:

A. Invention(s) previously reported—

Date Submitted	Contractor's Docket Number
none	

B. Invention(s) reported herewith—

1. Kerf Bit Lacing

none

2. Tee Head Splitter

none

C. Others (explain)—

.....

.....

.....

D. No inventions were made under the grant or contract. ☐

4. Patent application(s) filed and contemplated to be filed by Contractor under the terms of the grant or contract:

Application Serial No. . .	none				
Date of filing					
Contractor's Docket No. . .					

5. Subcontracts containing patent rights article:

☐ None. ☐ Listed below are subcontractors.

Name of Subcontractor	Address	Subcontract Number	Date Executed
(1)			
(2)			
(3)			
(4)			

6. Attach a copy of the patent rights article employed in each subcontract set forth in 5.

7. Contractor or Grantee certification.

I certify that this Summary Report of Inventions and Subcontracts including any attachments is correct to the best of my knowledge and belief.

Date 31 August 1981

Signature

Title

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