

Night Vision and Electronic Sensors Directorate

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Side Sweeping Blade, Concept Evaluation for Mine Clearing

by
Christopher Wanner

February 1995



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Executive Summary

This report covers the evaluation of a side sweeping concept for plowing buried landmines. The Clausen Power Blade prototype system was used to represent the side sweeping concept in a five week field test. The push force, power requirements, and limits of soil stripping capability were compared between the Clausen Power Blade and non-power blades performing the same tasks. Mine clearing and fuze responsiveness to plowing with the Clausen Power Blade was documented.

Measurements taken from the Clausen Power Blade and a standard angle blade show that the side sweeping concept reduces the force needed to push the plow. At 1 mph of forward speed, the push force is reduced nearly 15%.

The power expended by the power belt is used with roughly the same efficiency as the power expended by the vehicle tracks. The beneficial aspect of the side sweeping concept is that the power belt is able to deliver power to the soil removal task after the tractor has reached its traction limit, and can no longer deliver any additional, useful power.

Like the traction limit on the tractor, the side sweeping concept has a limit beyond which it is unable to deliver useful power. This limit is dependent upon vehicle traction and soil shear strength. The side sweeping concept is more productive in frictional soils and less productive in cohesive soils.

The Clausen Power Blade reliably cleared mines to a depth of six inches when operating at forward speeds of .5 mph or greater.

The Clausen Power Blade is similar to other mine plows in the response it evokes from the fuzes in the mines being cleared. A small percentage of pressure mines (4% in this case) detonates when being plowed, and a large percentage of magnetic mines detonates.

Side thrust from the side casting angle of the Clausen Power Blade affects performance in two ways. First, it costs the system much needed traction, and therefore plowing capability, when steering control is required. Second, mine clearing performance is additionally handicapped due to the corrective tilt used with the Clausen Power Blade to maintain steering control. Elimination of this effect would significantly improve the effectiveness of the side sweeping concept.

Section 1 Introduction

BACKGROUND

The mine plow is the most effective device currently available for breaching mined areas. Its low cost and high reliability are the most outstanding features of the plow when compared with available alternatives. Unfortunately, the plow also has several limitations. Among the most important of these are the depth of clearance and the time with which people and assets are exposed to fire during the breach. Various ideas have been studied and adopted over the years to make improvements in these areas. The current state of the problem is that, to raise plowing speed or increase plowing depth, one must be able to apply more power to the plow; apply more push force to the plow; or apply a greater degree of depth control. The control solution is an area of active research and will not be discussed further here. Typically, the ability to push or power a mine plow is limited by the weight and size the military can allow for a piece of equipment in a given mission. The concept researched in this program is to spend some of this limited weight, size, and power budget on a plow with a sideways moving belt in place of the moldboard. The sidecasting action of the belt will more quickly unload the plowed spoils reducing the push resistance encountered by the moldboard. The hoped for result is that, in so doing, the overall plowing efficiency will rise thus extending the plowing capability (speed and depth of cut) within a given weight and power budget (plow plus vehicle).

SCOPE AND OBJECTIVE OF EVALUATION

Comparative testing with the Clausen Blade and several non-power blades was conducted to evaluate the merits and drawbacks associated with incorporating a side sweeping conveyor surface into future mine plows. The side sweeping concept was evaluated on the basis of reduced pushing resistance and power usage, through field testing of the commercially available Clausen Power Blade. In addition, the mine removal performance of the Clausen Blade was documented. There are other earthmoving tasks that the Clausen Blade would be capable of performing such as trench filling, berm building, etc., which are not a part of this evaluation. The scope of this evaluation is narrowly focused on earthmoving tasks related to minefield breaching. The testing was conducted during the summer of 1994, at Fort AP Hill.

Section 2 Test Design

This introduction gives the purpose and rationale for the design of the tests conducted for the side sweeping blade evaluation. The instrumentation description describes how the data were collected, and the test chronology should make clear any uncertainty as to the order in which tests proceeded.

RATIONALE AND DESCRIPTION

The main objective in the evaluation boils down to answering one simple question. *Are we able to do more with less?* Is it possible to make a mine plowing system more capable with fewer resources? Capability is defined as useful work per unit time: yards of soil removed per hour, length of path cut per hour, number of mine removed per hour etc. Resources is defined as the amount of "stuff" assembled to produce the capability: size of tractor and blade, weight, prime power etc. The word "more" in the objective statement implies comparison. In this case, the comparison is between conventional plows and side sweeping plows (and everything required to make them work). Although it is plow concepts being compared in this project, field testing of representative hardware is required to make the evaluation. In these tests the side sweeping concept is represented by the Clausen Power Blade, and conventional plows are represented by the D7-G angle blade, and a V blade on the Counter Obstacle Vehicle.

Plowing Tests

Two main analyses are advanced in this report to make the required comparison. The first is on the basis of push force required to move the plows forward, and the second is on the basis of total prime power required to drive each of the vehicle/plow systems. In order to perform these analyses, measurements were taken relative to the push force and power consumption of each system. The measurements were taken while each of the systems were performing simple but identical (within our ability) plowing tasks. The tasks performed consisted of plowing 50 yard long lengths of flat terrain. Removed soil depth and forward plow speed were the main independent variables for these tests. These kinds of tests were performed multiple times (32 for the Clausen Power Blade) in order to cover the range of independent variables, give some repeatability to the measurements, and make up for instrumentation failures. The same "lanes" were used over and over again to provide identical soil. The plowed soil was compacted to a "standard" density for each run. In general, these tests were designed to quantify the answer to the question of how much capability the Clausen Power Blade provides.

To be able to expand the conclusions beyond the singular conditions imposed on the comparative plowing tests, additional plowing runs with just the Clausen Power Blade were performed. The objective of these tests was to compare the performance of the Clausen Power Blade in different soil conditions with its performance in the standard soil condition used in the comparative plowing tests. The conduct of these tests was the same as the comparative plowing tests with the exception that instead of operating in compacted soil, the Clausen Power Blade was operated in undisturbed soil and in non-compacted loose fill soil.

System Characterization Tests

Unfortunately, the objective of assessing whether more can be done with less is clouded by the fact that the D7-G with the Clausen Power Blade has more "resources" (weight, prime power, traction) than the D7-G with angle blade. Likewise, the Counter Obstacle Vehicle (COV) with "V" rake has still more "resources". Several operating characteristics of the Clausen Power Blade and the D7-G tractor were tested to quantify these resources, to aid in understanding the test results, and to help reduce the test data. Traction pull tests of the D7-G were conducted with the Clausen Blade and with the angle blade installed. The pull tests provided a measure of the amount of added traction the additional weight of the Clausen Blade brings to the D7-G. The frictional losses in the Power Blade were derived by measuring the initial belt power operating under no-load conditions. In addition, the Clausen Power Blade belt output power curve was generated by artificially loading the power belt to its limit. This test, like the traction test, was designed to document how much additional power resource is introduced when the Clausen Power Blade is installed on the D7-G tractor. The system characterization tests aided in separating the concept conclusions from the test measurements of push force and power consumption.

Mine Clearing

The emphasis of this evaluation was directed toward comparing side sweeping blade performance to conventional blade performance on the basis of earth moving measurements. Since the intended application is for mine clearing, surrogate mine plowing tests were designed to establish a link between earthmoving performance and mine clearing performance for the Clausen Power Blade. The tests consisted of plowing dummy mine bodies that were buried in the same lanes used for the comparative plowing tests. Mine movement during the plowing was recorded along with the same earthmoving measurements taken for the comparative plowing tests. A range of mine burial depths were used for these tests to compare "mine clearance depth" with "soil clearance depth".

The final series of tests involved plowing fuzed mines to provide a measure of the detonation sensitivity of the mines being cleared. The results of these tests are required for assessing the survivability of the side sweeping concept.

INSTRUMENTATION DESCRIPTION

Quantities Measured

To compare the performance of the Clausen Power Blade with the angle blade and "V" blade, it was necessary to record the following quantities as the plowing occurred: the belt drive power, the push power, the push force, the plowing speed, and the vertical reaction force on the blade. The push force is defined as the pounds of force applied by the tractor to move the plow, and the push power is the horsepower expended in developing the push force. The belt drive power is the horsepower expended in making the side casting belt turn on the Clausen Power Blade. The vertical reaction force is the pounds of lift force applied to the front end of the C-frame required to maintain the blade at a given height/depth. The vertical reaction consists of the blade weight

and the dynamic forces developed on the cutting edge in the vertical direction as the plow is pushed forward. This information was collected from on-board sensors that were used to monitor several key properties of the D7-G tractor, the COV, and the Clausen Power Blade. The sensor data was transmitted through a signal conditioning box mounted in the rear window of the tractor to a 486 laptop computer mounted on the driver's dashboard.

The primary sensors used for measuring the push force were strain gages on the plow/vehicle mounting structure. For the D7-G tractor this was the C-frame. For the COV this was the plow push beams. A full bridge was mounted on each side of the D7-G tractor one foot forward of the C-frame rear attachment pins. Likewise, a full bridge was mounted on each of the two COV push beams, midway along their length. With two gages on top of the frame (or beam) and two underneath, the bending stresses in the frame were canceled out of the bridge measurement leaving the axial strain as the measured quantity. The use of two gages at each location (one mounted axially, one transverse) also had the added benefit of providing compensation on each side of the bridge for temperature changes. The axial strain in each arm of the C-frame (or each of the push beams) was converted to axial force through material properties and cross sectional area. The axial force was then corrected for the amount of horizontal force applied to the C-frame through the lift cylinders to get the net push force applied to the plow. Measured push values were validated with data obtained by pulling rearward on the plows with cables and a load cell.

The vertical reaction force on the plow and the horizontal force applied to the C-frame from the D7-G tractor lift cylinders was derived from hydraulic pressure values in the lower side of the lift cylinders. The pressure transducer was placed at the last coupling on the hydraulic supply line feeding the lift side manifold for both cylinders. The vertical force was calibrated by comparing the pressure reading in the line required to hold the power blade off the ground with a load cell reading required to hold the power blade at the same height suspended by a cable. This information was used to convert subsequent pressure readings to vertical force in the tests involving the D7-G tractor. Since the lift cylinder and rod are pinned at both ends on the D7-G, the horizontal component from the lift cylinders is simply the tangent of the rod angle times the vertical force. An error of <10% over the range of lift adjustments was introduced into these measurements by assuming a fixed rod angle for computational purposes. On the COV, the vertical reaction force and horizontal force component from the lift cylinders was also obtained from pressure measurements in the hydraulic supply lines. The conversion from pressure to force was made on the basis of piston area and cylinder angles obtained from the COV drawing package. The error from assuming a fixed cylinder angle is less than that on the D7-G measurements.

The vehicle speed for both the D7-G tractor and the COV was measured by the use of a Dicky-John ground speed radar transmitter mounted on the rear of the vehicles. Speed data from the sensor was validated by comparison with timed runs over known distances. The measured speed values were also integrated over time to give the distance traveled down the plow lane. The speed and push force values were combined to give the "push power" delivered to each of the blades used.

The "belt power" for the Clausen Power Blade was obtained from the flow of hydraulic oil into and out of the blade manifolds. A pressure transducer was located at the input coupling to the

Clausen Power Blade motor supply manifold. A flow meter was located at the output coupling of the return manifold. The flow rate and supply pressure were combined to give the power flow into the belt drive motors. The actual belt power output can be estimated by taking into account motor efficiency, belt and bearing friction, and return losses in the hydraulic flow lines. The return loss was calculated at maximum flow conditions and found to be less than 1.4 hp. Motor efficiency is estimated at 80%. No load, top belt speed run conditions produced an input power of ~30 hp as the friction loss. For the Clausen Power Blade, belt power was added to push power to get total blade power. For the angle blade and the V blade, the push power is the total blade power. The total blade power for each system was integrated over time to give the total energy expended in plowing a given lane.

Data Collection/Processing

The laptop computer, Figure 1, served as a display screen for the tractor operator while recording the raw data and computing the derived quantities above. The block diagram for the data computation/acquisition on the D7-G with Clausen Power Blade is shown in Figure 2. This data was recorded at 220 millisecond intervals which translates to every 4-8 inches of forward tractor travel at typical maximum plowing speeds. A similar instrumentation set up was used on the COV except that the strain gages were positioned on the plow push beams, and of course, the plowing power/energy consisted only of the push power since there is no belt to drive.

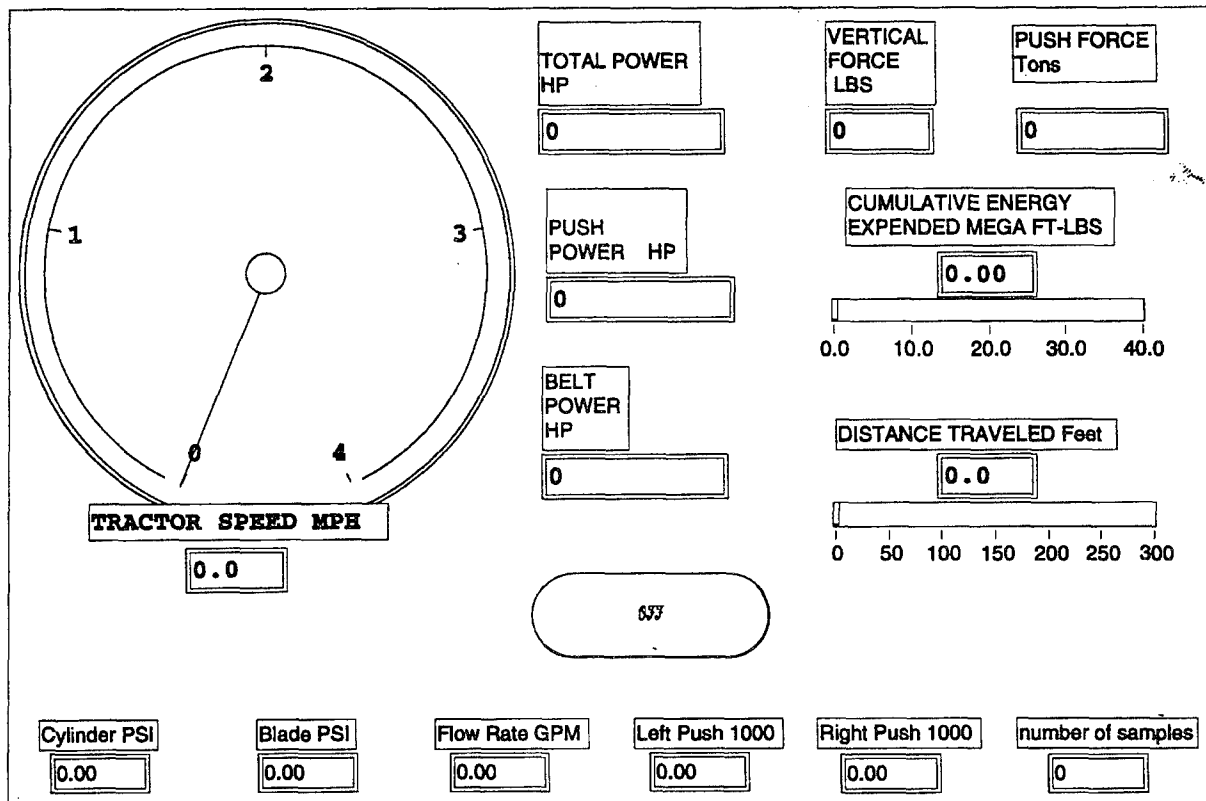


Figure 1. Recorded Quantities

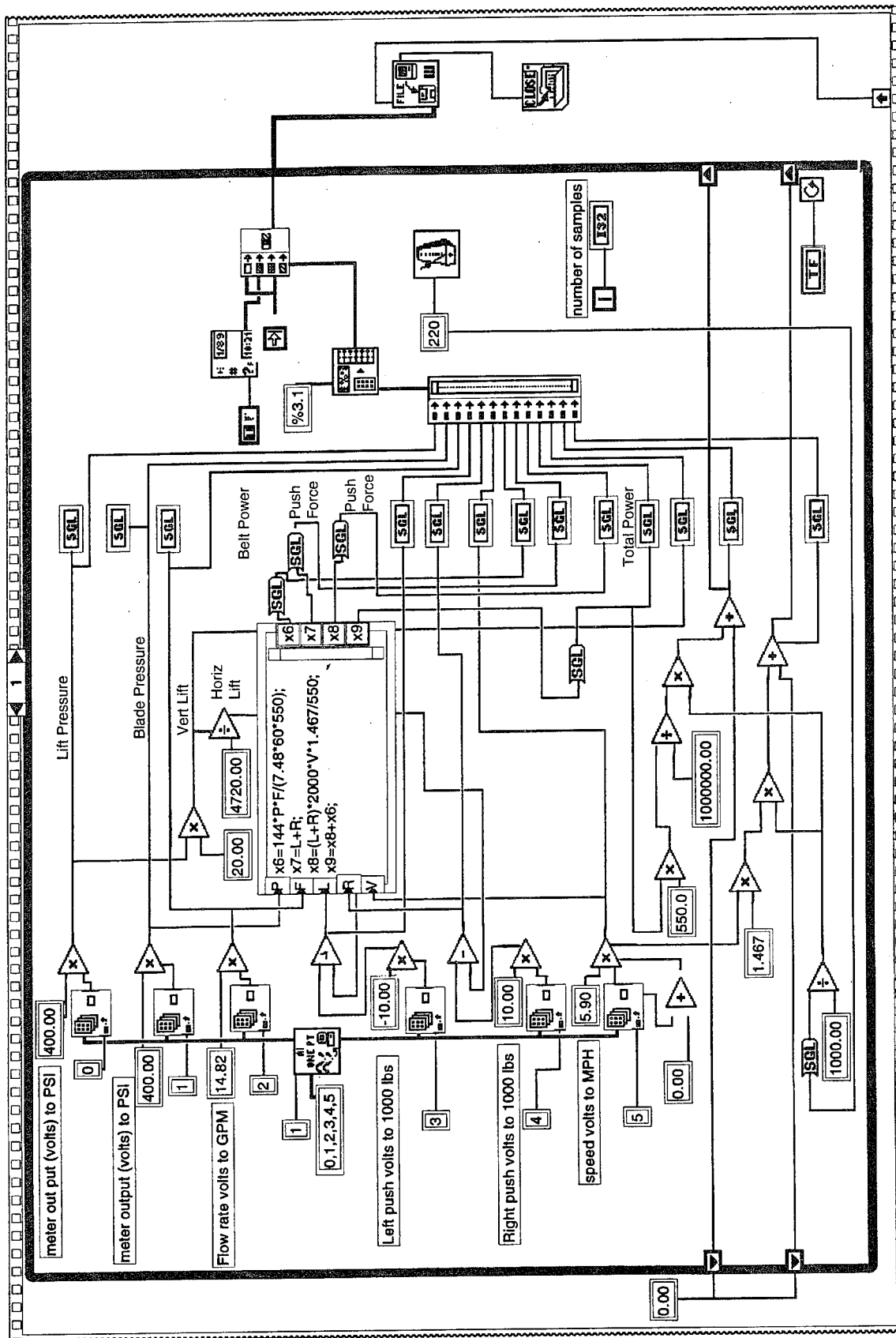


Figure 2. Data Acquisition/Computation Block Diagram

TEST CHRONOLOGY

The field test portion of this evaluation was conducted during the period from 16 June - 10 September 1994. Table 1 documents the tasks performed beginning with the arrival of the Clausen Power Blade.

Table 1. Test Chronology

Task/Test	Days
Installation of Power Blade and sensors on board D7-G	6/16 - 7/2
Transportation of Clausen Power Blade and D7-G to test site	7/3 - 7/6
Clausen Power Blade training	7/7
Clausen Power Blade Sensor calibrations	7/8 - 7/12
Clausen Power Blade belt power no load test and belt speed measurement	7/13
Clausen Power Blade and D7-G traction pull tests	7/14 - 7/16
Clausen Power Blade comparative plowing tests	7/16 - 7/25
Clausen Power Blade Surrogate mine plowing tests	7/26 - 7/29
Clausen Power Blade magnetic and pressure mine fuze plowing	7/29 - 8/2
Clausen Power Blade, more comparative plowing tests	8/2 - 8/10
Clausen Power Blade mine clearing demonstration	8/8 - 8/10
Clausen Power Blade, completion of comparative plowing tests	8/10
Clausen Power Blade system power output test	8/11
Angle blade installation	8/12 - 8/13
Angle blade comparative plowing tests	8/14 - 8/25
Angle blade traction pull tests	8/25 - 8/26
Angle blade/D7-G teardown	8/26 - 8/27
COV Sensor installation and calibration	8/28 - 8/30
COV comparative V raking tests	8/31 - 9/1
COV comparative V plowing tests (attempted)	9/2
Site teardown and test conclusion	9/3 - 9/10

Section 3 Test Platforms

The ideal hardware set-up for evaluating the side sweeping blade concept would consist of the side sweeping blade and baseline non-power blades mounted on the boom of an indoor, overhead crane or a set of floor mounted, rigid rails. The mount would have infinite power for forward locomotion and allow the ability to exercise complete control over speed and depth of cut. Testing would then consist of measuring the power and force required to plow a given depth at a given speed for each blade configuration. Plow and soil conditions could be held constant from test to test providing the perfect basis for comparing the performance of each blade. Practical matters of running an economical test program require the use of existing vehicles and field plowing conditions. The objective of evaluating the side sweeping concept remains the same as the ideal hardware set up described, but the limitations of the test hardware used tend to cause mixing of the concept characteristics and the test hardware capabilities. To the maximum extent possible these intertwined quantities have been separated, but the test parameters covered and the fidelity of the results remain limited by the available power and control in the host platform. The main features of each of the blade and vehicle systems employed in this project are described in the following paragraphs along with modifications, for test purposes, made at the CECOM R&D Center.

CLAUSEN POWER BLADE AND D7-G TRACTOR

The main subject of this evaluation was the Clausen Power Blade. The power blade is marketed commercially for stripping topsoil and back filling trenches in pipeline laying operations and is designed to be mounted on a Caterpillar crawler tractor. The Clausen Blade consists of a standard angled cutting edge, a steel dozer track laid on edge to form a belt traveling around two vertical axes, 5 hydraulic motors with sprockets in the blade to drive the belt, and an auxiliary power unit (APU) designed for mounting on the tractor's rear. The APU has a 200 HP diesel engine, and a hydraulic pump connected to the blade motors by two, 1.5" high pressure lines and one, 1" drain line. The blade attaches to the C frame on the crawler tractor and can be mounted straight on, or angled 24 degrees to the left or right of the vehicle path (24 degrees of yaw angle). Additionally, the blade is equipped with tilt control cylinders which can be driven by the tractor hydraulic system to actively control the angle of the blade transverse to the plowed path (roll angle).

The cutting edge is mounted 57 degrees from horizontal and is 14' 4" long. The 24 degree angled mounting of the blade gives a transverse path span of 13' 0". The front end weight of the system (cutting edge, hydraulic motors, belt, tilt cylinders, mounts, and support structure) is 16,000 pounds. The rear mounted APU engine, hydraulic pump, and support beams weigh 8,000 pounds for a total system weight of 24,000 pounds. The APU diesel throttle and pump flow controls are contained in a portable control panel which can be placed in the tractor cab next to the operator's seat.

The Caterpillar D7-G tractor used on this project was obtained from Naval war reserves. The D7-G has a 200 HP diesel engine and is rated by Caterpillar as having 75,000 pound static draw bar pull capability. The vehicle weight (with optionally installed winch) is just over 50,000

pounds and the top speed in first gear is 2.4 mph. The winch, winch control linkage, winch drive shaft, and winch hydraulic pump were removed from the tractor in order to accommodate the rear mounting structure for the Clausen APU. In addition, a hydraulic tilt control valve and circuit was installed on the existing dozer blade lift/lower circuit to provide tilt control to the power blade. These modifications each required about 10 man-hours of labor.

The Clausen Blade, Figure 3, was installed on the tractor in about 2 hours using an overhead crane, 4 men, and standard hand tools. The only modification required was a new control cable mounting lever/bracket on the APU to compensate for the control cable being too short to reach the tractor operator's seat through the side window.

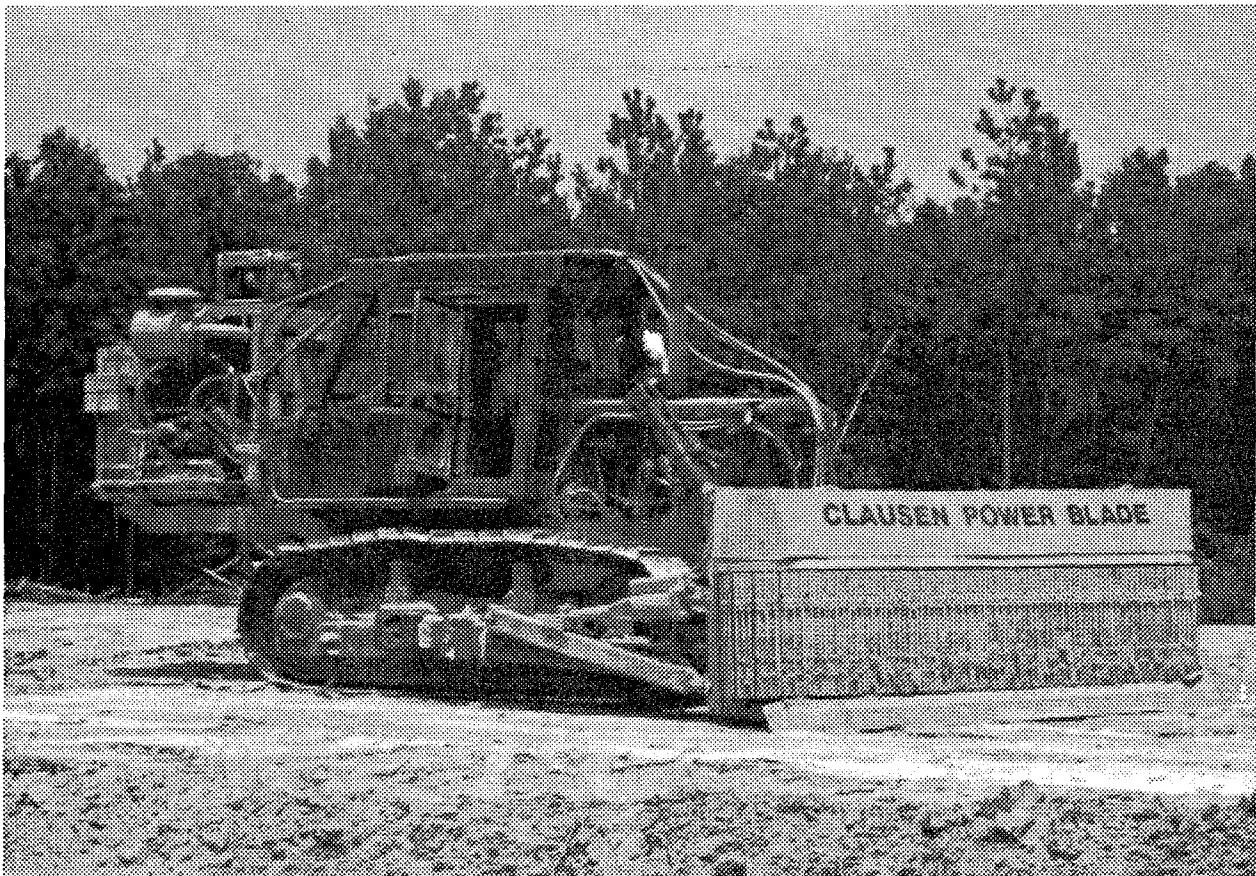


Figure 3. D7-G Tractor and Clausen Power Blades

Figure 4 sketches the basic configuration of the mounting of the Clausen Power Blade on the D7-G. Nominally, the Clausen Power Blade/D7-G plowing system is characterized as a 69,000 pound (50,000 D7-G - 3000 winch - 2000 angle blade + 24,000 Clausen Blade = 69,000 lbs.), 400 HP angled dozing system, with 2 degrees of blade control, and 13' of plowing width.

ANGLE BLADE AND D7-G TRACTOR

The standard angle blade furnished with the D7-G, Figure 5, is capable of the same mounting configurations as the Clausen Blade, 0° and $\pm 24^\circ$. The blade length is 14' 0", and the cutting edge is set 57° from horizontal. There are no tilt control cylinders on this blade. The weight of the blade and C-frame combined is about 7,000 pounds, of which 2,000 pounds are estimated for the blade alone.

Testing with this standard angle blade immediately followed the Clausen Power Blade tests and was performed with the same tractor used for the Clausen Blade tests. The winch was left off after removal of the Clausen Blade and APU, and installation of the angle blade. Nominally, this standard angle blade/D7-G plowing system (hereafter referred to as "angle blade") is a 47,000 pound, 200 HP angled dozing system, with 1 degree of control, and 12' 9.5" of plowing width.



Figure 5. D7-G Tractor and Non-Powered Angle Blade

“V” TOOTH RAKE AND COUNTER OBSTACLE VEHICLE(COV)

The Counter Obstacle Vehicle (COV) is a 900 HP experimental combat engineer vehicle. Due to its large size and power, the vehicle comes closest to the infinitely powered ideal test platform described in Section 1. The COV had excess power and traction over the range of plowing conditions established by the Clausen Power Blade. Its system loading characteristics did not therefore affect plowing performance. The static drawbar pull of the COV has been measured at 110,000 pounds, and the vehicle weight at 140,000 pounds.

The 12” teeth on the COV mine plow act as scarifiers at the plowing depths used in the power blade tests (see Figure 6). The “V” blade is more accurately described as a V rake since no soil removal was performed at these depths. The teeth are 1.25” wide, and are spaced 8 inches center to center. There are 21 teeth, and the span is 14’. Each wing of the V is swept back at 35 degrees. The available blade controls are lift/lower, tilt (side to side roll angle), and oscillation (pitch attitude). Nominally, the COV raking system is a 140,000 pound, 900 HP, V angled raking system, with 3 degrees of control, and 14’ 0” of raked width.

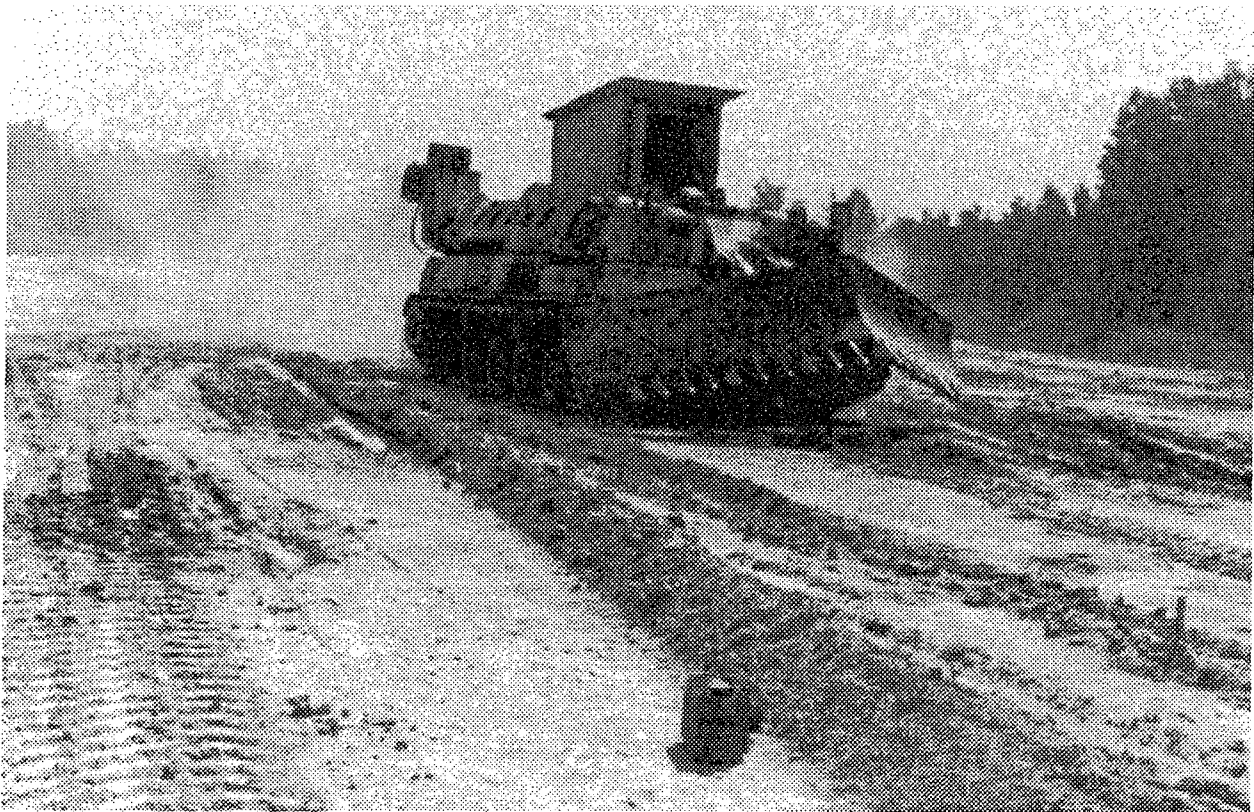


Figure 6. Counter Obstacle Vehicle and “V Teeth”

“V” PLOW AND COUNTER OBSTACLE VEHICLE

The teeth were removed from the COV plow with the intent of comparing the plowing characteristics of the V blade and the power blade in terms of the amount of soil moved for a given cutting depth. Unfortunately, the V plow was not designed for this kind of operation and the COV lift cylinders are too short to extend a level V blade into the ground without the teeth. Using the oscillation control, the blade was pitched forward such that the middle ground (9 foot strip) was plowed to the desired depth, and the outer portions were not plowed (see Figure 7). Since the track spacing is wider than the plowed strip, it was not possible to continuously increase plowing depth by driving into the already plowed hole, making collection of comparative data impossible.



Figure 7. “V Plow” with Teeth Removed

SUMMARY TABLE

Table 2 lists the main characteristics of these plowing systems as described.

Table 2. Plowing System Characteristics

System Name Name	Power (HP) (hp)	Plowing Width (Ft)	Weight (lbs)	Drawbar (lbs)	Degrees of control
CLAUSEN/D7-G	400	13' 0"	69,000	75,000	2
ANGLED/D7-G	200	12' 9.5"	47,000	75,000	1
V RAKE/COV	900	14' 0"	140,000	110,000*	3
V BLADE/COV	900	9' 0"	140,000	110,000*	2

**These figures are available traction, actual drawbar pull is higher.*

Section 4 System Characterization Tests

Several measurements of the Clausen Blade and D7-G tractor operating characteristics were made in order to help analyze and interpret the results of the plowing and mine clearing tests. The first of these was a traction pull test.

TRACTION

The drawbar reported for the D7-G refers to the ability of the tractor to develop the specified driving force (75,000 lbs). In most conditions, the amount of traction the soil can support is less than the drawbar. Measurement of the amount of pull the D7-G was able to apply in the soil at the test range was made both with the Clausen Blade installed, and with the non-power, angle blade. The measurements were made with cables attached to the apex of the C-frame and a load cell (see Figure 8). The amount of pull the D7-G was able to apply to the cell was 65,000 pounds with the power blade installed, and 43,000 pounds with the non-power, angle blade. The expected values based on Caterpillar published data of traction coefficient in the range of .9 for clay loam would equate to 62,100 lbs. for the power blade equipped tractor and 42,300 lbs. for the regular tractor, both in close agreement with the measured values.



Figure 8. Pull Test with D7-G and Clausen Blade

The Clausen Power Blade system established the baseline for all of the tests conducted in this evaluation. Since the COV has traction well in excess of that required to perform the comparative tests, no separate measurement of the maximum traction of the COV was needed for this evaluation.

One consequence of these pull tests is that it was expected that the power blade equipped D7-G would have up to 50% more capability than the angle blade equipped D7-G simply from the increased traction attributable to the 24,000 pound increase in vehicle weight. An interesting test would be to compare the performance of the D7-G with Clausen Blade to the D7-G with angle blade and 24,000 pounds of dead weight added.

Two additional observations concerning these traction results should be mentioned. The tractor is required to apply a vertical downward force to push both the Clausen Power Blade and the angle blade into the ground when plowing. This will tend to lighten the vehicle load on the tracks, causing a reduced ground pressure. The reduced ground pressure will in turn reduce the available traction when plowing. Also, the vehicle tracks do not have as much time to "dig in" while on the move as compared to a static pull test. This may contribute to even further reductions in available traction when plowing as compared with the static pull tests. This effect was seen in the performance test reported in the Section 5.

BEARING, BELT, AND MOTOR FRICTION LOSSES

The "belt power" measurements made on the Clausen Blade are recorded on the basis of power flow into the blade. The power output available from the belt is reduced by friction losses in the motors, friction losses in the bearings, friction losses in the belt, and losses in the belt-sprocket interfaces. The "push powers" recorded for the Clausen Power Blade/D7-G as well as all of the other systems are pure outputs, measured "down stream" of any losses. To be able to add or compare the belt and push powers, the belt input power for the Clausen Power Blade needed to be converted to a net output power. To accomplish this, the "no load" power input to the belt on the Clausen Power Blade was recorded while operating at a variety of belt speeds. Figure 9 depicts the results as a function of hydraulic fluid flow rate, with a maximum loss of 30 hp at full speed. These power losses are used throughout this report to correct the belt power measurements and give net belt power output for the Clausen Power Blade.

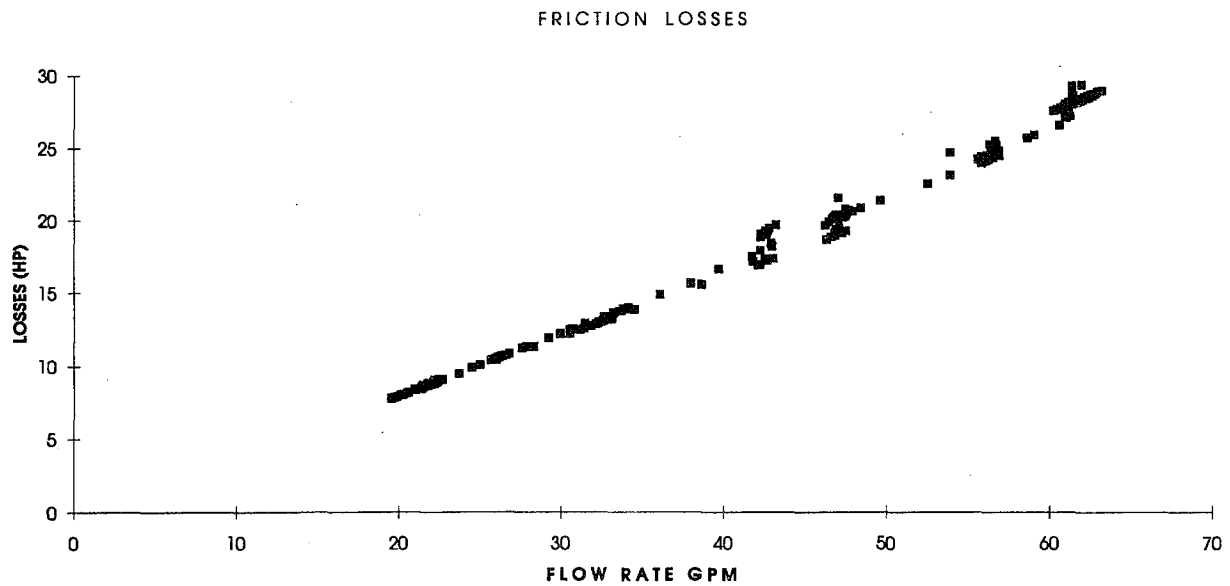


Figure 9. Frictional Power Loss in Clausen Blade and Belt

CLAUSEN POWER BLADE BELT POWER OUTPUT RANGE

The ability of the Clausen APU engine and hydraulic pump to deliver power to the power blade was tested to check whether the blade was operating on that portion of the system power curve where increased push against the belt face causes an increased amount of power to be delivered. Operating on this part of the system loading curve is desirable to avoid the situation where greater push force causes reduced blade power (ultimately ending with the belt grinding to a halt).

The APU throttle and flow control valves were set at maximum speed, and the belt was progressively loaded by pushing into the face of a 10 foot high soil bank. This allowed loading of the belt without significant cutting resistance. The Power Blade manufacturer had given design information for the hydraulic system with a maximum pressure of 4000 psi. This was the rating of the transducer used in the computer acquisition system. When the test was conducted, the transducer saturated at 4000 psi (see Figure 10). Manual reading of a pressure gage at the pump output, indicated that the pressure relief valve did not open until approximately 4200 psi. The delivered power estimated on this basis using the flow rate of 43 gallon per minutes (gpm) (the level flow on the right side of Fig. 10) gives an estimated maximum power delivery to the blade of 106.5 HP. Subtracting the internal losses (16 hp from Figure 9) gives a maximum output power of 90 HP.

By examining Figure 10, it can be seen that the belt power continuously rises to the point where the transducer is saturated. This pressure or power output level was not approached during the plowing tests performed. Therefore, neither saturation of the pressure transducer nor overloading the belt was of any concern for the plowing tests performed.

POWER FLOW & SUPPLY PRESSURE

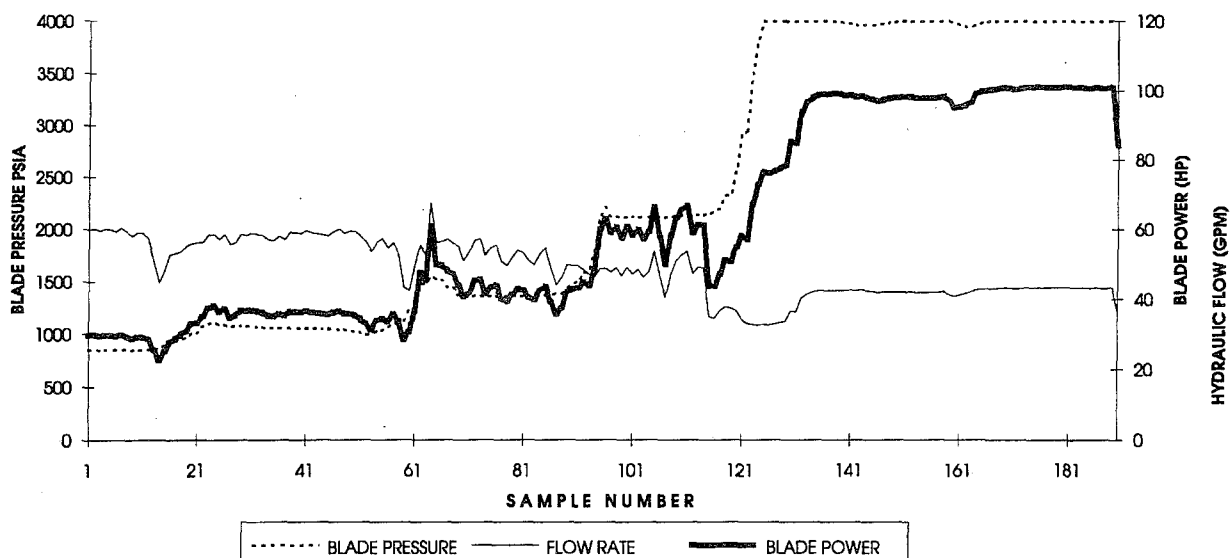


Figure 10. Output Loading of Clausen Blade

BELT SPEED

The Clausen Power Blade belt speed is a useful quantity to know for analysis of the earthmoving and mine plowing results. Since the belt is driven with positive displacement motors, the speed can be computed from the hydraulic supply flow rate minus any motor seepage. This net flow was the quantity being measured for use in the power analysis. With a measured belt length of 30 feet, the graph in Figure 11 was constructed from timed revolutions of the belt at various flow rates.

RANGE OF OPERATION

The maximum depths of cut which could be produced with the Clausen Power Blade equipped tractor operating with a speed of at least .5 mph are listed in Table 3 for various soil conditions.

The measurements described in this section were designed to help characterize the Clausen Blade and aid in the analysis of comparative plowing between each of the test bed systems described in the Section 5.

BELT SPEED vs. HYDRAULIC FLOW

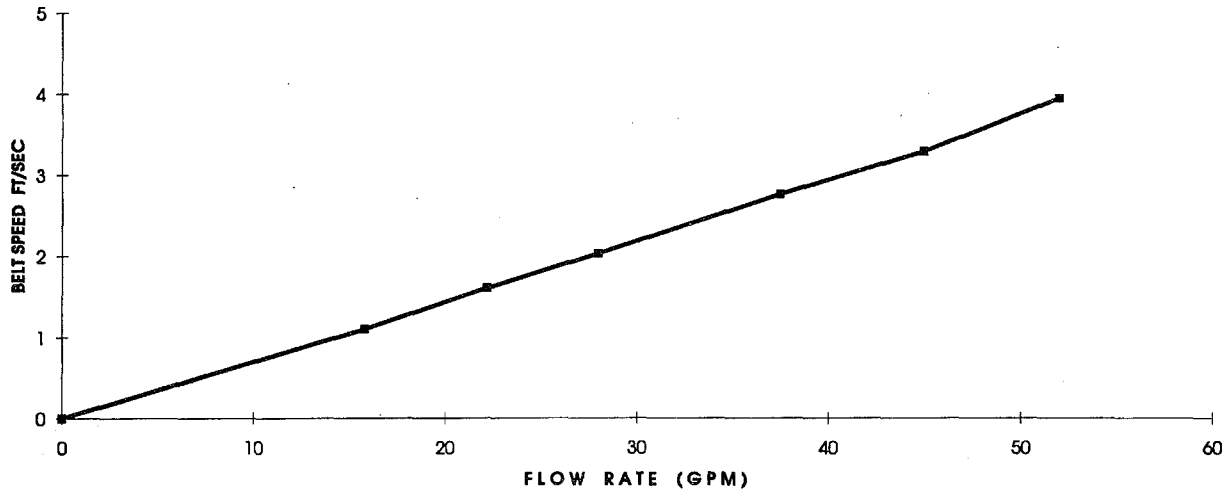


Figure 11. Operating Belt Speeds for Clausen Power Blade

Table 3. Plowing Depth of Clausen Blade at 0.5 mph

Soil Condition	Maximum Depth Plowed
Undisturbed	5.41"
Compacted (dry)	7.25"
Compacted (damp)	7.36"
Loose Fill*	>5.46"

**Although plowing of loose fill was performed, no attempt to seek a maximum plowing depth was attempted in loose fill."*

Section 5 Plowing Tests

DESCRIPTION OF TEST CONDITIONS

All plowing was conducted at Fort A.P. Hill, Virginia on trial lanes marked for this purpose. The range surface was uniformly level (< 1% slope) and stripped of trees, topsoil, and vegetation. The soil present on the site ranged from clay to sandy clay. Soil density was used to characterize the site, and cone index readings recorded on each of the test lanes prior to plowing. The dry density on site averaged 104 lbs/cubic foot of soil. An additional 7-10 pounds of water per cubic foot was typically present. The majority of the plowing, and all of the comparative tests, was performed on dry lanes which were previously plowed and uniformly compacted to a standard density. A limited number of plowing runs were made for other purposes on lanes which had been undisturbed for 12 months (since initial clearing of the range), in loose fill, and in damp soil. The cone index for the loose fill was less than 30 psi, the index for damp compacted soil ranged from 65 - 165 psi, the index for the dry compacted soil ranged from 165 - 325 psi, and the index on the undisturbed soil ranged from 325 - 485 psi. Average values are given in Table 4.

Table 4. Cone Index for Test Lanes

Soil Condition	Cone Index (psi)
Undisturbed	390
Compacted (dry)	210
Compacted (damp)	130
Loose Fill	6

COMPARATIVE PLOWING TEST RESULTS

The primary focus of the field test was on performing a given plowing task, recreating that task with each of the test systems, operating under similar conditions, and comparing the measurements obtained. Since the Clausen Power Blade conceptually represents the subject of the investigation, it was used to establish the performance range over which the other systems would be tested. Each system, however, has its own particular quirk uniquely identifying its performance from the others. To the extent possible these distinctions were suppressed in testing or in this analysis. The various widths of the plowed paths, for example, can be divided out when comparing push forces in order to give a push per unit width. Where the performed task remains distinct among the alternatives, raking versus plowing for example, the analysis may be somewhat qualitative. The fact that not all variables are controlled precisely in these tests does not diminish their importance.

The plowing lanes used for these tests were 50 yards long. Elevation measurements of the lanes were recorded before and after each plowing run to determine depth of cut and soil volume moved.

Push Force Analysis

The dependence of push force on depth is modeled here as being linear, and least squares line passing through the origin were fit to the test data collected. Although linear dependence is not immediately apparent due to the scatter in the data, there is reason and precedence for modeling the push force as linear. The weight of soil to be moved increases linearly with depth, suggesting linear moldboard loading. The area of sheared soil surface created by the cutting edge increases linearly with depth. While the soil shear strength may increase with increasing soil pressure as one moves deeper, the effect would be slight over the 0"-8" of depth encountered in this testing. The cutting resistance therefore may be exponential over a large range of depth, but is adequately modeled as linear for these tests where the range of depth is small. Computer modeling performed in the General Dynamics mine plow development contract for the M1 tank predicts push forces linearly dependent on plow depth over the range of 0" - 12", ref. 1. The experimental models given below present a consistent and believable view of the mechanics involved in plowing. The scatter in data is mainly attributable to the inability to completely control the test variables as was described in the discussion of the ideal test platform.

Clausen Power Blade Results. Twenty-two plowing runs with the Clausen Power Blade were made in compacted soil in which the amount of push applied by the tractor to the plow was recorded. The force readings for portions of each plowing run where the depth of cut was within plus or minus one inch of the average depth of cut for the entire run were averaged and recorded as a function of depth of cut and plowing speed. These average force readings were placed in one of three groups defined by the following speed ranges: .2 - .7 mph, .7 - 1.2 mph, and 1.2 to 2.0 mph. These data are plotted in Figure 12 along with the least squares line for each group. The first group of runs had an average speed of .51 mph and a least squares line slope of 3392 pounds of push force per inch of plowed depth. The second group average speed is .83 mph with a slope of 3680 pounds per inch, and the third group speed and slope were 1.6 mph and 4018 pounds per inch.

Angle Blade Results. Similarly, the D7-G tractor with angled blade was used to plow the same reworked/compacted plow lanes. Eight runs were conducted covering a smaller range of depth and speed than that covered with the Clausen Power Blade. The data were averaged as above, and all placed in the one speed group having a range of .9 to 1.3 mph. The data are plotted in Figure 13 with the least squares line. The average speed for this data group is 1.0 mph, and the slope of the fitted line is 4363 pounds per inch of cut.

V Rake Results. As a third comparison, a couple of runs were made in which the COV plow teeth were used to rake the soil to a depth of 6 inches. Because raking removes no soil, there is no depth of cut left to measure following a run. However, at this depth, the COV and plow offer a very stable platform. Raking to the given depth was possible by observation since soil does not accumulate in front of the plow when raking and the tines remain visible. The bottom six inches of the tines were painted orange to aid in making these observations during the runs. Since only two runs were made, no regression was performed; however, the data are plotted on the comparison summary chart, Figure 14.

Comparison of Clausen and Angle Blade Push Forces to Measured Traction. It is interesting to note the maximum push forces present in the experimental plowing data. In Figure 12, the largest push forces recorded for plowing with the Clausen Blade are ~ 28,000 lbs. For the angle blade, Figure 13, the largest push forces are ~18,000 lbs. These values are considerably less than measured in each of the respective pull tests earlier. Three phenomena seem to be the cause of this reduction in available push force. The first is that in pushing the blades into the ground, there is a vertical, upward resisting force developed which tends to lower the vehicle ground pressure. This reduced ground pressure in turn, tends to lower the amount of available traction. The second effect is that the vehicle tracks do not have as much time to sink in place while on the move as during a static pull test. And finally, the 24 degree angle of the blade transverse to the plowing path creates a turning moment on the tractor. In order to counter this effect and keep the dozer plowing straight, the tractor must continuously be steered to the right. This is accomplished by activating the clutch on the right tracks, causing some loss in power. Further, the left track which ends up pushing harder may exceed available traction and start to spin, even though, on average, the tractor is operating at less than the traction limit. The ratio of the maximum plowing force with the angle blade to the maximum plowing force with the Clausen Power Blade is nearly identical to the ratio of available traction documented with the pull tests earlier:

Max. Push Force Ratios	Pull Test Ratios
$18,000/28,000 = .64$	$43,000/65,000 = .66$

This indicates that both the angle blade and the Clausen Blade were equally handicapped (on a percentage basis) by these effects.

Comparison of Push Forces Between Clausen Power Blade, Angle Blade, and V Rake.

Interpolating between the .83 and 1.6 mph data groups plotted in Figure 12 for the Clausen Blade gives a slope of 3755 lb/inch for the Clausen Blade operating at 1.0 mph in compacted soil. Scaling up the slope of the angle blade results by the difference in span of the Clausen Blade (156") and the angle blade (152.5") gives $4363 \times (156/152.5) = 4463$ lb/inch for the angle blade operating at 1.0 mph in compacted soil with an equivalent span to the Clausen Blade. Similarly, the COV raking results can be scaled down by $168"/156"$ to give a width equivalent to the Clausen Blade results. The average raking speed with no scaling was 1.0 mph. These lines with the scaling adjustments described are plotted for comparison in Figure 14.

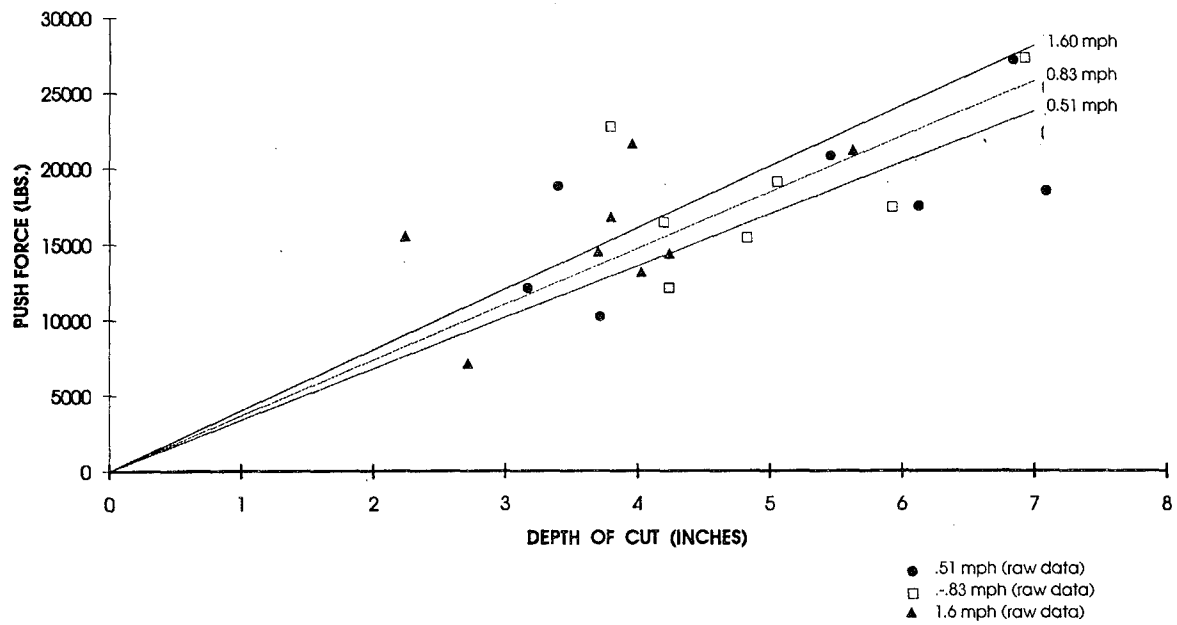


Figure 12. Push Force vs. Plow Depth, Clausen Blade

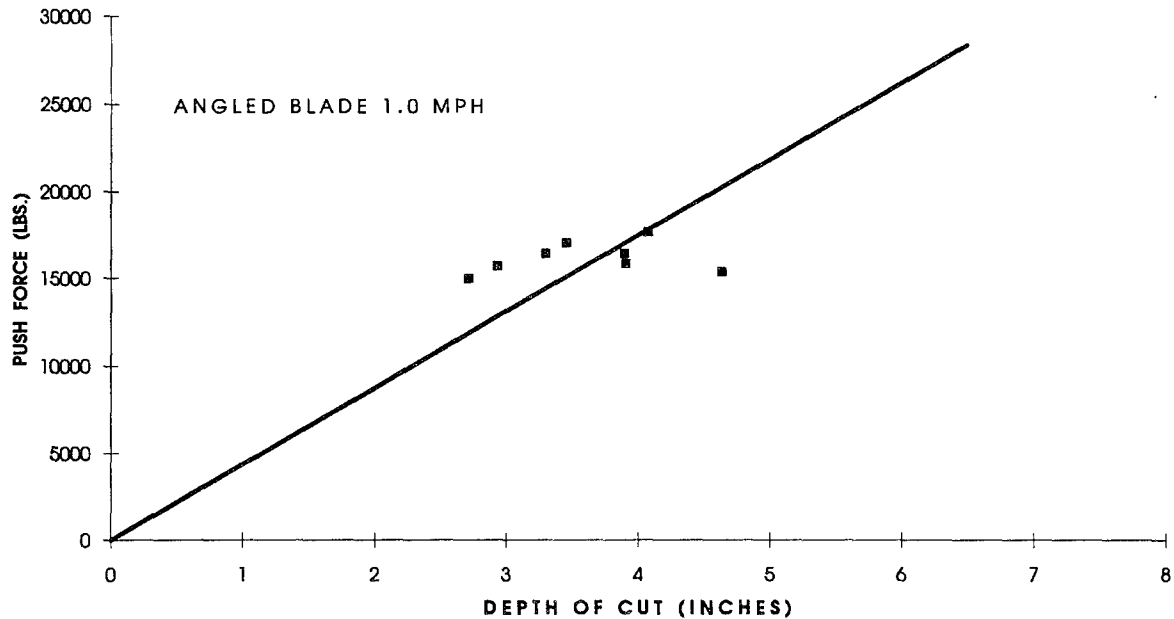


Figure 13. Push Force vs. Depth of Cut (D7-G with Standard Angle Blade)

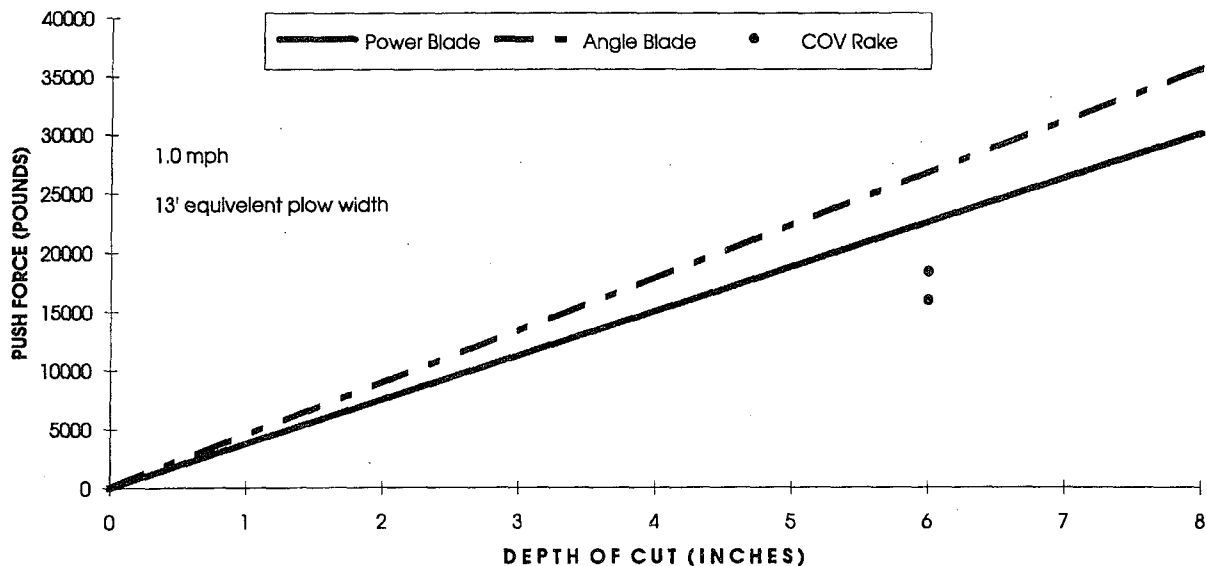


Figure 14. Push Force vs. Depth at 1.0 mph, 13' Equivalent Width

Analysis of Clausen Benefits on Push Force. As might be expected, the non-power angle blade requires the highest push force to plow at a given depth, followed by the Clausen Power Blade which lowers the push resistance by reducing the amount of soil carried on the blade face. The COV rake data points show the least push force since no soil is carried forward and resistance consists only of soil shearing. In addition, the discreteness of the tines versus the continuous cutting edge on the blades result in less shearing surface created per lane width using tines only.

In summarizing the comparison between these systems, the obvious conclusion is that the less soil carried against the blade or rake, the better the ability to plow. Where possible, raking, which produces almost no soil movement is the best choice for low push force. Raking may not always be possible due to soil conditions, (tine clogging etc.) and may not fulfill mission requirements (sift small mines, move soil etc.) Comparing the D7-G with Clausen Power Blade to the D7-G with angle blade, the data show the power blade equipped tractor to have about twice the depth cutting capability. By using the maximum push forces of 18,000 and 28,000 pounds for each of these systems and the line slopes of Figure 14 of $m_1 = 4463$ lbs./inch (angle blade) and $m_2 = 3755$ lbs./inch (Clausen Power Blade), a theoretical maximum plowing depth of $18,000/4463 = 4.03''$ for the angle blade and $28,000/3755 = 7.45''$ for the Power Blade in this soil was obtained.

The additional 3.42'' of plowing depth the Clausen Power Blade equipped D7-G has over the angle blade equipped D7-G can be incrementally attributed to: (1) increased traction, (2) soil unloading, and (3) a synergy between the two as follows. The additional plowing depth solely attributable to the increased system push force (resulting from increased weight) is given by $\Delta F \times 1/m_1 = (28,000 - 18,000)/4463 = 2.24''$. The additional depth solely attributable to the reduced slope of the push force data line of Figure 14 is $F \times (1/m_2 - 1/m_1) = 18,000 \times (1/3755 - 1/4463) =$

.76". The synergistic effect of the additional push acting with the lowered slope is given by $\Delta F \times (1/m_2 - 1/m_1) = (28,000 - 18,000) \times (1/3755 - 1/4463) = .42"$.

In summary, adding the Power Blade to the D7-G increased the capability in terms of depth of cut from 4" to 7.4" at 1.0 mph, or approximately 84%. Figure 15 shows the distribution of this increase due to added traction, lowered plowing resistance, and the bonus effect from the two combined. The power consumption analysis, to be discussed later in this text, will cover these capability differences in terms of the "costs" of prime power used to achieve these increases.

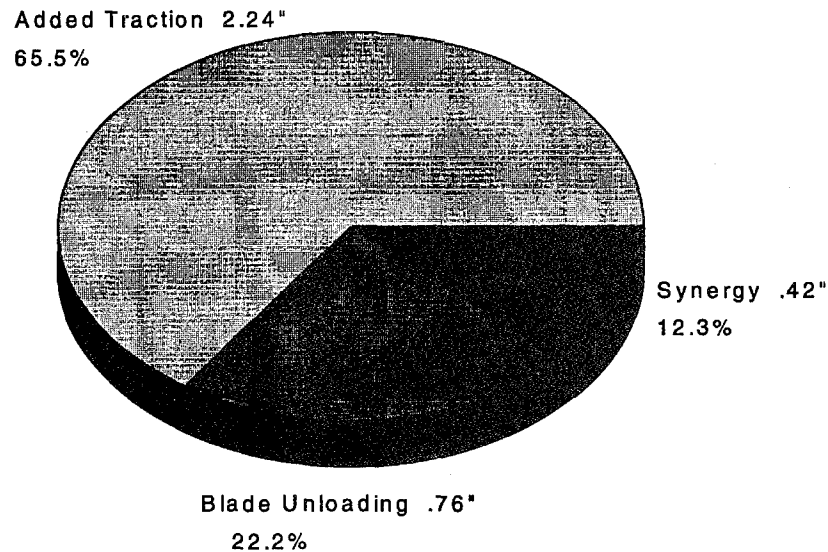


Figure 15. Increased Capability at 1.0 mph

Power Consumption Analysis

Examination of the power used in pushing the blades and in turning the power belt is purposeful both for revealing the ability of the Clausen Blade to deliver useful work to the soil removal task, and in revealing the efficiency with which the side sweeping concept makes use of this power.

Belt Power Consumed by Clausen Power Blade. A plot of the belt power versus depth of cut derived from the Power Blade runs used in the force analysis is shown in Figure 16 along with a least squares fit line. The powers used in the Figure were reduced by the amount of frictional losses measured in the belt and motors (see Figure 9) in order to conduct these analyses on the basis of output power actually delivered to the soil. The push powers reported in the next paragraph were measured "downstream" of any losses and therefore already represent a net work output. The fitted line suggests that there is negligible loading on the belt until the blade reaches a depth of 2". The cutting edge on the blade is 6" high and apparently acts as a moldboard, tumbling and pushing the plowed spoils for shallow cuts. As the blade is pushed deeper, soil covers the cutting edge and begins loading the power belt.

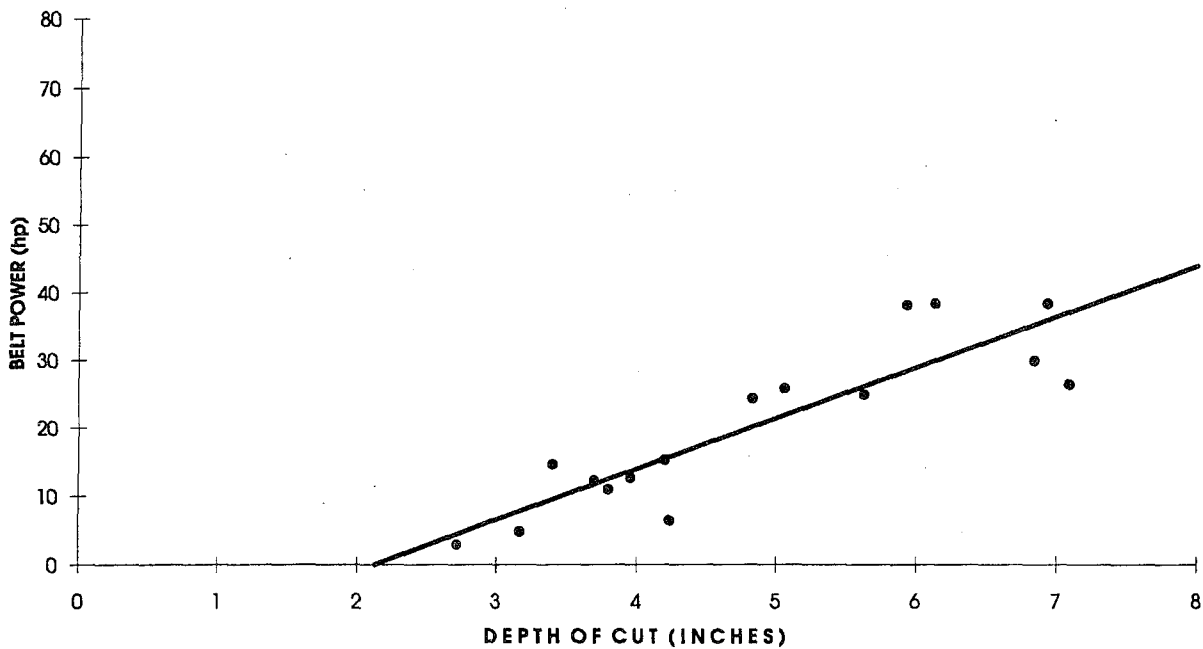


Figure 16. Consumed Belt Power vs. Depth of Cut (Clausen Blade)

Comparison of Power Consumption Between Clausen Power Blade System and Angle Blade

System. The total push power for the angle blade, D7-G, is compared with the push power for the Clausen Blade D7-G and the sum of the push power and belt power for the Clausen Blade D7-G. Figure 17 is constructed using data from the same runs reported in the force comparisons. Each system performed 150' plowing runs at an average speed of 1.0 mph. Again, data for the angle blade has been scaled up by 2.3% to account for the difference in path width.

Notice that although the power blade equipped D7-G requires less push power to perform the same cut, on average, the total power (push power plus belt power) is nearly identical to the D7-G angle blade push power. This would indicate that in a power limited vehicle, the effectiveness of adding more power would not be dependent upon whether the power is added to the vehicle tracks or to the power blade belt.

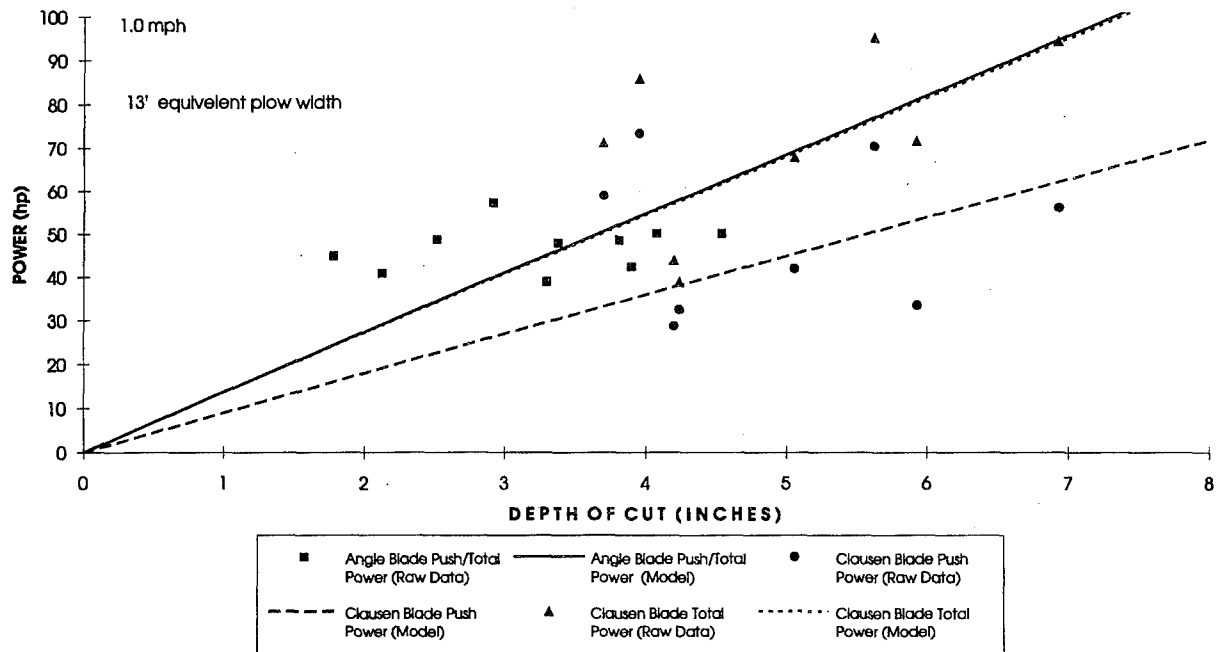


Figure 17. Comparison of Consumed Power at 1.0 mph vs. Depth of Cut

Host Tractor Available Power Limits for Clausen Power Blade and Angle Blade. Figure 18 shows the drawbar and power output characteristics of the D7-G derived from the Caterpillar Performance Handbook.² The vehicle drawbar in Figure 18 can be used to find the speed below which the D7-G becomes limited by traction and not power. As stated earlier, the D7-G tractor with angle blade exceeds available traction at ~18,000 pounds. From Figure 18 this is below 1.95 mph. For the Clausen Blade equipped D7-G the traction was ~28,000 pounds corresponding to a speed of 1.55 mph. Figure 19 shows the net output power which the D7-G engine is able to couple to the ground with these traction limitations included.

Deliverable Power Limits for Clausen Power Blade and Angle Blade. In Figure 19, it can be seen that at 1.0 mph the D7-G tractor has about 135 horsepower available at the tracks, but is only able to deliver about 50 horsepower to the plowed ground. The additional power above 50 hp cannot be delivered as useful work, and ends up being lost in frictional slippage between the tracks and ground and as heat in the steering clutches of the tractor (see discussion of side thrust). The weight of the power blade increases this deliverable fraction of tractor power from 50 to 80 horsepower. Returning momentarily to Figure 17, the fitted lines extend across the range of depths from 0 to 8 inches. This was done in order to compare the usage efficiency of power between the two different systems, but it is misleading from the stand point of this discussion of limited ability to deliver power. Examining the raw push power data in Figure 17 shows that the angle blade equipped D7-G data was all obtained at or below ~50 horsepower. Similarly, the Power Blade equipped D7-G raw push power data is at or below 80 horsepower. Thus the “angle blade” fitted line of Figure 17 should really terminate at 4” because the tractor cannot deliver any additional power even though such power is available from the vehicle engine.

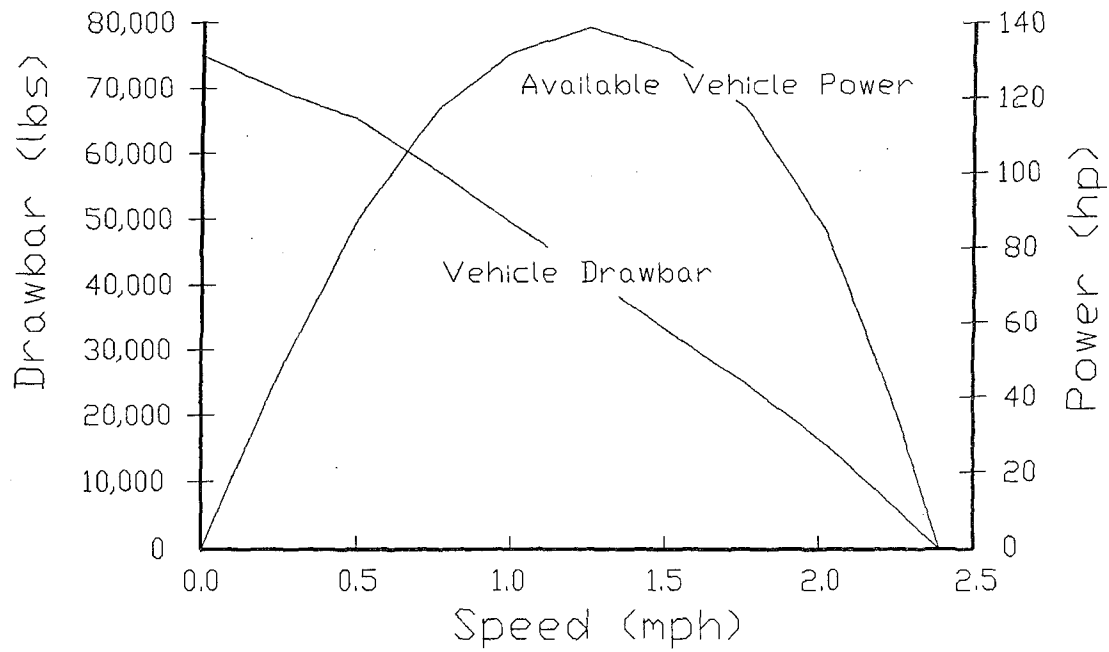


Figure 18. D7-G Drawbar and Available Power

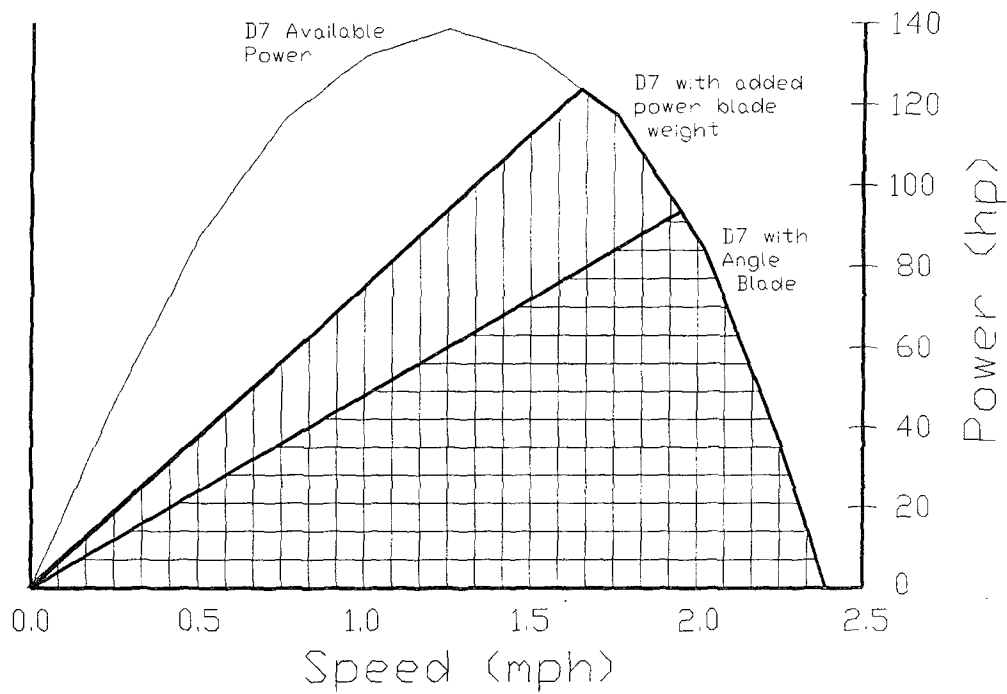


Figure 19. Usable Tractor Power with Limited Traction

Deliverable Power Limits (Clausen Power Blade). In the Clausen Power Blade equipped D7-G, the 80 hp deliverable vehicle power limitation does not limit the cutting depth to the expected 6' because the belt is capable of delivering some additional power to the plowed soil. Unfortunately, the power blade also has an operating regime analogous to a traction limited vehicle. There is a point beyond which adding additional power to the blade buys little additional capability because there is also a limit to the amount of power that can be coupled to the soil through the side sweeping belt. For a discussion of the mechanics of why this limit exists see the analysis of "Belt Speed". For an estimate of the numerical value of this limit consider Figure 16 which shows belt output power recorded at various plowing depths. It is known from the previous discussion that by the time 6 inches of plowed depth is reached, the tractor is delivering its limit of 80 horsepower. Therefore, the depths reached deeper than this are limited by either the available power in the Clausen Power Blade, or in the amount of power the Power Blade belt is capable of coupling to the plowed soil. The available belt output power of the Clausen Blade was measured to be at least 90 horsepower, prior to opening of the hydraulic relief valve. As a result, it must be concluded that the maximum output powers recorded in the raw data of Figure 16 represent the limit of deliverable power from the Power Blade belt. This limit is about 38 hp.

Summary of Power Comparison and Usage. In summary, the usage efficiency of output power is roughly equivalent between the side sweeping belt and the vehicle tracks. Thus, in a power limited vehicle, the beneficial effect of adding additional power would depend very little on whether the additional power was added to the vehicle or to a side sweeping power belt. In a traction limited vehicle, however, the extra power would be better spent by introducing the side sweeping power belt because the vehicle tracks have already delivered the greatest amount of power they can couple to the soil. Most of the plowing performed during this test falls into the category of traction limited. Unfortunately, the Power Blade also has a limit on the amount of its available power which can be delivered as useful soil moving work. Raising these limits requires additional traction (weight) in the case of the vehicle power limit and additional push force in the case of the side sweeping blade power limit. Since the additional push force also requires additional traction, the deliverable power limit of the side sweeping blade is directly linked to the deliverable power limit of the vehicle itself. Figure 20 now includes the Clausen Power Blade on the "deliverable power" diagram.

Effect of Power Usage on Plowing Performance. The limiting value slopes of the push force vs. depth line (Figures 12 and 13) was estimated as the plowing speed is reduced to zero for the Clausen Power Blade and the angle blade. In doing so, depths of cut can be associated with the plowing speeds in Figure 20 in order to fully describe the benefits of the side sweeping concept. Table 5 is constructed from Figure 20 and provides the plowing speed and expended power for the range of depths. With access to the perfect testbed platform described in Section 3, it would be possible to measure this data directly. Instead it must be derived, and the estimation of the zero speed force slopes cast the resulting numbers as predictions illustrative of the trends rather than factual data.

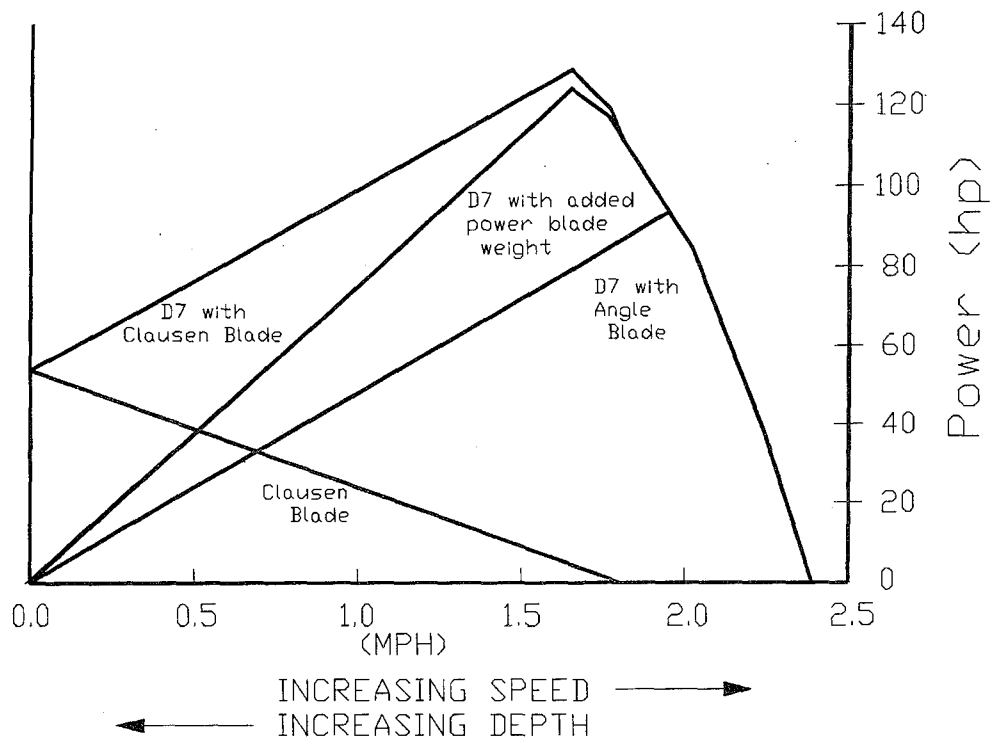


Figure 20. Deliverable Power for D7-G/Angle Blade, D7-G/Angle Blade + 24,000 lbs, and D7-G/Clausen Blade

Table 5. Estimated Maximum Power Performance of D7-G with Angled Blade, D7-G with Angled Blade + 24,000 lbs Added Ballast, and D7-G with Clausen Blade

Depth	0"	1"	2"	3"	4"
Standard Angle	2.4 mph 0 hp	1.85 mph 92 hp	1.29 mph 62 hp	.75 mph 38 hp	.22 mph 11 hp
Angle + 24,000 lbs	2.4 mph 0 hp	1.95 mph 92 hp	1.65 mph 73 hp	1.34 mph 101 hp	1.0 mph 80 hp
Clausen Blade	2.4 mph 0 hp	1.95 mph 92 hp	1.87 mph 91 hp	1.6 mph 113 hp	1.34 mph 116 hp
Depth	5"	6"	7"	8"	9"
Standard Angle	0	0	0	0	0
Angle + 24,000 lbs	.64 mph 50 hp	.28 mph 21 hp	0	0	0
Clausen Blade	1.08 mph 108 hp	.8 mph 95 hp	.53 mph 80 hp	.26 mph 41 hp	0

SOIL TYPE DEPENDENCE

Push Force Dependence on Soil Type

The comparative plowing runs were conducted in previously plowed, compacted soil in order to have common conditions for making the plowing comparisons. A limited number of runs with the Clausen Power Blade were conducted in undisturbed soil (bank condition) and in loose fill dirt in order to be able to assess how well the results apply to other soil conditions. Figure 21 shows the push force data for these runs. Although there are few data points, the least squares lines have been drawn in as well as the 1.0 mph line in compacted soil copied from Figure 12.

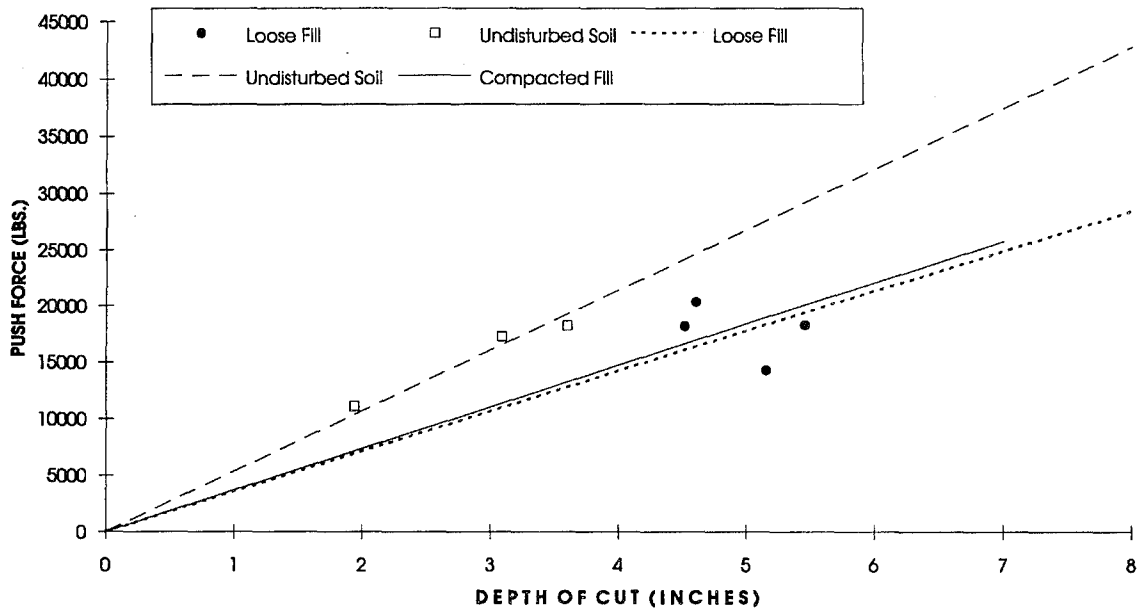


Figure 21. Push Force vs. Depth of Cut (Clausen Blade in Different Soil Conditions)

Power Dependence on Soil Type

The belt power and total power for the bank condition and loose fill runs is plotted in Figure 22. If the belt powers of Figure 22 are expressed as a fraction of the total power expended for these data and for the data from the plowing done in compacted soil reported earlier, the average values are 14% in bank soil, 32% in compacted soil, and 35% in loose fill. This trend is not unexpected since the belt is loaded with a nearly fixed volume of soil dependent only on the depth of cut while the cutting edge is loaded with the increasingly shear resistant conditions shown by the 3 lines in Figure 21. This raises the portion of work delivered through pushing while holding the belt power relatively constant as one moves from loose soil into increasingly shear resistant soils.

This data documents another aspect of the side sweeping concept. The more cohesive the soil, the smaller the work fraction the power blade is able to deliver, and conversely, the more the soil is characterized as frictional, the better the power blade is able to couple useful work to the moving soil mass.

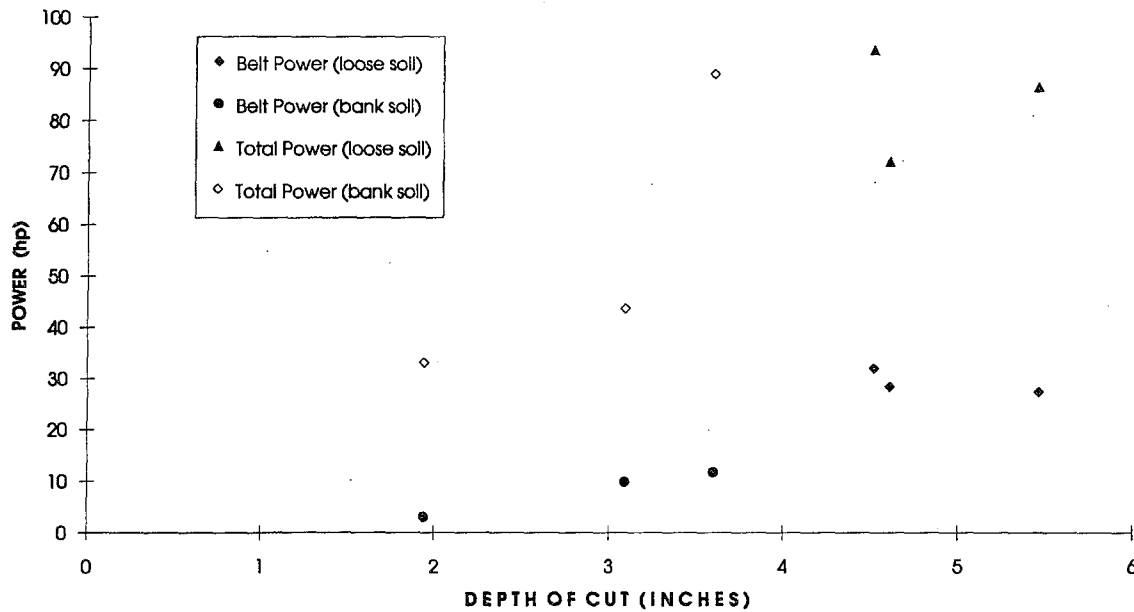


Figure 22. Claussen Blade Power Consumption in Various Soils

SIDE THRUST

A V blade has two inherent advantages over an angled blade with respect to making a single, straight cut. The first of these is that soil is, on average moved a shorter distance transverse to the plowing direction, requiring less work. The second advantage is that the side thrusts from each side of the blade cancel one another, whereas there is the large unbalanced side directed force, with the angled blades, mentioned earlier. This unbalanced force produces a turning moment, creating a tendency for the tractor to turn away from the side on which the spoils are being left. NCEL measurements of the natural drift of the Claussen Power Blade plowing hard clay, ref. 3, suggest that side thrust, if not compensated for, will cause the tractor to turn on an arc of 228' radius. Such an arc would turn the tractor through an angle of 92 degrees during a 100 meter minefield crossing. An examination of the available data and dozer geometry will give an indication of the magnitude of the problem and suggest some improvements.

Calculation of Side Thrust

Figure 23 diagrams the main loads acting on the plow front. The cutting force is a distributed load acting normal to the blade. This force is assumed to be constant across the width of the blade. The pressure on the moldboard is also normal to the blade but increases from left to right as the soil accumulates higher on the face from left to right. The normal force equivalent to these distributed loads is slightly right of blade center. There will also be a distributed frictional force from the sideways flow of soil across the cutting edge which is tangent to the blade front. This force is equal to the friction coefficient (assumed .2 for metal to soil) multiplied by some fraction of the normal load. There will also be a tangential force on the power blade resulting from the side thrust of soil by the belt. Using typical measured values of 32 hp for the loaded belt output

power and 4.4 ft/sec for the belt speed, the reaction to the soil thrust is calculated as ~4000 lbs. The frictional force is small in comparison with the soil thrust, which is itself small in comparison with the normal forces. If the frictional force is ignored, the force equilibrium on the plow front is completely known if the typical measured axial push force of 28,000 pounds is used. Using vector addition with the equivalent normal force and equivalent tangential force, and then resolving the result into components which are parallel with the plowed path and transverse to it allows calculation of the transverse component and results in a force equal to 16,850 lbs.

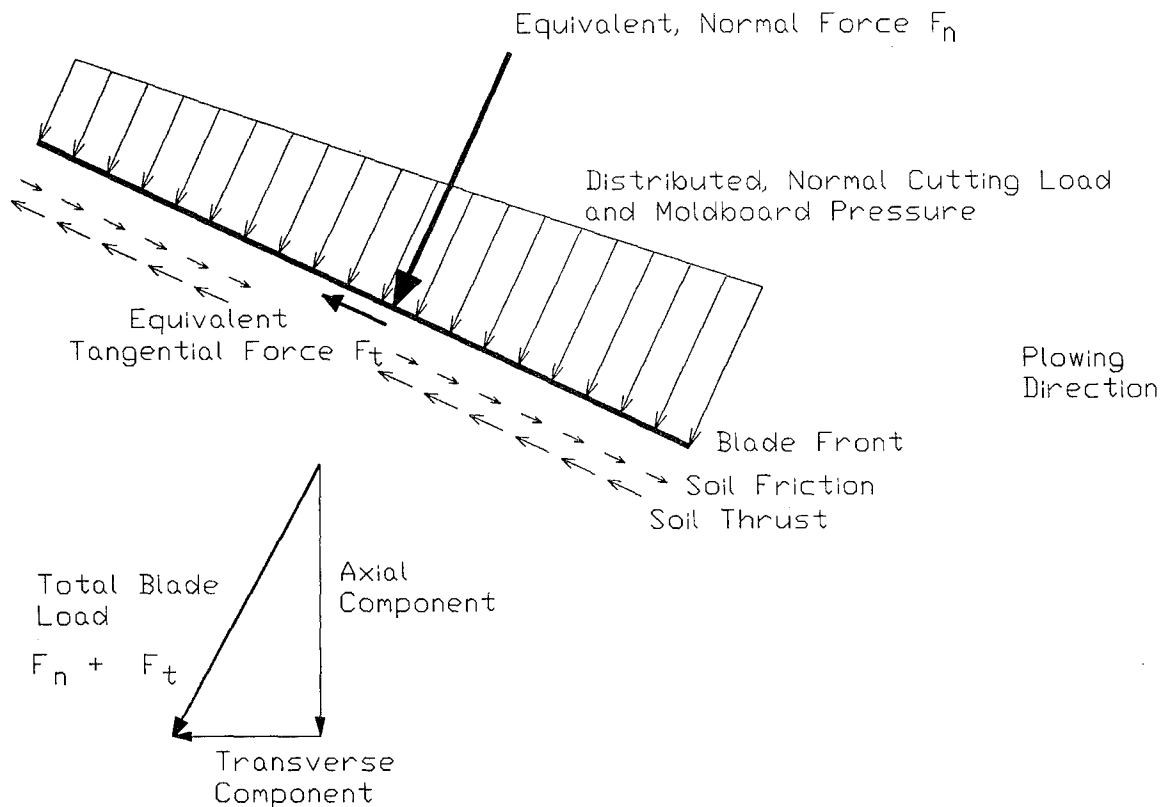


Figure 23. Loads on Clausen Blade Front with Level Plow

Impact of Side Thrust on Plowing Performance

From Figure 2 it can be seen that this 16,850 lb force has a moment arm on the vehicle center of mass which is between 120 and 145 inches. Assuming the point of application is a quarter of the way from the blade midpoint to the right tip gives $r=135''$ resulting in a left turning moment of 189,500 ft-lbs. The axial component will balance this somewhat. However, the moment arm is much smaller, $r=37.5''$, and the resulting right turning moment is 87,500 ft-lbs. The net result is a left turning moment of 102,000 ft-lbs which must be countered. To attempt to counter this moment completely with steering control would be futile. The axial push of the tracks is located only 42'' from the center of mass. This would require the left side to push 27,800 lbs. harder than the right side, giving a right track push of 100 lbs. and a left side push of 27,900 lbs. The

available traction for each track is considerably smaller than the 27,900 lbs. required on the left side, making compensation by steering impossible. Also the steering is accomplished by applying a clutch to the "weak side", thus causing a net loss of pushing effort.

Additional Impact of Side Thrust on Mine Clearing Performance

Countering the side thrust problem unfortunately had a direct negative effect on mine clearing performance. Since it is impossible to get complete directional control by steering, the operator would gain control by tilting the blade to the soil deposition side (right side in the setup). The resulting cut, shallower on the left side and deeper on the right, forces a change in the distribution of the normal loads as diagrammed in Figure 24. The application point of the equivalent load is moved further to the right of blade center giving the axial component a larger moment arm on which to act to counter the left turning moment of the transverse component.

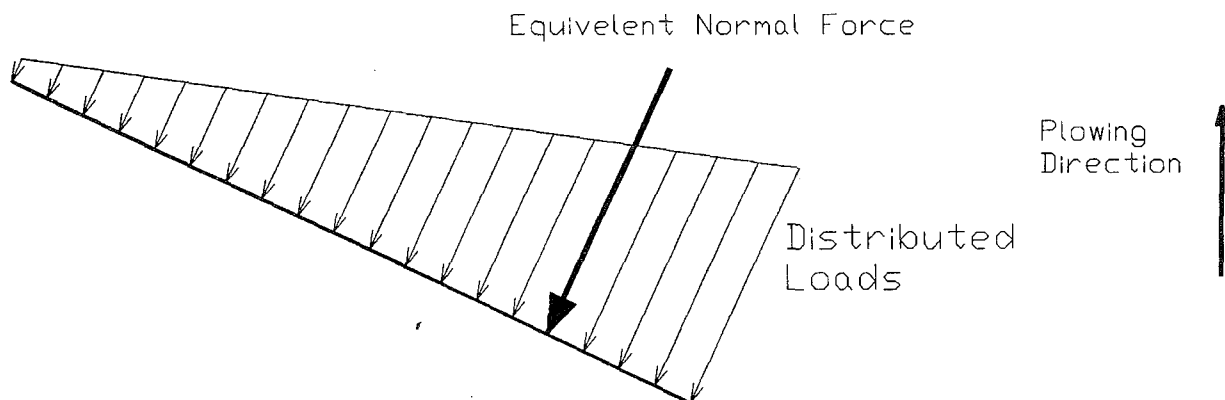


Figure 24. Redistributed Normal Loads on Clausen Blade Front

Review of the experimental data show that, on average, the operator kept the amount of unbalance between the push of the right and left tracks to about 5000 lbs. As much as 3 degrees of tilt to the right was required to accomplish this force balancing on the deepest cuts. The depth data cited in this report are the average across the width of the lane. With 3 degrees of rightward tilt, the left side of the cut is 4" shallower than the average, and the right side is 4" deeper than the average. If a minimum plowing depth is required, there will be up to 8" of unnecessary plowing done on the deep side in order to maintain the shallow side at the minimum depth.

BELT SPEED

Conceptually, it would appear that the minimum expended work would be performed in soil removal if the belt face and soil moved in lock step perpendicular to the plowed path. In practice, soil is going to be carried down the path and there is going to be relative motion between the belt and soil. As a starting point for this discussion, Figure 25 shows the velocity vectors for the tractor (and cutting edge), the belt face, and the plowed soil. These data were

obtained from a typical mine plowing run in compacted soil. The soil velocity was calculated from the mine movement reported in the next section.

Notice from Figure 25 that the belt face has a small net velocity up the path (toward page bottom) despite the tractor velocity down the path (toward page top). In an earlier study of the Clausen Blade, NCEL reported a diminishing return on increasing belt speed beyond 4 ft/sec. with a tractor speed of 2 ft/sec, ref. 3. The NCEL report characterizes blade performance by the relative soil volume carried on the blade face with and without the power belt running. The beneficial aspect of the power blade is termed "unloading factor" which expresses the volume fraction of soil which has been unloaded by the belt.

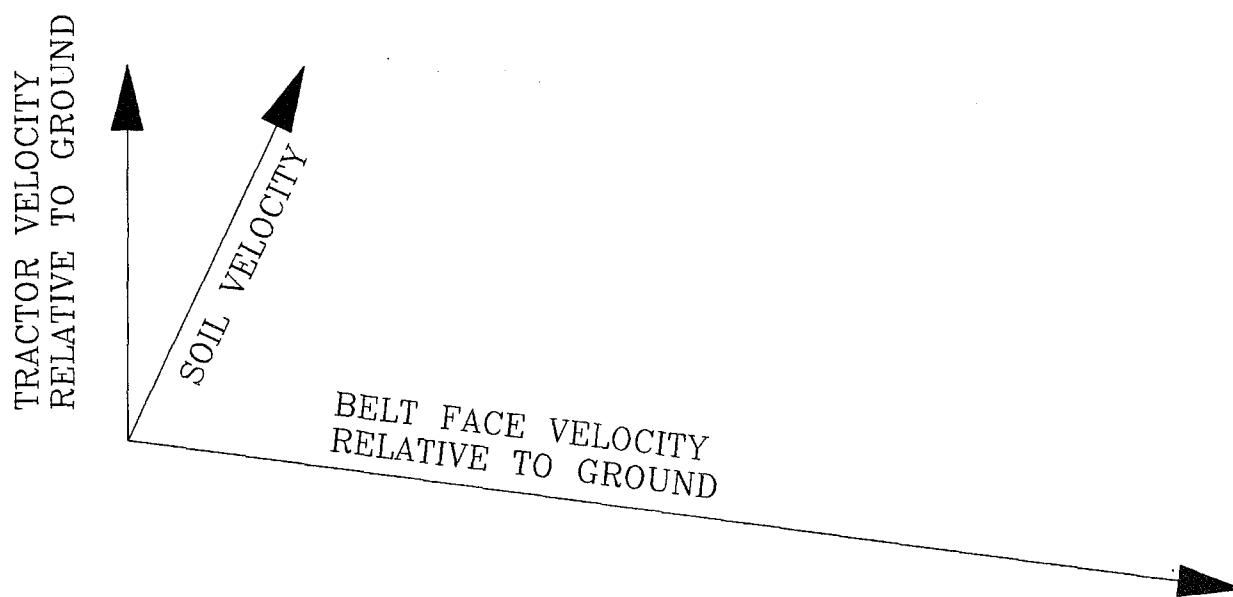


Figure 25. Typical Plow and Soil Motions, Clausen Power Blade

Figure 26 presents the unloading factors measured by NCEL along with the belt velocity vectors, tractor velocity vector, and assumed soil velocity vector. The belt velocities and unloading factors are presented for the four different belt speeds at which the measurements were reported. Note the difference between belt speed which is measured relative to the tractor, and the belt velocities which measure speed and direction relative to the (unplowed) ground. The assumed soil velocity was based on the mine movements reported in the next section, scaled up proportional to the difference in tractor speed between those mine tests and the plowing tests NCEL used to compute the unloading factors. The incremental benefit to increased belt speed steadily declines as the belt velocity vector becomes perpendicular to the direction of tractor travel. The first increment (from 0 to 1 ft/sec) is very effective in unloading the blade (22%). At this belt speed, the belt face is moving to the right at the same rate the soil is moving to the right. Effectively, the belt has removed the frictional drag the soil would have encountered sliding laterally over the face of a non-powered, angle blade. The next belt speed increment (from 1 to 2

ft/sec) produces 17% more unloading. The amount of slippage between the belt and the soil (the horizontal distance between the arrow tips) is about the same as the amount of slippage that was removed in going from 0 to 1 ft/sec; however, the slippage is in the opposite direction. The next increment (from 2 to 3 ft/sec) produces 10% more unloading. Not only is the velocity vector continuing to lay over farther and farther out of alignment with the normal force that provides the static friction needed to move the soil with the belt, but the normal force has been reduced by the smaller moldboard soil volume carried. By the time the final measured increment (from 3 to 4 ft/sec) of belt speed is reached, the belt is moving nearly perpendicular to the dozer travel, and the amount of added unloading is down to 3%.

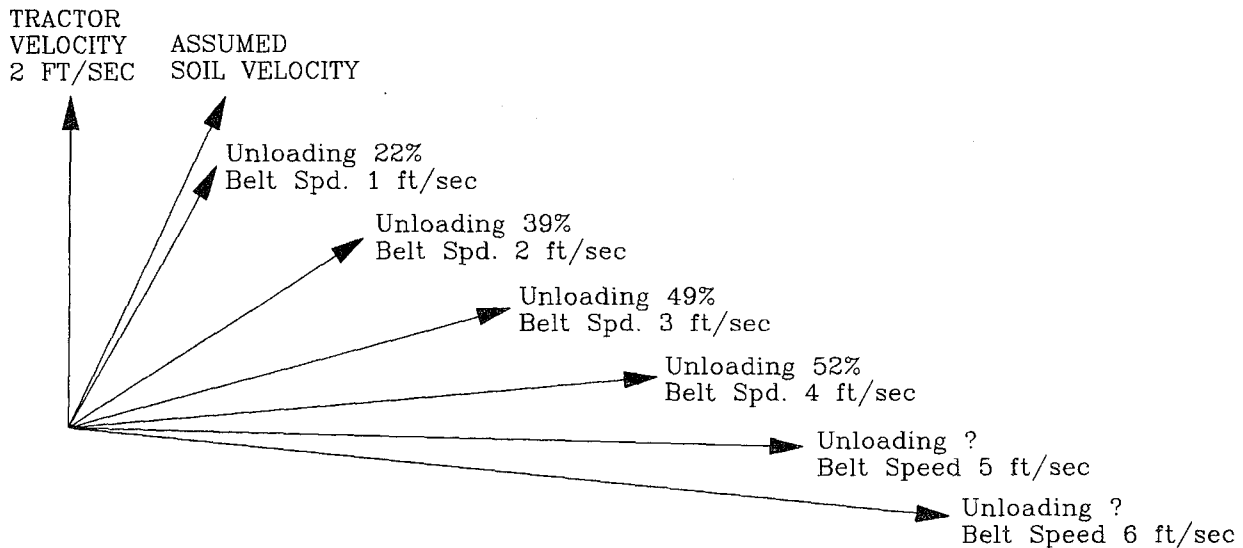


Figure 26. Unloading Factors and Belt Velocities

The conclusion drawn from this is that in order to maximize belt efficiency, the sweeping blade needs to be sized such that when loaded, the tractor and belt motor speeds produce a belt velocity with an angular offset about 25 degrees clockwise from the blade normal. This is equivalent to the tractor velocity which is offset 25 degrees counterclockwise from the blade normal. In general, the belt velocity angular offset should be equal and opposite the tractor velocity angular offset from blade normal. For the tractor running at 2 ft/sec as in Figure 26, this is a belt speed of 2 ft/sec. To maximize, (within reason) the belt power coupled to the soil, the belt motors must be sized such that the belt moves nearly perpendicular to the plowed path. Increasing belt speed beyond this will require prime power which mainly feeds internal friction losses with little increase in unloading.

Section 6 Mine Clearing

MINE SURROGATE PLOWING

Dummy mine bodies were plowed with the Clausen Power Blade in order to assess several issues. The first issue is the question of whether there is any characteristic concerned with clearing mines from the side sweeping plow path which distinguishes its performance from soil clearing. The second goal of these tests was to document mine movement to assist in the belt speed analysis. The final objective was to gain some measure of the mine clearing reliability of the side sweeping concept. A word of caution concerning this final objective is that the test results are intended to be interpreted as an indication of, rather than a comprehensive examination of, mine clearing efficiency. There were no pass/fail criteria for the test; the mines were emplaced in regular patterns at known locations.

The Clausen Power Blade was used to plow mine bodies from the plow lanes in 6 separate tests. Each time, the mine bodies were laid over a 100 yard length of lane. As with the comparative plowing, elevation measurements of the lane were taken before and after each run. Mine locations before and after plowing were also recorded. Figures 27 - 32 show maps of the mine locations and movement when plowed. The outer box around the mines approximates the swath left by the cutting edge. The inner box traces the outer edges of the D7-G tracks. Numbers corresponding to each mine are shown outside the lane just to the right of its original location. The numbers of mines which were not picked up by the cutting edge, or which were left within the inner box, are circled. All burial depths are recorded on the basis of measurement from the lane surface to the bottom of the mine.

The shallowest field used mines buried 4". Figure 27 shows the Clausen Power Blade had no problem reaching or clearing these mines. The average plowing depth for this lane was 5.1", and the speed was 1.07 mph. Rain the previous night had left the lane wet with one 4' wide puddle. The surface cone index was 65 psi, probably the softest of the compacted soils plowed over the course of this evaluation. The plowed soil came up in a cohesive sheet like the peel coming off an apple peeler.

The next mine burial depth was 5". Figure 28 shows each of these mines was engaged and cleared by the Clausen Power Blade. The average plowing depth for this lane was 7.03", and the speed was .62 mph. A light sprinkle the afternoon before had dampened the lane. The soil was compacted and the cone index was 143 psi.

The 6" depth was the first in which problems were encountered in reaching every mine. Figure 29 shows that 2 of the 27 mines engaged were left unplowed (the final three mines were not engaged). The average plow depth was 6.77", and the plowing speed was .87 mph. The lane was dry compacted soil.

The regular pattern of the other minefields was changed to the staggered pattern of Figure 30, with mines buried 6" for a demonstration. The ground was dry, compacted soil and the cone index was 260 psi. Figure 30 shows that 5 of the 20 mines engaged were left unplowed. The average plowing depth was 3.38". Plow speed was not recorded.

A third minefield using 6" burial was plowed. The first half of the lane was on dry compacted, soil. The second half was undisturbed (bank) soil. The purpose of the test was to document the mine fuze responsiveness to being plowed, but it also served as a comparison of the difficulty of clearing mines in the undisturbed soil and in the compacted soil used for the bulk of this evaluation. Smoke-fuzed pressure mines were used for this test. Figure 31 shows that all of the mines engaged in the compacted soil were cleared. However, in the undisturbed soil, 5 of the 15 mines were left unplowed.

The deepest minefield had mines buried at 7". The soil was compacted, and slightly damp. Figure 32 shows that 4 mines were unplowed, and another 4 were left in between the dozer tracks. The remaining 22 mines were cleared. The average plowing depth was 6.83", and the plowing speed was .43 mph. Soil conditions were similar to the 5" lane above, and plowing depth achieved between the two are similar.

The maps of mine movement consistently show the same trajectories for the mine bodies dependent mainly upon its initial location relative to the lane centerline. This repeatability validates mine movement as a measure of soil movement for the belt speed analysis. Many of the mines on the right hand side of the lanes appear in the maps as though they had not been moved or plowed. The peak of the berm left in the wake of the Clausen Power Blade is roughly even with the edge of the blade. The base of the berm is roughly 7' wide. There is some soil flow and mine movement around the end of the Clausen Power Blade. The mines were not marked as uncleared in the maps unless they rolled back in the path of the D7-G tracks. Table 6 summarizes the clearing performance. Again, these values are not comprehensive. The test was limited to one soil type, and clearing performance was probably enhanced by giving the tractor operator prior knowledge of the mine placements.

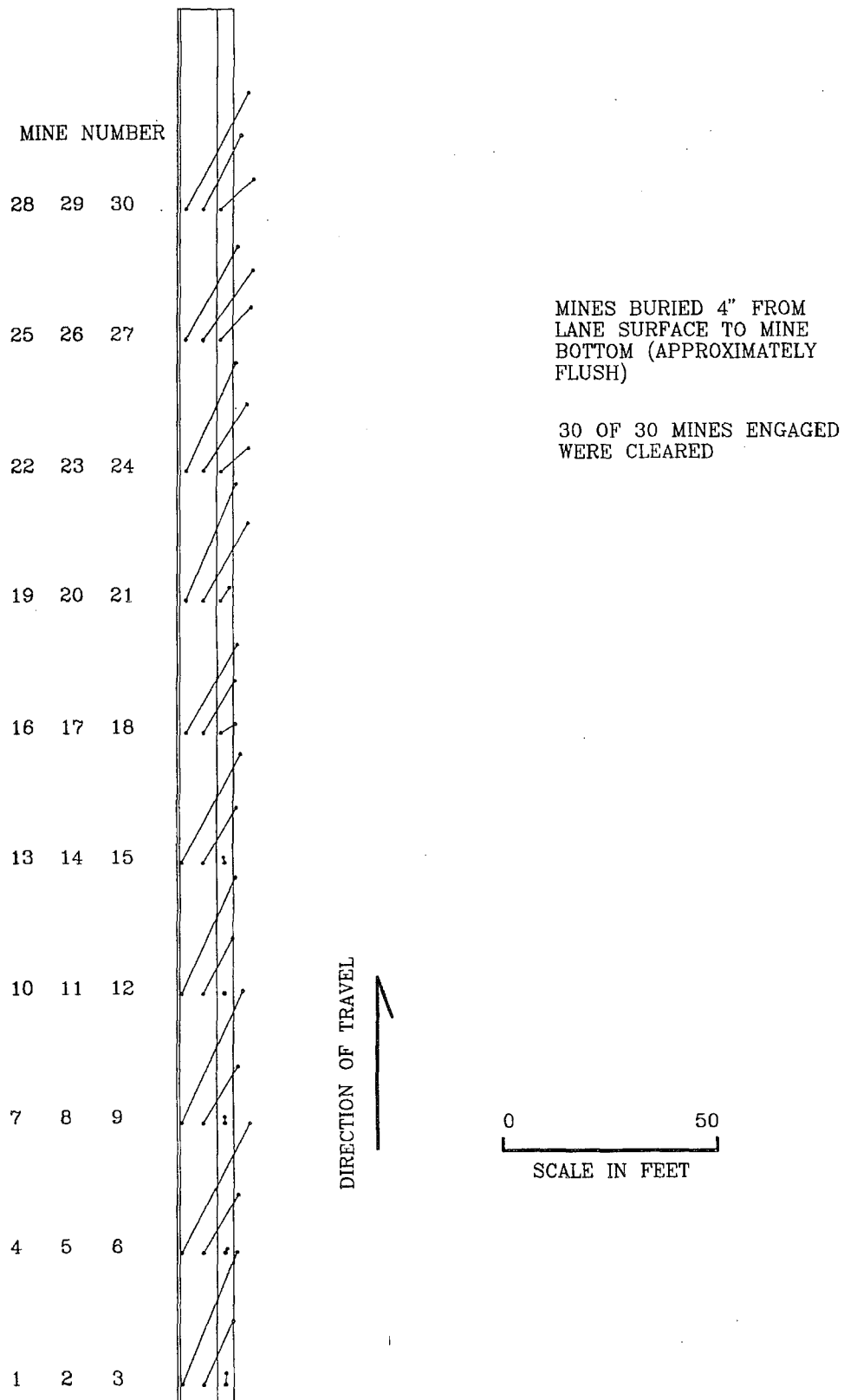


Figure 27. Breaching Mines at 4", Compacted Clay

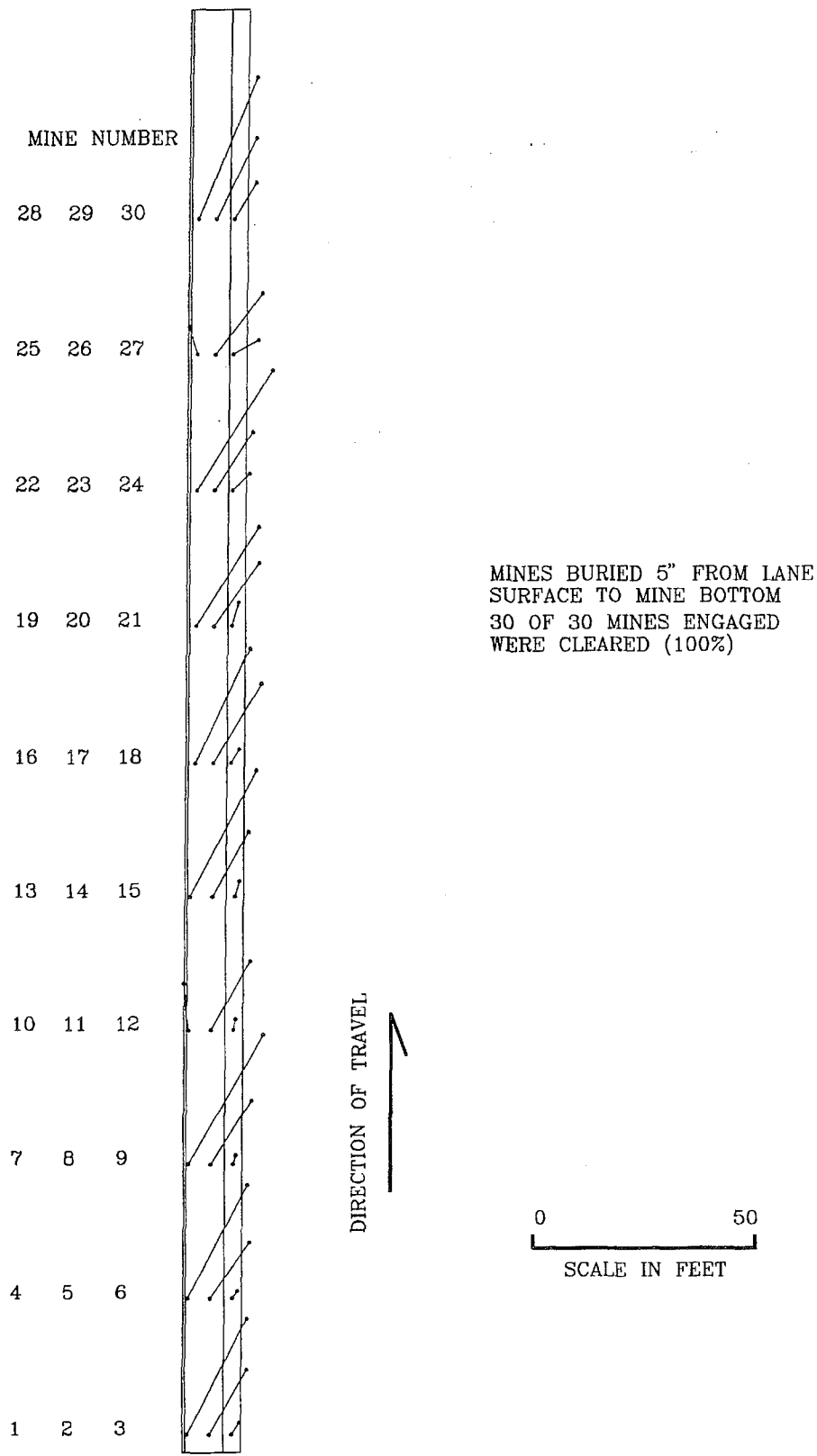


Figure 28. Breaching Mines at 5", Compacted Clay

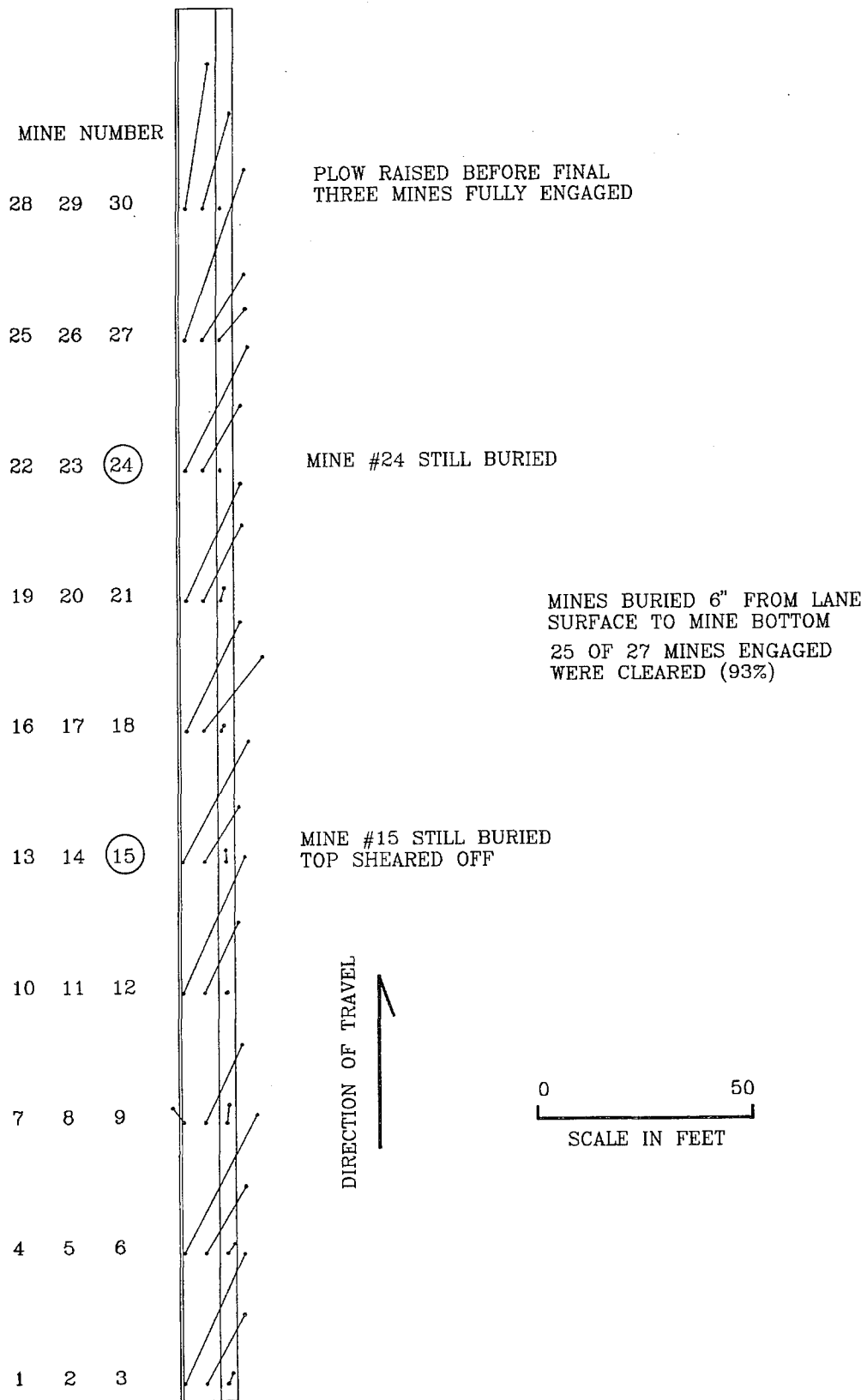


Figure 29. Breaching Mines at 6", Compacted Clay

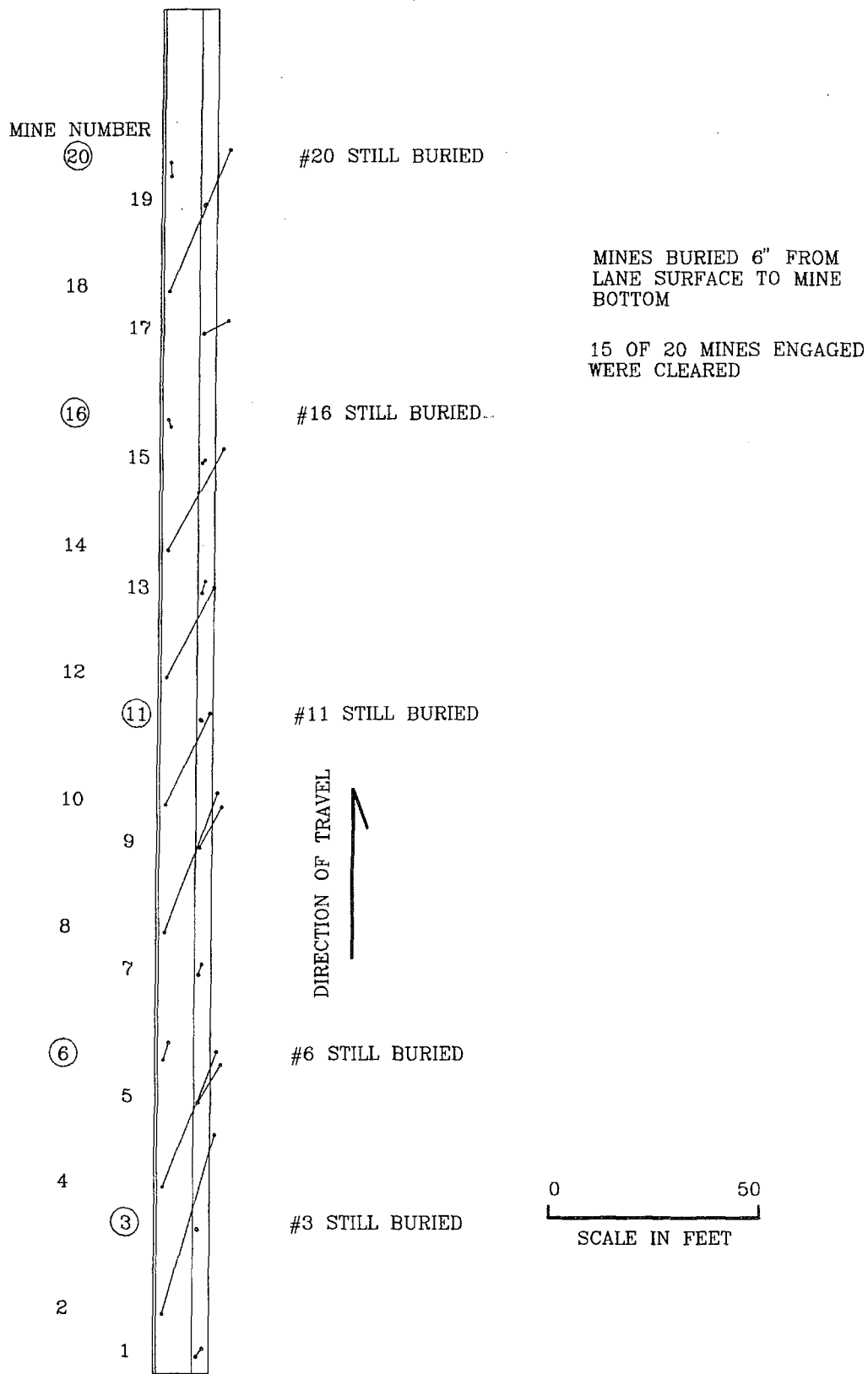


Figure 30. Staggered Pattern with Mines Buried at 6", Compacted Clay

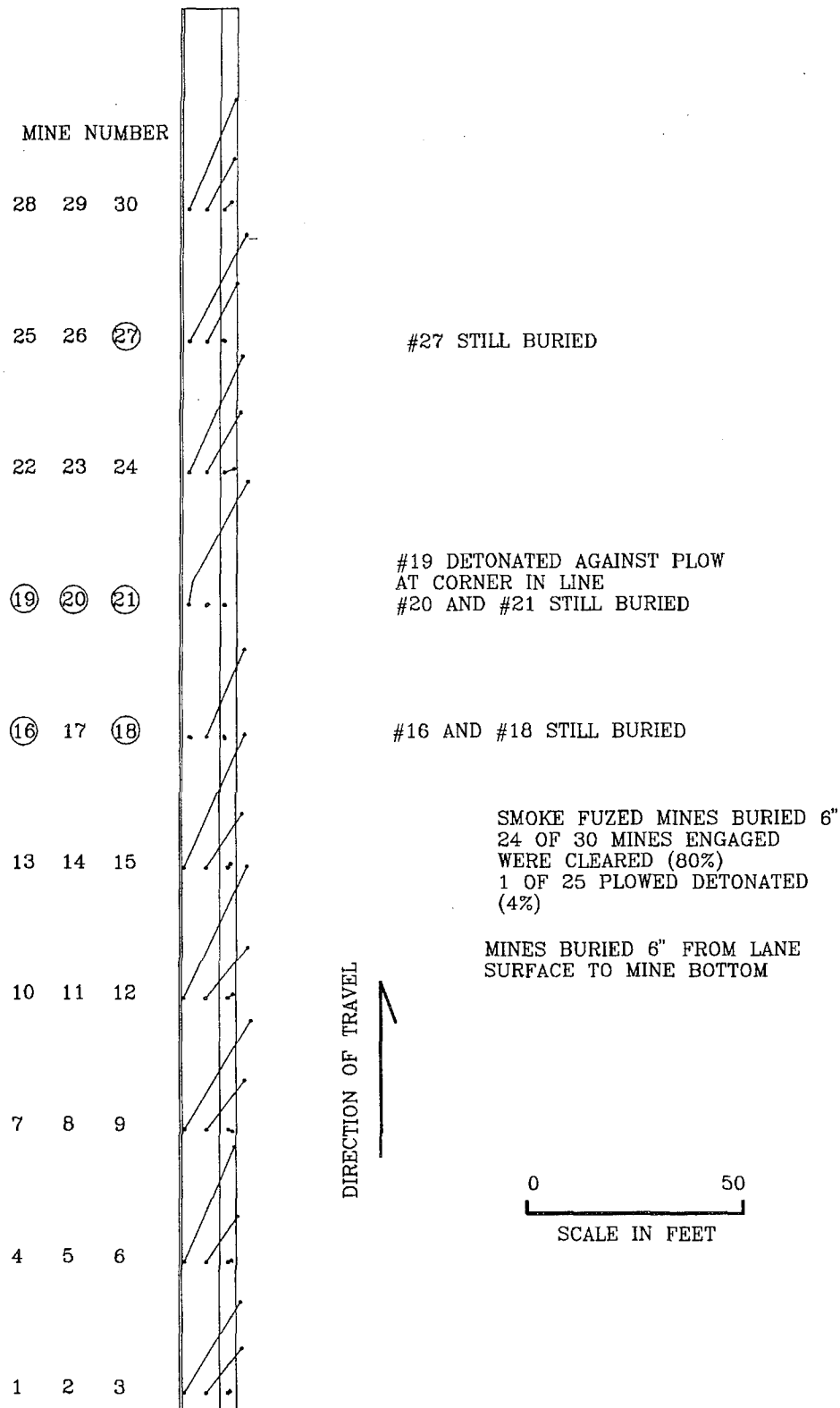


Figure 31. Breaching Mines at 6", Compacted Clay First 150', Undisturbed Clay Second 150'

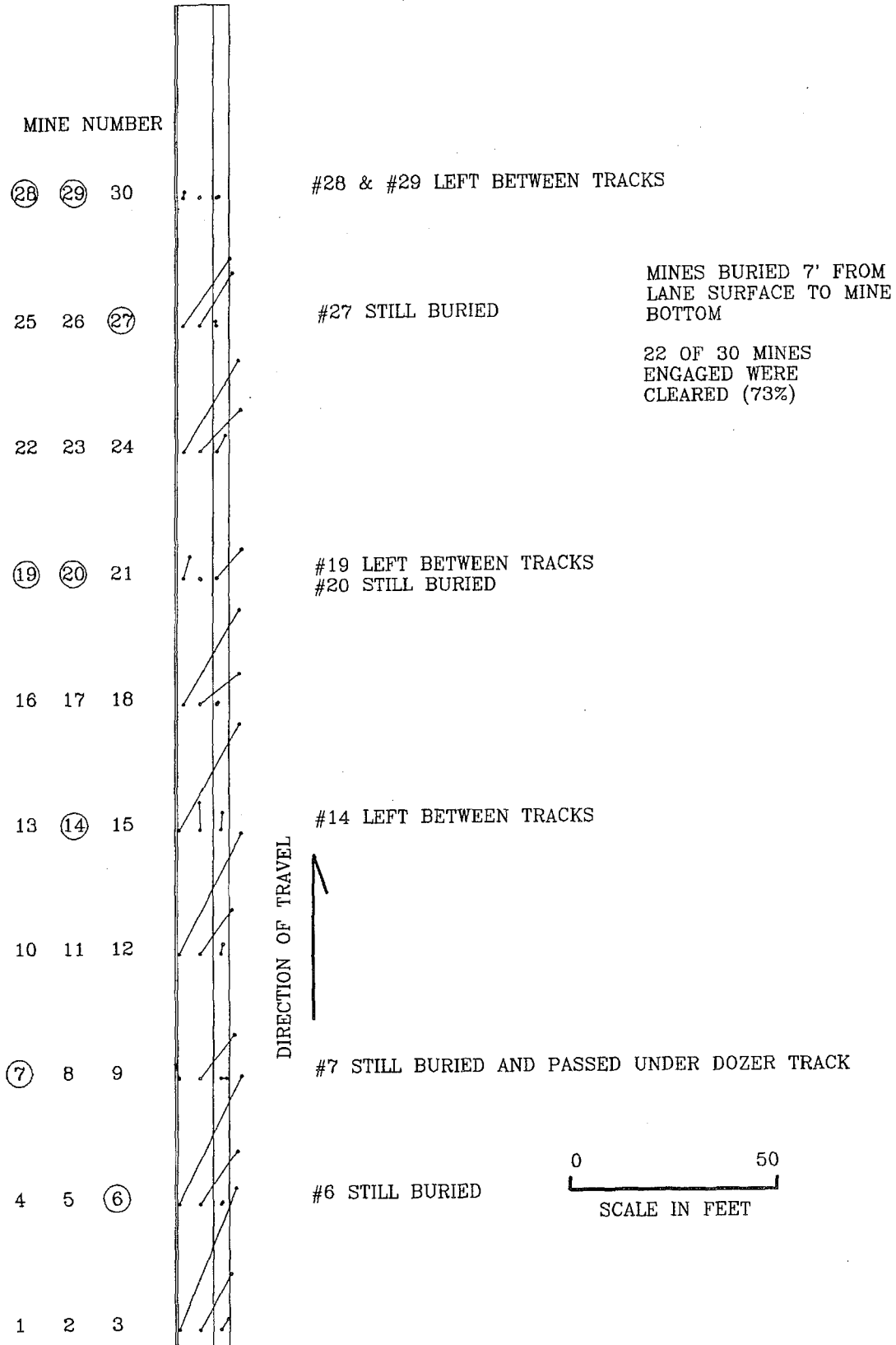


Figure 32. Breaching Mines at 7", Compacted Clay

Table 6. Mine Clearance

Mine Burial Depth	Mines Engaged	Clearance Percentage
4"	30	100.0%
5"	30	100.0%
6"	77	84.4%
7"	30	73.3%

MINE FUZE RESPONSIVENESS

The propensity of mines to detonate during plowing with the Clausen Power Blade was tested to aid the vulnerability assessment of the side sweeping blade concept. Plowing tests were conducted with mines fuzed to provide a detonation indication without posing a significant threat to the tractor. The smoke charged pressure mines mentioned above were used as well as magnetic mines with 1 gram clearing charges.

The pressure mines were laid out in a mine lane (see Figure 31) exactly as the rest of the clearing tests reported above. One of the 25 mines "cleared" from the lane detonated when it had been pushed about 5 feet from the point of its first contact with the blade. Although one detonation out of twenty five is a small number on which to base a statistical analysis, this is generally within the range expected on the basis of testing with other plow systems.

Magnetic mines typically present a greater problem for mine plows. Magnetic scatter mines were plowed with the Clausen Power Blade one at a time in an attempt to capture information concerning where and when they detonate during a plowing operation. Although the scatterable mine is surface laid, the fuze in the mines used for these tests is generally representative of magnetic mines as a class. Some of these tests were conducted with the mine buried at 4".

Seventeen of the 21 magnetic mines plowed did detonate in the soil pile in front of the plow. (1) The tumbling of the magnetic sensor in the presence of the earth's field and (2) the varying magnetic reluctance the sensor encounters tumbling near an iron mass are believed to be the triggers causing detonation. The results are presented as a probability function of the distance the mines were pushed when detonation occurred. Figure 33 gives this tumbling distance distribution. The average distance between the plow face and the mine at the time of detonation was 22 inches.

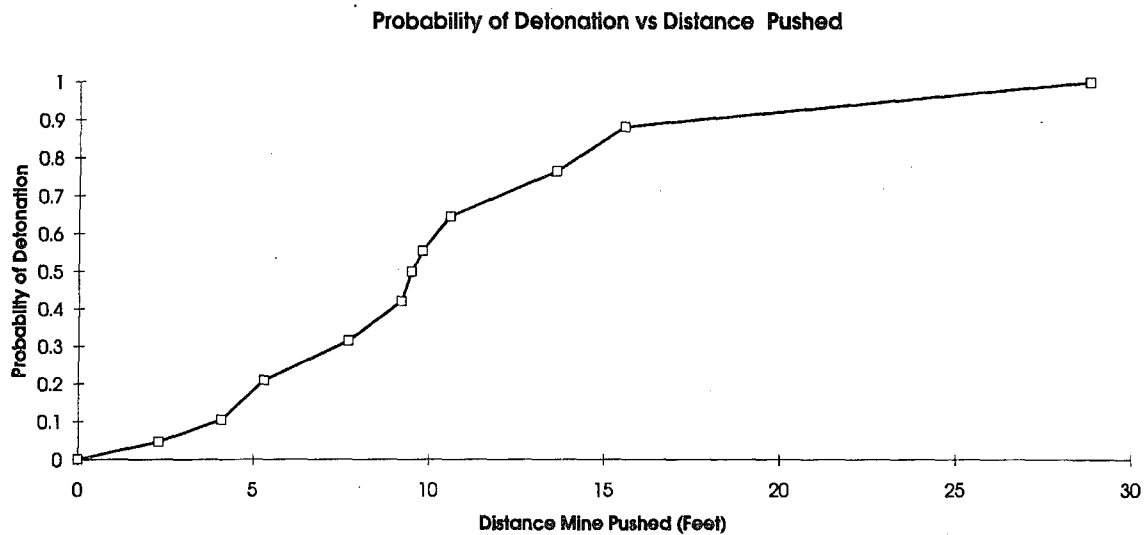


Figure 33. Magnetic Mine Probability of Detonation vs. Distance Pushed

On balance, the Clausen Power Blade performance as a mine removal tool was equivalent to existing mine plows. That is, it is distinguished by its ability to create a deeper or faster cut, but the removal of mines from that cut, and the fuze responsiveness of the mines is not significantly different. Mines are generally cleared if the plow can reach deep enough. On average some small percentage of pressure mines (4% in this case) detonate when being plowed, and a large percentage of magnetic mines detonate.

Section 7 Summary

RESULTS

During a 5 week test period at Ft. AP Hill, the side sweeping concept was evaluated by comparison of the Clausen Power Blade with other plowing systems (mainly the non-power angle blade).

The concept has a proven ability to reduce the pushing resistance the plow encounters. Such reduction makes faster or deeper plowing possible. The "cost" of this reduced resistance is (1) power supplied directly to the blade and (2) added system weight. Analysis indicates that power is spent with equal efficiency whether turning the side sweeping belt or in pushing the tractor. However, the side sweeping blade is able to deliver a fraction of power available, but undeliverable by the tractor because delivery would require the tractor to push with more traction than can be developed between the tracks and the soil. In addition to the lowered push resistance, the weight of the Clausen Blade increased the vehicle traction, significantly raising the fraction of power the vehicle is able to deliver to the soil. Also noted, but not studied in depth, is the indication that the relative effectiveness of the side sweeping blade is higher in sand and loose fill than in the cohesive soil in which this evaluation was conducted. Conversely, in more shear resistant soils the power blade performance would be expected to be reduced. There were times when the tractor seemed to be completely stalled against the resistance of the cutting edge in undisturbed soil and the belt was spinning freely, unable to deliver its power.

There is a minimum depth at which belt loading of the Clausen Blade occurs. This was asserted to be the result of the cutting edge acting as a mold board at the shallow depths.

The side thrust of the power blade is mainly attributable to the 24 degree cutting edge angle. This thrust is a significant problem, costing the system much needed traction (from the track imbalance), power (from the clutch driven steering), and plowing depth (from the need to tilt blade to limit the imbalance).

The side sweeping action has no observable characteristics which make its mine removing ability distinguishable from existing mine plows beyond the obvious one of increasing the depth of cut. The Clausen Power Blade, like any plow, is very reliable at clearing mines within the range of soil depths to which it is capable of cutting. For the Clausen Blade on a D7-G in the soil tested, this depth is about 6". Conclusions concerning mine clearing efficiency should be qualified with the particulars concerning the test conditions, namely, operator knowledge of mine burial locations and the assumption of the desirability of a straight line breach.

As expected, the pressure fuzed mine generally did not detonate when being plowed, and the magnetic fuzed mine generally did detonate when being plowed.

CONCLUSIONS

The side sweeping concept meets one important criteria needed to recommend its use. From a technical standpoint, it extends angled dozing performance beyond the traction limit characteristic of the soil, with an efficiency at least as good as the basic dozer. The question of whether the side sweeping concepts can be effectively employed in a military mine plowing system will depend on solving a host of other operational issues and requirements such as the side sweeping blade vulnerability, added maintenance/logistics overhead, favorable cost/benefit analysis etc.

Finally, there is a point of diminishing returns to adding capability to the side sweeping blade. At low speeds the tractor is limited by the amount of traction it has available. The side sweeping blade will also be limited by the amount of "traction" the blade face develops from soil pressure. Therefore, the side sweeping blade will ultimately be limited by the amount of traction the vehicle develops. For the 69,000 pound system weight of the D7-G plus the Clausen Power Blade, a blade power output in the range of 30-40 hp would be more closely sized to the characteristics of the D7-G.

RECOMMENDATIONS

The Clausen Power Blade used as the test bed in this project is the prototype system developed by the Clausen Power Blade company. These recommendations are intended to serve as general ideas for applying the side sweeping concept and the results of this analysis to future side sweeping configurations for mine clearing.

The power usage limit on the Power Blade suggests one of two ideas. One is accepting the limit and sizing the blade smaller relative to the tractor. In the 69,000 lbs D7-G system, a power blade output in the range of 30-40 hp would produce the same performance as the 90+ hp of the Clausen Power Blade. Alternatively, some concept or device which aids the belt in coupling power to the soil would raise the usage limit. Possibilities include NCEL ideas of adding grousers to the belt face, or loading the soil on the belt by turning it horizontally.

Clausen used a standard cutting edge in fabricating the Power Blade. An edge which is shorter (top to bottom) may allow the face to load up more quickly and provide an increase in the amount of coupled power from the belt as well. In fact, in order to generate the system curve (Figure 10), the power blade had to be lifted up, and pushed into the side of a dirt pile in order to bypass the cutting edge and load the belt enough to generate the parts of the curve above 38 hp. The risk in shortening the cutting edge is that the wedge it forms will not be large enough to break the soil chips free before the belt arrives.

Using teeth instead of the cutting edge may reduce the shearing work and leave more traction available for loading the belt. The more the soil may be characterized as frictional instead of cohesive, the larger the teeth, and the smaller the side sweeping motor required, as this soil will more naturally rake. For more cohesive soil, smaller teeth and larger side sweeping motor(s) are recommended to move soil which does not rake.

A "V" configuration for the sweeping blade is recommended where the soil and mine casting on both sides is not a problem. On average, the soil is moved a shorter distance requiring less work, and the side thrust problem is not present. If a curved breaching path is acceptable or if the angled geometry is to be retained for soil deposition reasons, the recommended solutions are to offset/extend the blade further to the angled side and distribute the system weight further away from the angled side. If the blade is angled to leave the spoils on the right side, moving the blade 20" to the right of the center pivot point would eliminate the turning moment completely. Also, some of the parasitic weight on the blade and the APU should be shifted left to help increase the left track traction and allow greater steering compensation. Another recommendation is to use the blade on vehicles with drive trains not employing clutch based steering in order to conserve power currently lost in the D7-G.

Definition of Terms

Push Force (lbs). Net horizontal force tractor applies to plow

Vertical Reaction (lbs). Net vertical, dynamic force tractor applies to plow

Push Power (hp). Power delivered to plow from tractor through plow mounting structure

Belt Power (hp). Net power output of power blade belt (Clausen Power Blade only)

Total Power (hp). Sum of Push and Belt Power for Clausen; Push Power for Angle Blade and V Blade

Speed (mph). Forward Vehicle Speed

Drawbar (lbs). The amount of force the vehicle tracks are capable of applying

Traction (lbs). The amount of force the vehicle tracks apply to the soil before slipping begins

Available Power (hp). The amount of power the vehicle or the power belt can develop at a given track or belt speed

Deliverable Power (hp). The fraction of available power the vehicle or power belt is capable of delivering as useful work in a given plowing situation at a given track or belt speed.

Bank Soil. Soil in its natural, undisturbed state

Compacted Soil. Soil which has been previously plowed and then compressed with a roller

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