UNIVERSITY OF NEWCASTLE UPON TYNE
DEPARTMENT OF GEOTECHNICAL ENGINEERING

STUDIES IN THE EXCAVATION OF SELECTED ROCK MATERIALS WITH MECHANICAL TOOLS

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To the memory of my brother,

AYHAN

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ABSTRACT

This work covers laboratory studies in the excavation of selected rock materials with mechanical cutters.

Cutting head design of rock excavation systems employing drag tools or disc cutters is investigated by considering their practical cutting action. Effects of tool tilt angle on the performance of roadheaders with longitudinal cutting heads are investigated in detail. Along with tilt angle, optimum tool spacing between adjacent cutters, cutting head geometry and mode of operation of roadheaders are also studied. Experiments with disc cutters covered mainly the effect of disc edge angle on disc performance.

When the practical cutting action of drag tools is considered the trend of forces and specific energy becomes somewhat different from those obtained during flat rock surface cutting trials; however, the definition of optimum tool spacing with respect to drag tools confirms previous findings.

Tilt angle has a significant influence on the performance of cutting tools; in particular, with corner cutting tools. It was found that individual tool forces are proportional to the cross-sectional area cut by the corresponding tool.

Roadheader cutting heads with combined geometry offer better performances than those with spherical geometry when the tool spacing is kept constant around the cutting head.

In arcing mode tool duties are also affected by boom length.

Cyclic deepening of grooves exists when cutting with discs, discs having smaller edge angles requiring more successive passes to produce a complete breakout between adjacent grooves.

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NOMENCLATURE

Relief Cut : cutting midway between the tools of previous sequence.

Groove Deepening Cut : successive deepening of adjacent grooves.

Cut Spacing (S) : spacing between the tools in a cutting sequence.

Line Spacing (S_L) : spacing between the neighbouring tools regardless of the order of cutting sequences.

θ_h : hypthetical breakout angles.

θ_m : measured breakout angles.

Traversing Tool : cutting tool having zero tilt angle.

Gauge Tool : cutting tool with a tilt angle greater than zero, excluding corner cutting tool.

Corner Cutting Tool : last tool at the nose side of a cutting head.

* * *

1. INTRODUCTION

The increasing demand for rapid and economic underground construction techniques has stimulated a large number of research projects into all aspects of mechanical rock excavation. In the last decade, the number of machines employed has increased along with an increase in the strength of the strata that can be mechanically excavated at economical rates.

Understanding the principles of rock cutting mechanics has made a contribution to the design of the new generation of heavier roadheader excavation machines. Unfortunately, just scaling up the older, smaller machine designs has not necessarily increased the strength of the strata to be cut, because the cutting energy is still transmitted into the rock material through drag tools. Although some improvements have been made in tool materials and tool design. The main area for improvement is in the even distribution of cutting duty between each tool on a cutting head.

This work is concerned with the cutting head design of the excavation systems through the use of mechanical cutters. The laboratory trials were designed in such a way as to take into account the practical cutting action of actual machines, and some operational parameters. Cutting machines employing drag tools such as roadheaders were the main concern of this study. However, performance of disc cutters was also included in the experimental programme.

It is hoped that the information provided by these investigations will further add to the present understanding of cutting head design, particularly where comparative performance of various cutting heads and mode of cutting operations are concerned.

* * *

2. REVIEW OF PREVIOUS RESEARCH

This chapter will briefly review the research into rock cutting mechanics relevant to the objectives of these investigations.

2.1 Classification of Machines and Cutting Tools

A general classification for all rock cutting machines is given by Mellor (1) in accordance with the characteristic motion of the cutting elements and the type of tools employed. This is shown in Figure 1. For analytical purposes, machines are classified as 'Transverse rotation', 'Axial rotation', or 'Continuous belt', whilst the action of cutting tools is divided into 'parallel motion' and 'normal indentation'.

A few machines and operations do not fit neatly into Mellor's classification. For example, certain roadheaders and ripping booms used in mining sump-in by axial rotation and produced largely by transverse rotation, and there may be some question about the classification of tunnel reamers and tapered rock picks. However, this classification has been found to be satisfactory for general mechanical analysis.

The rock excavation machine types which are found in mining and civil engineering practice are generally in the form of full-face and partial-face machines. Historical background and a description of some of these machines is given by Muirhead and Glossop (2). The full-face tunnel boring machines (Plate 1) usually employ rolling

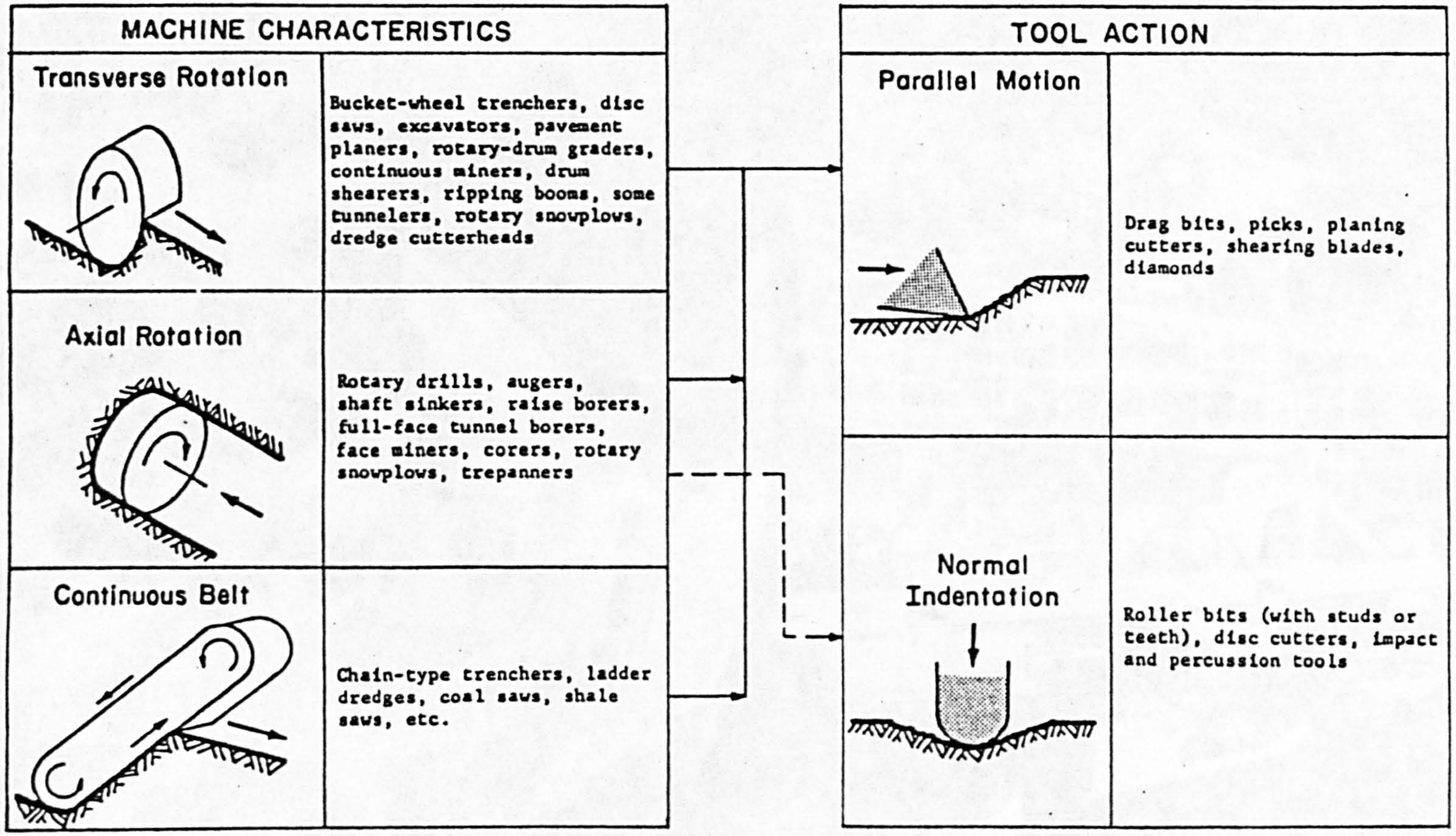


Fig. 1: *Classification of machines and cutting tools for analytical purposes.*
(After Mellor) (1)

PLATE 1

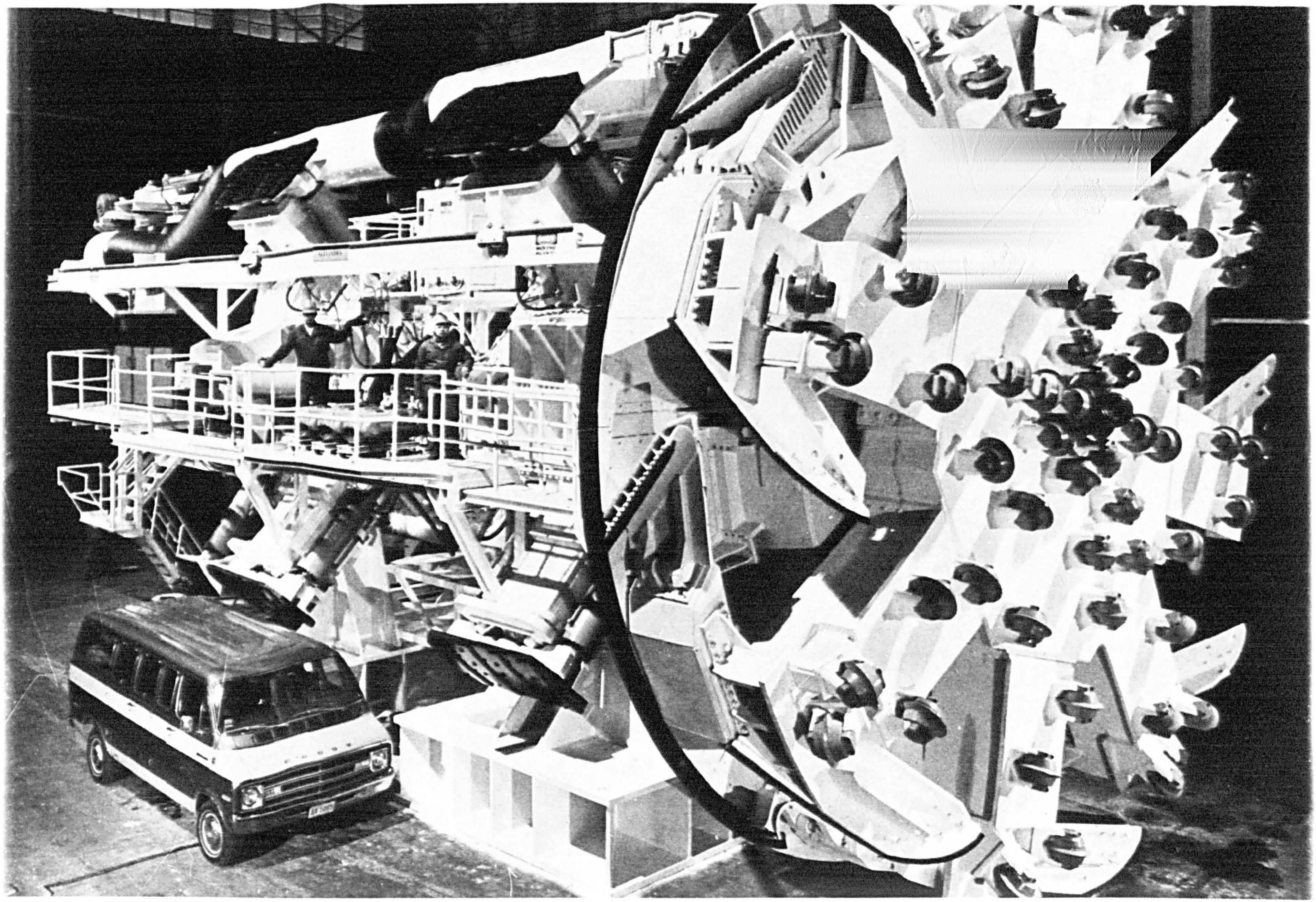


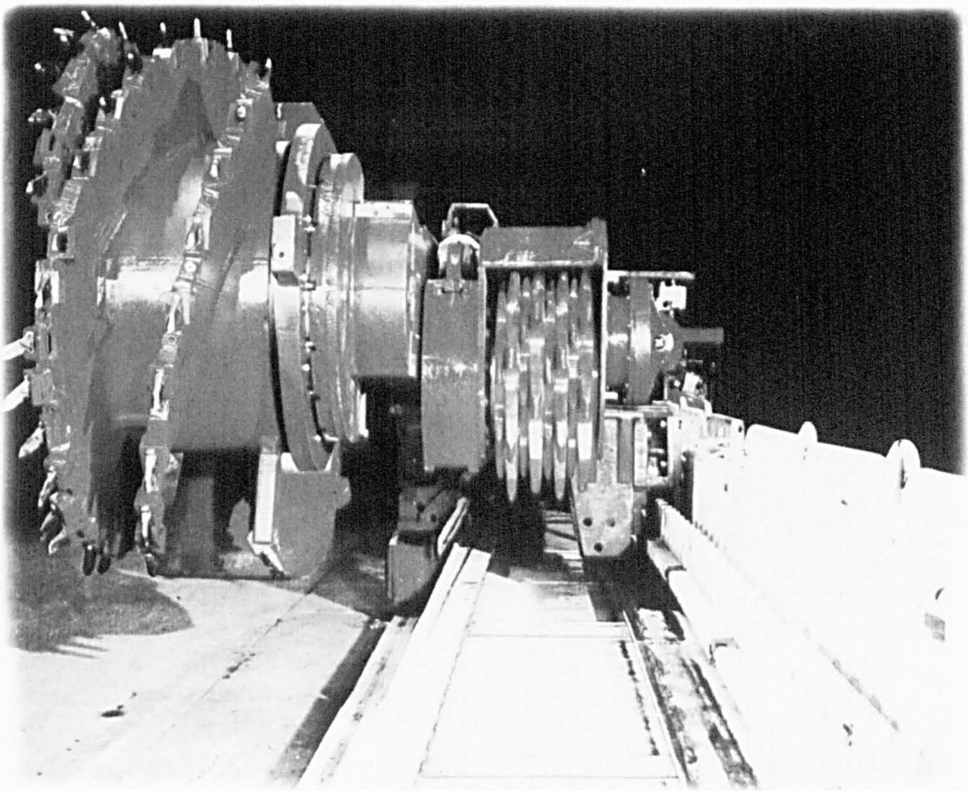
Plate 1

cutters, such as discs, in medium to hard rock and button cutters in very hard rock formations. However, when working in soft rock conditions, drag tools are also employed on these types of machines.

The most common partial-face machines in today's mining industry are boom-type roadheaders, shearer drums and continuous miners, all of which are fitted with drag tools. Roadheaders are versatile machines, as they are capable of excavating circular, rectangular, or arched roadways. They also have a selective capability in being able to excavate the weaker rocks exposed on the tunnel face first, thus easing the removal of hard rock exposed. Since they are the main concern of this work, a more detailed review is given in the next chapter.

Shearer drums (Plate 2) are, in general, used for the purpose of bulk material extraction, and they are the most common machine employed in longwall coal winning. Barker (3) and Brooker (4) conducted extensive studies on these machines. Recent technological development has introduced a new type of cutting machine which is based on the design principle of shear-loaders (Weber (5)). The machine can be used as a roadheader when driving arched or rectangular roadways, as well as in room and pillar operations.

The continuous miners (Plate 3) are operated in both roadway drivage and bulk material excavation. Currently, they are mostly employed in the USA and South African coal mines, where room and pillar methods are applied (6).



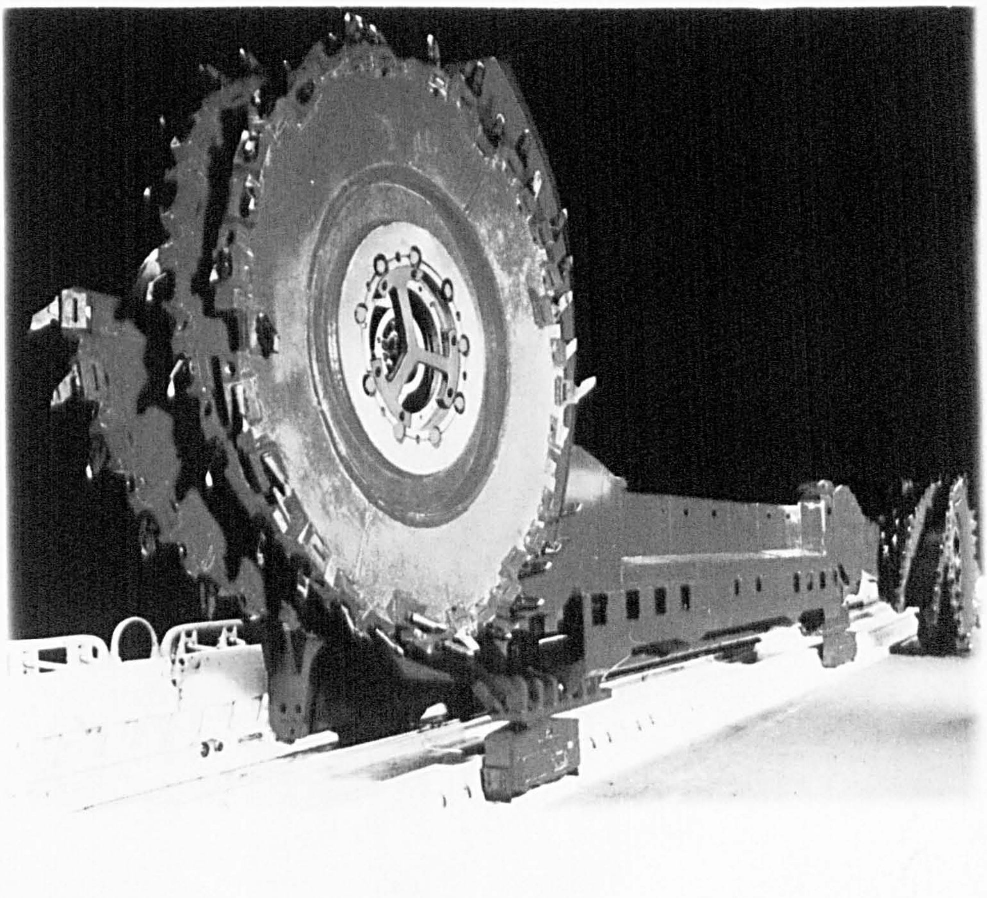


Plate 2. Anderson Strathclyde AM500 Shearer Drum

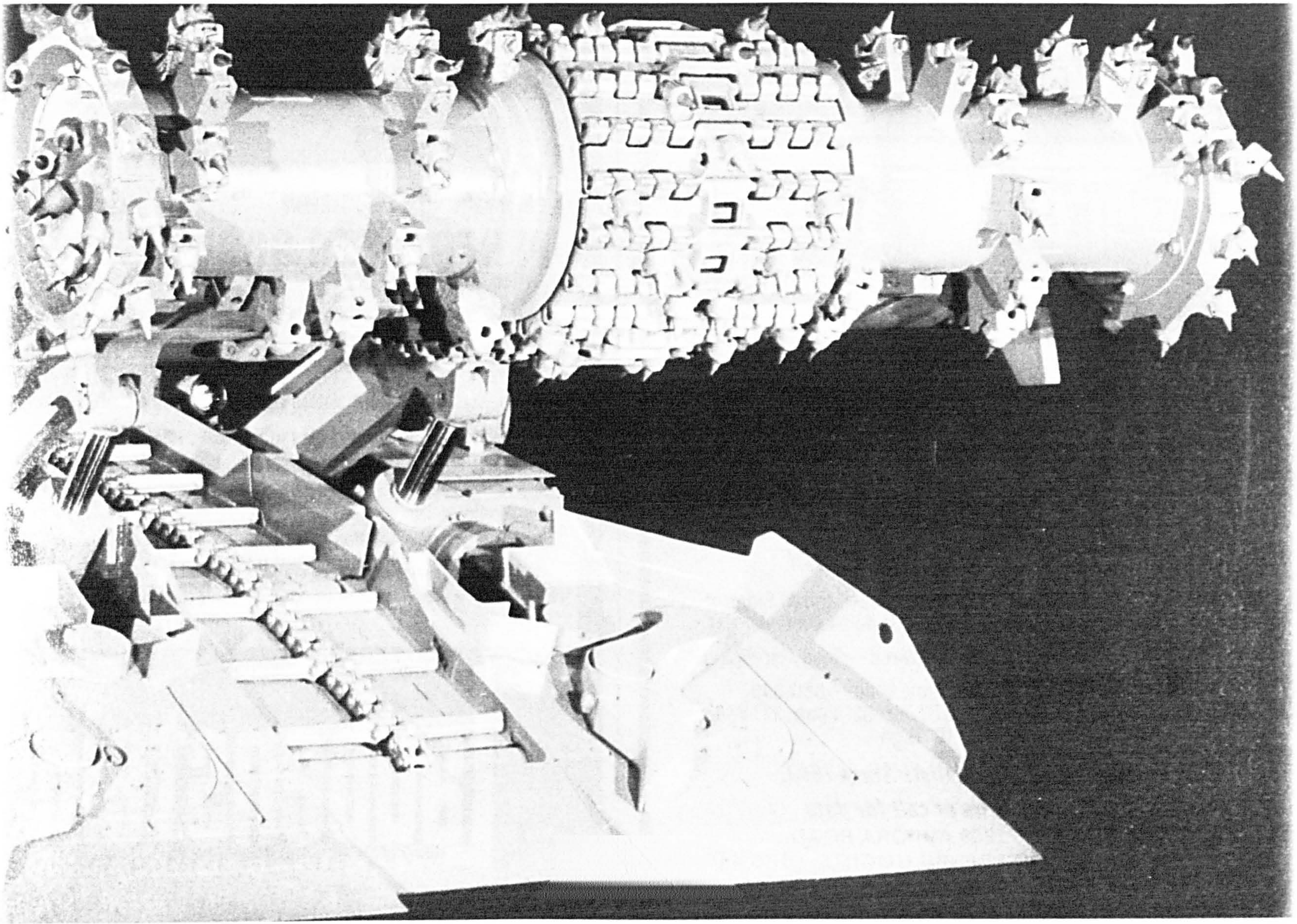


Plate 3. Joy 12CM Continuous Miner

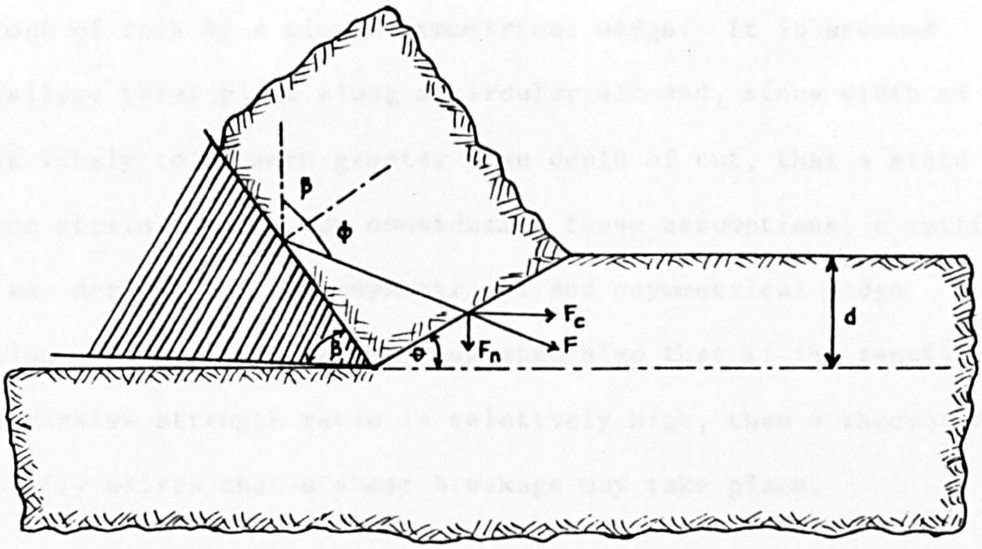
2.2 Review of Rock Cutting with Drag Tools

2.2.1 Theoretical aspects

The earliest cutting theory for metals is given by Merchant (7) and this predicts the cutting force required to cut a continuous strip from the plane surface of a metal. This theory is based on the assumptions that shear failure takes place over a straight line, rising from the tip of the tool, and making an angle with the direction of cutting. The geometry of Merchant's model is illustrated in Figure 2.

Nishimatsu (8) also puts forward a model based on Merchant's metal cutting theory, in order to describe the action of a drag pick in rock. He used Mohr's failure envelope instead of Merchant's single value for the shear strength to define the strength of the rock material. The theory proposes a failure process involving the primary and secondary crushed zones associated with coarse chip formation, and assumes that shear failure will occur along a line from the tip of the tool to the surface of the rock. Furthermore,it is assumed that the stress at any point on this line will be proportional to its distance from the surface raised to some power (i.e. stress is zero at the surface of the rock and a maximum at the tip of the tool). Nishimatsu's theory is shown in Figure 3.

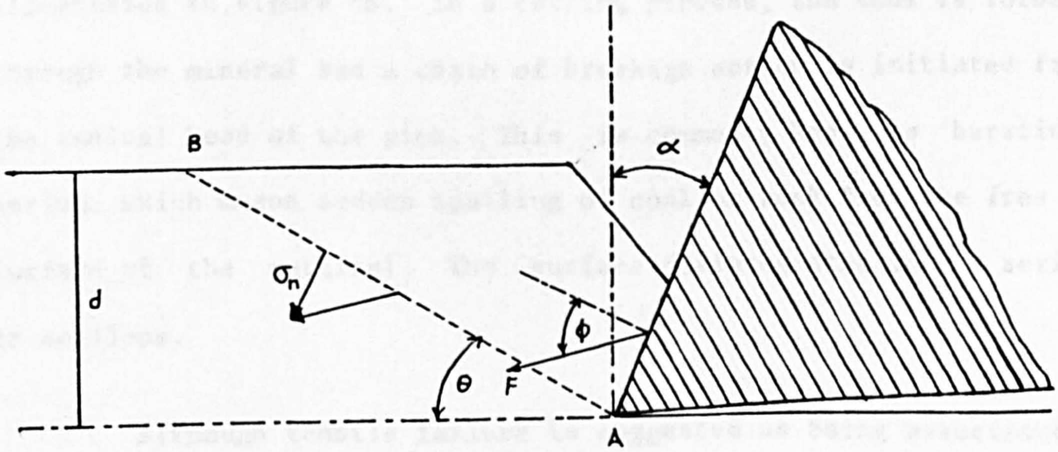
Evans developed a cutting theory which is based on the observation that wedge penetration of a rock produces cracks attributed to tensile failure (10). The basic theory is for the penetration of



$$F_c = 2 . d . Ss . \tan((\beta + \phi) / 2)$$

where Ss = Shear strength
d = Depth

FIG. 2 ILLUSTRATION OF MERCHANT'S THEORY OF METAL CUTTING



$$F = \frac{2}{n-1} . Ss . d . \frac{\cos K}{1 - \sin(K - \alpha + \phi)}$$

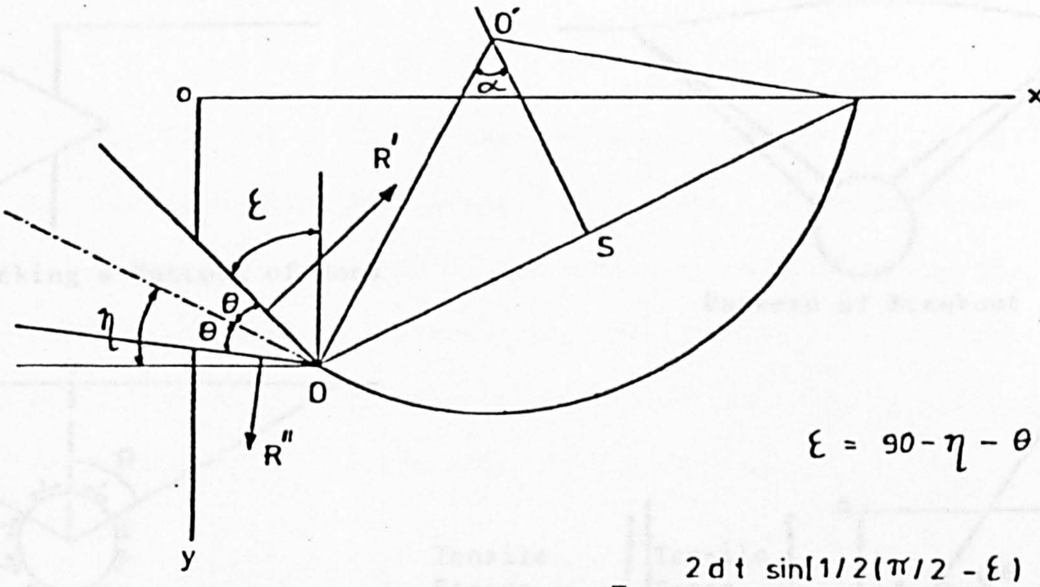
where K = Angle of internal friction of the rock
n = Stres distribution factor

FIG. 3 ILLUSTRATION OF NISHIMATSU'S THEORY OF ROCK CUTTING a buttock of rock by a simple symmetrical wedge. It is assumed that failure takes place along a circular arc and, since width of tool is likely to be much greater than depth of cut, that a state of plane strain exists. By considering these assumptions, a cutting force was derived for both symmetrical and asymmetrical wedge conditions (Figure 4a). Evans suggested also that if the tensile to compressive strength ratio is relatively high, then a theoretical possibility exists that a shear breakage may take place.

Amongst all these theories, Evans' theory is most widely accepted in rock and coal cutting. Practical application of this theory can be found elsewhere (12, 14, 17).

Hurt and Evans (15) studied the mechanics of the breaking action of the pencil point tool and they attributed failure of the mineral to tensile breakage. The assumption of breakage theory is illustrated in Figure 4b. In a cutting process, the tool is forwarded through the mineral and a chain of breakage action is initiated from the conical head of the pick. This is commonly known as 'bursting' action, which means sudden spalling of coal or rock from the free surface of the material. The surface disintegrates into a series of scallops.

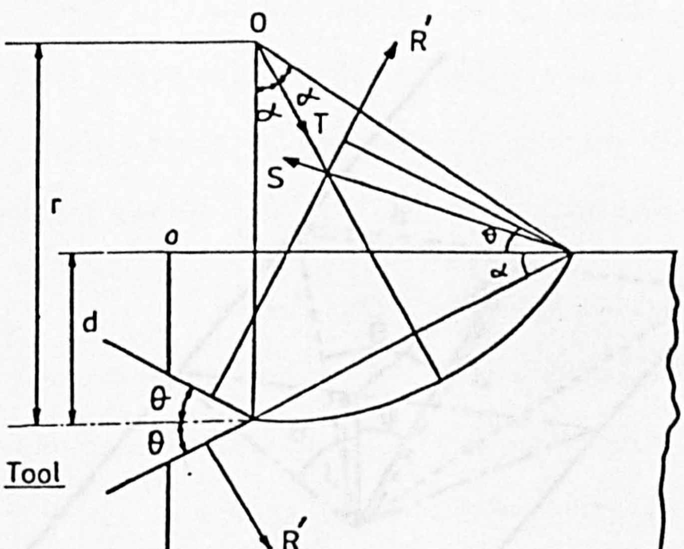
Although tensile failure is suggested as being associated with the proliferation of cracks, Fowell and Tecen (16) propose a shear failure which is evident at the slope face of the rock, close to the bottom of the groove.



$$\varepsilon = 90 - \eta - \theta$$

$$F_c = \frac{2dt\ \sin[1/2(\pi/2 - \varepsilon) + \varphi]}{1 - \sin[1/2(\pi/2 - \varepsilon) + \varphi]}$$

Illustration of the assumtions of cutting
by asymmetric wedge (after Evans)

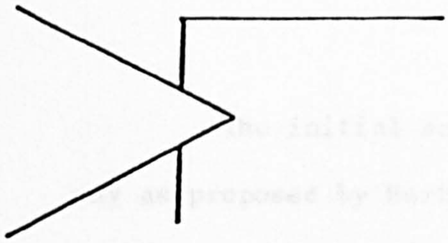


$$F_c = \frac{2td\ \sin(\theta + \varphi)}{1 - \sin(\theta + \varphi)}$$

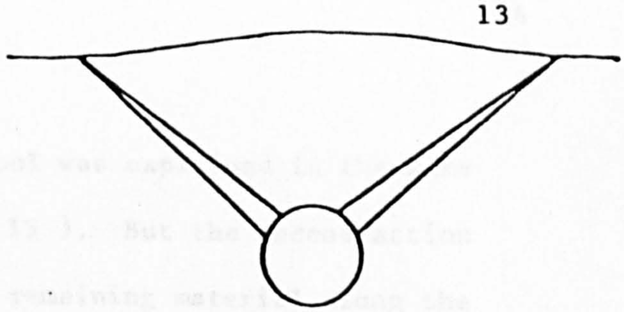
t : tensile strength
φ : angle of friction between the wedge and coal

(Symmetrical wedge)

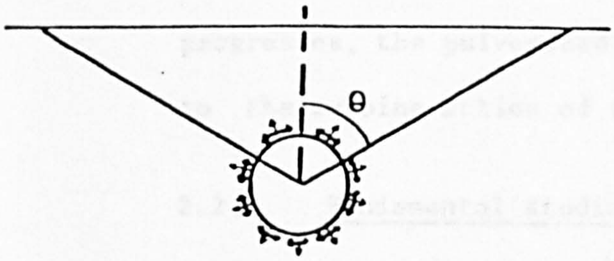
Fig. 4a: Illustration of the assumptions of Evans Tensile breakage Theory (10)



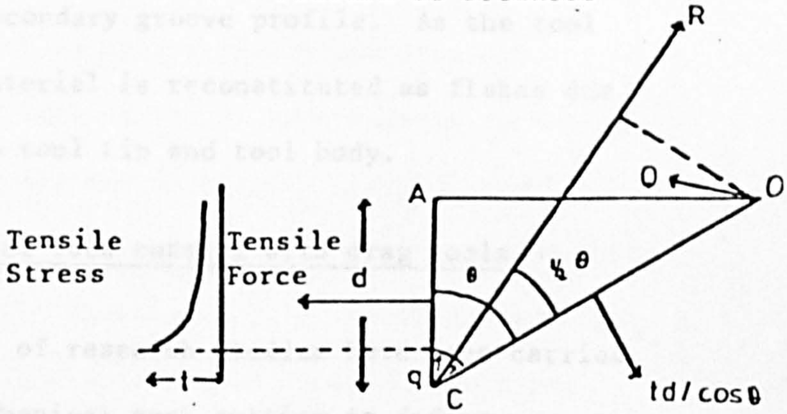
Pencil Point Attacking a Buttock of Rock



Pattern of Breakout



View along Direction of Cut



Stress on Half-Segment

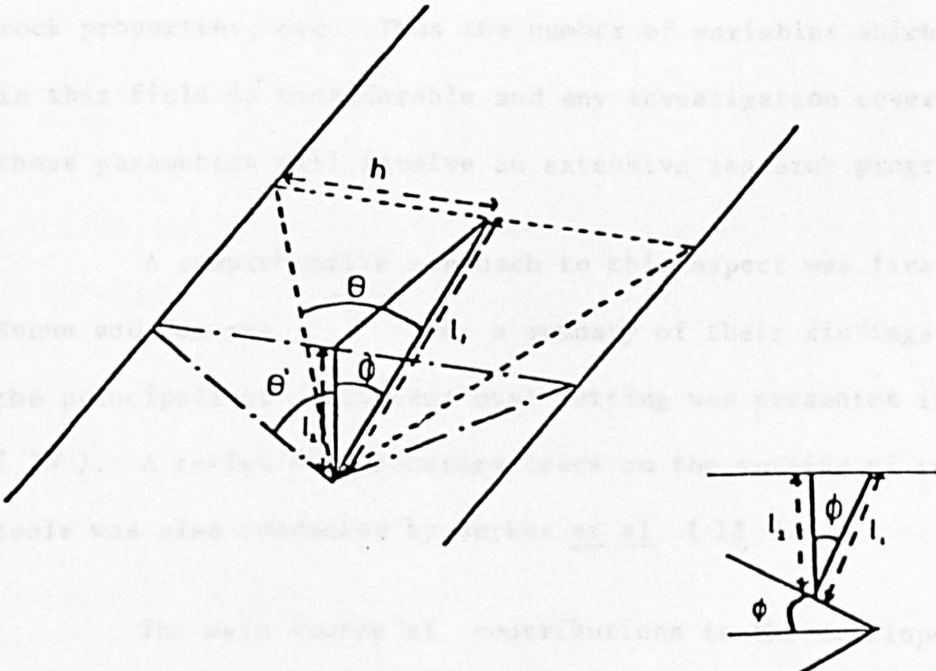


Fig. 4b:- Relation Between V-Angles at Various Inclinations

(After Hurt and Evans) (15)

The initial action of the tool was explained in the same way as proposed by Hurt and Evans (15). But the second action of the tool was the shearing of the remaining material along the path of the cut, leaving a secondary groove profile. As the tool progresses, the pulverised material is reconstituted as flakes due to the rubbing action of the tool tip and tool body.

2.2.2 Fundamental studies of rock cutting with drag tools

A significant number of research studies have been carried out on various aspects of mechanical rock cutting to define fundamentals of the mechanics of rock cutting. Most of the practical developments have, in the main, been focussed on factors such as: tool spacing, depth of cut, tool geometry, machine design, cutting speed, tool wear, composition of cutting tool material, effects of rock properties, etc. Thus the number of variables which are involved in this field is considerable and any investigation covering all of these parameters will involve an extensive research programme.

A comprehensive approach to this aspect was first made by Evans and Pomeroy and a summary of their findings, giving the principals of efficient coal cutting was presented in a monograph (17). A series of laboratory tests on the cutting of rock with drag tools was also conducted by Barker _et al_. (18).

The main source of contributions to the development of this art are those from the Mining Research and Development Establishment

(MRDE), National Coal Board (NCB) and The Department of Mining Engineering of the University of Newcastle upon Tyne.

Allington (20) developed and formulated testing techniques as well as studying the effects of tool geometry and spacing. Fowell (21) investigated the application of percussively activated tools to reef cutting in South African Quartzite. Further work involving the use of drag tools in some selected rocks were undertaken by Roxborough and Rispin (22-24). Phillips (13) and Bilgin (14) studied the mechanical cutting characteristics of some medium and high strength rocks related to excavation system design. McFeat-Smith (25) studied the machineability of rocks and rock properties. In the Department of Mining Engineering, Dunn (26) and Hewitt (27) included aspects of corner cutting in their respective works.

Recent developments in high pressure water jet assisted rock cutting have attracted worldwide attention and brought a new dimension to the rock cutting field. Extensive laboratory investigations into this aspect have been conducted in the Department of Mining Engineering.

Although must of the early studies have emphasised the definitions of efficient rock cutting systems, work carried out on the cutting head design of rock excavation systems, in particular with roadheaders, is rather limited.

2.2.3 Research on the cutting head design of excavation systems with drag tools

In practice, the tools work in concert and a proper disposition of the tools is, therefore, desirable for efficient cutting.

Barker *et al.*(18) designed the MRE Large Pick Shearer Drum by considering the deep cutting principle. Brooker (4) investigated the theoretical and practical aspects of cutting and loading by shearer drums and also remarked on the importance of the drum design.

Pomeroy and Robinson (28) also studied aspects of corner cutting conditions which is an important factor when considering machine design.

Hurt (29) compared the performance of a number of roadheader cutting heads with the aid of a computer program. He pointed out the significance of adapting a cutting pattern for efficient cutting.

Hurt and McAndrew (30) investigated the cutting performance of various tool layouts by using a roadheader test rig and summarised the general principles on which a roadheader cutting head should be designed.

Arrangement of drag tools on a full-face tunnel boring machine was also studied in the Department of Mining Engineering, University of Newcastle upon Tyne (22-24) and TRRL (33).

2.3 Research on Disc Cutters

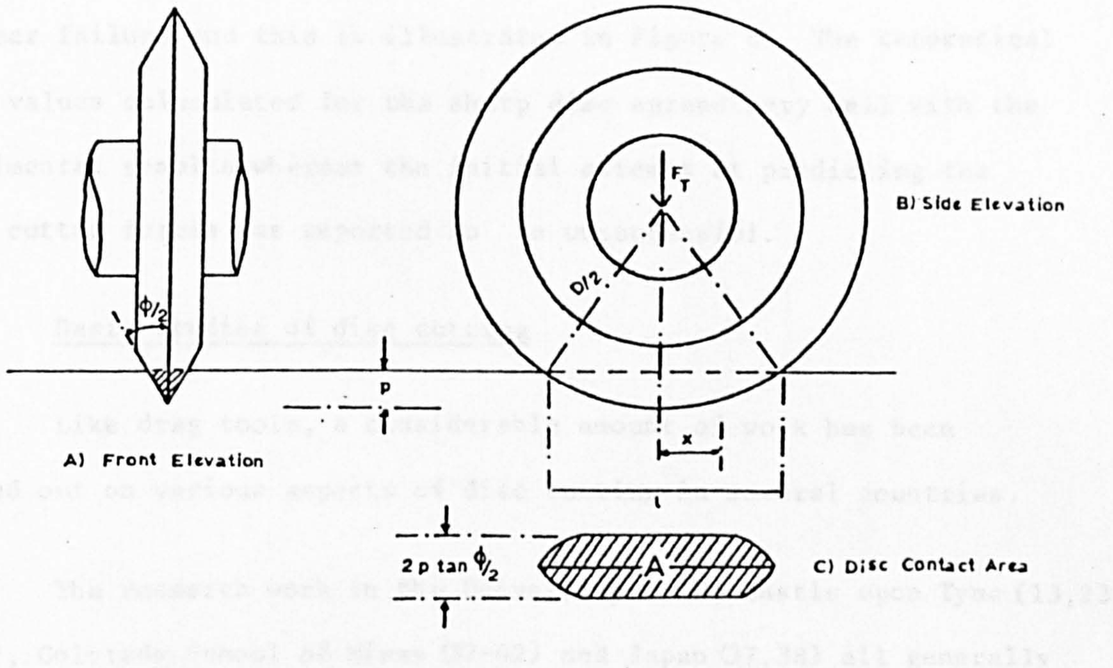
Disc cutters are the most commonly used tool for full-face tunnel boring machines as they have shown several advanges over the other types of cutters. They are more efficient than button cutters, since the rock degradation is more by cutting, rather than a grinding action.

2.3.1 Disc Cutting Theories

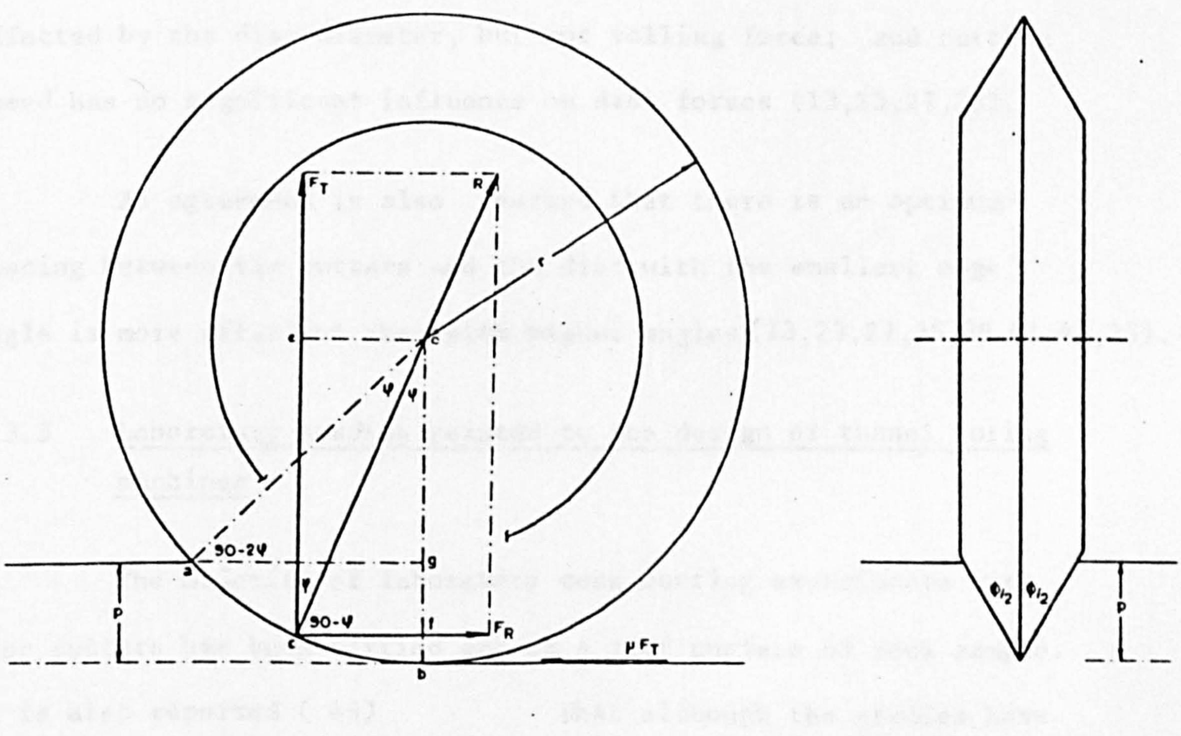
Evans, when comparing relative efficiency of picks and discs, put forward that the force on a wedge required for penetration is identical in form with the calculation of passive earth pressure against a retaining wall in soil mechanics. Based on this assumption he formulated thrust force and groove angle. Details of his theory can be found elsewhere (34).

Roxborough and Phillips (35) also predicted the performance of disc cutters by a theoretical approach. They assume that thrust force equals the uniaxial compressive strength of the rock times the disc contact projected area. The resultant force is further assumed to pass through the centre of the disc and to bisect the arc of contact. Optimum spacing-penetration ratio, thrust and rolling forces were derived as shown in Figure 5.

Özdemir et al.(36) developed predictor equations for the performance of a sharp and blunt disc operating in a multiple cut situation. The rock breakage between the adjacent cuts was defined



GEOMETRY OF DISC PENETRATION



ORTHOGONAL FORCES ACTING ON A DISC

Fig. 5: Theoretical Model of the Action of the Disc Cutters (After Roxborough and Phillips)(35)

as shear failure and this is illustrated in Figure 6. The theoretical force values calaculated for the sharp disc agreed very well with the experimental results whereas the initial attempt at predicting the blunt cutter forces was reported to be unsuccessful.

2.3.2 Basic studies of disc cutting

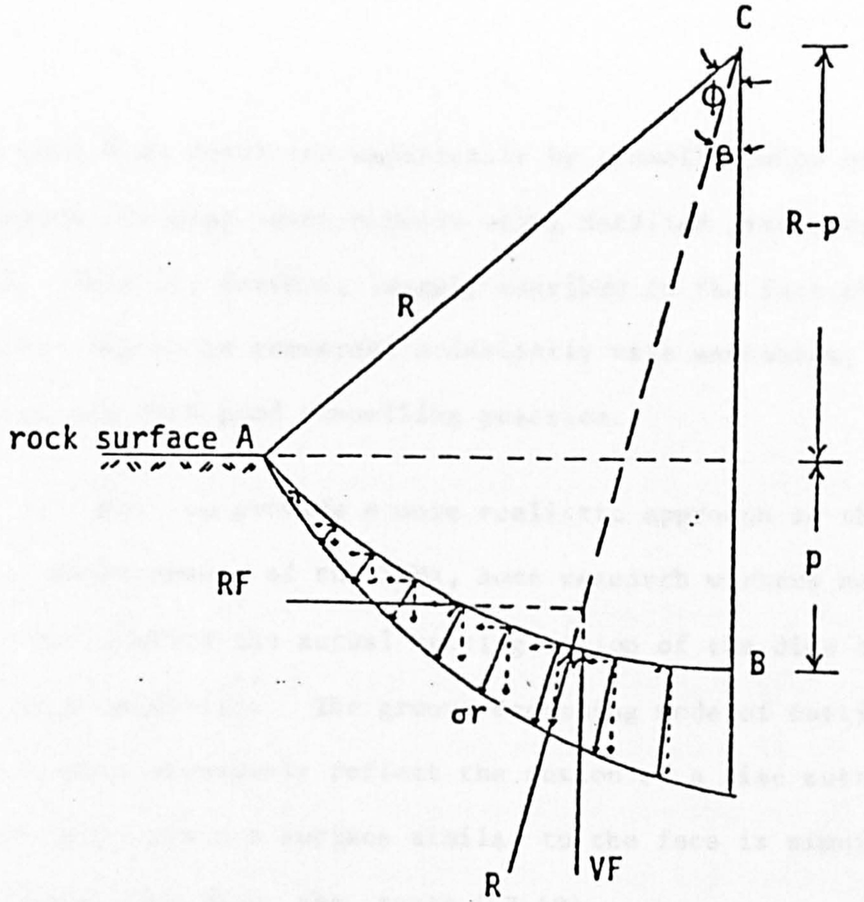
Like drag tools, a considerable amount of work has been carried out on various aspects of disc cutting in several countries.

The research work in the University of Newcastle upon Tyne (13,23, 27,35), Colorado School of Mines (37-42) and Japan (37,38) all generally showed an agreement that increasing penetration results in rapid increase in both thrust and rolling forces, and a decrease in specific energy consumption. Further, it was found that the thrust force is affected by the disc diameter, but not rolling force; and cutting speed has no significant influence on disc forces (13,23,27,35).

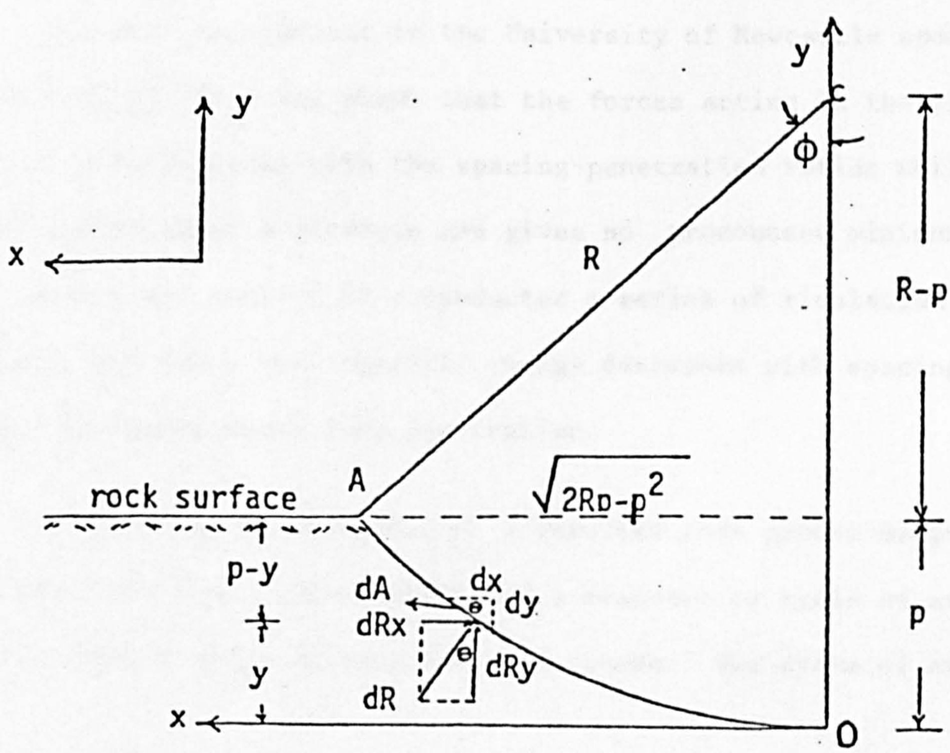
An agreement is also reached that there is an optimum spacing between the cutters and the disc with the smallest edge angle is more efficient than with higher angles (13,23,27,35,39,41,42,45).

2.3.3 Laboratory studies related to the design of tunnel boring machines

The majority of laboratory rock cutting experiments with disc cutters has been carried out on a flat surface of rock sample. It is also reported (46) that although the studies have been useful in design, the majority of successful disc cutter tunnelling



-Representation of the resultant force and its vertical and rolling components acting on the cutters-rock contact surface.



- Representation of force acting on a small element dA along the penetrating edge of the cutter.

Fig. 6: Theoretical Model of Disc Cutting (After Özdemir et al) (36)

machines have been developed empirically by a small number of manufacturers, in many cases without using detailed predictor equations. This is, further, largely ascribed to the fact that good machine design is concerned principally with mechanics, with the system, and with good tunnelling practice.

In order to provide a more realistic approach to the practical developments of the TBMs, some research workers have attempted to simulate the actual cutting action of the disc cutters in laboratory conditions. The groove deepening mode of cutting is reported to most accurately reflect the action of a disc cutter at the tunnel face, since a surface similar to the face is simulated and maintained throughout the tests (47-49).
Özdemir (36) pointed out that it is essential to prepare the rock surface in order to attain a stable cutting regime.

Research carried out in the University of Newcastle upon Tyne (Potts et al.(49)) has shown that the forces acting on the disc cutter steadily increase with the spacing-penetration ratios while specific energy shows a decrease and gives no pronounced minimum value. Kutter and Sanio (52) conducted a series of simulation experiments and found that specific energy decreases with spacing and shows an independence from penetration.

Howarth and Roxborough (53) reported that groove deepening experiments with disc cutters indicated a sequence or cycle of events associated with a progressively deepened groove. The cycle of events manifested in curves of disc performance criteria is directly attributable to the gradual deepening of groove and subsequent breakthrough of the rib of rock between adjacent cuts. They further concluded that:

> "... on the basis of the total or overall specific energy required in incremental groove-deepening, disc cutters are far more efficient than chisel picks."

Snowdon and Ryley (54), having investigated the characteristics of multiple pass (groove deepening) cutting in Shap Granite and compared it with single-pass cutting in the same material, also found a cyclic variation in forces and specific energy. It was concluded that sufficient torque and thrust are available, whereas, for short lengths of tunnel in extremely strong rocks involving very high tool forces, even at low penetration rates, the use of multiple-pass cutting may provide a reasonably energy efficient method of excavation.

* * *

3. REVIEW OF BOOM-TYPE ROADHEADERS

3.1 Historical Background

Because of their low installation costs, versatility and suitability for selective mining, the boom-type roadheaders are being used increasingly in today's mining and civil engineering industries. A brief review of their development history is given below based on reference 56.

The first successful boom-type roadheader, the Hungarian F2 machine, was used in Hungarian coalmines in the 1950s. It was a very light machine, fitted with a twin contrarotating cutting head arranged at right angles to the axis of the boom. The cutting head was driven by a 50 hp electric motor and the machine was only capable of cutting coal and soft rocks below 40 MPa. Later versions of this machine, the F4 and F5, were introduced in the late 1950s. These machines were followed in 1960 by the Soviet PK3 roadheader, which again, was a relatively light machine. The essential difference between this machine and the F4 was the cutting head, which was arranged coaxially on the PK3 and driven by a 40 hp electric motor. Both machines were crawler mounted; debris disposal systems differed; the F4 had gathering arms and a central conveyor and the PK3 was fitted with a single-chain paddle-flight conveyor, which ran across the debris-gathering apron and encircled the machine.

The first boom-type roadheader to be used in Western Europe was a Soviet PK3 which was imported by the National Coal Board in 1961.

It went into operation in Ellington Colliery in the Northumberland Area in November 1961 and was later transferred to Lount Colliery in the East Midlands Area. The first British roadheader was designed and manufactured at the National Coal Board's Central Engineering Establishment (now MRDE) in 1962. This machine, the Bretby MKI Roadheader, was a track-mounted machine, fitted with a coaxial-type cutting head driven by a 40 hp electric motor; debris disposal was by gathering arms and a central conveyor. It went into operation at Daw Mill Colliery in 1963 and was later transferred to Littleton Colliery.

Further development at CEE resulted in the design of the Bretby MK2, which was an improved version of the MKI. This was followed by the MK2A machine. Six of these machines were manufactured for the NCB, two each by Anderson Boyes, Distington Engineering and Mavor and Coulson. The Central Engineering Establishment also designed and developed a telescopic boom for use on the Bretby MKI and MK2 roadheaders.

At about the same time, Dosco Overseas Engineering Ltd. were developing their first machine, the Dosco Roadway Cutter Loader (DRCL), which was basically a more robust version of the Soviet PK3 machine which they had converted for the NCB from electric to electrohydraulic track drives. The development of these machines provided the foundation for the British roadheader industry as it is today.

Further developments took place in the 1960s and early 1970s. Anderson Boyes produced a number of models, including the RHI and RH2D machines of which more than 30 were sold to the National Coal Board. Dosco Overseas Engineering produced the DRCL and the later MK2A machines and almost 1000 of these have been supplied to the National Coal Board.

Exploitation of boom-type roadheaders in other countries of western Europe during the 1960s was very limited; a few Dosco DRCLs were installed in the German coalmines, but these did not prove suitable for the conditions. Some of these machines were modified by the Germans and are still working, but they are limited to cutting smaller roadways in coal and soft rock.

It was not until the late 1960s and early 1970s that the European manufacturers began to develop large boom-type roadheaders and since then significant progress has been made.

To meet the requirements of the German coal mining industry in particular, companies such as Alpine, Demag, Eickoff, Paurat and Westfalia Lunen developed a range of heavy duty roadheaders. British manufactures, Dosco and Anderson Strathclyde, followed quickly with their heavy duty roadheaders. The most recent developments by the National Coal Board Mining Research and Development Establishment have produced a new range of super heavy duty cutter booms for use on either conventional track-mounted roadheaders or circular tunnelling shields.

Figure 7 shows the year of introduction of the range of roadheaders used in NCB coalmines and indicates the cutting capability of the various machines. Some of the earlier types of machine are now obsolete.

The following sections describe the longitudinal type roadheader currently in operation in NCB coalmines.

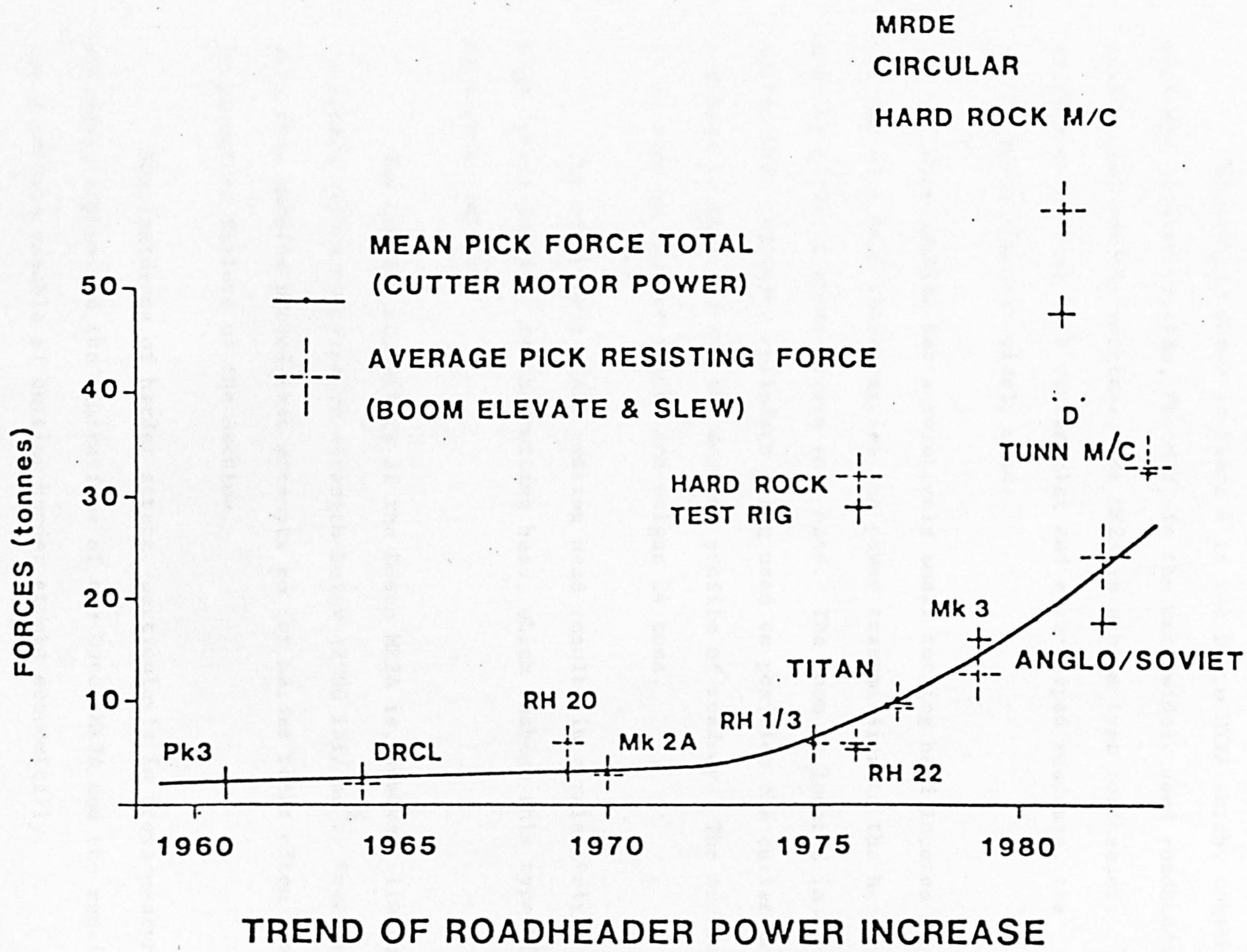


Fig. 7: Introduction of Roadheaders in NCB Coalmines (56)

The machine shown in Plate 4 is the Dosco MK2A which, together with the earlier version, the MK2, is the most widely used roadheader. Unlike coal heading machines, the MK2A is a boom-type roadheader, capable of cutting both rectangular and arch-shaped roadways, the latter being the most widely used.

This machine has a relatively small cutting head located at the end of a boom which carries the power transmission to the head. A 65 hp electric motor drives this head. The boom is located in a turret with hydraulic cylinders being used to position the cutter boom and head in order to cut the desired profile of roadway. The machine is mounted on crawler tracks and weighs 24 tons.

The relatively small cutting head results in a relatively high 'power density' at the cutting head, which enables this type of machine to cut rock.

The cutting capability of the Dosco MK2A is, however, limited to strata with a compressive strength below 12000 lbf/inc^2. Experience with this machine proved that attempts to cut harder rocks often resulted in premature failure of the machine.

The incidence of harder strata, particularly in cross-measure drivages, emphasised the limitations of the Dosco MK2A and the requirement for a machine capable of cutting harder strata economically.

The requirement for a powerful machine led to the development of the medium range roadheaders. These machines are of the same configuration as the Dosco MK2A, but vary in the method of debris

Plate 4 Dosco MKIIA Roadheader

collection in that gathering arm loaders replaced the chain conveyor system. They are, by necessity, more powerful and heavier.

The Anderson Strathclyde RH22 (Plate 5) is an example of a 'medium range' roadheader. The crawler-mounted roadheader weighs 40 tons, with a cutting head driven by a 120 hp electric motor. The boom of this machine is fitted with a telescopic section which is used to sump in the cutting head. Roadheaders without this feature rely on the crawler tracks to sump in the cutting head. A telescopic boom is, therefore, advantageous when working on steep rising gradients, particularly when floor conditions are bad and the strata is hard.

A larger version of the Anderson Strathclyde RH22 roadheader are the RH1/3 and RH1/4. The RH1/4 is shown in Plate 9. These machines are basically the same as the RH22, but are higher, which enables them to cut larger roadways. The machines weigh 50 tons. The additional weight provides a marginal increase in stability which improves their performance in harder strata.

The Dosco MK2B is a relatively new design of medium range roadheader with a specification almost identical to the Anderson Strathclyde RH22. This is shown in Plate 6.

Another recent addition to the medium range of machines is the Thyssen Titan E169. The cutting head of this machine is driven by a 110 hp electric motor.

The performance of the medium range of machines has proved to be better than than of the Dosco MK2A and they have certainly been more reliable. However, these machines again failed to meet the NCB

The Anderson Mavor RH22 roadheader has been developed to fulfil the need for a rugged type machine suitable for cross measure drivages and gradient work while allowing for rapid rates of excavation.

Following the successful concept of unit construction as proved by Anderson Mavor power loaders, the RH22 offers the customer a selection of interchangeable major assemblies to meet the required specification for any application.

In developing the RH22, special consideration was given to the following main points:

1 Versatility and interchangeability of major assemblies.

2 Reliability.

3 Safety and ease of operation

Similar to our early range of roadheading machines, the RH22 is built around a centre main frame which supports the cutting boom turret. The centre conveyor structure is located on the inside of the side frames at the front and supported at the rear on the main cross tie. The main frame, turret, gathering arm loading system, conveyor assembly, rear cross tie, hydraulic power pack and electrical components are common to all machine configurations.

CUSTOMER OPTIONS

Cutting booms

Choice of 65 hp or 120 hp (48·5 kW or 90 kW) cutting boom assemblies.

Machine propulsion

Machine conveyor

TECHNICAL SPECIFICATION

Length : 27' 7" (8·41 metres)

Height : 6'-9" (2·05 metres)

Width : 11'-6" (3·5 metres)

Weight (crawler) : 32·75 tons (33·27 tonnes)

Installed power : 240 hp, 185 hp or 130 hp (180 kW, 138 kW or 97 kW)

Minimum excavation height : 10'-0" (3·05 m)

Minimum excavation width : 12'-0" (3·65 metres)

Maximum cutting height, telescopic section retracted : 17' 6" (5·33 metres)

Cutting width from one position (floor level) : 17'-0" (5·18 metres)

Depth of cut below track level : 5" (127 mm)

Diameter of cutting head : 32" (813 mm) minimum to 42" (1067 mm) maximum

Depth of web : 20" (508 mm)

Ground clearance : 6" (150 mm)

Ground pressure (crawler) : 20 psi (1·41 kg/cm^2)

MAJOR ASSEMBLIES

1 Fabricated main frame and turret
2 Crawler side frames
3 Rear tie bracket and conveyor support
4 Centre conveyor assembly
5 Loading apron equipped with gathering arms
6 65 hp or 120 hp (48·5 kW or 90 kW) cutting boom assembly
7 Hydraulic power pack and controls
8 Electrical equipment

MAIN FRAME

The fabricated main frame forms the backbone to which all other major assemblies are attached. The cross roll bearing, turret and slewing jacks are mounted on this main frame.

SIDE FRAMES

The crawler side frame is fitted with heavy duty roller type chains together with the drive motor, gearbox and sprockets.

REAR TIE BRACKETS

This fabrication completes the support for the side frames, supporting the machine conveyor, and provides fixing points for service jacks. It also provides fixing for the rear wall sprag jacks. If an auxiliary winch is fitted, it is also mounted on this bracket, on left or right hand side as required.

CENTRE CONVEYOR

This is fabricated in sections which are bolted together to form a rigid structure which is fitted to the machine as a complete unit. It is designed to accept 14 mm twin strand outboard chains.

Abrasive resistant alloy steel is used for the deck plates for longer life.

It is driven by an hydraulic motor at the delivery end assisted by the gathering arm motors through the tail shaft. The minimum throat clearance under the turret is 15" (381 mm).

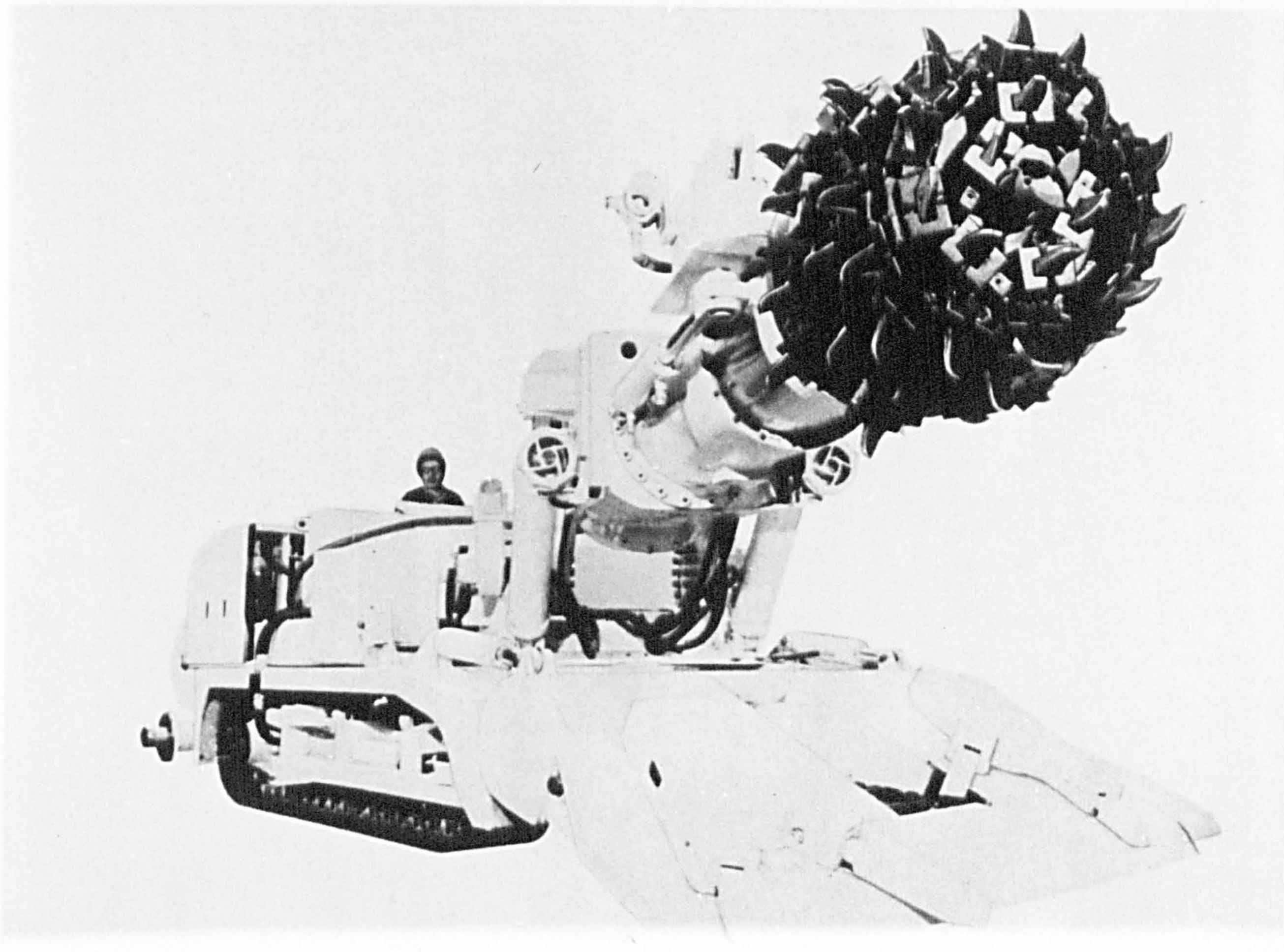


Plate 5. Anderson Strathclyde RH22 Roadheader

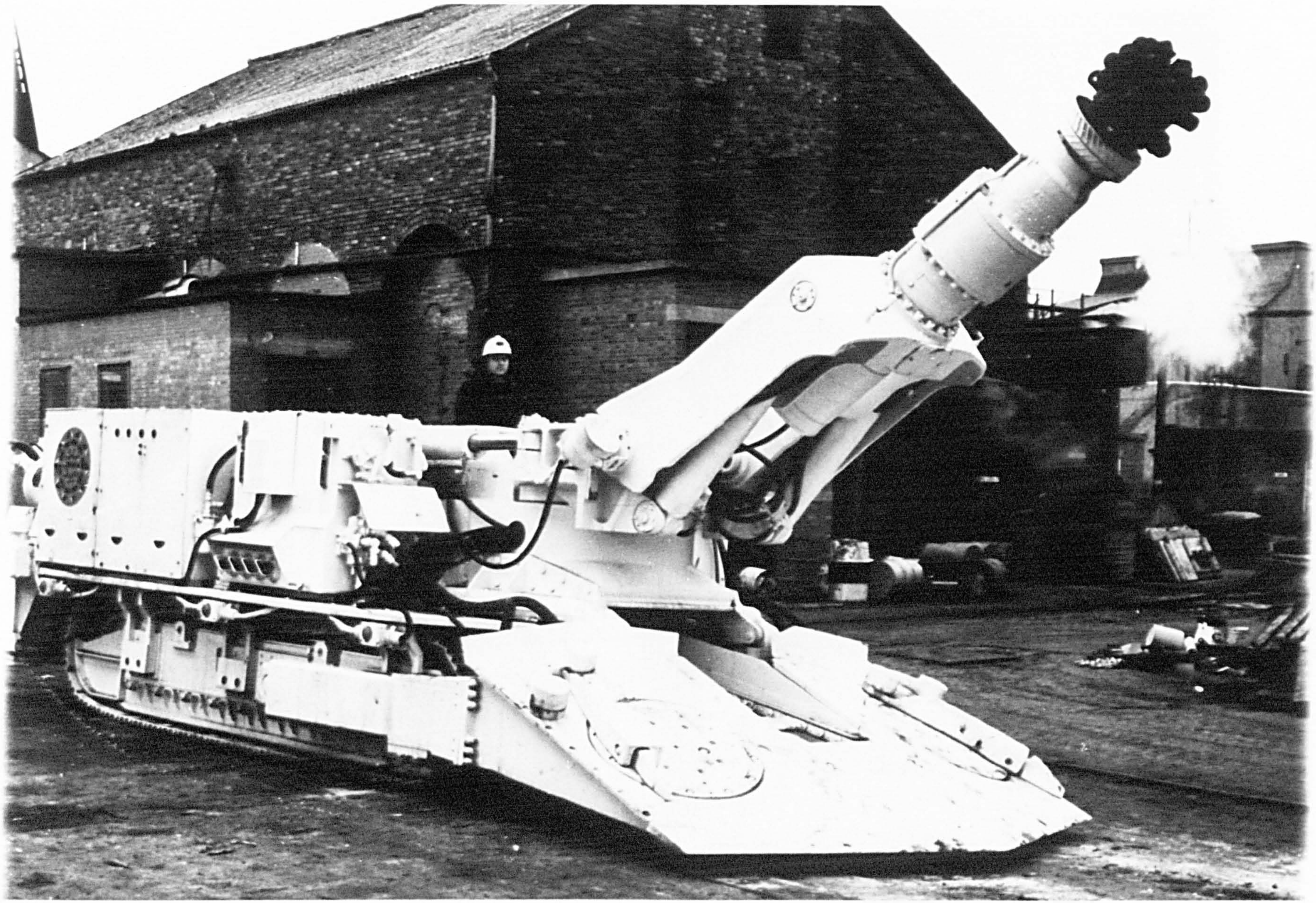


Plate . 6 Dosco MK2B Roadheader

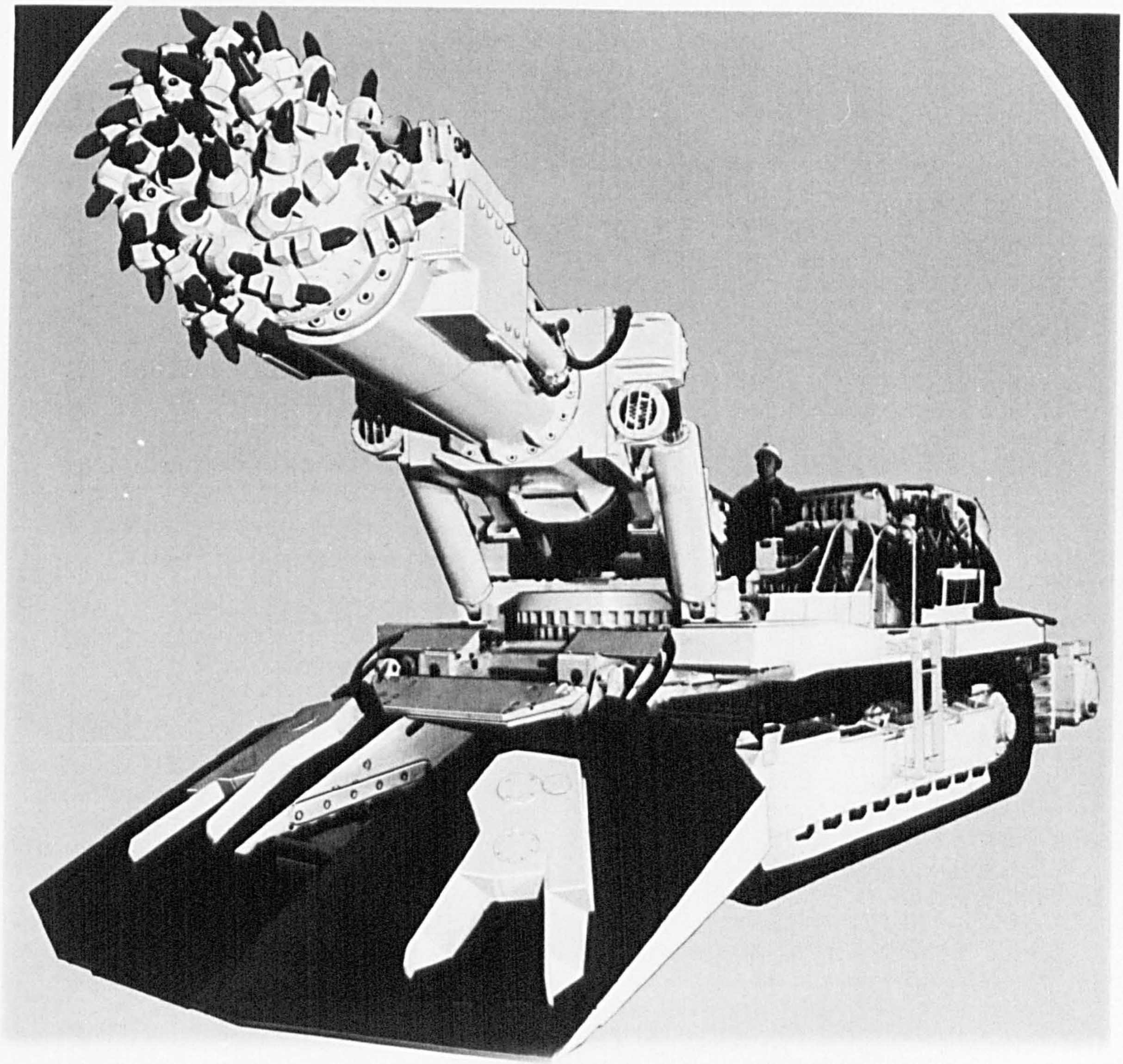


Plate 9. Anderson Strathclyde RH1/4 Roadheader

requirement to cut harder strata, larger roadways and give increased rates of drivage. Consequently, this requirement led to the development of even larger and more powerful roadheaders.

The first of these large roadheaders to be introduced into NCB coalmines was the Thyssen Titan E134 (illustrated in Plate 7). This machine is of the same basic design as a roadheader, but has a different type of debris collection system. This consists of twin conveyors instead of the usual gathering arms. The cutting head of this machine is pwoered by a 260 hp two-speed electric motor. The machine weighs in excess of 65 tons.

The Dosco MK3 heavy duty roadheader (Plate 8) was also developed to cut harder strata and the cutting forces installed in it exceed those of the Titan E134. The cutting head is driven by a 190 hp motor and the machine weight exceeds 70 tons.

A new machine under construction, the Anglo-Soviet Roadheader, is the largest of the heavy duty roadheaders, weighing over 85 tons. This machine, a joint development of the NCB and the Soviet Ministry of Coal, features a telescopic boom and also a slewing debris collection apron. The cutting head is powered by a 200 hp motor. This, together with high stability forces, produces a machine with a cutting capability superior to the other heavy duty machines. The prototype machines are now being produced, one in the UK and the other in the USSR.

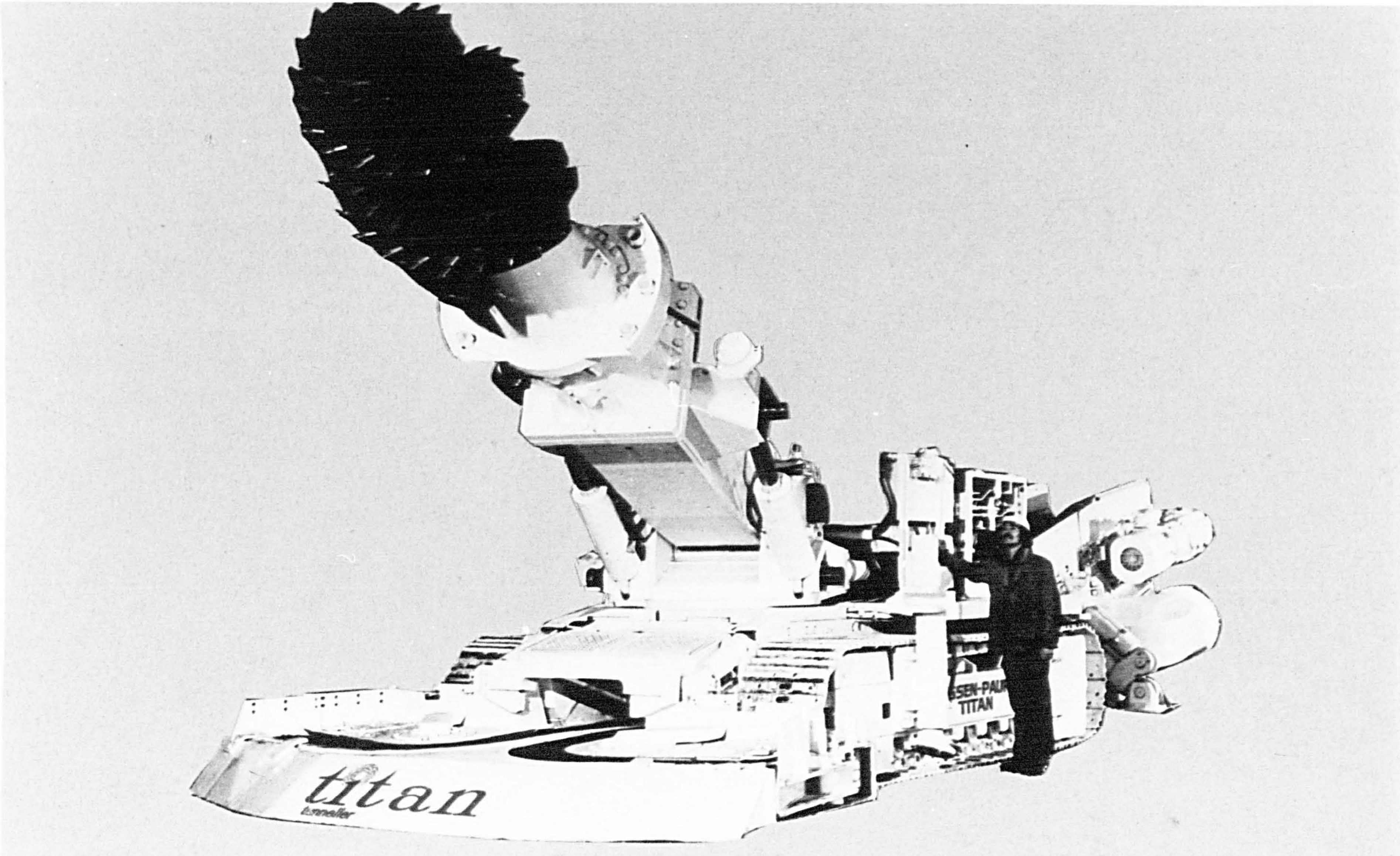


Plate 7. Thyssen Titan E134 Roadheader

Plate 8 Dosco MKIII Roadheader

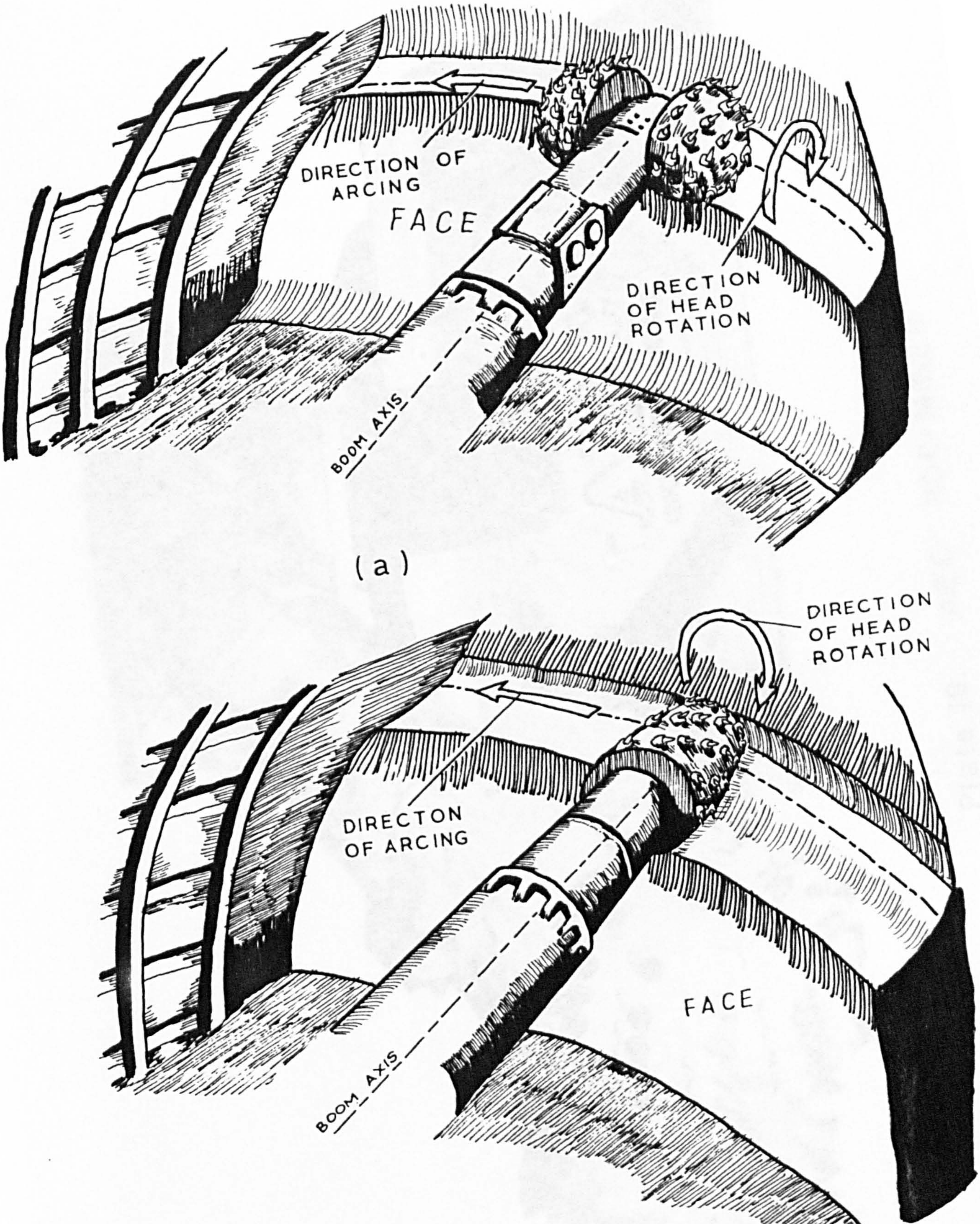
3.2 Roadheaders with Longitudinal and Transverse Cutting Heads

Boom-type roadheaders may have longitudinal (forward-rotating or milling-type) or transverse (ripper-type) cutting heads. These differ in accordance with whether the rotation of cutting head is in a radial or axial direction.

As illustrated in Figure 8b, longitudinal cutting heads rotate coaxially to the cutter boom and the slewing direction (Horizontal thrust) of the boom is at right angles to the axis of rotation of the cutting head. On transverse heads, the direction of rotation is perpendicular to the cutter boom (Figure 8a) and the main slewing direction of the boom lies in the same direction as the axis of rotation of the cutting head. The principal manufacturer of roadheaders with this type of cutting head are 'Voest-Alpine' and AEC of USA (Plate 10).

In the USA, Canada and Mexico, 75% of all roadheaders have ripper-type cutting heads. In the UK, practically all roadheaders use the longitudinal heads. In West Germany, where both types of machine are manufactured, 65% use the longitudinal and 35% employ transverse cutting heads.(60).

Menzel and Frenyo (57) reported that establishment of a qualitative relationship for the various characteristics of one particular head is not easy due to the fact that various advantages and drawbacks are involved. However, with respect to the head geometry,



(b)

Fig. 8 Cutting action of roadheaders with
(a) transverse cutting head and
(b) longitudinal cutting heads.

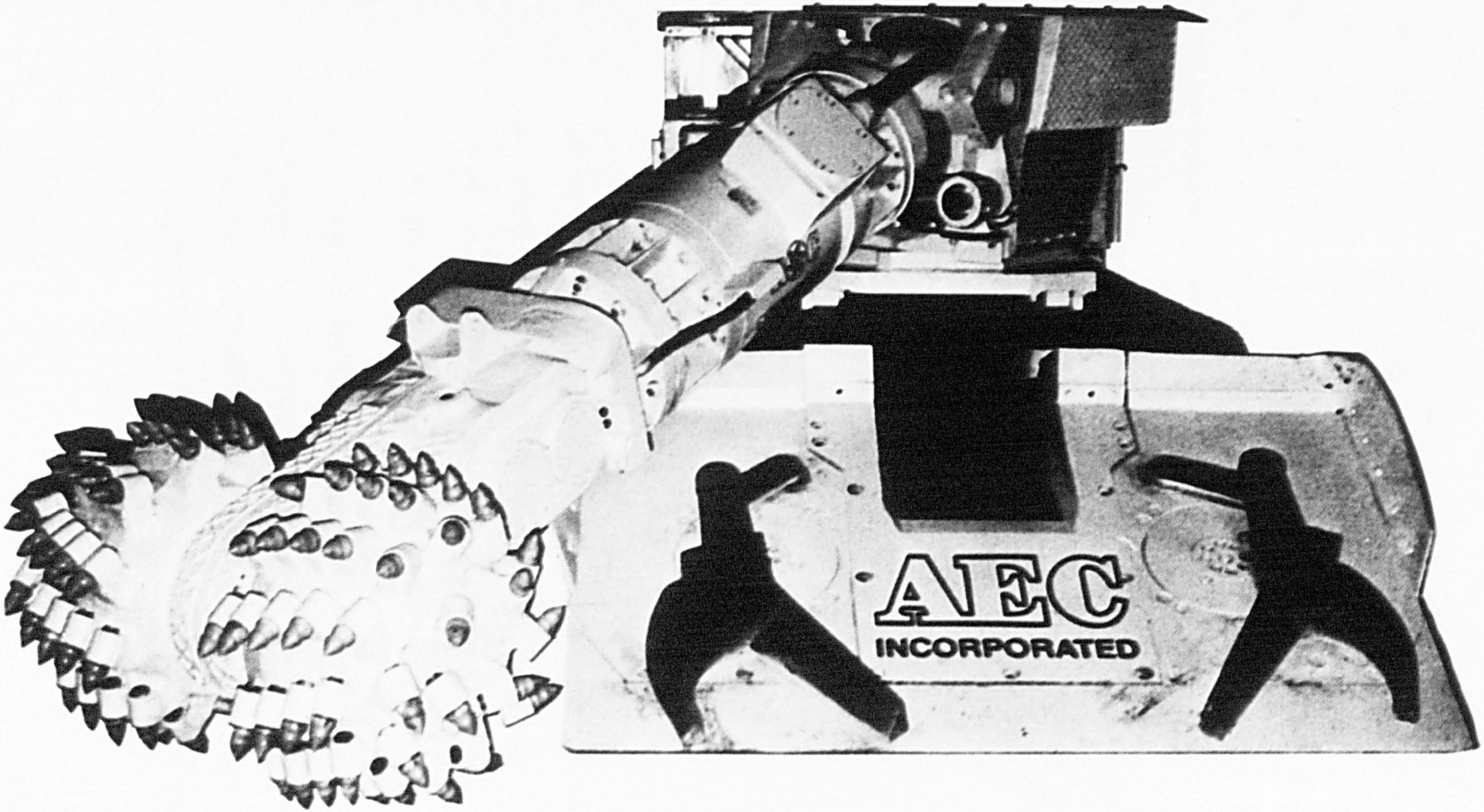


Plate 10. AEC ROC-MINER

the longitudinal cutting head would produce a smoother roof or wall surface, and the cost of lining may be reduced (Figure 9). Furthermore, horizontal stability is very seldom a problem with transverse machines while, in longitudinal heads, the horizontal stability is to be reinforced by means of articulated jacks.

Kleinert (58), after a series of experiments, reported the major design characteristics of longitudinal and transverse cutting heads, and gave the differences as follows:

(1) A transverse cutting head can be more easily matched to the cutting requirements of hard rocks;

(2) Pick lacing on a transverse cutting head is much more complicated than that on a longitudinal head. Minor irregularities result in substantial negative effects in terms of efficiency and tool wear;

(3) On a transverse cutting head, an efficient cutting performance is basically dependent on the available lifting force. On longitudinal cutting heads the main cutting force is rotational force.

(4) A longitudinal cutting head can more easily be maintained in its predetermined cutting path. In other words, pre-set burdens and depth of sump require more sensitive control when using the transverse cutting heads,

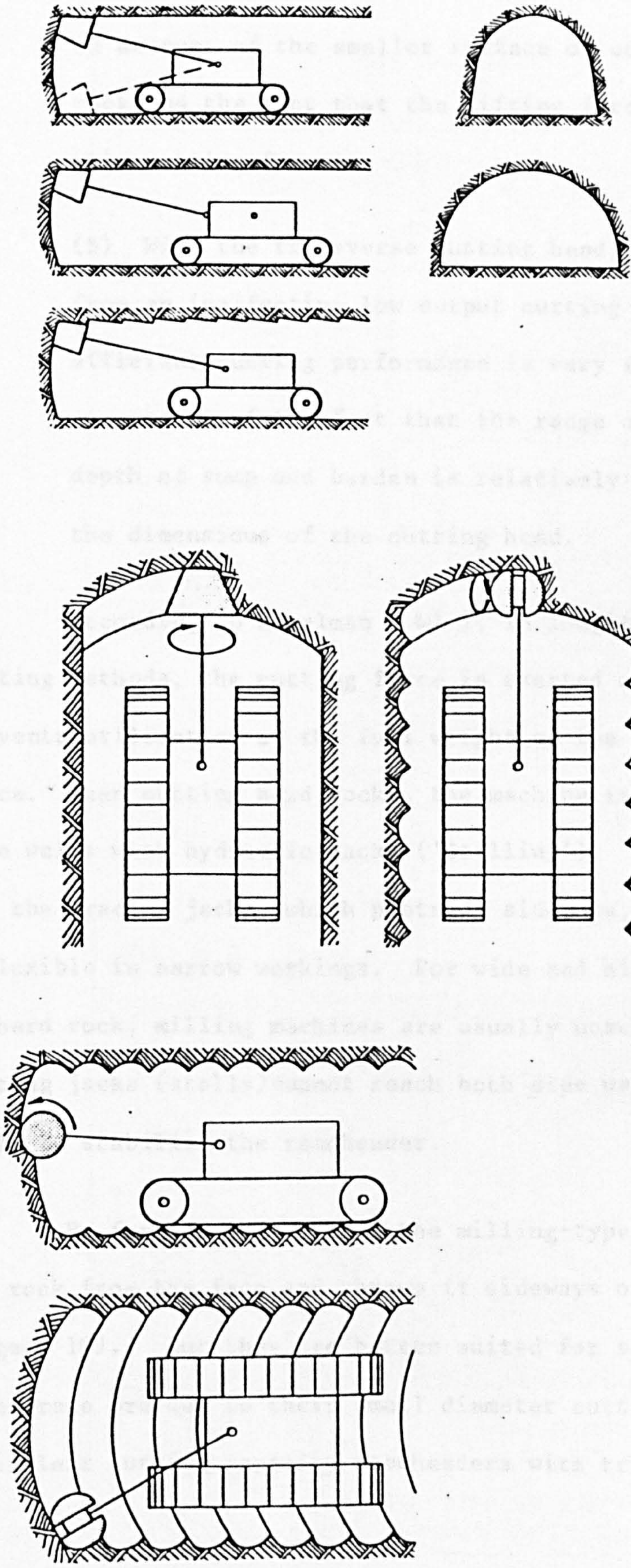


Fig. 9: Roadheaders with Longitudinal and Transverse Cutting Heads (After Menzel and Frenyo)(57)

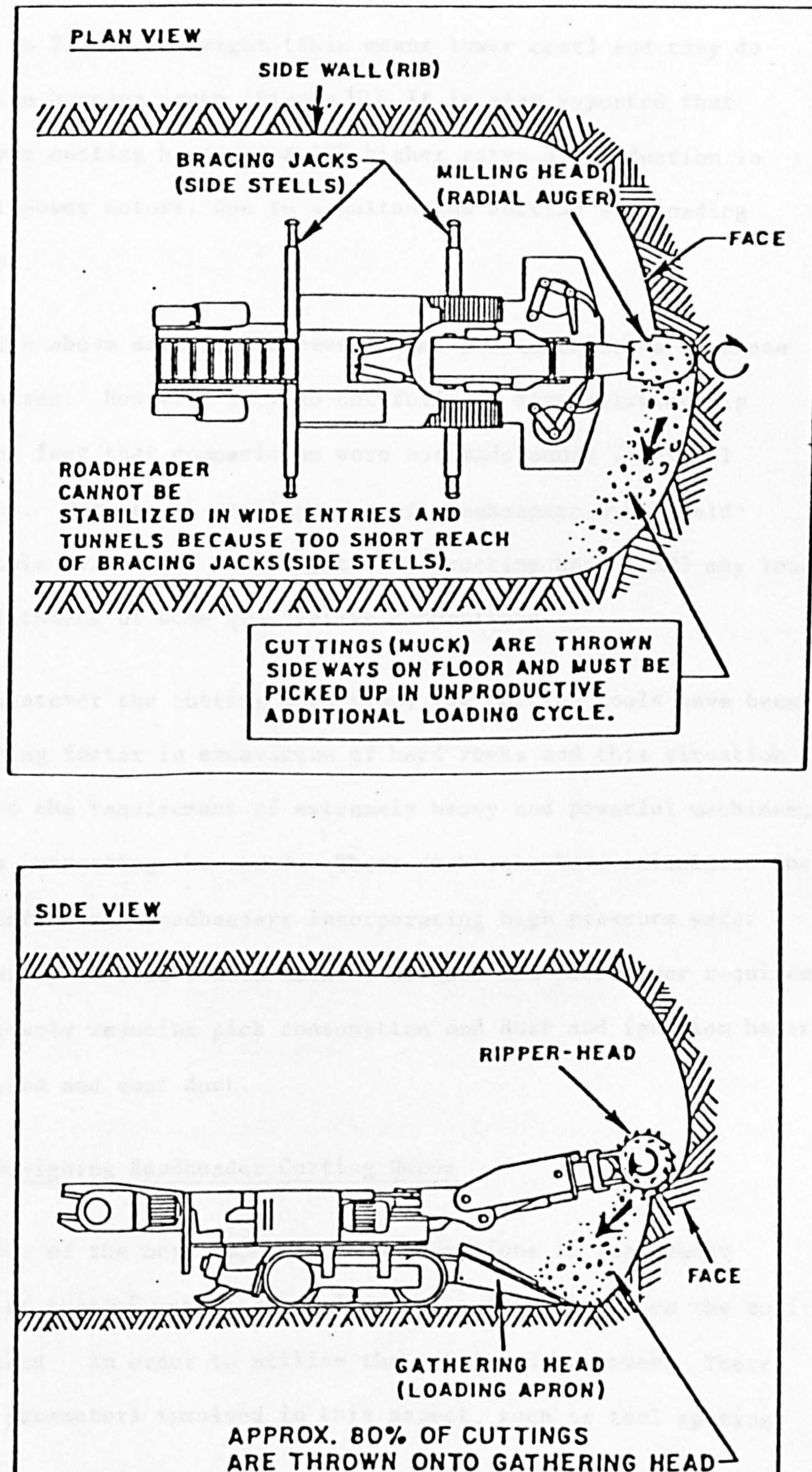
on account of the smaller surface of contact in the rock and the fact that the lifting force provides the main cutting force.

(5) With the transverse cutting head, the transition from an ineffective low output cutting action to an efficient cutting performance is very finely balanced, on account of the fact that the range of variation of depth of sump and burden is relatively small due to the dimensions of the cutting head.

According to Kogelman (60), in longitudinal (milling-type) cutting methods, the cutting force is exerted mainly sideways, which prevents utilisation of the full weight of the machine as a counter force. When cutting hard rocks, the machine is braced against the side walls with hydraulic jacks ('Stelling'). This consumes time, and the bracing jacks, which protrude sideways, make the machine inflexible in narrow workings. For wide and high tunnel cross-sections in hard rock, milling machines are usually unsuitable because their bracing jacks (stells)cannot reach both side walls (ribs) or the roof, to stabilise the roadheader.

He further states that the milling-type cutter head rips the rock from the face and throws it sideways onto the floor (Figure 10). But they are better suited for selective mining of high-grade ore due to their small diameter cutting heads. Also, for equivalent cutting capacity roadheaders with transverse cutting heads

Milling (in-line auger) — type boom miner: machine stabilization and loading cycle.



Ripper-type cutter head has 30% higher rate of production than milling (auger) head powered by identical motor because of simultaneous cutting and loading operation.

Fig. 10: Roadheaders with Milling and Ripper-type Cutting Heads (After Kogelmann) (60)

have 20% to 25% lower weight (this means lower cost) and they do not require bracing jacks (Figure 10). It is also reported that ripper-type cutting heads have 30% higher rates of production in identical power motors, due to simultaneous cutting and loading operations.

The above definitions reveal some characteristics of these cutting heads. However, they do not fulfil a firm relationship due to the fact that comparisons were not made under identical conditions. But recent developments of roadheaders with field-exchangeable transverse and longitudinal cutting head (AEC) may lead to establishment of some qualitative comparisons.

Whatever the cutting head type, the cutting tools have been the limiting factor in excavation of hard rocks and this situation has led to the requirement of extremely heavy and powerful machines, thus also increasing the costs. These drawbacks have stimulated the development of new roadheaders incorporating high pressure water jets in order to reduce both machine weights and horsepower requirements, simultaneously reducing pick consumption and dust and ignition hazards from methane and coal dust.

3.3 Designing Roadheader Cutting Heads

One of the most important considerations in roadheader practice is that of proper disposition of cutting tools on the entire cutting head in order to utilise the total machine power. There are many parameters involved in this aspect, such as tool spacing, tool lacing, arrangement of gauge or corner cutting tools, pick cutting positions, cutting head geometry and some kinematic considerations associated with the rotation action of the head.

3.3.1 Spacing between adjacent tools

Lateral spacing of adjacent tools is of importance since this influences the level of pick forces and accounts for the cutting efficiency. Many research workers have investigated this aspect under laboratory conditions.

Barker (18) conducted a series of rock cutting experiments which led to the design of MRE large pick shearer drum. He suggested when spacing equals tool width (w)(at a particular penetration), specific energy consumption reaches a minim, i.e. 100% coverage gives the most efficient working.

Evans (63,64) suggests that for groove depths from 0.5 w to 2w, the lateral spacing, S, should be between 2w and 5w. As a design compromise, S = 4w is suggested, and S = 3w was apparently found to be satisfactory on a coal shearer.

Roxborough (12) and Roxborough and Rispin (23) defined the optimum spacing by considering the occurrence and minimum specific energy. They found that interaction between the adjacent cutters on a flat rock surface, begins when $S = w + 2d \tan\theta$ and specific energy is minimised with $S = w + kd$, where d is depth of cut and k has values ranging from 1.5 to 3 for various materials. It is reported by Mellor that this approach may be logical but some practical aspects should be considered, since the depth varies from zero to some maximum value in transverse rotation machines. Hence he relied on Barker's results, taking $1 < S/w > 2$ as a general range, with close spacing in tough materials and wider spacings in more friable materials (65).

The majority of the laboratory rock cutting studies are based on the experiments carried out on a flat rock surface and results have shown that there is a minimum value at a certain spacing to depth ratio. However, if the action of a practical machine is considered the results may present some different trends. The main source of information is Hurt (66) on this subject. By using various practical drag tools, he conducted a series of experimental work at which the action of a roadheader is simulated in such a way that each tool cuts midway between the tools of a preceding sequence. It was found that specific energy decreased with S/d rapidly at first, and then more slowly; thus the remarkable minimum in specific energy as occurring on a flat rock surface does not happen. Based on this result, Hurt and Evans (67) suggest that efficient cutting of hard rock can best be achieved by giving tunnelling machines the capacity to take greater depths of cut and selecting tools capable of withstanding the associated high forces. Under these circumstances of efficient cutting, the relative merits are of secondary importance and tool life, not cutting efficiency, should be the primary selection criterion.

Ramman (68) reports that practically the torque is not the limiting machine parameter, but slewing force. The specific energy may, therefore, not be the main criterion for optimum tool spacing. His experimental results on optimum tool spacing also confirm those of previous investigators.

Despite these definitions for optimum tool spacing, the machine designer tends, in most cases, to make a choice, drawing on personal experience and knowledge of relevant rock properties.

3.3.2 Disposition of Cutting Tools

Cutting tool arrangement on a roadheader's cutting head is somewhat inspired by shearer-drum design, where a helical tool array is the most common sense. It, therefore, seems to be worthwhile to mention the design aspects of shearer-drums.

The picks on a wide drum may be arranged symmetrically in straight lines along the generators of the drum, more or less like the vanes of a simple paddle wheel. In practice, this arrangement emerges to be very poor, as it would lead to serious vibrations during cutting, unless the number of picks per line is very large. However, if the drum shell is twisted so that the rows become helices, the cutting sequence is staggered and smoothed, while at the same time, the helical arrays from scrolls that can be adopted for lateral transport of cuttings (Mellor, 65). Furthermore, with suitable design of helical arrays, it is possible to improve cutting efficiency by forming lateral steps across the advancing face and giving each bit an additional free surface for breakout of chips.

Since the tools cut in an array to benefit from the breakout left by the preceding tool, in shearer drums the cutting sequences are recommended to start to cut from the machine side and move progressively to the face side (3,4) This method is reported to be advantageous for the corner cutting tools (Roxborough (69)), and for tool holder clearance in roadheader cutting heads (Hurt (29)). Pomeroy and Robinson (28) found that lower pick forces can be achieved when cutting from the machine side to the nose (face)side. However, in roadheader practice, cutting appears to progress from the nose of the head to the free surface, perhaps to satisfy a loading requirement.

3.3.3 Cutting Position of Tools

Although arrangement of cutting tools on roadheader cutting heads is a complex subject, as well as being of importance in machine design, the amount of research directed to this aspect is extremely limited.

Hurt (29) emphasised the importance of a proper cutting head design when investigating the performance of a number of road-header cutting heads. He further suggested that the duty of each tool should be equal on the cutting head and that adapting a cutting pattern or sequence would give better distribution of cutting duties.

Hurt and McAndrew (30) reported that there are two important parameters concerned with the tool spacing. The cut spacing (S) is the distance between the centres of adjacent cuts in a sequence

(Figure 11). The parameter cutting line spacing (S_L) which is measured around the cutting head periphery can also exercise a critical influence on the cutting performance. S_L is determined by the relative positioning of tools between the cutting sequences. For a two-sequence cutting head if $S = S_L$ the tool layout is known as 2 tools per line (this mode produces a groove deepening cutting action and is found in laboratory experiments to be not very efficient). The most usual alternative has S_L approximately equal to S/2, which gives a cutting head with 1 tool per line.

Furthermore, to minimise vibration during cutting and to prevent any particular tool from experiencing a disproportionately high loading, the forces imposed on every tool should be about the same. Because the forces on the tools are usually proportional to the cut spacing, S, this can be achieved by keeping S approximately constant around the entire cutting head periphery. Finally, they suggest that, for conical heads, the toolholders should be placed so that the tool axis is normal to the cone surface, rather than normal to the axis of rotation. Failure to do this results in the tools cutting predominantly on one side, resulting in inefficient cutting and, in extreme cases, the large side loading induced can push off the tool tip.

The cutting tools on roadheader cutting heads have tilt angles inclining the tools towards the nose of the head. This situation also reflects the head geometry and may influence the duty of picks, in particular with the performance of corner cutting tools

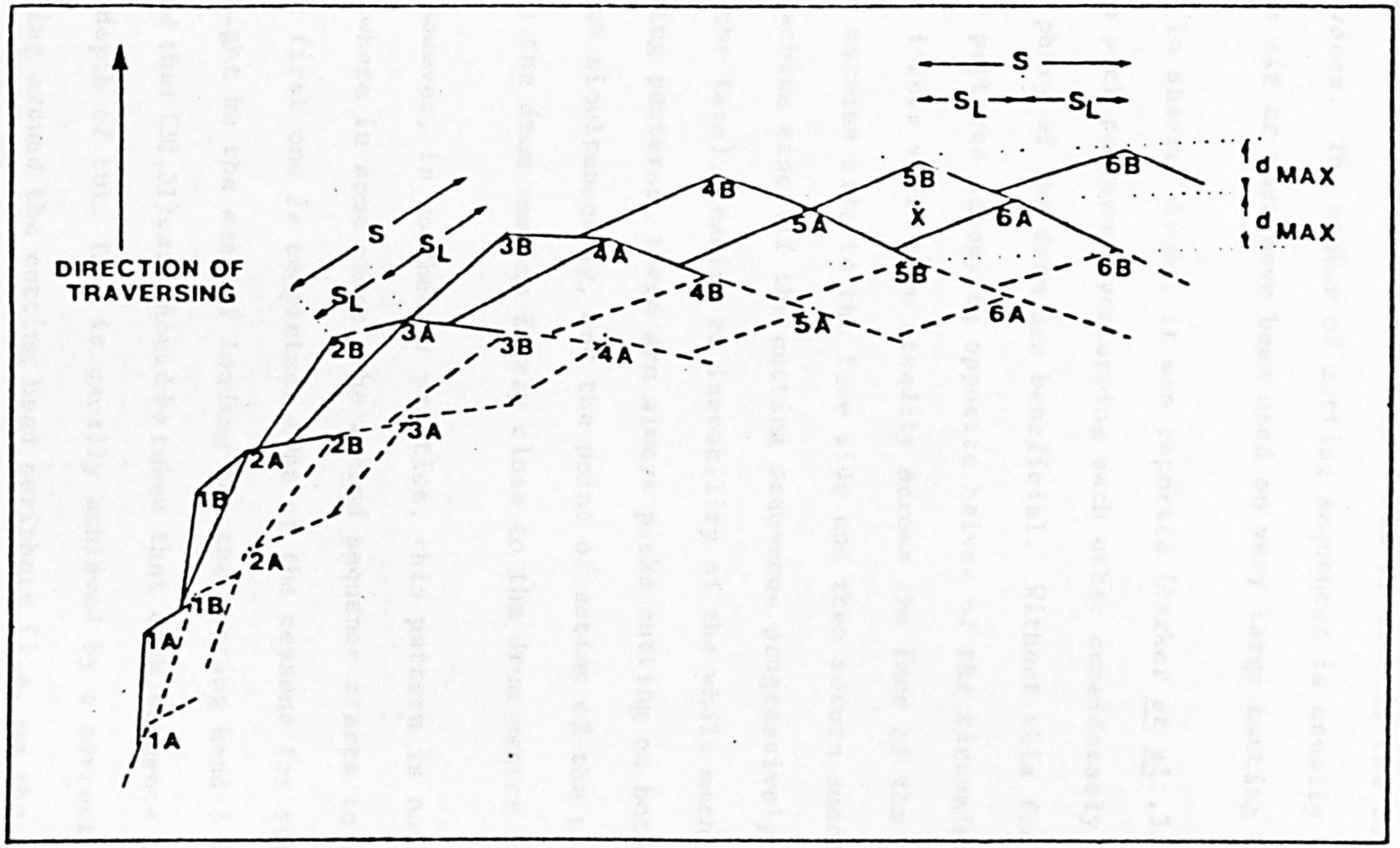


Fig. 11: A Cutting Pattern illustrating Spacing and Depth of Cut Parameters (2 Revolutions shown)

(after Hurt and McAndrew)(30)

The cutting action of a cutting head or drum consists during each revolution of a discrete number of sequences of adjoining cuts. These sequences are sometimes termed starts even if the cutting head has no vanes. The number of cutting sequences is usually two, although six or more have been used on very large cutting heads.

In shearer drums, it was reported (Barker et al.,3; Brooker,4) that two pick patterns overlapping each other considerably around the periphery of the drum are beneficial. Without this feature, i.e. two patterns occupying opposite halves of the circumference, the pick forces would move steadily across the face of the drum from the machine side to the face side and then return suddenly to the machine side (if the cutting sequences progressively cut towards the face), leading to instability of the whole machine. By overlapping patterns, there are always picks cutting on both halves of the web simultaneously, and the point of action of the pick forces on the drum remains fairly close to the drum centre line.

However, in roadheader practice, this pattern is not always adopted, where in some cases, the second sequence starts to cut after the first one is completed. (One of the reasons for this pattern might be the ease of loading for the cutting head.) It is also emphasised that (30,31) care should be taken that each sequence takes the same depth of cut. This is usually achieved by a correct angular tool spacing around the cutting head periphery (i.e. on the plane perpendicular to the boom axis, for longitudinal cutting heads).

which may be subjected to very high loading. The author has found no research work on this aspect of roadheader cutting head design.

3.4 Drag Tool types used on Roadheader Cutting Heads

Although the investigations have, so far, shown that in the sharp conditions a chisel-type cutting tool is the most efficient, in practice, the cutting tools used are of more complex geometry. The most common picks are 'radial tools' and 'point attack' (pencil point) tools. In terms of tool durability, the latter has been shown to have a longer life in abrasive rocks. This is usually ascribed to its ability to maintain a stabilised geometry by rotation in the tool holder. It should be noted that the geometry attained by rotation is not as efficient as the pristine tool.

Hurt and Evans (67) reported that, with all tools in the sharp condition, the point attack required the highest cutting and normal forces, whereas blunting had a much greater effect on the wedge (radial) tools, so that after 600m of cutting in an abrasive sandstone, the point attack tool had the lowest forces. These results also indicated that the tool forces on a pencil-point tool can be just as large as those of grossly blunt non-rotating tools. The reason is that as the tool rotates a larger cone angle (approximately equal to twice the angle of attack) is formed on the tip, and the back clearance angle is consequently reduced to zero. However, angling the tool by about 5^{o} from the cutting line, i.e. introducing an angle of skew is sometimes claimed to aid rotation of the tool.

The cutting position and (wedge) cone angle of the point attack tools are important variables significantly affecting the tool performance. Hurt and Evans (67) found minimum cutting forces forthe 75° cone angle tool, at an angle of attack of 50°. Werner and Kleinert (58) report that in order to avoid extreme forms of wear, such as fracturing of the hard metal, large wedge angles are used when cutting hard rocks. They further report that since the cutting of a longitudinal head describes a cycloid and its degree of elongation is dependent on the rotational speed, the angle of attack must be matched to the rotational speed and should be at least 45 degrees. At high rotation speeds, for example in soft rocks, a larger angle of attack must be selected, since the tangent to the cutting path is flatter and hence the angle of attack is reduced when the head is in motion. The angle selected should never exceed 48°.

Detailed information on the performance of point attack and other commercially available drag tools can be found elsewhere (70,71).

3.5 Kinematics of Roadheader Cutting Heads

A conventional roadheader has two cutting modes of operation; the cutting head is first advanced axially or sumped into the rock force and the boom is then moved so that the cutting head 'traverses' or arcs across the face. Sumping action will not be considered in this work as it forms only a small part of the cutting cycle.

Although the kinematics of transverse rotation machines are detailed by Mellor (65), some aspects are quoted as below:

Also, the main cutting modes of traversing may be distingished as illustrated in Figure 12 . In upmilling, (or up-cut milling) the cutting rotor is sunk into the rock to a depth less than the diameter, the axis of rotation is parallel to the primary free surface, and the direction of rotation is such that the cutters move upward on the loading side of the rotor. In climb-milling (or down-cut milling), the cutting rotor is sunk into the rock to a to a depth of less than the diameter, the axis of rotation is parallel to the primary free surface, and the direction of rotation is such that the cutters move downward on the loading side of the rotor. In the slot milling or traversing mode, the rotor is cutting across its complete semi-circumference, and the axis of rotation is normal to the primary free surface.

The depth taken by each tool (chipping depth) also continuously varies as a consequence of rotational and traversing speed of the head. When a cutting rotor is upmilling at typical speeds (Figure 13), each tool enters to the rock at Point A, with a depth that is virtually zero. The depth increases progressively through the working sweep, reaching a maximum value as the pick leaves the work at Point C. If the rotor is climb-milling, each tool enters the work at Point C, taking maximum depth at the point of entry and tailing off to virtually zero depth at point of exit A. If the rotor is slot-milling, each pick

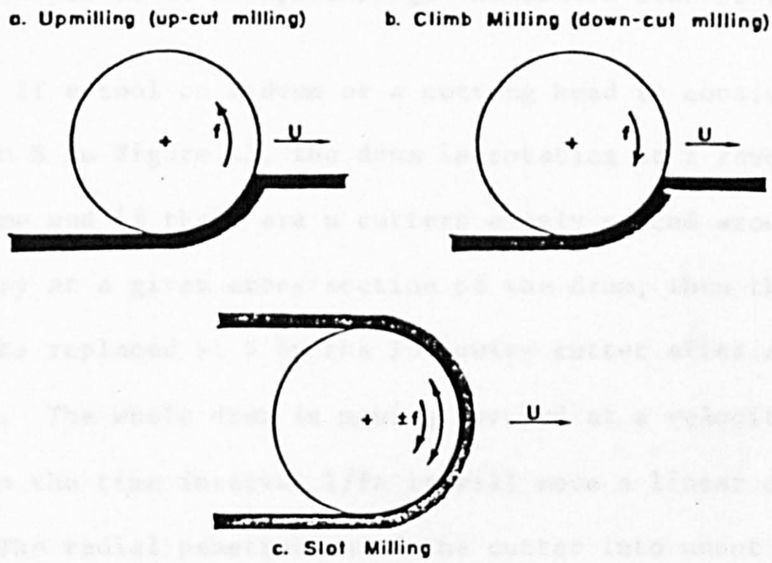


Fig. 12: *Cutting modes for transverse rotation devices.* (After Mellor) (65)

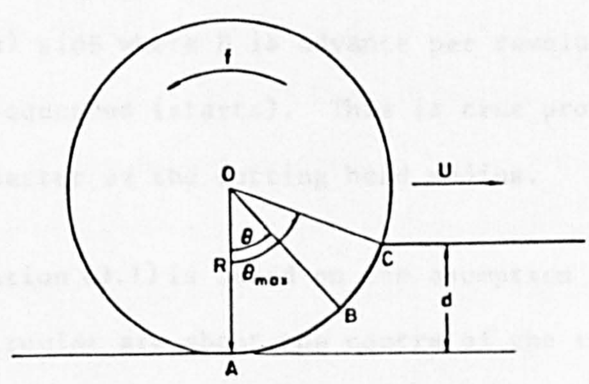


Fig. 13: *Geometry of an upmilling rotor.* (After Mellor) (65)

enters and leaves the work with virtually zero depth, and takes its maximum depth as it sweeps through the centre line of the slot.

If a tool on a drum or a cutting head is considered at position B in Figure 13, the drum is rotating at f revolutions per unit time and if there are n cutters evenly spaced around the periphery at a given cross-section of the drum, then the cutter at B will be replaced at B by the following cutter after a time interval of 1/fn. The whole drum is moving forward at a velocity u, and, therefore, in the time interval 1/fn it will move a linear distance of U/fn. The radial penetration of the cutter into uncut material, i.e. the theoretical radial chip thickness, is therefore:

$$\ell = \frac{U}{fn} \sin\theta \qquad \text{..... (3.1)}$$

Definition of depth of cut is likely to result in some confusion. A reasonable definition is given by Hurt and McAndrew (30) and Hurt et al. (31), in such a way that for traversing picks only $d = (D/n) \sin\theta$ where D is advance per revolution, n is number of cutting sequences (starts). This is true provided D is less than about one-quarter of the cutting head radius.

Equation (3.1) is based on the asumption that each pick moves through a circular arc about the centre of the rotor, whereas for other purposes, e.g. calculation of pick trajectories, it is necessary to consider the path of the pick tip relative to the rock. In this case, the traversing action of the rotor has to be added to the rotational motion. The trajectory of a pick tip may be explained as below (65):

If the motion of a single tooth is considered after it enters the rock at Point A (Figure 13), and Point A on the rock is taken as the origin of the coordinates, the traverse direction is the x-direciton and the y is normal to the traverse direction. After the rotor has turned through an angle θ, the tip of the pick has progressed through a distance R (1 - cosθ) in the y-direction, and through a distance ($U\theta/\omega$ + R sinθ) in the x-direction, where w is angular velocity of the rotor (=$2\pi f$). Thus the equation of the locus for a tooth tip on an upmilling rotor is:

$$x = \frac{U\theta}{\omega} + R \sin\theta$$

$$y = R (1 - \cos\theta) \qquad \ldots\ldots (3.2)$$

when the rotor is more than axle deep in the work ($d/R > 1$) and θ is greater than 90^{o}, the value of R sinθ decreases progressively as θ increases in the second quadrant. Maximum extent of the tip trajectory in the x-direction is reached when $\cos\theta = -U/\omega R$ and the trajectory starts to loop back against the machine's traverse direction when $wR \cos\theta$ is numerically greater than U.

If the rotor is climb-milling, i.e. rotating in the opposite sense to the wheel shown in Figure 13, it is convenient to take the point of the tip exit as the origin (Point A)while retaining the original definition of angular position. The equation of the tool tip locus for climb-milling then becomes the same as in the upmilling mode except for x-direction where $x = (-U\theta/w) + R\sin\theta$.

Figure 14 shows tool trajectories for various values of traverse speed relative to rotational speed, for both upmilling and climb-milling. The x and y values are normalised with respect to R, i.e. x and y are given as fractions of multiples of the rotor radius. The parameter of the curves is U/wR, or $U/2\pi fR$. When the value of $U/2\pi f$ is high, the tool tends to make a long forward sweep relative to the rock, but when $U/2\pi f$ is small, the tool comes close to sweeping through a circular arc. Typical values of $U/2\pi fR$ for existing rock cutting machines are in the range 0.005 to 0.05, and for this range, the tool sweep is almost circular.

If $\theta_{max} \leqslant 2\pi/n$ a complete trajectory can be traced out by a single tooth before the next tool enters the working sweep, but if $\theta_{max} > 2\pi/n$, the trace left by one tool is being affected by the following tool before the first has finished its working sweep. It is easy to see that serious vibrations would be set up with $\theta_{max} < 2\pi/n$ unless some damping arrangements were made. A simple way of smoothing out these potential vibrations is to stagger laterally adjacent rings of cutters; for example, by setting cutters along helical paths.

3.6 Forces acting on the cutting tools and the cutting boom

Forces acting on a tool tip can be resolved into radial F_R and tangential components F_θ (Figure 15) and these are approximately

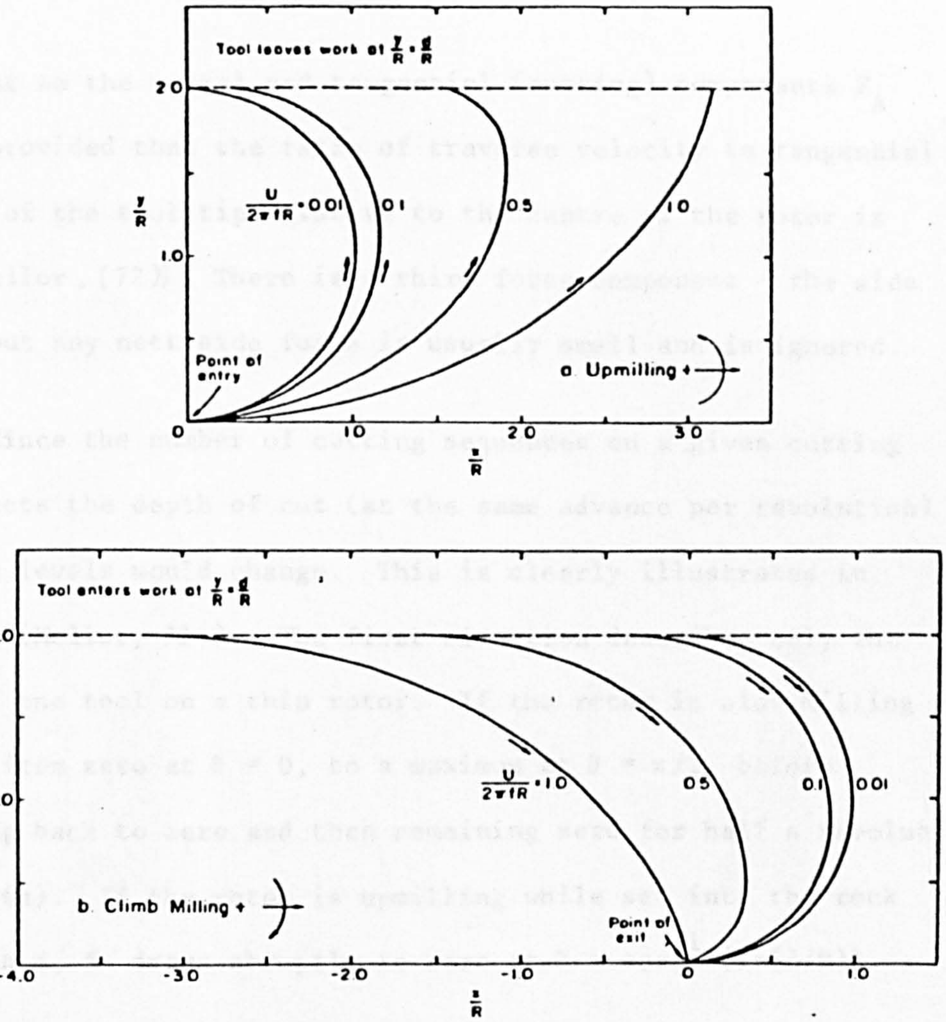


Fig. 14: *Tooth-tip trajectories for upmilling and climb milling rotors (N.B. Values of U/2πfR approaching 1.0 are not likely to occur in normal operations).* (After Mellor) (65)

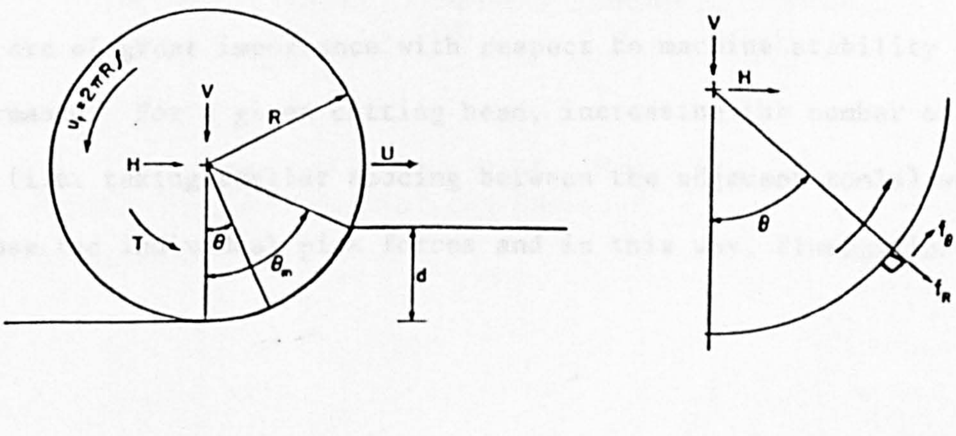


Fig. 15: Force Components Acting on a Drum and on a Tool Tip (After Mellor) (65)

equivalent to the normal and tangential (cutting) components F_A and F_c, provided that the ratio of traverse velocity to tangential velocity of the tool tip relative to the centre of the rotor is small (Mellor, (72)). There is a third force component - the side force - but any nett side force is usually small and is ignored.

Since the number of cutting sequences on a given cutting head affects the depth of cut (at the same advance per revolution) the force levels would change. This is clearly illustrated in Figure 16 (Mellor, 72). The first situation describes only the action of one tool on a thin rotor. If the rotor is slot milling F rises from zero at $\theta = 0$, to a maximum at $\theta = \pi/2$, before decreasing back to zero and then remaining zero for half a revolution (Figure 16a). If the rotor is upmilling while set into the rock to a depth d, f drops abruptly to zero at $\theta = \cos^{-1}(1-(d/R))$.

If there are two diametrically opposed cutting tools considered (Figure 16b) under the same conditions, the force values (f_θ) are only one-half the corresponding values for the single-cutter case.

These situations also provide some insight into the fluctuations in torque, horizontal and vertical reactions of the cutting boom. These are of great importance with respect to machine stability and performance. For a given cutting head, increasing the number of tools (i.e. taking smaller spacing between the adjacent tools) would decrease the individual pick forces and in this way, fluctuations in

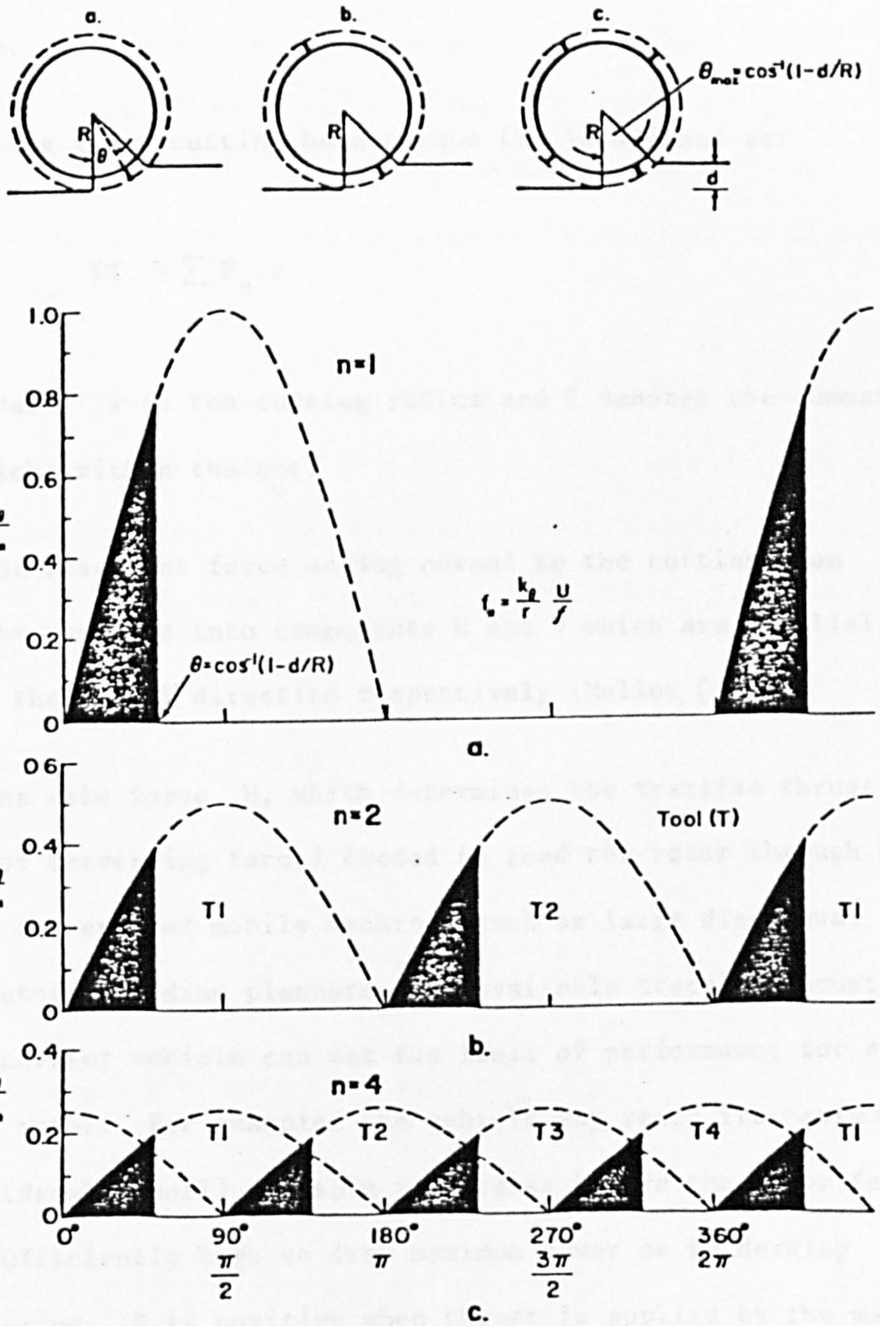


Fig. 16: *Variation of tool force f_θ with angular position θ for different numbers of tracking cutters (assuming f_θ proportional to ℓ).*

(After Mellor) (72)

these parameters can be reduced. The power and traversing force available from the machine determines the rate of cutting in a given rock.

For a given cutting head torque (T) is defined as:

$$\Sigma T = \sum F_c . r$$

where r is the cutting radius and Σ denotes the summation for all picks within the cut.

The resultant force acting normal to the cutting boom axis may be resolved into components H and V which are parallel and normal to the travel direction respectively (Mellor, [72]).

The axle force, H, which determines the tractive thrust (slewing or traversing force) needed to feed the rotor through the rock. In the case of mobile machines such as large disc saws, wheel ditchers, or drum planners, the available tractive thrust from the carrier vehicle can set the limit of performance for an upmilling rotor. For example, the vehicle may reach its maximum traction (drawbar pull) and spin its tracks before the rotor feed rate is sufficiently high to draw maximum power or to develop maximum torque. H is positive when thrust is applied by the machine in the direction of travel.

The axle force, V, which is perpendicular to the direction of travel and to the work surface, determines the downthrust needed to maintain a given depth of cut, d. On mobile machines, this downthrust is often provided by hydraulic activators, and an upper limit to positive downthrust is set by the weight and balance of the machine. If the force V exceeds the thrust capability of the actuators or the available reaction, then cutting depth d or forward speed U will have to change in order to limit V. The vertical force V is positive when thrust applied by the machine is downward into the rock.

Tilt angle of the tools on roadheader cutting heads is also considered for the calculation of H and V, since the effective normal force components in the plane of horizontal and vertical reactions is $Fn.\cos\alpha$, where α is the tilt angle (Hurt 1980). Thus H and V are given as:

For upmilling cutting mode:

$$H = F_n \sin\theta \,.\, \cos\alpha + F_c \cos\theta \qquad \text{..... (3.3)}$$

$$V = F_n \cos\theta \,.\, \cos\alpha - Fc \sin\theta \qquad \text{..... (3.4)}$$

For climb milling cutting mode:

$$H = F_n \sin\theta \,.\, \cos\alpha - Fc \cos\theta \qquad \text{..... (3.5)}$$

$$V = F_n \cos\theta \,.\, \cos\alpha + Fc \sin\theta \qquad \text{..... (3.6)}$$

In climb milling mode the level of slewing force (H) may be lower than that of upmilling mode. However, deep cutting and aggressive attack in the former, are usually not very practical, since the cutters enter the rock with maximum depth of cut and this results in severe vibrations (Mellor,(72)) and possible impact damage to the tools.

3.7 Specific Energy

The specific energy of a cutting machine is defined as the energy required to cut unit volume of material. The overall specific energy for a complete machine is based on the total power output of the machine which comprises the rotor power (P_R), the thrust power (P_H) and the power loss (P_L). In this context, P_L does not contribute directly to the cutting process. Also, in many cases, P_H is smaller than P_R and, therefore, it can sometimes be neglected for practical purposes (Mellor (72)). Thus the specific energy (E_S) in the resulting simplified form may be expressed as follows:

$$E_S = \frac{P_R}{\dot{V}} \approx \frac{2\pi f\ T}{\dot{V}} \qquad \text{..... (3.7)}$$

where f = number of revolutions of the head per unit time (rev/min, rev/sec)

T = cutting torque

$\dot{V}$ = volumetric cutting or excavation rate given as UBd where B is drum length and d is depth of cutting rotor in the rock.

This analysis has considered a parallel drum cutter of the type used as a longwall shearer, whereas the geometry of roadheader cutting heads may be conical, spherical or a combination of both, and the analysis of these head geometries is covered in Chapter Ten.

* * *

4. OBJECTIVES OF THE RESEARCH

The objective of this study is to investigate, in a systematic way, cutting head design of rock excavation systems, taking into account the practical excavation action of the actual machine, with a view to assisting in further development of optimal cutting head design. This entails providing quantitative data on the cutting duties of the tools, effects of cutting head profile, and the mode of operation on performance and efficiency of the cutting machines.

Investigations into the even distribution of the relative cutting duties requires a careful field or laboratory study, as this is a complex subject. The field trials can be very rewarding in this aspect, though they do not always offer the desired control over the parameters considered. The need for strict control over a whole range of variables, together with the reduced experimental cost make laboratory investigation attractive. However, the laboratory trials on the simulation of cutting heads is extremely tedious and laborious.

This research work is concerned only with the laboratory simulated rock cutting conditions which were designed to represent the practical cutting action of the actual machines, during which the forces and specific energies of cutting tools on various cutting heads were recorded and analysed. The aim of this research can be detailed as follows:

SECTION ONE

1. To determine the composition of an artificially made rock salt material for a wide range of rock cutting experiments with drag tool cutters.

SECTION TWO

2. To investigate the optimum tool spacing by simulating the practical cutting action of commercially used drag tools.

SECTION THREE

3. To simulate a series of roadheader cutting heads systematically with the object of investigating the effects of tilt angle on the duty of cutting tools.

4. To study the kinematics and energetics of these cutting heads with the aid of a computer programme by using the data obtained from previous simulation experiments.

5. To examine the effects of varying the total number of picks on roadheader cutting heads, with regard to the cutting duties of the tools.

6. To investigate the influence of starting the cutting sequence from the nose of the head on the performance of picks in the cutting array.

7. To study the effects of arcing mode of operation on machine performance.

SECTION FOUR

8. To study the performance of disc cutters by considering their practical cutting action by simulating the cutting action of a full-face tunnel boring machine.

In Section One of the experimental programme, the mechanical cutting characteristics of an artificial rock salt material was investigated and compared with natural rock salt. This artificial material was further planned to be used as a medium for future large scale rock cutting trials.

For Section Two of the experimental programme, point attack tools and radial tools were used and the main variable was tool spacing, while depth of cut was kept constant.

For Section Three pick tilt angle, cutting head profile and mode of machine operation were investigated at a constant advance per revolution of the cutting head.

For Section Four of the experimental programme the main variables were disc edge angle, depth of cut and skew angle which were investigated at an elementary level.

* * *

5. EXPERIMENTAL EQUIPMENT AND TECHNIQUES

In this chapter, the equipment which was used during the experimental programme and the techniques and methods used to simulate the action of practical rock cutting machines are described. A more detailed description of the techniques developed specifically for the simulation experiments is given in the appropriate chapter of this work.

To undertake fundamental rock excavation research the basic requirement is the measurement of the orthoganal force components acting on a mechanical tool when cutting rock under a variety of simulated practical conditions in the laboratory.

The laboratory cutting rig may have either a linear or rotary cutting action which may use single or multiple tools. For these fundamental studies it was considered advantageous to use linear cutting rigs where the depth of cut is constant rather than continually changing. The linear cutting rigs were were used for drag tools and disc cutting experiments in this work were developed by previous workers (20, 74).

5.1 Experimental Equipment and Techniques for Drag Tools

5.1.1 Instrumented Rock Cutting Rig

This is a modified 26" Butler Shaping machine with a dynamometer mounted on the crosshead (Plate 11). The sample is rigidly mounted on the machine table, and the dynamometer in which the tool is

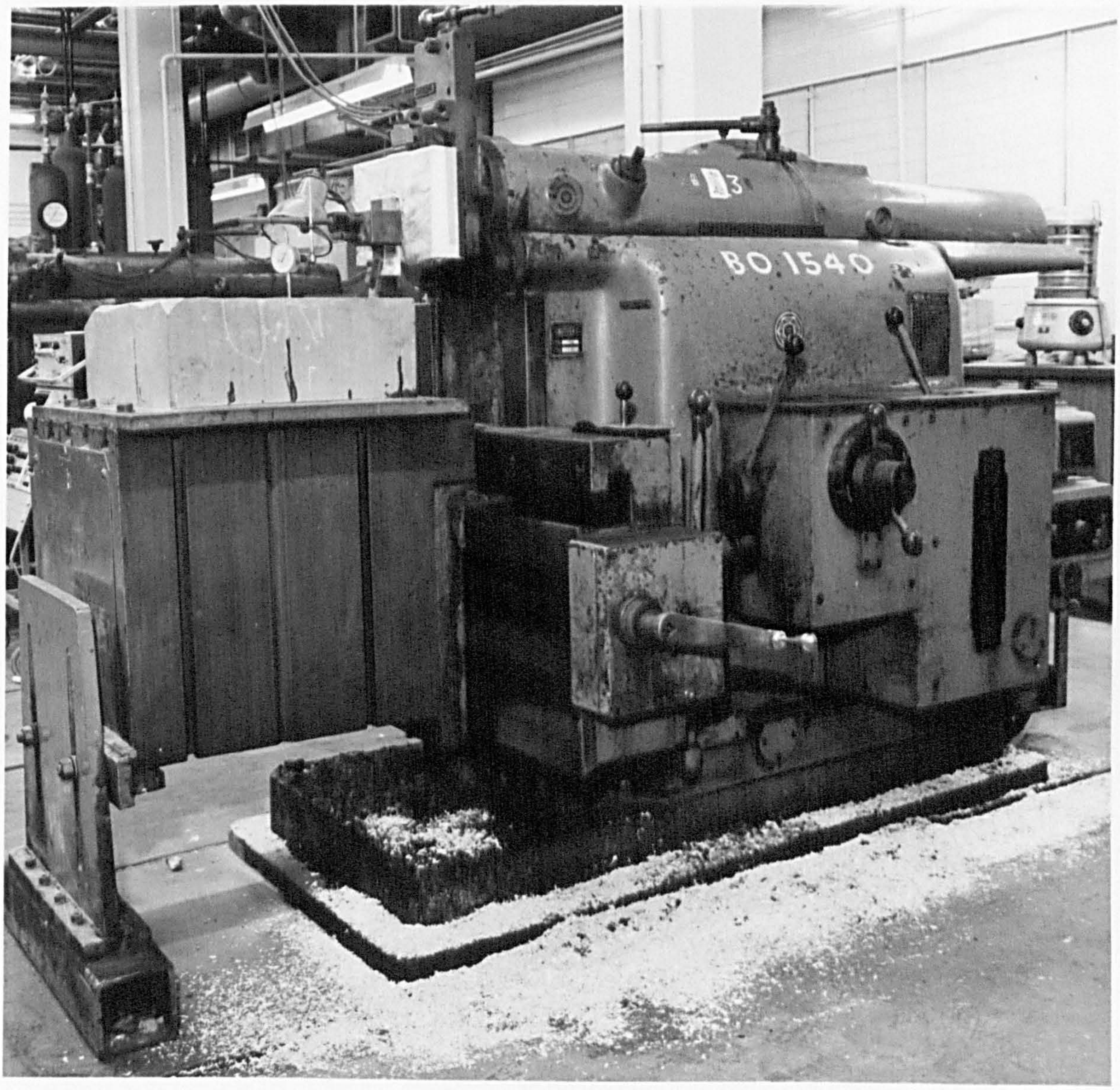


Plate 11. Instrumented Shaping Machine

mounted is shown in Plate 12. The signals from the dynamometer are amplified and recorded on an SE 300626 UV paper chart recorder.

The traversing speed is variable between 7.62 and 38.88 metres per minute, depending upon the stroke length and gears engaged. The crosshead of the machine can be orientated at various tilted positions on either side, with respect to the cutting direction, and moved vertically within its limits by use of a screw mechanism. The depth of cut can be either set by movement of the crosshead with respect to the fixed machine table, or by movement of the table. The maximum in-line thrust of 5 tons can be applied by the machine to the rock.

5.1.2 Instrumentation

5.1.2.1 Triaxial Dynamometer

The triaxial dynamometer is a specially designed instrument monitoring the magnitudes and direction of the forces acting on the tool during a cutting experiment. The electrical signals which are generated by the dynamometer are amplified and recorded by the UV chart recorder. The three strain gauge bridges on the arms of the dynamometer provide electrical signals proportional to the three mutually perpendicular (orthogonal) force components acting on the cutting tool. These force components are:

(1) Cutting Force : acting in the direction of cutting;

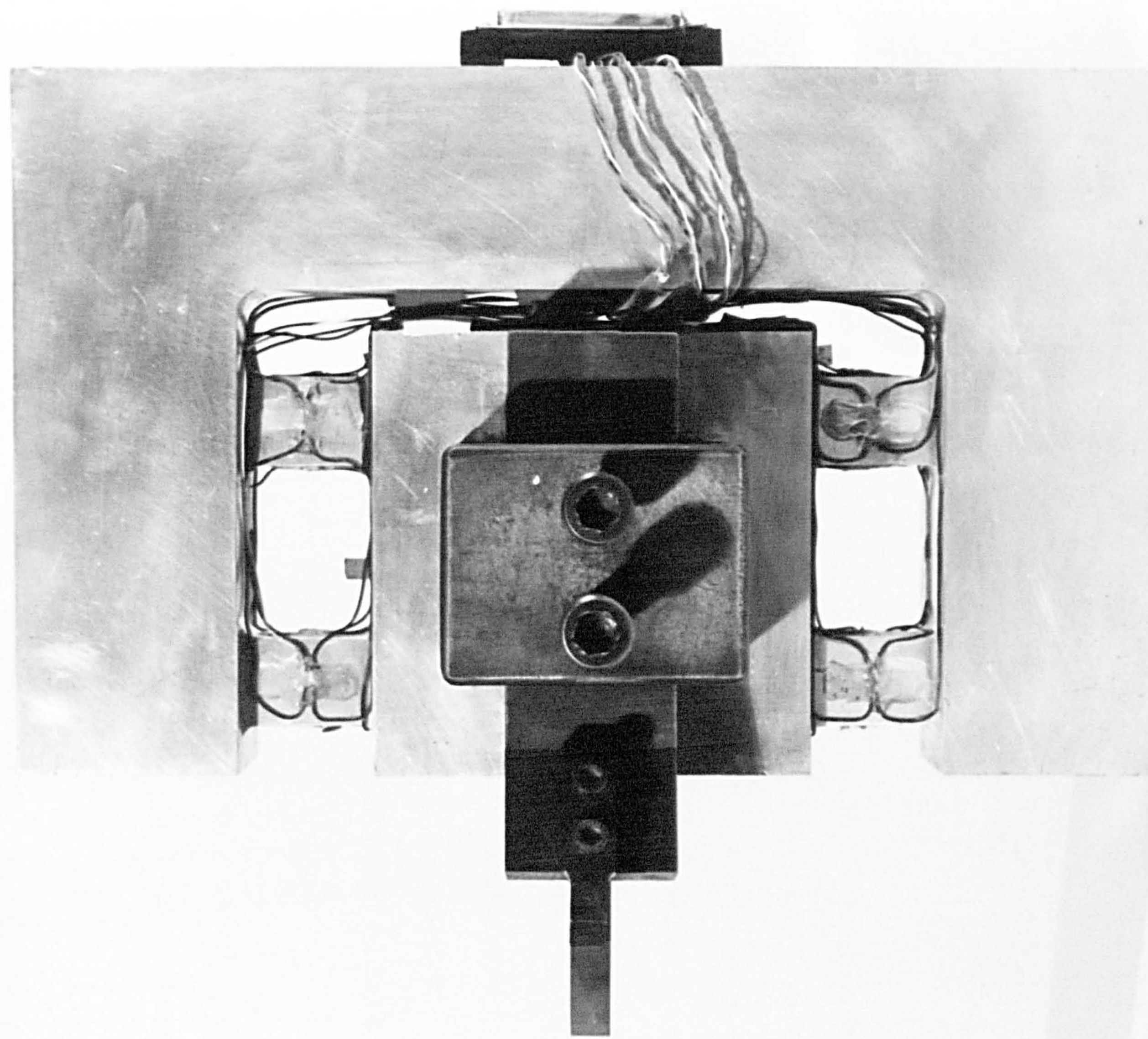


Plate 12. Triaxial Dynamometer

(2) Normal Force : acting perpendicular to the direction of cutting, and required to maintain the tool at the required depth in the rock; and

(3) Lateral or Sideways Force : perpendicular to both the cutting and normal forces, tending to cause lateral movement of the tool. Usually small in practice with symmetrical tools and symmetrical loading conditions.

The dynamometers which were used throughout the experiments with drag tool cutters were both of the solid plate type, differing only in the material used in their fabrication. One is made of aluminium alloy and the other of carbon steel. The steel dynamometer can stand forces up to 100 kN in cutting and 50 kN in both normal and sideways directions, while the limits of the aluminium dynamometer are 20 kN in both cutting and normal, and 10 kN in sideways. The dynamometers are based on the solid plate design outlined by Whittaker (75,76) with a rigid central plate supported by four parallel beams which are attached to a rigid frame.

A tool clamp holds the cutting tool in the central plate, and the whole dynamometer is bolted to a backing plate which is fixed to the crosshead of the cutting rig.

Since the force component is proportional to the strain on the beams, the load's action on the tool can be determined by the strain gauges. The beams are proportioned so that the deformations are elastic and within the designed range of the dynamometer.

Cemented on the four connecting beams there are a total of 24 strain gauges in the form of three bridges, and unaffected by each other. Any interaction between these force components is caused by a small misalignment of the strain gauges; therefore, the gauges are aligned and bonded very carefully. The sensitivity of the dynamometer is dependent on the dimensions of the beams, elastic properties of the material from which it is machined, alignment and number of strain gauges.

5.1.2.2 Recording Instrumentation

Continuous recording of signals from the dynamometer was provided by the recording system shown in Plate 13. The recording instrumentation used was an SE 4000 type, which consists of a power supply unit, an amplifier and integrator unit for each strain gauge bridge circuit of the dynamometer, connected to a 12-channel ultra violet chart recorder. Thus an analogue record of the forces which were generated during the cutting action was produced on UV sensitive photographic paper. The recording system includes an SE4101/O/S/SC monitor unit, and the variable resistors necessary to balance the individual arms of each bridge. The power supply unit provides a constant 5 volts KMS at a frequency of 10 kHz to each bridge circuit of the dynamometer. The output from each bridge was amplified by an SE4000 carrier amplifies to a gain of range 22 to 450. The amplified signals from both amplifiers and integrators are then simultaneously passed to an SE3006DL UV chart recorder, to provide traces on the 150mm wide UV paper, driven by an SE3010 unit at a

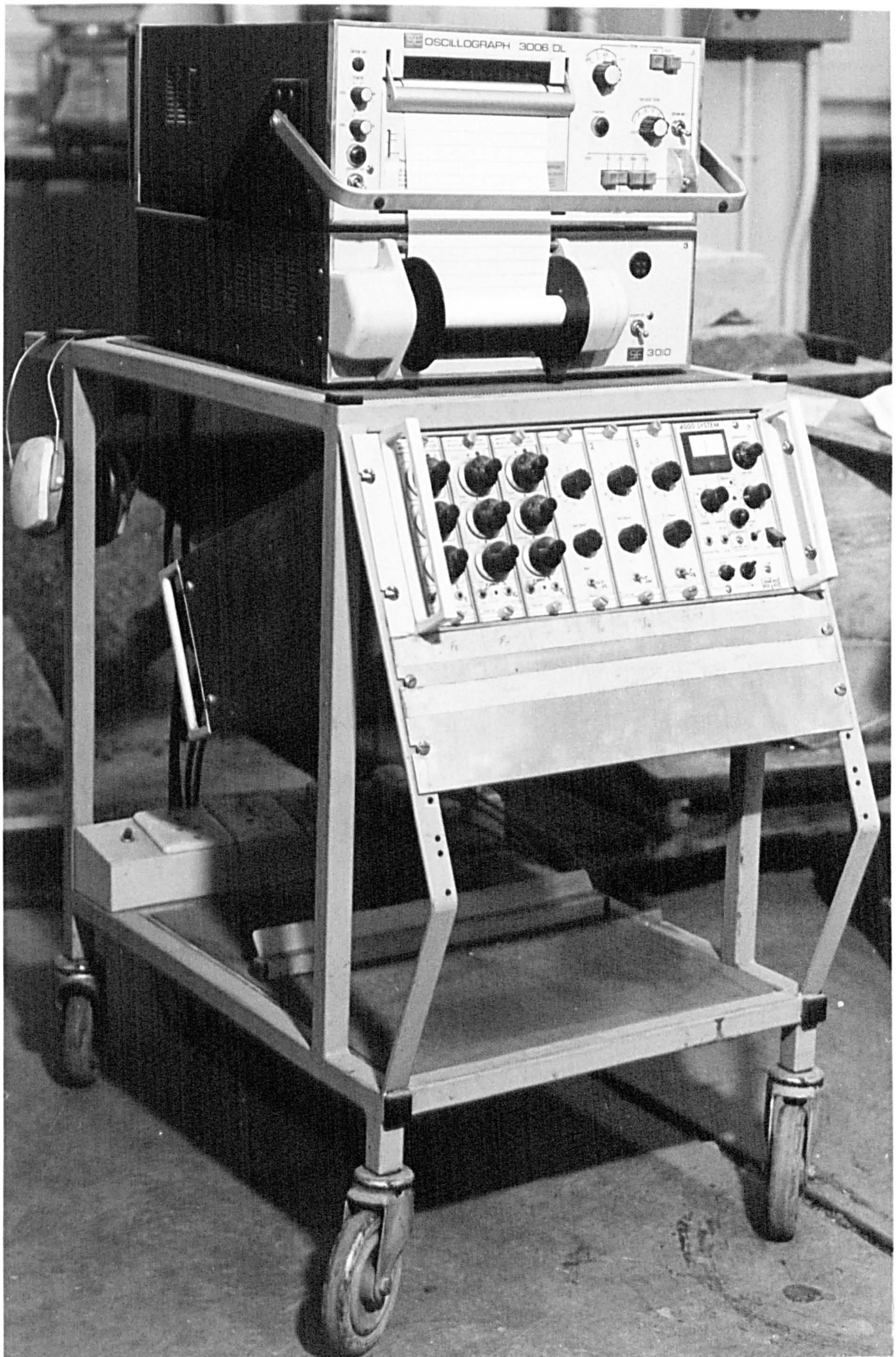


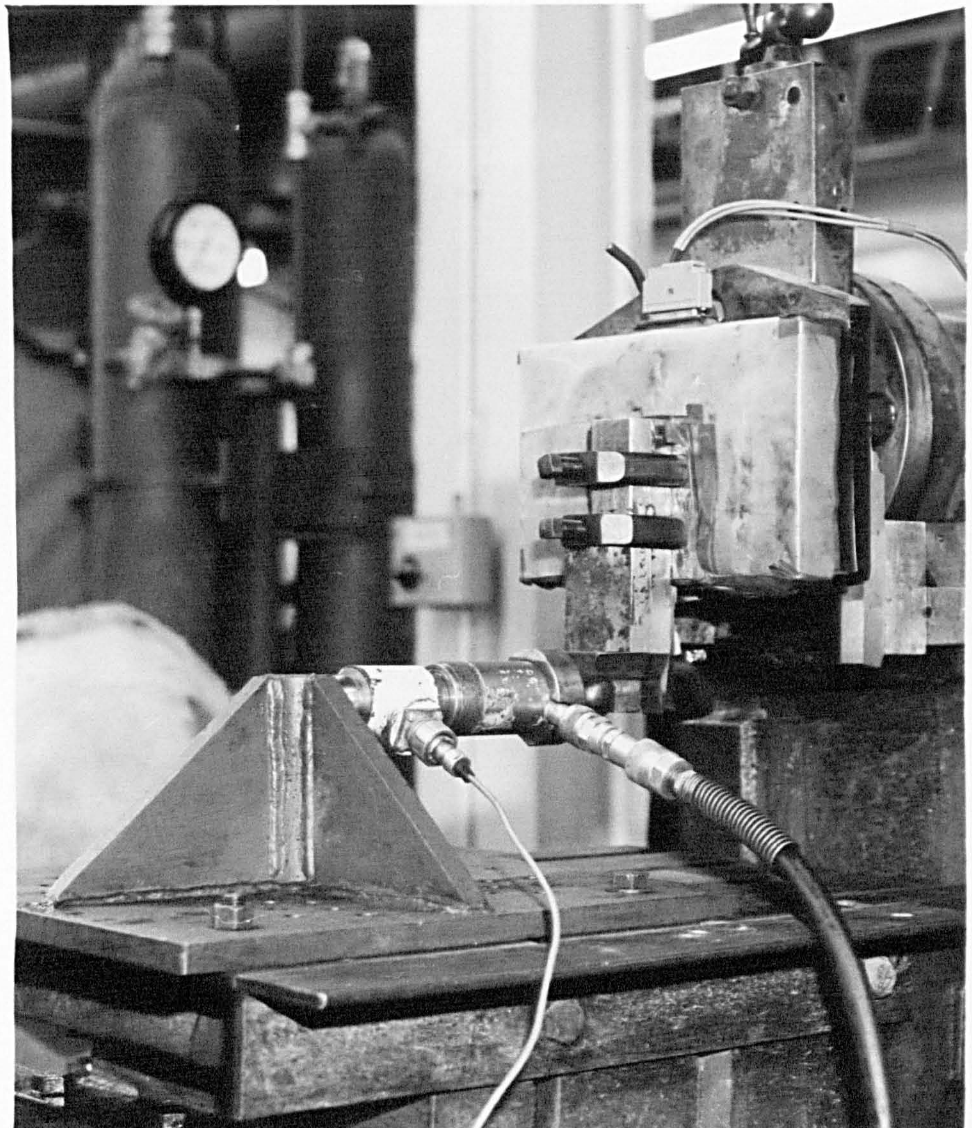
Plate 13. UV Recorder with Amplifiers

speed of 125mm/sec. The UV recorder gave instantaneous magnitude of the components. The UV recorder was fitted with six A1000 Hz galvonometers, each with a sensitivity of 3.5mA/mm. Outputs from each amplifier and integrator, powered their respective galvanometers. For a linear response over the range of chipping frequencies the galvanometers must be matched with the bridge circuit resistance.

5.1.2.3 Calibration of the Instrumentation

For the purpose of determining the relationship between loads applied to the cutting tool and the output of the recording system, the instrumentation must be calibrated. The calibrations are, in most cases, carried out at the beginning and at the end of the experiments.

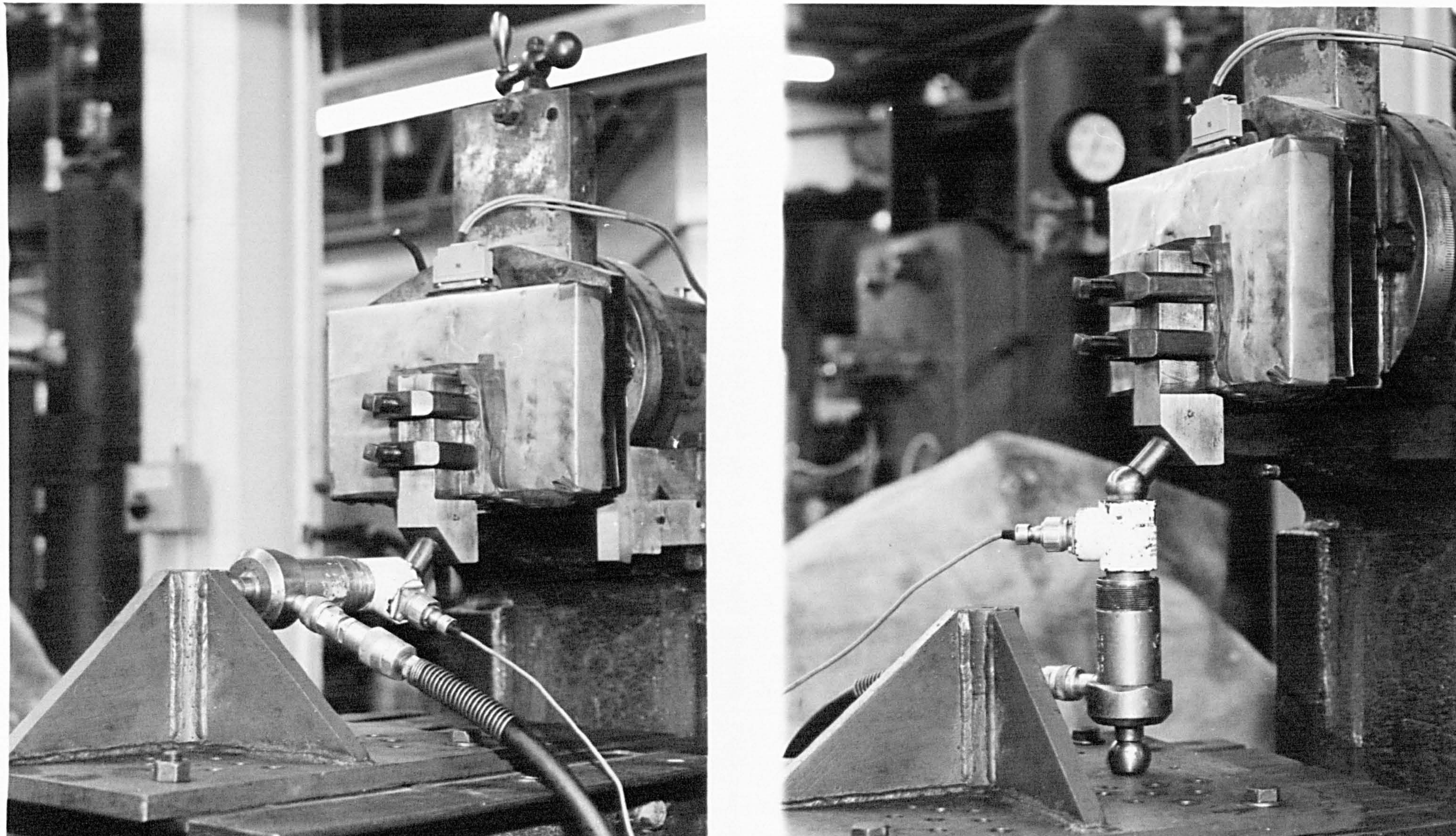
Loads were applied to the special pick on the dynamometer in each orthogonal direction by means of a hydraulic ram, operated by a hand pump. The pick with a 38mm diameter ball at its top provided an accurate alignment of the direction of the applied force. The ram has spherical seatings at both ends; one end of the ram engages the ball at the tip of the tool post and the other sits on the corresponding ball, which is mounted rigidly on the supporting frame on the machine side. An initially calibrated load cell, in conjunction with an electronic strain indicator, was placed between the ram and the pick to determine the magnitude of the applied load (Plates 14,15) Accurate alignment of hydraulic ram and load cell is essential in order to reduce the interactions in the dynamometer.



a) Cutting Force Direction

b) Normal Force Direction

Plate 14. Dynamometer Calibration for Radial Tools



a) Cutting Force Direction

b) Normal Force Direction

Plate 15. Dynamometer Calibration for Point Attack Tools

In each orthogonal direction, the known loads were incrementally applied to the dynamometer and at each increment the record of direct and integrated forces were taken. The calibration constants were calculated through the analysis of these records.

The calibration of integration and force channels was carried out simultaneously at different integration and amplification settings. However, calibration at a particular reference setting is adequate to determine the constants for all other combinations of settings, providing that the ratios between different integration and amplification settings of the recording instrument is known. This is achieved by the use of calibration unit (passive strain simulator) which eliminated the cumbersome and arduous loading of the dynamometer with the hydraulic ram and pump.

5.1.3 Specimen preparation and mounting

The rock specimen must have at least one smooth surface to be mounted on the metal plate which is bolted to the machine table. By using a diamond saw the irregular rocks were first dressed to have smooth surfaces. A rock block higher than 0.35mm is not suitable for mounting on the rig.

The rock specimens were bonded to a mild steel plate by using Araldite 2003A epoxy resin. Prior to bonding, the steel plate is cleaned, first with a disc grinding machine, and then with carbon tetrachloride in order to remove any grease, and the rock surface is also dusted and cleaned thoroughly. In order to fill the pores and any concave hollows, a sealing coat of Araldite was applied to the rock surface 24 hours prior to the final bonding. Finally, a coat of Araldite was spread over both mating surfaces and the steel plate and the rock specimen brought together tightly and left for further curing.

Although the bonding procedure involving the use of adhesive was adequate for the sandstone, the procedure was not suitable for the rock salt specimens as the coated epoxy resin, Araldite, came off the surface of the rock salt after a series of cutting experiments.

5.1.4 Techniques for the Experimental Rock Cutting Procedure

The experimental procedure for the simulation of the actual cutting action of practical machines naturally required a different procedure from those planned to be carried out on a flat rock surface, the experimental programme included two cutting modes:

(1) Simulated Cutting :The rock surface was initially prepared until a desired cutting regime was reached. The detailed procedures appear in the appropriate chapters.

(2) Flat Surface Cutting : The top surface of the specimen was trimmed to a flat surface and the desired cutting position was obtained by traversing the table. Furthermore, the depth of cut was set using a micrometer dial gauge to a tolerance of $\pm$ 0.1mm.

Once the rock was brought to a desired cutting position on the machine, suitable integration and amplification settings were selected on the recording instrumentation to limit the galvanometer's deflections to the width of the UV paper. Before taking each cut, the integrators and amplifiers were balanced with the intention of eliminating any drift already present in the channels.

The signal output from the dynamometer to the galvanometers was recorded on ultraviolet sensitive paper to provide an analogue trace of the forces acting on the tool during cutting. The debris from each cut was collected, avoiding large end chips. The length of cut was also measured and recorded for further necessary calculations of the cutting parameters.

5.1.5 Drag Tools and Tool Holders

Since the main objective of this work mostly involved the cutting head design of practical machines, it was thought that, through the use of practical tools a better approach to this aspect would be obtained and throughout the cutting experiments, commercially available point attack and radial tools were employed, with the exception of some saltcrete materials, for which it was more convenient to use standard, chisel-shaped tungsten carbide cutting inserts (Figure 17).

Slender-type point attack tools with 87° cone angles were used for the majority of drag tool experimental programmes. They were machined in the Department's workshop in order to fit the previously

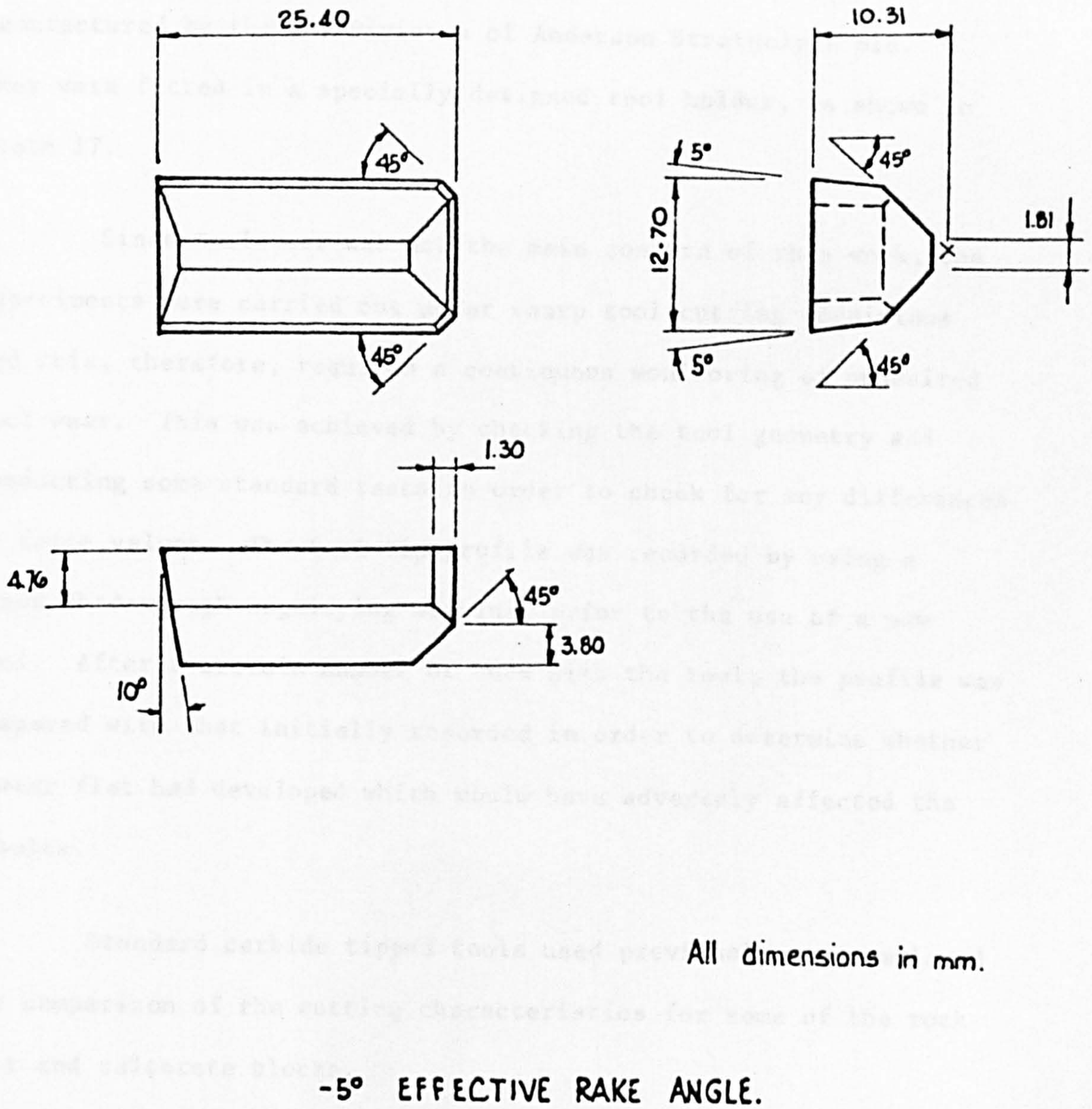


Fig. 17 Tungsten Carbide Tip Used in the Cutting Experiments

designed tool holders (Plate 16). The tool holders allowed the point attack tools to have an angle of attack of 45 degrees.

The radial tools used are of heavy-duty type and are manufactured by the Hoy Division of Anderson Strathclyde plc. They were fitted in a specially designed tool holder, as shown in Plate 17.

Since tool wear was not the main concern of this work, the experiments were carried out under sharp tool cutting conditions and this, therefore, required a continuous monitoring of undesired tool wear. This was achieved by checking the tool geometry and conducting some standard tests in order to check for any differences in force values. The tool tip profile was recorded by using a Nikon Shadowgraph magnifying machine, prior to the use of a new tool. After a certain number of cuts with the tool, the profile was compared with that initially recorded in order to determine whether a wear flat had developed which would have adversely affected the results.

Standard carbide tipped tools used previously were employed for comparison of the cutting characteristics for some of the rock salt and saltcrete blocks.

5.1.6 Parameters measured and calculated

The measured and calculated parameters obtained for each experimental cut are listed below:

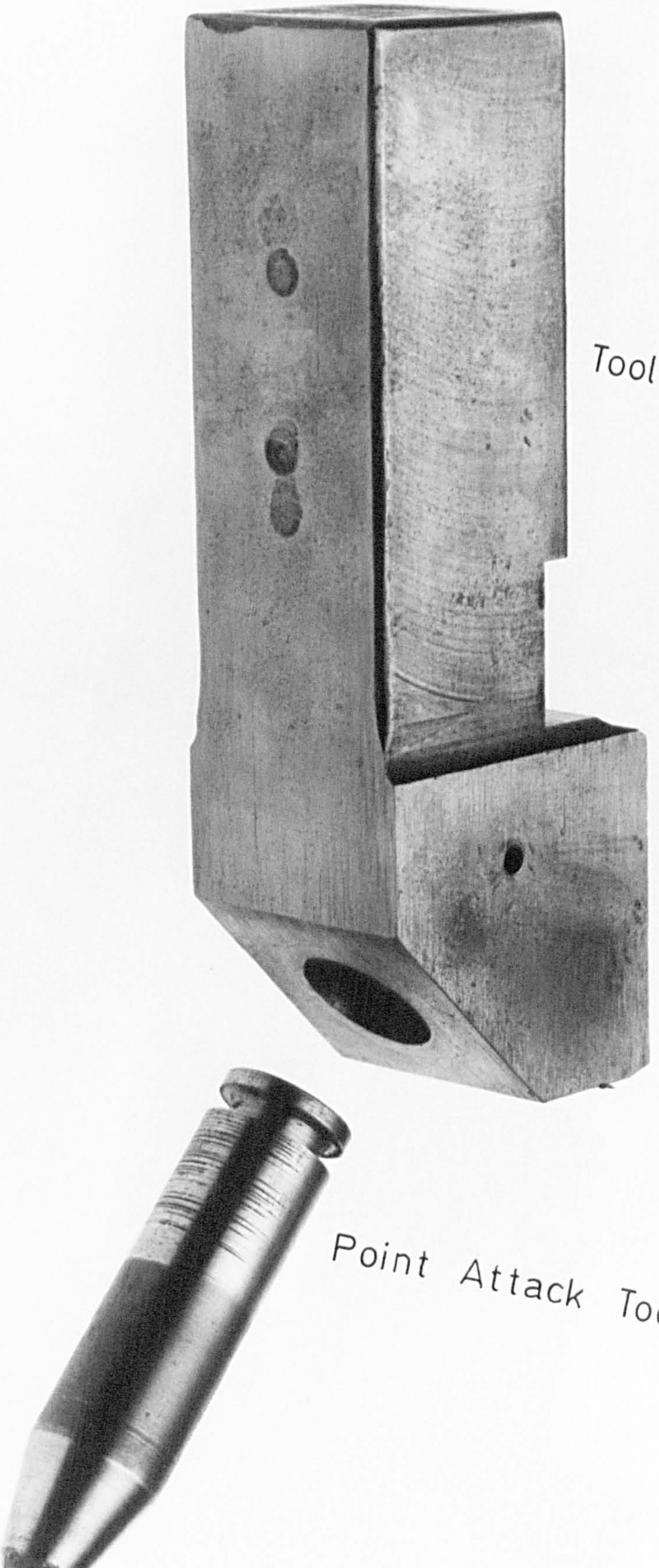
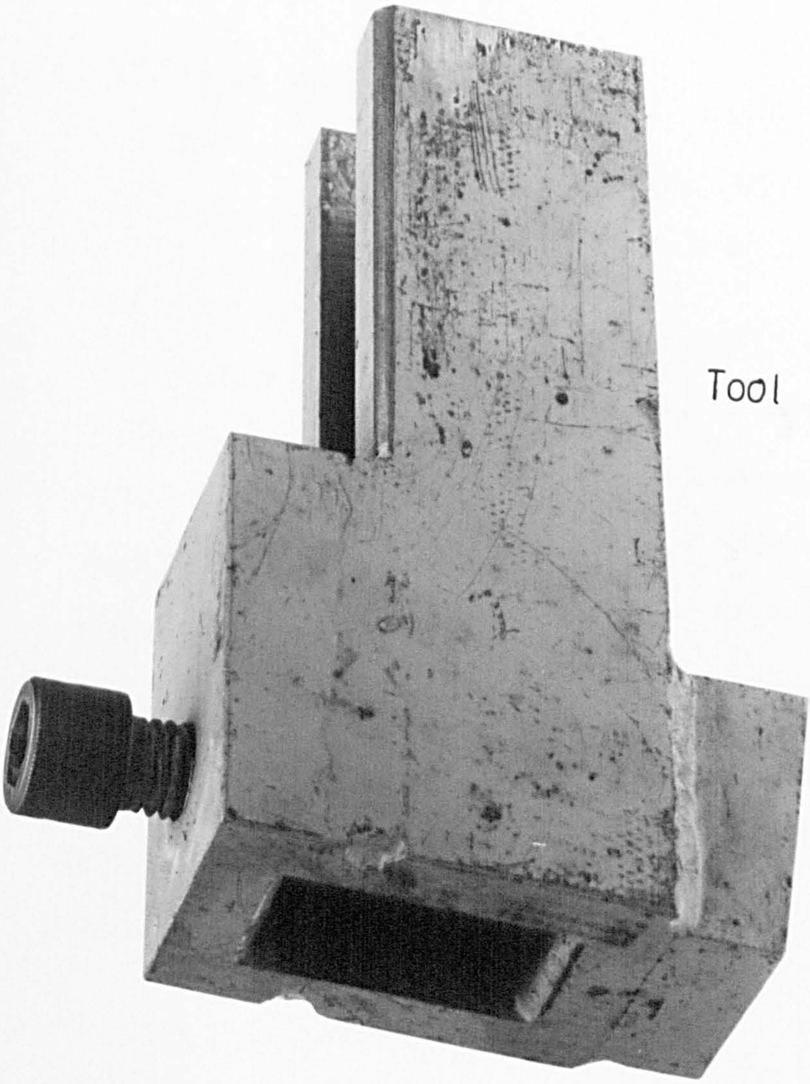


Plate 16



Tool Holder

Radial Tool

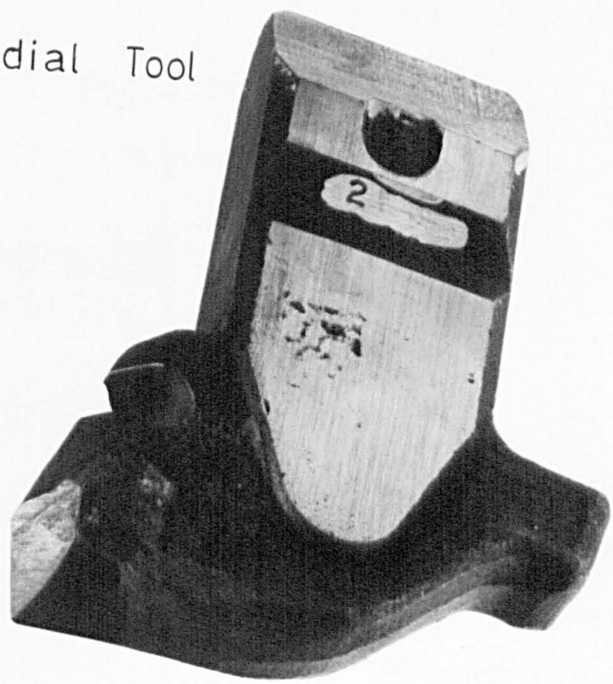


Plate 17

(1) Mean Cutting Force (MCF)(kN) : Average force on the tool in the direction of cutting. Multiplying the distance cut gives the amount of work done.

(2) Mean Peak Cutting Force (MPCF)(kN) : The average of the peak forces acting on the tool in the direction of cutting. This is relevant to the mechanical strength of the tool design and its holder. As all tests were conducted at 150 mm/s, peaks for 0.1s intervals were taken.

(3) Mean Normal Force (MNF) (kN) : The average forces tending to push the tool out of the rock. This value is the thrust required to maintain the tool at its required depth of cut.

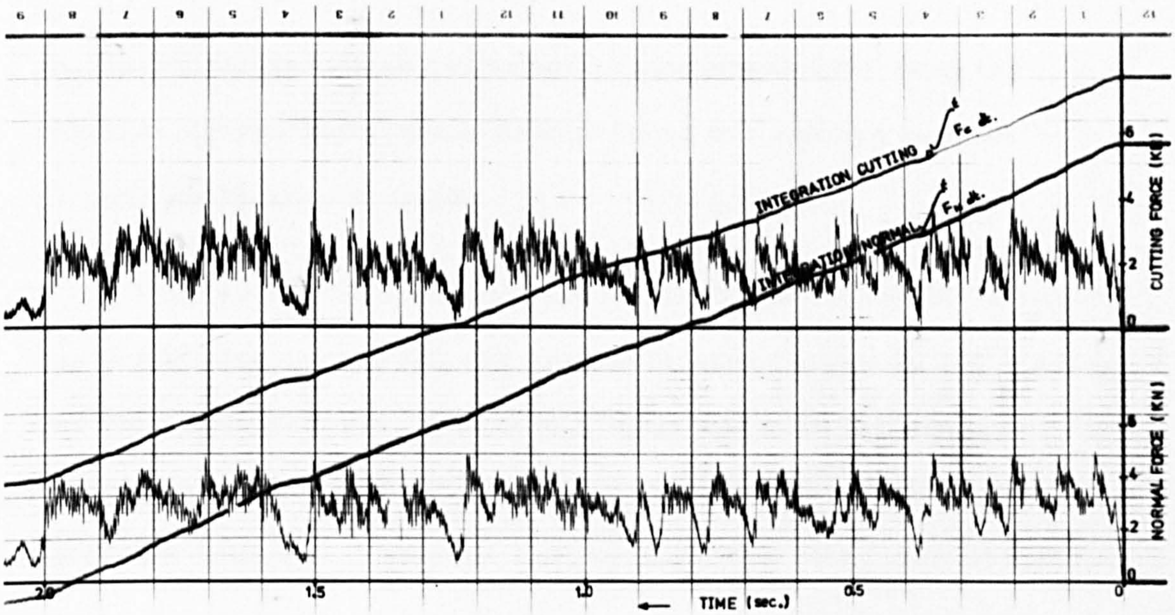
(4) Mean Peak Normal Force (MPNF) (kN) : The average of the peaks of the normal force component (0.1s intervals).

(5) Yield (Q) (m^3/km) : The quantity of rock produced expressed as volume per unit distance cut.

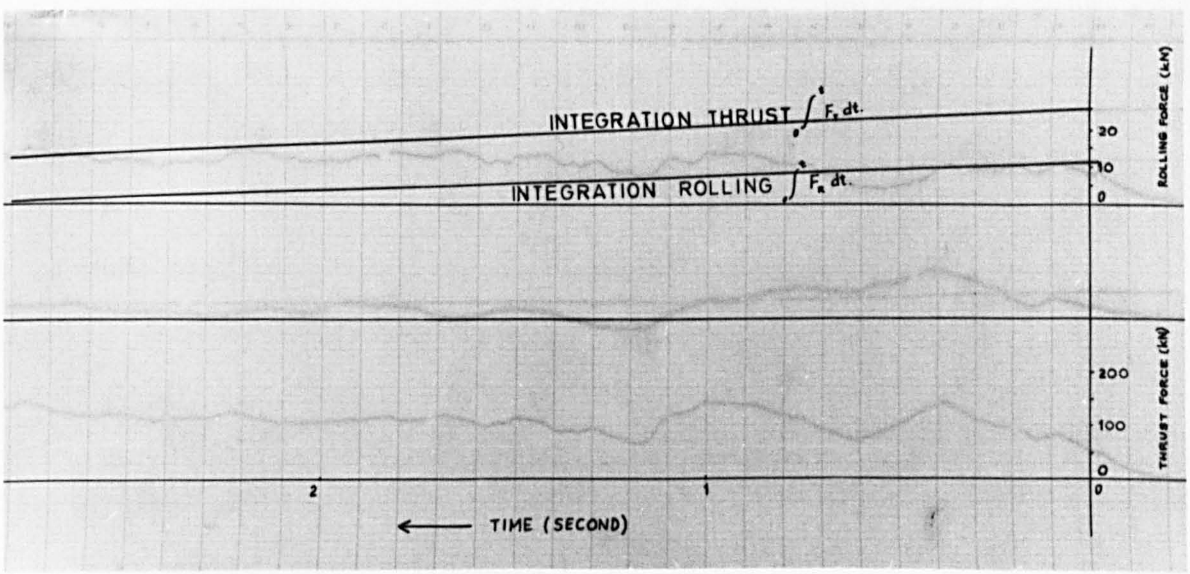
(6) Specific Energy (SE) (MJ/m^3) : The energy required per unit volume of rock cut.

5.1.7 Analysis of Recorded Traces

The analogue traces obtained from the recording instrumentation, as outlined in Section 5.1.2.2 provided the measurement of forces. A typical analogue output is given in Plate 18. Although it was possible



a) Drag Tools



b) Discs

Plate 18. Analogue Force Traces

to record all the three orthogonal force components from the triaxial dynamometer, the sideways force was omitted because it is very small in most cases.

A typical UV trace provides four force component records; two for direct forces and two for integrated forces in the cutting and normal directions. The direct components of the analogue traces, as in Plate 18, consist of traces indicating the chip formation process. When the tool attacks the rock, the forces acting on it increase rapidly and as the chip breaks off, the trace drops to the zero position, only to rise again to form a new chip. The maximum direct forces are known as peak forces.

The mean forces and the resulting work carried out during cutting are obtained by measuring the total area under these direct force traces against time. This measurement is done by the integrating circuits incorporated in the recording instrument, which provide inclined lines, the gradient of which provides the mean force components for the length of cut considered.

The data points on the chart record were selected in such a way that the cut length was chosen to exclude areas of unrepresentative cutting such as the beginning and the end of the cut. These correspond to the initial impact and end chip formation respectively. The average of maximum peak forces selected at 0.1-second time intervals for each orthogonal component, gave the Mean Peak Force value.

Once the data points were identified, they were transferred to punched cards by means of a D-Mac digitising table. The punched cards were then input to the IBM370 computer of the University's Central Computing facility and analysis of the data was performed by a program written in FORTRAN.

5.2 Experimental Equipment and Techniques for Disc Cutters

5.2.1 Rock Cutting Apparatus

Experimental programmes with disc cutters were carried out using a 50-tonne rock planer which was designed and built in the University. The disc cutter dynamometer and some structural and operational modifications were made to the rig to allow full-scale disc cutting experiments to be conducted, as shown in Plate 19.

The cutting rig consists of the main body and hydraulic system unit. The entire rig is mounted on a sturdy frame which includes a rectangular base frame and four columns. The main columns at the rear of the rig are integral with the frame and serve as the main support and guides for the cutter slide assembly and are mutually stiffened by a large diameter transverse tube at the top and rear of the machine. The front columns are bolted to the base and provide only increased stiffness of the cutter slide assembly rod.

The tool holder slides along a heavy steel plate (steel track) on which the large diameter tube is welded via a number of saddles in order to provide a rigid beam. The whole cutter slide assembly is attached to the main frame by four pairs of shoes sliding

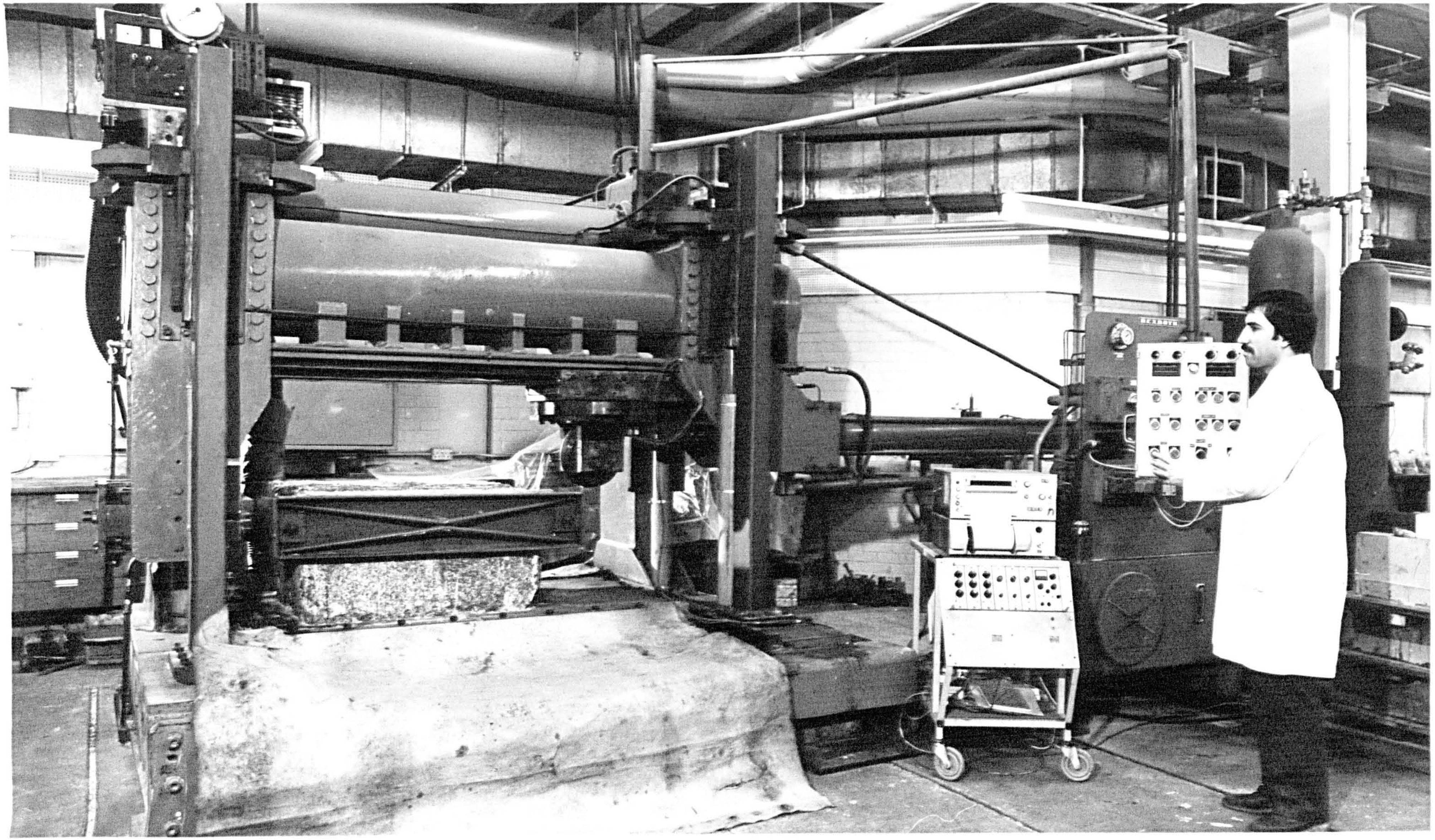


Plate 19. Disc Cutting Rig

along vertical guide plates on the rear columns. As disc cutters generate high levels of thrust force needed for efficient cutting, the cutter assembly is susceptible to vertical slipping and the stiffness of this assembly emerges to be of significant importance. For this reason, the cutter slide assembly is clamped to the columns during instrumented cutting tests. A double-acting ram is attached to the rear of the cutter assembly in order to push the disc cutter through the rock sample at the required penetration depth.

There are two independent hydraulic systems. The first one is the main system and provides the power to operate the cutting tool, and the second is the clamping circuit operating the large clamps, as mentioned above.

A brief summary of the rig specification is given in Table 47 and detailed information on this apparatus can be found elsewhere (Table 1).(47).

The position of the rock with respect to the toolholder is achieved by lateral traversing of the table and depth of penetration can be set by vertical movement of the cutter slide assembly. The horizontal position of the rock and the vertical position of the tool is displayed in digital form on the control panel.

5.2.2 Instrumentation

Unlike plate-type dynamometers, the strain gauges are located on the tool axle supports to measure the face components on

Maximum specimen size	1.5m x 1.0m x 1.0m
Maximum table travel	0.90m
Speed of table traverse	0.34m/minute
Maximum cutter slide travel	0.60m
Speed of cutter slide traverse	0.03m/minute
Maximum thrust (vertical) force	500 kN
Maximum rolling (cutting) force	
@ 500 psi	80 kN
@ 3000 psi	500 kN
Maximum cutter stroke	2.0m
Cutter speed	0.0 - 0.13 m/s

TABLE 1 LINEAR CUTTER RIG SPECIFICATIONS

acting on the disc cutter shaft. As can be seen in Figure 18, the side members are attached to a circular base plate which may be clamped in any position to provide any required angle of skew relative to the cutting direction. In order to minimise the interaction between thrust force and rolling force, the disc is fitted with a roller bearing which transmits radial forces to the shaft without imparting appreciable torque which would be taken as an additional rolling force. Also, the disc is positioned laterally by wing spacers as required and thrust bearings (Plate 20).

Each side member has a portion of reduced section which is fitted with resistance strain gauges which sense the local strains on each side member.

Since the tool and toolholder with force transducer form an integral unit, the disc can be orientated to the rock surface in a variety of configurations. When the toolholder is clamped directly to the cutter slider setting of any degree of skew is possible by rotating the tool holder. Furthermore, the cutter can be tilted with respect to the slider by installing a pair of circular wedges. By having two wedges of the same angle, the tilted position at any angle from $+25^{o}$ to -25^{o} can be set while maintaining the longitudinal axis of the toolholder parallel to the direction of advance.

Multiple disc cutting tests can also be undertaken. This can be achieved by placing the discs at various spacings along the shaft.

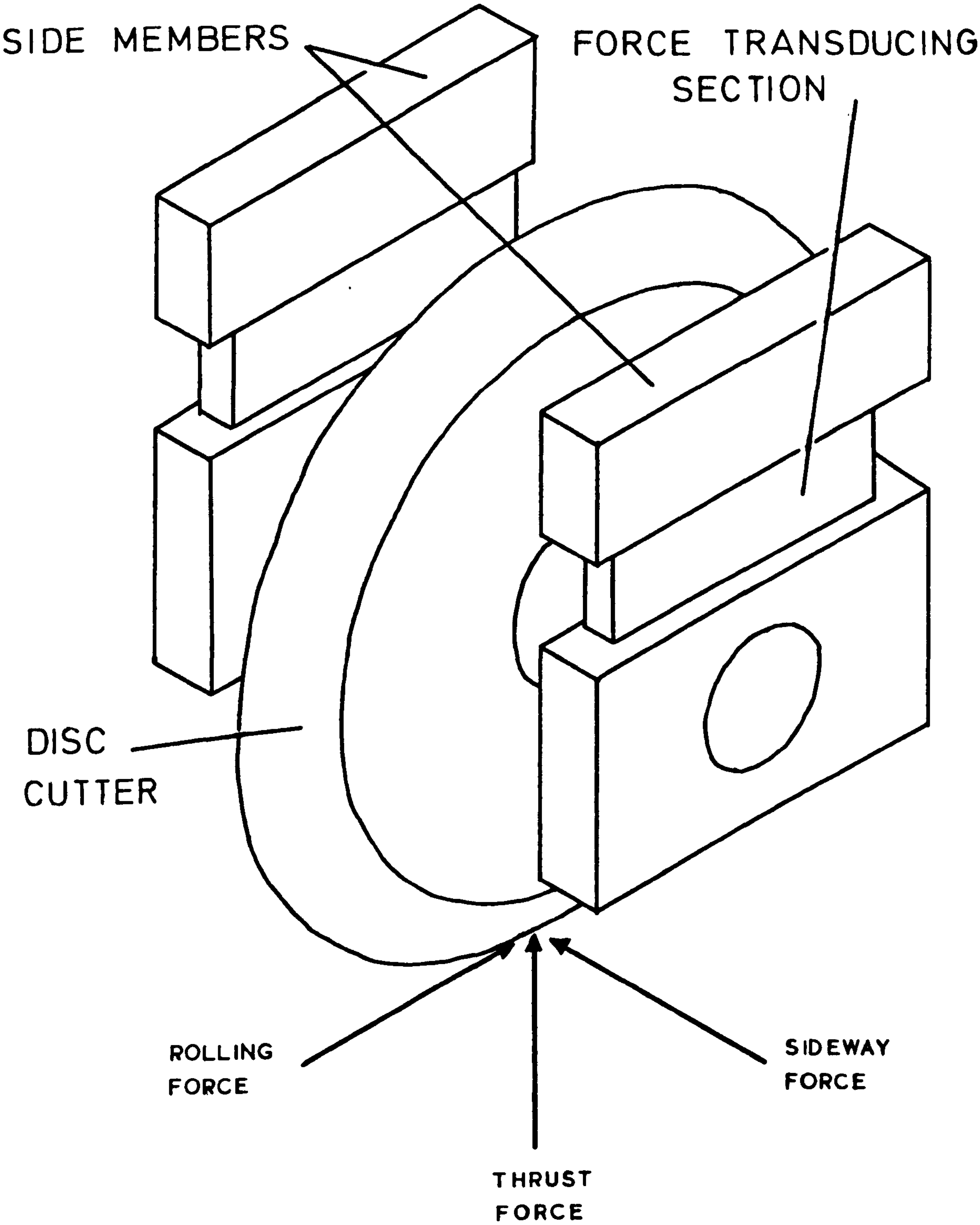
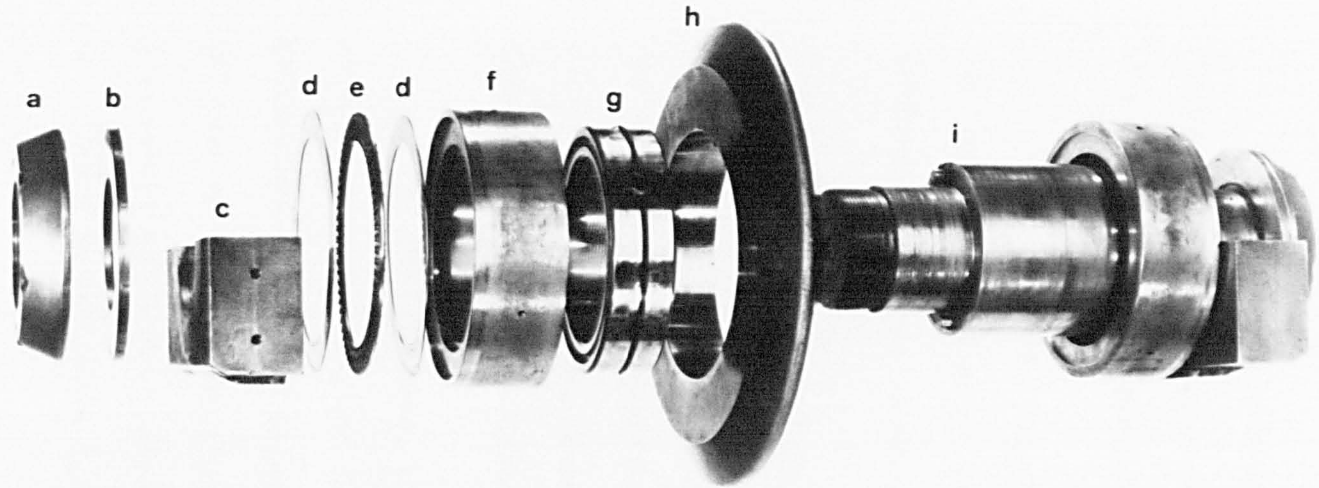


Fig. 18 Disc dynamometer and resolution of the forces.



Cutter / Shaft Assembly

Key

a. Nut

b. Washer

c. Shaft retaining cap

d. Bearing race

e. Axial thrust bearing

f. Spacer

g. Disc bearing

h. Disc cutter

i. Cutter shaft

Plate 20

The recording instrumentation which was described in Section 5.1.2.2 was also used during all disc cutting experiments and the same method was applied for the analysis of analogue traces.

Furthermore, the calibration procedure was also based on the same principal as in Section5.1.2.3. The dyanamometer was uniaxially calibrated and this is shown in Plate 21.

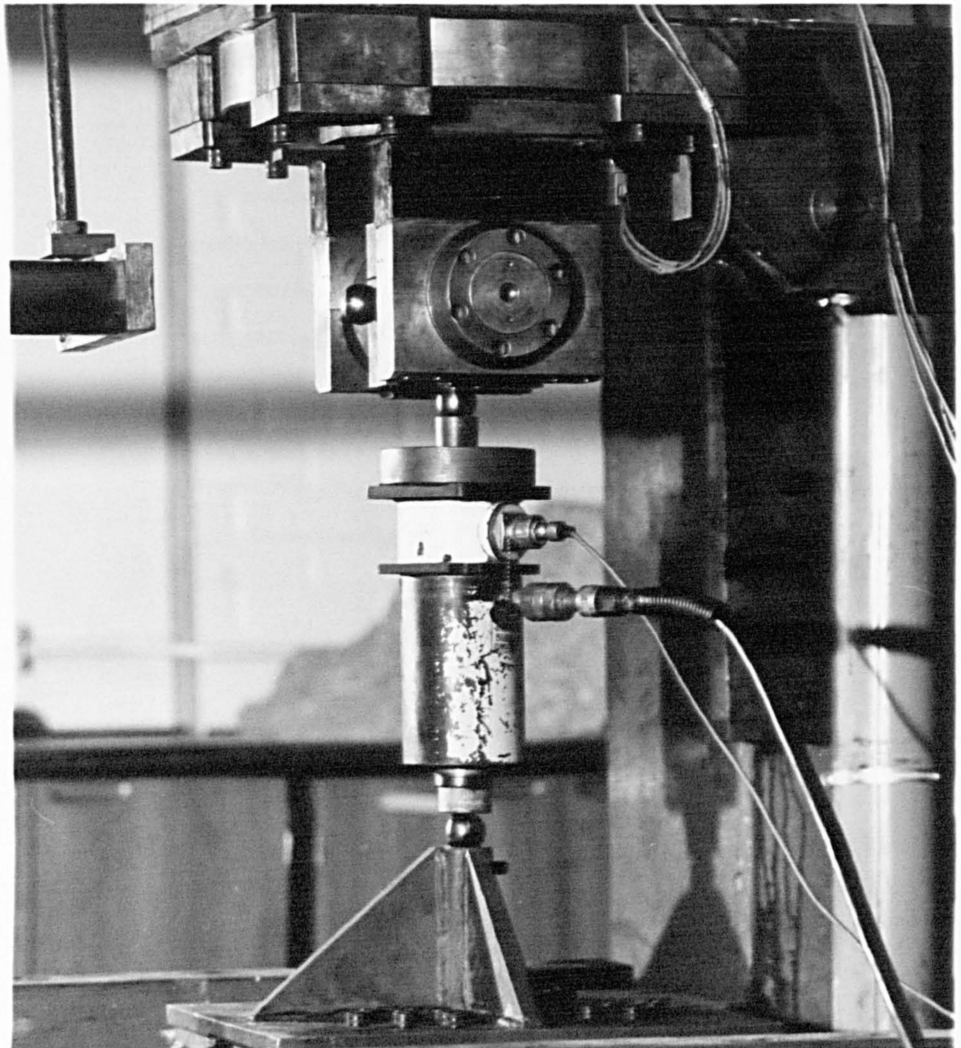
5.2.3 Preparation and installation of the rock specimen

Since large rock specimens are required and high forces are generated during cutting, the method of preparation and mounting of the sample has been found to be most important in order to obtain representative results without premature sample failure.

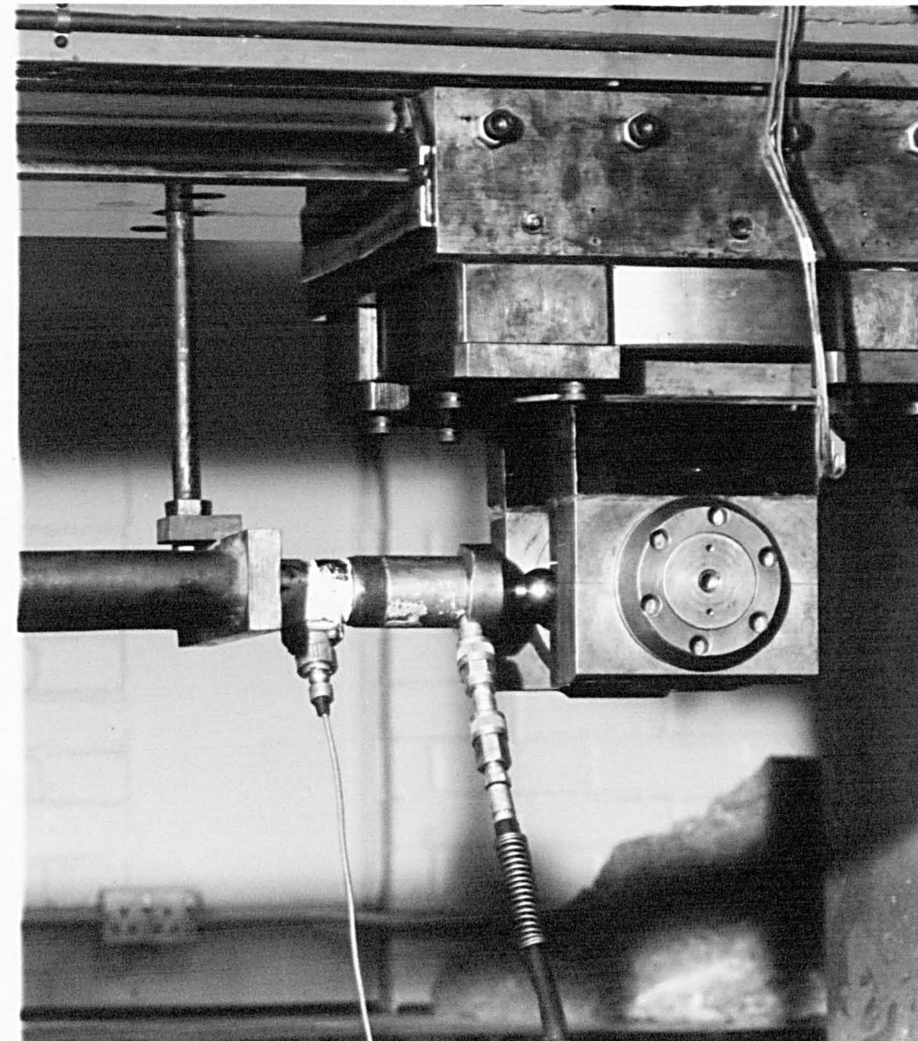
For this purpose, the steel plate was fitted with an array of projecting dowels, and then bolted to the machine table. A corresponding array of holes was drilled into the flat surface of the rock specimen using a pneumatic percussive drill (Plate 22). A polyester resin was poured into the drilled holes and allowed to set. Prior to the resin forming a jelly the block was positioned on the plate.

In order to maximise the rock surface and to prevent splitting and side breaks, it was necessary to confine the side surfaces of the rock. This was achieved by using a steel frame.

During the initial tests, it was found that all these procedures were insufficient since the block tended to move. This



a) Thrust Force Direction



b) Rolling Force Direction

Plate 21. Disc Dynamometer Calibration

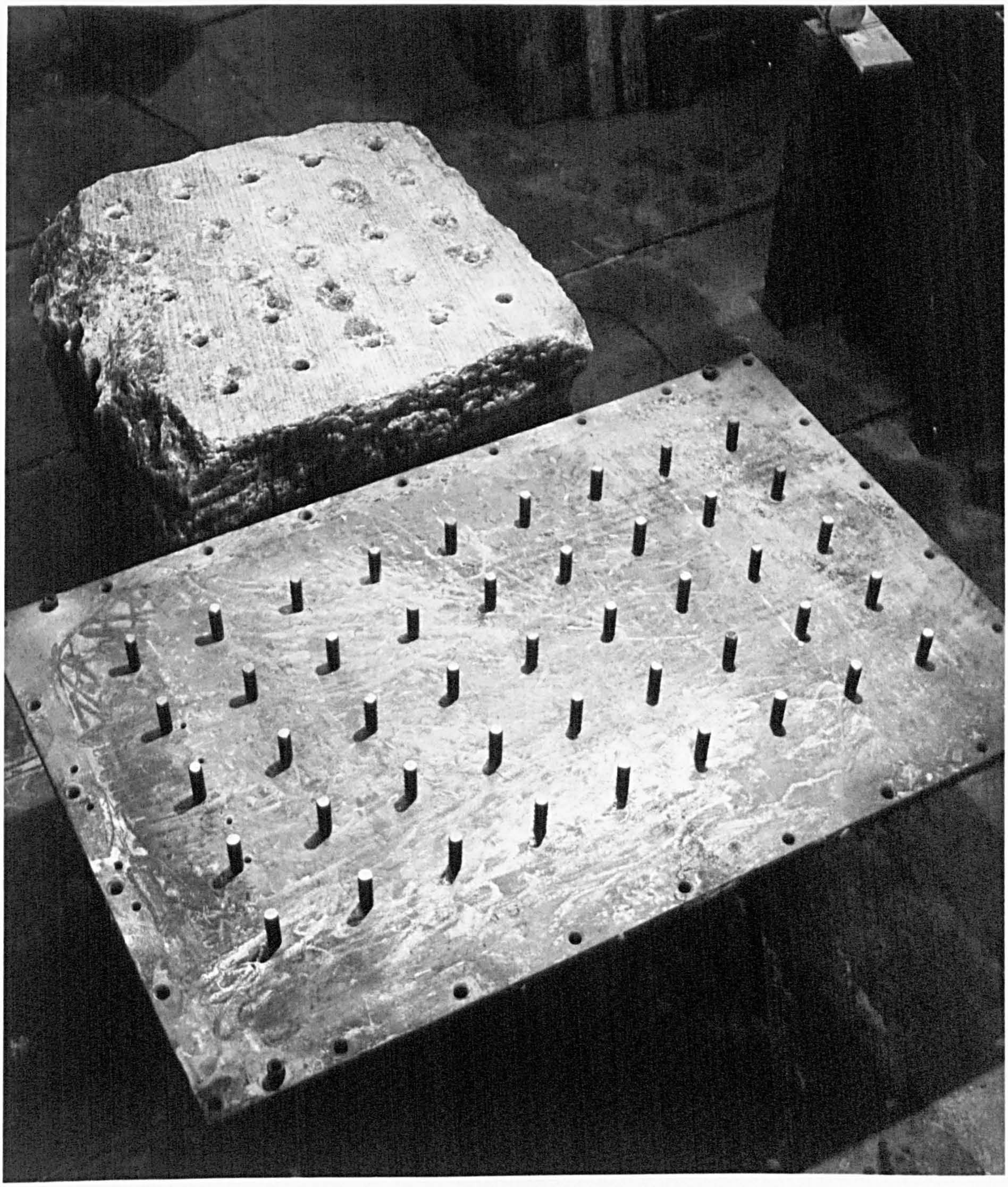


Plate 22. Specimen Table and Rock

problem was attributed to the small size of the dowels and the type of resin which failed to secure the rock to the table and dowels.

It was also observed during the initial tests that when the cuts became closer to the side edge of the block, large side breaks and cracks frequently occurred and this situation interrupted the course of the experimental programme and limited the range of experimental levels (Plates 23,24).

Although the low strength and inherent discontinuities, as well as the heterogenous structure of the rock salt specimen, played an important role in these occurrences, it was thought that improving the contact area between rock block and confining steel frame interface would considerably assist in overcoming this problem. Thus, all the faces of the rock sample were trimmed to produce flat and parallel surfaces. Initially, the rock was placed and secured on the specimen plate at a desired position and then trimmed. As a result of this procedure, the above problems did not occur and excellent cutting conditions were obtained.

5.2.4 Experimental Technique

The disc cutting experiments were aimed at simulating the practical action of a full-face tunnel boring machine; therefore, the flat surface cutting condition was not included within the experimental programme.

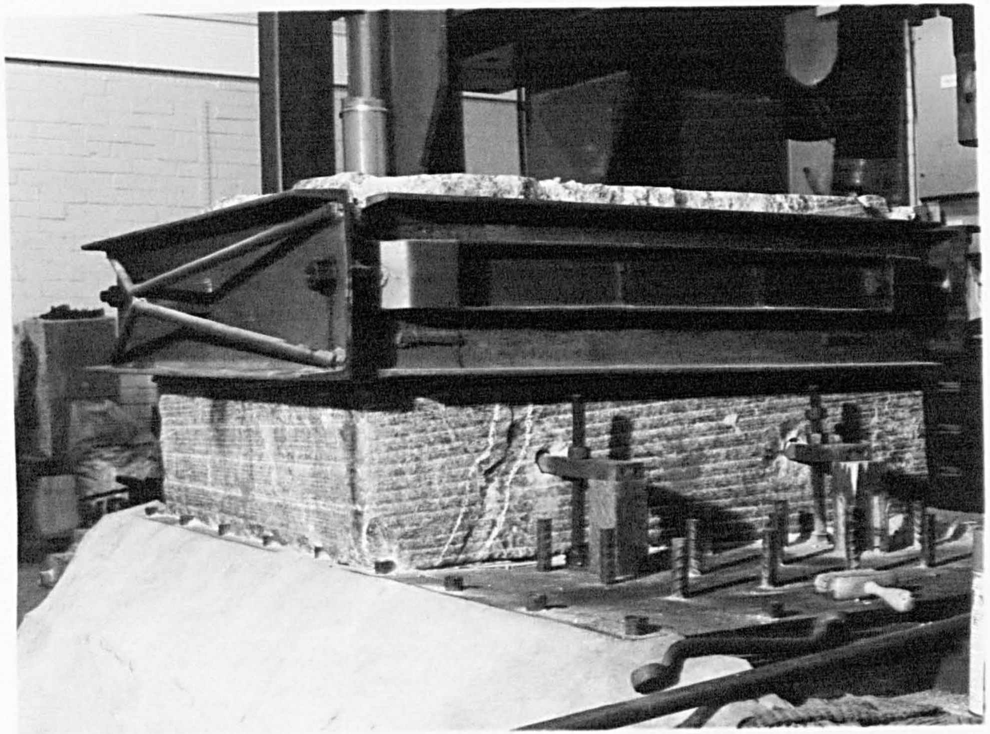


Plate 23

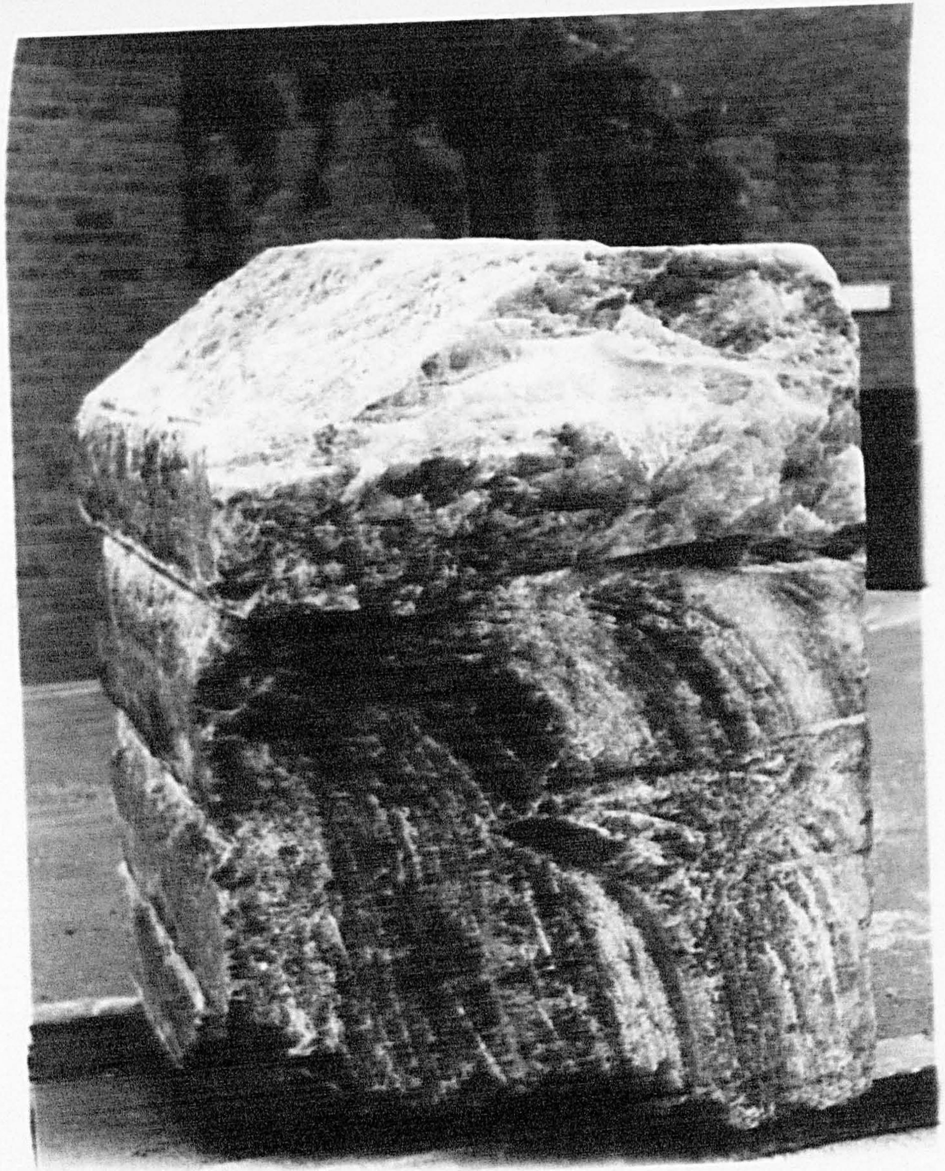


Plate 24

A description of the experimental method employed appears in the chapter on disc cutting experiments.

5.2.5 Disc Cutters

The discs used throughout these experiments were based on a nominal disc diameter of 300mm and had a tip radius of 4.5mm. The only difference was the disc edge (kerf) angle, being 40^{o} and 60^{o}. They were fabricated from tool steel, heat treated, and then ground to the final dimensions.

Details are given in Appendix 1.

5.2.6 Parameters measured and calculated

The measured and calculated parameters obtained for each cut are defined as below.

(1) Mean Thrust Force ($\overline{FT}$)(kN) : The average force acting normal to the direction of cutting, which maintains the disc at the required level of penetration.

(2) Mean Peak Thrust Force (F'T)(kN) : The average of the peak thrust forces acting as above.

(3) Mean Rolling Force ($\overline{FR}$)(kN) : The average force on the disc in the direction of cutting which causes the disc to roll at the required level of penetration.

(4) Mean Peak Rolling Force (F'R)(kN) : The average of the peak forces acting on the tool in the direction of cutting.

(5) Yield (Q)(m^3/km) : The volume of rock extracted by the disc per unit distance travelled.

(6) Specific Energy (SE)(MJ/m^3)

The work done per unit volume of rock for each cut taken was obtained from the following formula:

$$SE = \frac{\text{Mean Rolling Force}}{\text{Yield}}$$

5.2.7 Analysis of Chart Records

A typical analogue trace obtained from the disc cutting experiments is set out in Plate 18.

The methods which were used for the analysis of the recorded traces were the same as those described in Section5.1.7, except for the selection of the data points for peak forces.

The method adopted for drag tool cutters, as previously mentioned, tended to use the definition in which the maximum peak within a 0.1 second interval was averaged over the length of the cut. Since, at similar cutting speed conditions, fewer peaks were produced by disc cutters, the criterion ceases to provide the same sort of information. Consequently, the peak force for each identifiable chipping event has been measured and the average is recorded as the mean peak force component for the cut.

* * *

6. PHYSICAL AND MECHANICAL PROPERTIES OF THE EXPERIMENTAL ROCKS

Although the objective of this work is not concerned with relationships between rock material properties and corresponding cutting characteristics, some physical and mechanical properties of the rock salt and Springwell sandstone (being the main experimental rocks) are presented and briefly described in this chapter. The values quoted for some tests were obtained from a large number of experiments previously carried out within the Department of Mining Engineering on the same rock materials. Details of these tests can be found elsewhere(90). Results are presented in Appendix 2.

Furthermore, during the investigations of artificial cutting material, saltcrete, some rock property tests were also carried out. The results appear in appropriate chapters of this work.

6.1 Uniaxial Compressive Strength

In order to compare different rock types, these tests must be carried out under standard conditions.

Cylindrical specimens of 41mm diameter, having a height to diameter ratio of 2 were used. All specimens were air-dried and dry steel platens were used throughout the testing programme. The samples were loaded at a rate of 0.69 MN/m^2 per second.

6.2 Uniaxial Tensile Strength

This test is mainly aimed at strength classification and characterisation of intact rock. In rock cutting mechanics, the

the relatively weak properties of rock in tension is found to be beneficial. Thus, an accurate knowledge of the tensile strength of a rock is essential in this respect.

There are three methods for deforming the static tensile strength (a) direct pull test, (b) indirect disc (Brazilian) test, and (c) bending test.

The indirect disc (Brazilian) test method was employed in determination of the tensile strength of the experimental rocks, on account of the simplicity of this method. This method involves compressing a cylindrical test specimen in the form of a disc to failure across a diameter. If the diameter of the specimen is D, the width t, and the load at failure is P, applied along the width of the specimen, then the tensile strength is given by (82):

$$T_S = \frac{2P}{\pi Dt}$$

The disc samples used for the tests were of 41mm diameter and 20mm thickness.

6.3 Elastic Properties

The elasticity of the material is a measure of the resistance to deformation in the material.

The objectives of the test are to determine the stress-strain relationship and the two elastic constants, namely Young's modulus and Poisson's ratio. For each rock the stress-strain relationship in uniaxial compression up to failure load was recorded and the static elastic modulus was determined from the slope of the tangent drawn at 50% of failure load.

Dynamic modulus was also measured for the experimental rocks. This was achieved by using a 'Pundit sonic Velocity Testing Equipment' which measured the time interval for the wave to travel from the pulse generator to the receiver(83) Previous experiments (84) indicate that the specimen length should be more than 50mm as a specimen length less than this value gives low and non-constant values.

The elastic modulus values for each rock were obtained by using the following formula:

$$E_d = (V)^2 \times D \times 10^{-6}$$

$$V = L/T$$

where E_d = dynamic elastic modulus in MN/m^2

V = wave velocity in m/s

L = length of the specimen in m

T = time of travel (s)

D = bulk density of a specimen in kg/m^3

6.4 Shore Hardness and Plasticity

This method is used to measure the rebound hardness of rock materials by using a shore scleroscope. This test is based on the idea that materials with different hardness have different elastic limits to absorb kinetic energy. Soft materials have low elastic limits and thus deform plastically, absorbing more kinetic energy whilst little of the kinetic energy is absorbed by hard materials having high elastic limits.

The test consists of dropping a tungsten carbide tipped or diamond tipped mass on the surface of the rock specimen from a predetermined height. The mass is fitted into a vertical tube and is allowed to fall freely onto the surface of the specimen. After striking the surface, the mass rebounds freely and the height of the rebound which is read off the graduated tube, gives the measure of 'shore hardness' of the specimen.

Each reading only corresponds to the measurement of a small area of the specimen and this is not sufficient to represent the average value, since the presence of a large number of hard and soft crystals in the same material produces different hardness values it is, therefore, necessary to to take a large number of readings (about 20 for homogeneous rock).

Plasticity is another parameter which can be determined with the shore scleroscope; local compacting of material under the dropped mass causes the rebound values to increase gradually. After a number of impacts the values tend to an approximately constant value. The percentage change in rebound value is then taken as a measure of the plasticity of the specimen and calculated by the following equation (85):

$$P = \frac{H_L - H_F}{H_L} \times 100$$

where P is the coefficient of plasticity (%)

H_F is the first reading being close to the average shore hardness

H_L is the last reading remaining constant after a number of strikes.

6.5 Schmidt Hammer Test

The Schmidt Hammer is a portable hand operated field device and works on similar principles to those of the shore scleroscope. Although it was originally designed to test the compressive strength of concrete, it has found a wide range of applications in rock testing. The measurements are recorded by means of the rebounding mass and a pointer on a linear scale of 1 to 100. When the catch is releaed, a steel mass travels a fixed distance under spring pressure and rebounds from the surface of the rock.

It has been shown (86) that rebound values obtained by this instrument do not relate linearly to the compressive strength of the rock. The instrument is relatively insensitive to high strength rocks and over-sensitive to low strength rocks.

6.6 Cone Indenter Test

The NCB cone indenter is a portable instrument designed and developed at MRDE by the National Coal Board (NCB) in order to determine the resistance of the rock to indentation by a tungsten carbide stylus of 40^{o} cone angle. The instrument consists of a flat spring-steel beam which is mounted in a rigid frame. A dial gauge is in contact with the beam to measure the deflection and hence the force on the beam. Also, a hand operated micrometer screw is connected to the cone and measures the full advance of the cone into the rock specimen. The indenter can accommodate any small, flat specimen with a size of up to 25mm x 25mm x 6mm.

The cone indenter hardness value for any particular test is obtained by dividing the force (i.e. spring deflection) by the amount of penetration that has occurred (87). Thus:

$$I = \frac{D}{P}$$

where D = nominal deflection of steel strip

P = penetration of specimen by cone.

For Standard Cone Indenter Number (Is), a standard load of 40N (i.e. 0.635mm deflection of steel beam) is applied, whereas for weak rock a load of 12N (or 0.23mm deflection) is applied to obtain indenter number.

* * *

7. USE OF ARTIFICIAL SALT MATERIALS FOR LABORATORY CUTTING EXPERIMENTS

7.1 Introduction

Fundamental studies in rock cutting have contributed considerable insight to the aspects of rock excavation system design. However, results of this work do not fully meet the needs for the practical development of rock cutting machines, since the majority of this research was based on cutting tests conducted on flat rock surfaces.

In-situ trials can be an ideal approach to this matter, but this emerges to be costly; alternatively, laboratory studies on the practical action of the actual machine can be a realistic approach. In general, this may be achieved in two ways; use of the actual machine, which is adapted to laboratory conditions, or through the use of a linear cutting rig well suited for simulation trials. Each method has advantages and drawbacks. In the former case, initial and maintenance costs, i.e. rock sample preparation, may be higher, while the experimental procedure is more likely to provide simultaneous measurements of several variables in a short period of time. The latter may offer lower experimental costs, but the test methods and techniques involved are extremely laborious and tedious.

In the Department of Mining Engineering of the University of Newcastle upon Tyne, a Dosco MK2A type roadheader cutting rig has recently been constructed and instrumented for large-scale cutting rock cutting trials (Speight (86)). By its nature, the rig requires large blocks of rock and provision and preparation of such large specimens would obviously increase the cost of the experiments. For this reason, it was decided to use artificially made materials as a medium for the original rock that is intended to be cut.

In the Department of Mining Engineering, one of the major projects which has been planned to be undertaken with this rig is that of investigating the performance of boom-type roadheaders when cutting an evaporite rock salt. This chapter deals with finding an appropriate artificial material which has a similar cutting characteristic to that of natural rock salt for the purpose of simulation trials.

Several salt materials with different rock salt to cement ratios were cast and cutting tests were carried out at regular intervals. The results were compared with those obtained from natural rock salt. Further, some tests on the mechanical and physical properties of these materials were also carried out for comparison purposes. However, the latter tests were not the main criterion for selection of the relevant material since the cutting characteristics of a particular rock are not generally a direct function of its individual mechanical and physical properties respectively. Accordingly, the materials were mainly compared on the basis of their cutting characteristics.

7.2 Previous Research

The only economic method for formation of an artificial rock salt material appears to be bonding rock salt aggregates by means of cement and thus salt to cement ratio, which significently affects the material properties is of paramount importance.

To the author's knowledge, the only research conducted on this aspect is that of Foster (89). His work is also concerned with the artificial rock salt materials and can be briefly summarised as follows:

In Meadowbank Rock Salt Mine, Cheshire (UK), it was suggested that an artificial support should be introduced into the old cavities in an effort to maintain stability. Thus this required the investigation of mechanical properties of an artificial material likely to prove useful in establishing additional pillar or massive underground support. Finally, concrete was intended to be used as a medium for artificial support. The least expensive and most readily available aggregate at the mine was found to be rock salt; the term 'saltcrete' was coined for concrete having a rock salt aggregate and since saltcrete was intended as the support medium, the investigations were aimed at the mechanical properties of the material.

Initially, a number of saltcrete specimens were cast at different mix proportions. The rock salt aggregates which were used consisted of primary crushed and cutter dust materials. The maximum grain size of the primary crushed aggregates was taken at -1½ inches (38.1mm). The saltcrete specimens with different salt to cement ratios are given in Table 2, The specimens were prepared in 6-inch cubes respectively and tested in compression. The compressive strength values of corresponding materials are presented in Table 3.

7.3 Preparation and casting of the different saltcrete specimens

Similar procedures to those described by Foster were employed for specimen preparation and casting.

7.3.1 Selection of salt to cement ratios

In Table 2 several salt to cement ratios are given for different mixtures. However, there is no need to test all of these ratios since some of them were unsuitable for this investigation. By reducing the quantity of cement, the cost of any specimen would reduce and hence this provides a more homogeneous material, due to the increasing proportion of salt. However, reducing the cement proportion in a particular mix would result in an improper bonding of the aggregates and the material can present a crumbly character. As a consequence, under the cutting action of a tool, the rock salt aggregates existing in such materials may effectively be gouged out rather than be cut.

The compressive strength values given in Table 3 for each composition indicate low strength properties for the saltcrete materials with high salt to cement ratios. However, these values

TABLE 2

Ratios of rock salt to cement for saltcrete cubes.

Specimen.	Mixture Ratio.	Composition.
A	5 : 1	Cutter dust : cement.
B	2.5 : 1	Cutter dust : cement.
C	7.5 : 1	Cutter dust : cement.
D	10 : 1	Cutter dust : cement.
E	4 : 2 : 1	Primary crushed (-1½") : cutter dust : cement
F	3 : 1.5 : 1	Primary crushed (-1½") : cutter dust : cement
G	6 : 3 : 1	Primary crushed (-1½") : cutter dust : cement
H	2.5 : 2.5 : 1	Graded -1½" + 7 B.S. : - 7 B.S. + 0 : cement

(after Forster) (89)

TABLE 3

Compressive strengths of various concrete mixes at various ages.

Specimen.	Compressive Strength p.s.i.			
	1 week	4 weeks	13 weeks	40 weeks
A	1965	2860	3700	3000
B	3980	5130	6100	6470
C	927	1038	2180	2800
D	380	427	583	625
E	3800	4340	4600	5730
F	4250	5080	5900	6250
G	2140	2840	3440	3000
H	3880	4190	4730	6060

(after Forster) (89)

were not the main criterion for the selection of the characteristics of a rock material as the action of drag tools does not solely depend upon its compressive strength value.

Saltcrete materials, having moderate salt to cement ratios, were found to be relevant to the objective of this work; thus mixture ratios and compositions chosen are given as follows:

Specimen A : Among the specimens requiring only one type of salt aggregate, this has a moderate ratio. By the use of only cutter dust, a more homogeneous material may be obtained.

Specimens E and F : Both have a reasonable amount of cement and the mixtures may offer a more compact specimen, as the small salt particles tend to fill the gaps between the coarse ones.

7.3.2 Sampling the aggregate

The rock salt aggregates were first sieved in order to obtain the particles with a grain size less than 1½" (38.1mm).

The sampling of the aggregates was carried out according to British Standard Specifications (94). The main sample was obtained by drawing and combining at least ten samples from different parts of the bulk supply. This main sample was reduced by applying the quartering process. The quartering process merely involves mixing the material thoroughly and building it up into a cone by placing successive portions of the sample on the apex of the cone and allowing the material to fall evenly down the sides of the cone. The cone was flattened and divided into equal quarters by splitting it about two diameters mutually at right angles. A pair of diagonally opposite quarters were rejected and the other two remixed and this process was repeated until a sample of the desired quantity had been obtained.

7.3.3 Mixing of the Saltcrete

The sample of aggregate was thoroughly mixed with the correct proportion of Portland Cement. Water was added sparingly until all the constituents were wet, and the mixings were carried out simultaneously. The material was mixed on a steel plate to prevent absorption of water by the laboratory floor. Sufficient saltcrete material was mixed at one time to make three specimens.

7.3.4 Compaction of Saltcrete mixes

Since the natural rock salt is of a compact material because of its crystalline nature, saltcrete materials are also required to have a similar structure.

The purpose of compaction in concrete is to reduce the air voids to a minimum and hence obtain as dense a mass as possible. Friction between particles of concrete and between concrete and mould has the effect of reducing compaction or reducing the friction and it is normally necessary to add more water than can combine with the cement. But excessive water would form water voids which have as harmful an effect in reducing the strength of the concrete as air voids. It is preferable to use slightly too much water than to run the risk of inadequate compaction.

Two methods of compaction were employed:

(1) tamping with rods; and

(2) vibration.

The act of vibration does not contribute to saltcrete any special properties, except that it normally provides a higher state of compaction than is attained by hand tamping.

The water-cement ratio was taken at 0.45 for hand tamped specimen and 0.35 for vibrated specimen.

Compaction of the specimens by means of vibration was carried out by using a vibratory table in the Department of Civil Engineering. The specimens were vibrated for 30 minutes at a frequency of 50 cycles per second.

7.3.5 Curing Conditions

The specimen casts were stored at a temperature of 64°F (17.7°C) and a humidity of 55 percent. After three days they were removed from the boxes and then stored at the same curing conditions until time for testing.

7.4 Cutting characteristics of mechanical and physical properties of saltcrete specimens

As previously mentioned, the primary aim of this investigation is to use saltcrete to model rock salt for large scale cutting trials and, therefore, the saltcrete mixes were compared with rock salt on the basis of their cutting characteristics and hence the mechanical and physical properties are of secondary importance.

The cutting experiments were carried out on the flat surface of the materials by using standard tungsten carbide tipped tools and point attack tools. Furthermore, the experiments were carried out at regular intervals.

7.4.1 Initial trials on hand tamped saltcrete materials with different mixtures and composition

Three different saltcrete mixes were cast by using hand tamping methods and these were tested after one month of casting. Unrelieved cutting experiments with chisel type tools were carried out at 5mm depth of cut. The results are presented in Table 4 together with those obtained from natural rocks. The table suggests that saltcrete F has the nearest cutting characteristics to that of rock salt, and only this mixture can be used for further trials. Some mechanical and physical properties of these materials are given in Tables 5,6. It can be seen that the mixture F has a higher mechanical strength, due probably to the higher salt to cement ratio.

These initial trials on hand tamped specimens provided guidance on the selection of the appropriate saltcrete mix. Although specimen F

Type	MCF +s.d. (kN)	MPCF +s.d. (kN)	PCF +s.d (kN)	. MNF +s.d. (kN)	MPNF +s.d. (kN)	PNF +s.d. (kN)	Q +s.d. gr/cm	S.E. +s.d. (MJ/m^3)
A	0.35 0.02	0.99 0.18	1.43 0.23	0.15 ±0.054	0.38 0.042	1.50 0.06	1.90 0.30	3.5 0.62
E	0.68 0.09	1.70 0.22	2.43 0.19	0.21 0.03	0.70 0.06	0.92 0.08	1.76 0.20	7.7 ±0.30
F	0.93 0.07	2.24 0.14	2.90 0.42	0.41 0.02	0.99 0.11	1.24 0.22	1.91 0.08	10.13 0.64
Rock salt	1.30 0.05	3.07 0.16	4.33 0.41	0.65 0.04	1.45 0.08	1.98 0.18	2.46 0.21	11.60 0.69

MCF = Mean Cutting Force

MPCF = Mean Peak Cutting Force

PCF = Maximum Peak Cutting Force

Q = Yield

MNF = Mean Normal Force

MPNF = Mean Peak Normal Force

PNF = Maximum Peak Normal Force

S.E. = Specific Energy

TABLE 4 Cutting Characteristics of the Hand Tamped Saltcretes with chisel type drag tools (one month after cutting)

Specimen Type	Compressive Strength (MPa)±s.d.	Tensile Strength (MPa)±s.d.	Bulk Density (gm/cc)
A	17.09 ± 1.57	1.56 ± 0.08	1.83
E	14.97 ± 1.62	1.45 ± 0.07	1.99
F	24.15 ± 1.59	2.21 ± 0.21	2.07

TABLE 5 Compressive and tensile strength and bulk density of the hand tamped saltcrete materials.

Table 6

Mechanical and Physical Properties of Rock Salt

Compressive Strength (MPa)	:	28.30 ± 0.20
Tensile Strength (MPa)	:	1.96 ± 0.21
Static Elastic Modulus $10^4 MN/m^2$	:	0.14 ± 0.05
Schmidt Hammer Rebound Number	:	30.28 ± 2.02
Cone Indenter Hardness	:	1.81 ± 0.11
Shore Hardness	:	20.05 ± 3.50
Shore Plasticity Coefficient	:	44.10 ± 4.51
Bulk Density (gm/cc)	:	2.18

Shear strength (after Szeki and Mirza):

(a) Direct Shear Test:

$$\tau = 3.11 + \sigma_N \tan 49.9^\circ$$

(b) Triaxial Test:

$$\tau = 4.8 + \sigma_N \tan 46.5^\circ \quad (\sigma_3 = 0 - 10.5 \text{ MPa})$$

$$\tau = 17.3 + \sigma_N \tan 30.7^\circ \quad (\sigma_3 = 10.5 - 21.0 \text{ MPa})$$

Where: τ = shear stress

σ_N = normal stress

σ_3 = confining pressure.

presented the closest cutting characteristics to that of natural rock salt, the force values are low and, therefore, hand tamped specimens were thoughtto be unsuitable for the objective of the investigation and further experiments were carried out on the vibrated saltcrete materials having the composition F.

7.4.2 Cutting characteristics of vibrated specimens

The vibrated saltcrete specimens having the mixture F were used and tungsten carbide tipped tools and point attack picks were used.

7.4.2.1 Cutting with tungsten carbide tipped tools

The experiments were carried out in unrelieved mode at a standard depth of 5mm. The results are set out in Table 7 with respect to curing period.

The results show that during early weeks the force values are relatively high. As curing time increases, forces become slightly lower. This may be attributed to the moisture content which is initially high and thus causes the generation of slightly higher forces.

The mechanical properties of the same saltcrete material (given in Table 8 a) also indicates that increase in compressive strength values does not affect the force levels, due mainly to the moisture content. Phillips (88) found that a saturated sandstone specimen gives higher force values than those obtained from the same

AGE	MCF	MPCF	PCF	MNF	MPNF	PNF	Q	S.E.
4	1.10±0.13	2.47±0.15	3.06±0.20	0.41±0.05	1.13±0.11	1.56±0.30	1.98±0.10	11.51±1.89
8	1.00±0.06	2.21±0.08	2.81±0.23	0.36±0.03	1.21±0.15	1.73±0.30	1.88±0.08	11.05±0.49
12	0.91±0.05	2.25±0.05	3.13±0.23	0.35±0.01	1.12±0.12	1.63±0.18	2.01±0.05	9.65±0.60
17	1.07±0.05	2.48±0.09	3.17±0.28	0.40±0.02	1.14±0.06	1.51±0.16	2.00±0.09	11.44±0.87
ROCK SALT	1.30±0.05	3.07±0.16	4.33±0.41	0.64±0.04	1.45±0.08	1.98±0.18	2.46±0.21	11.60±0.69

TABLE 7 Cutting characteristics of Saltcrete
(Unrelieved cuts with chisel-type tungsten carbide insert tools)

Mechanical and physical property ± s.d.	AGE		
	4 weeks	8 weeks	12 weeks
Compressive strength (MPa)	28.80±0.32	33.75 ± 1.83	35.71 ± 1.71
Tensile strength (MPa)	2.20±0.12	2.93 ± 0.26	2.95 ± 0.09
Static Elastic Modulus ($10^4 MN/m^2$)	-	-	0.41 ± 0.04
Schmidt Hammer Rebound Number	26.79±3.83	26.17 ± 3.62	26.98 ± 4.11
Cone Indenter Hardness	_	_	1.95 ± 0.28
Shore hardness	-	-	16.64 ± 3.50
Shore plasticity coefficient	-	-	36.10 ± 7.50
Bulk Density (gm/cc)	-	-	2.13

TABLE 8a Some mechanical and physical properties of the vibrated saltcrete materials

specimen when dry, while the compressive strength of the dry specimen was higher than that of the saturated specimen.

After about 17 weeks, slightly higher forces were again presented. This may be ascribed to the stiffness of the cement gained by the moisture loss. However, the variation in forces is small and not particularly significant. Furthermore, the specific energy values for the saltcrete are very similar to those of rock salt though the force level of the natural rock salt is relatively higher.

7.4.2.2 Cutting characteristics of the saltcrete under the action of a point attack tool

Cutting experiments with point attack tools were carried out in unrelieved and relieved cutting modes in order to establish relative cutting characteristics of both natural rock salt and the saltcrete. Further, the standard tests with tungsten carbide tipped chisel tools as outlined in the previous section indicated that about three or four months after the casting, the excessive moisture in the saltcrete is almost dehydrated and thus the cutting parameters tend to reach a steady level. Since the large scale cutting trials were required to be conducted at this steady level, the experiments with point attack tools were, therefore, carried out about 17 weeks after casting.

Unrelieved cutting results obtained from both the natural rock salt and the saltcrete at a depth of 5mm are presented in Table 8b. It can be seen that the force levels are reasonable similar and the specific energy values for both materials are very close.

Material type	MCF (kN) ±s.d.	MPCF (kN) ±s.d.	MNF (kN) ±s.d.	MPNF (kN) ±s.d.	Q (m^3/km) ±s.d.	S.E. (MJ/m^3) ±s.d.
Rock Salt	1.91±0.39	3.01±0.24	1.83±0.55	2.30±0.52	0.680±0.041	27.94±5.61
Saltcrete	1.75±0.03	2.76±0.08	1.61±0.15	1.98±0.16	0.667±0.023	26.24±0.93

__TABLE 8b__ Unrelieved cutting results for rock salt and saltcrete, with point attack tools

The relieved cutting experiments were carried out on a flat rock surface as described in Section 5.1.4. The results of each cutting parameter were plotted respectively. Variation in force values for both materials followed the same trend where a gradual increase at lower S/d tended to level out towards higher S/d values (Figures 19 and 20).

The values for yield, as shown in Figure 21, tend to vary but having a very similar trend. There was no marked difference between yield values for both materials.

Specific energy values also vary in a similar manner and an optimum value tends to occur at S/d of between 4 and 5 (Figure 21).*

7.4.3 Discussion

The results obtained from the cutting trials have shown that the hand tamped specimens were unsuitable as a medium for the objectives of this investigation due to the fact that an adequate compaction was not provided and the materials were not as tough as the natural rock salt.

Results obtained from the vibrated specimens were closer to those of natural rock salt; however, there were slight differences in force values.

It should be strongly emphasised that due to its heteto-geneous and crystalline structure, the results from the natural rock salt were widely scattered and this was evident when considering the

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* Results for relieved cuts are presented in Appendix 3.

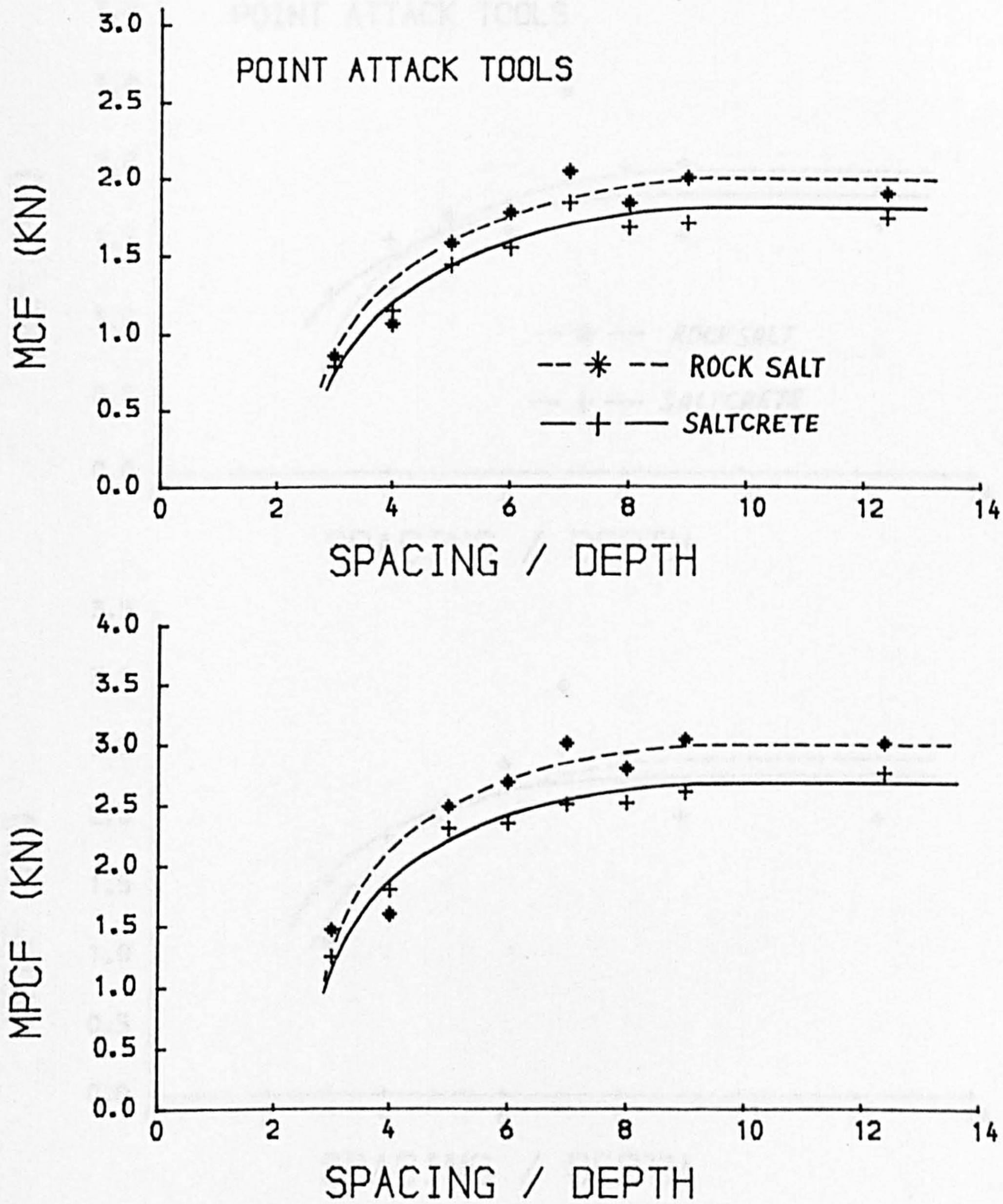


FIG. 19 VARIATION OF CUTTING FORCES WITH S/D RATIO . DRAG TOOL CUTTING OF ROCKSALT AND SALTCRETE.

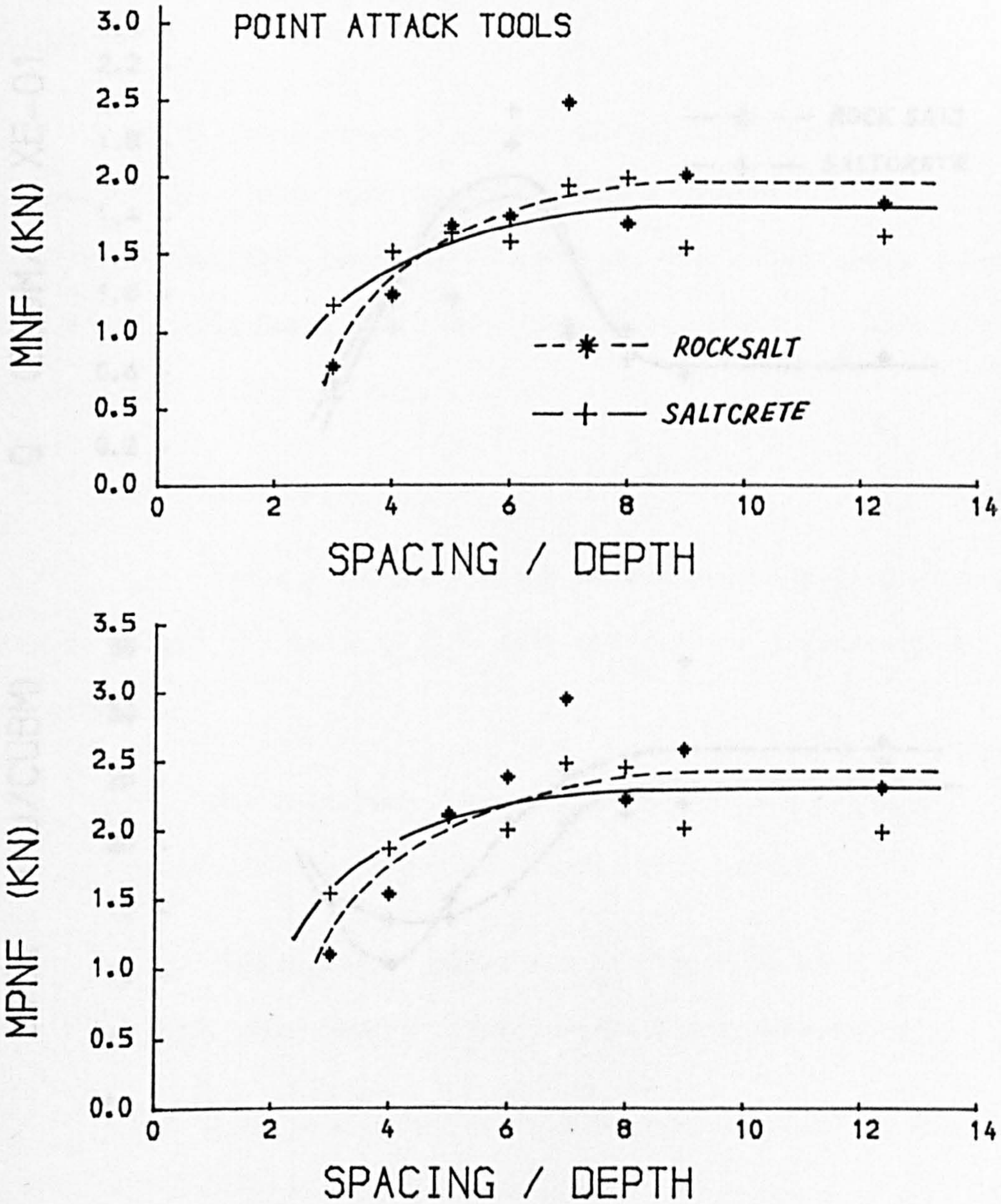


FIG. 20 VARIATION OF NORMAL FORCES WITH S/D RATIO , DRAG TOOL CUTTING OF ROCKSALT AND SALTCRETE.

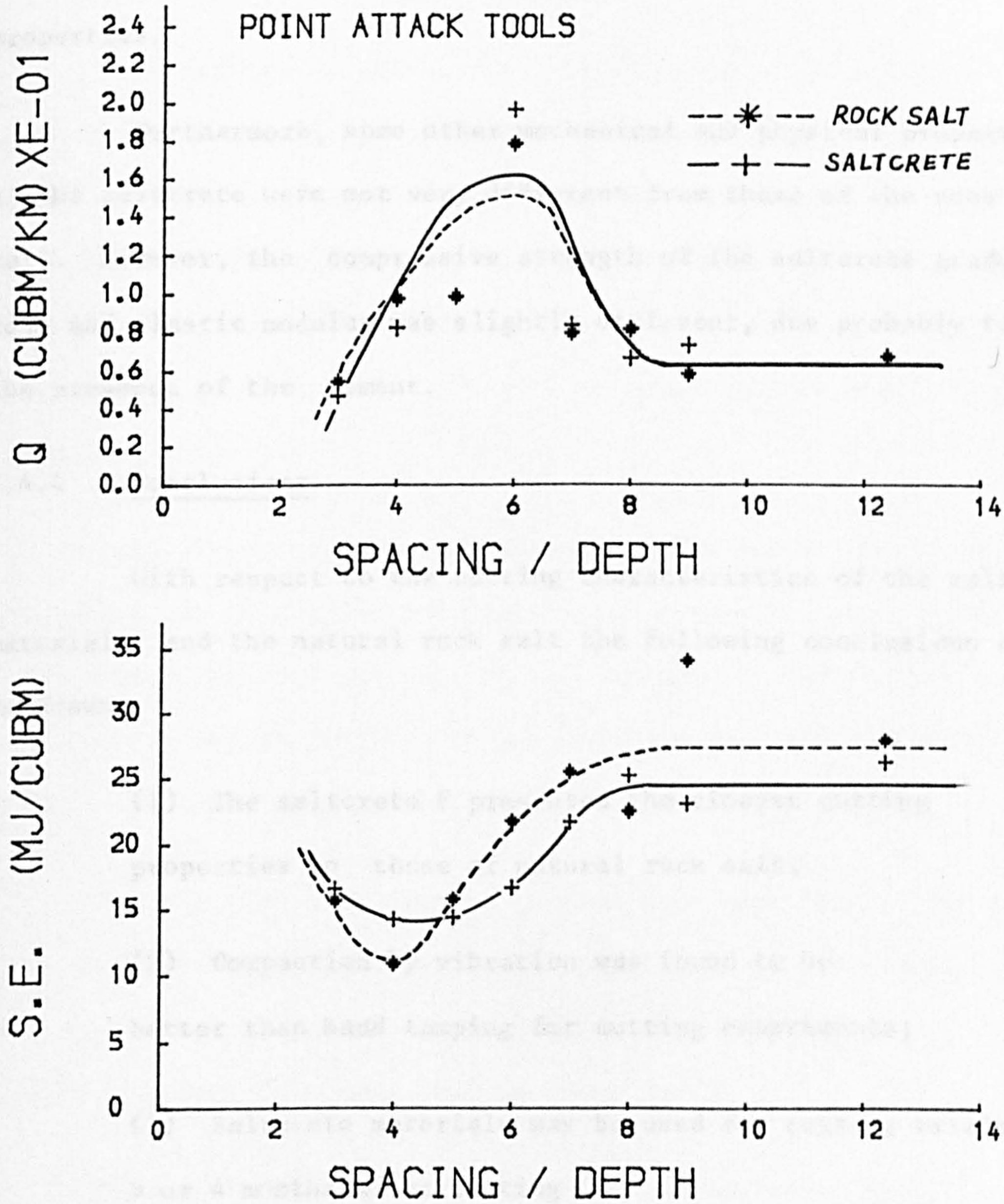


FIG. 21 VARIATION OF YIELD AND S.E. WITH S/D RATIO , DRAG TOOL CUTTING OF ROCKSALT AND SALTCRETE.

standard deviations of the cutting parameters. Therefore, the saltcrete may not form a perfect alternative to rock salt, though cutting trials with point attack tools have given similar cutting properties.

Furthermore, some other mechanical and physical properties of the saltcrete were not very different from those of the rock salt. However, the compressive strength of the saltcrete gradually rose and elastic modulus was slightly different, due probably to the presence of the cement.

7.4.4 Conclusions

With respect to the cutting characteristics of the saltcrete materials and the natural rock salt the following conclusions can be drawn:

(1) The saltcrete F presented the closest cutting properties to those of natural rock salt;

(2) Compaction by vibration was found to be better than hand tamping for cutting experiments;

(3) Saltcrete materials may be used for cutting trials 3 or 4 months after casting

(4) Natural rock salt gave more scattered results than did the saltcrete.

8. PRELIMINARY INVESTIGATIONS FOR SIMULATION EXPERIMENTS WITH DRAG TOOLS

8.1 Introduction

This chapter describes the initial steps of a laboratory approach to the designing of roadheader cutting heads with a consideration of theoretical and practical aspects of rock cutting machines. Experiments in this section involve mainly the investigation of lateral spacing between adjacent tools and this will provide initial values for a cutting head which will be considered in detail later in this work.

Lateral tool spacing and advance of the cutting head per revolution are most important operational parameters along with the rock's properties and the cutting tool geometry. Each cutter may take benefit from relief provided by the previous tool and individual tool forces vary significantly with the spacing and depth taken.

So far, most rock cutting studies have been carried out on flat rock surfaces with idealised parallel cuts of equal depth. The amount of laboratory work on simulating the cutting action of a practical machine has been limited (Hurt, (66)).

Simulation of a cutting head in laboratory conditions is dependent on the head's cutting pattern. Laboratory experiments thus require a knowledge of the tool lacing used on the head under consideration. As the order of the cutting action of successive tools in an array is determined, the cutting pattern of the head may then be adapted to the laboratory situation by maintaining a similar position and location of adjacent tools.

Tests on a simulation of a cutting pattern are generally too laborious and rigorous, particularly with those of roadheaders, because of the head geometry. If a drum lacing is considered it may be seen that the cutting pattern is easily adaptable and involves reasonably convenient experimental procedures. Drum lacing is universal and tool lacing of roadheaders and drums generally tend to be in the form of helical arrays to assist loading. Also, on some roadheaders, the cutting head includes a number of traversing tools which may be directly compared to those of a shearer drum. However, the geometry of the nose portion of the head is unique to the roadheader.

For the above reasons, although drums are not the main objective of this work, it was thought that a simulation of a simplified drum lacing would be more convenient for the purpose of spacing experiments and the possible results obtained from these experiments could be applicable to some aspects of roadheader cutting head design.

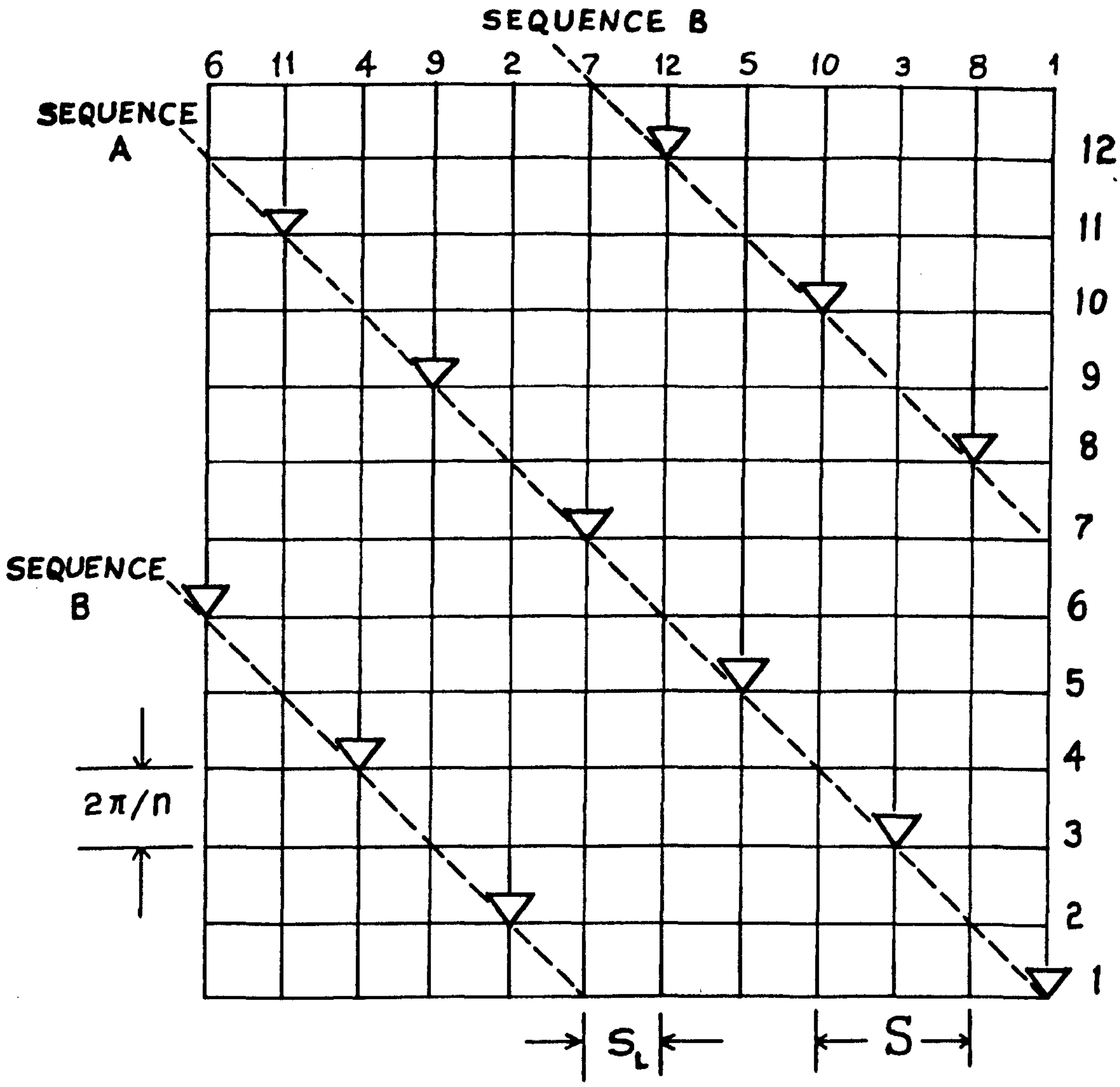
8.2 A simplified Drum Cutting Pattern

The specifications for an efficient drum were given in Chapter Three. The drum lacing pattern which was taken for the initial experiments was assumed to be based on these good cutting principles. It should also be noted that the investigation is only concerned with the cutting pattern and for the time being, complex situations such as loading and the positions of corner cutting tools are not considered.

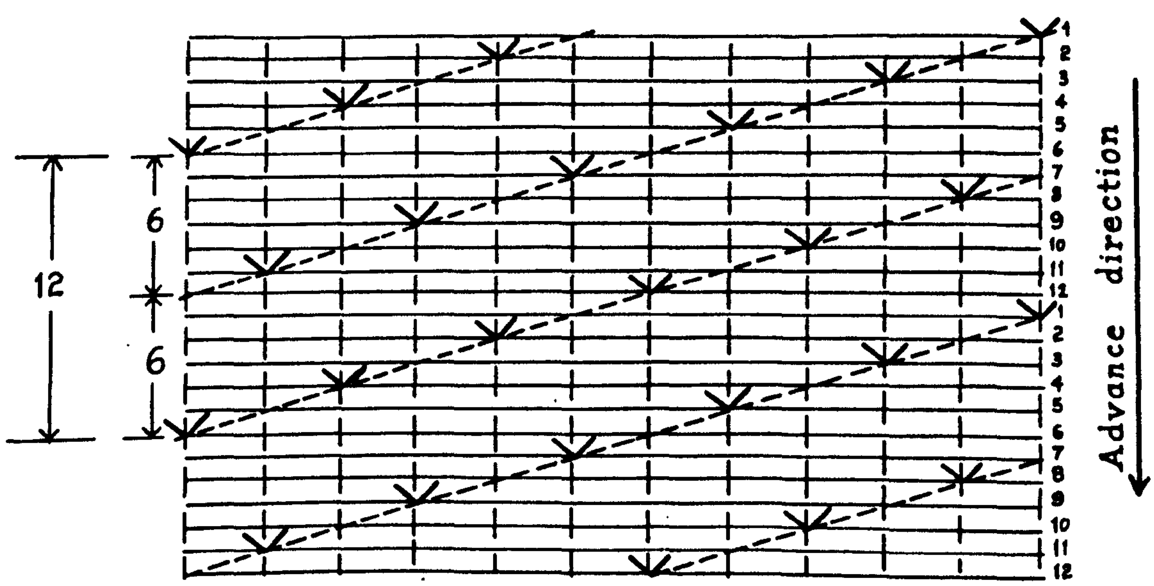
The pick layout adopted is shown in Figure 22 and the main features are as follows:

Picks, in the form of two starts, are fitted on drum shell in such a way that one pick is located per line. In order to avoid a sudden move of cutting forces from one side of the drum to the other, an overlapping pattern of cutting sequences is adopted. The tools are placed in an equal angular position, around the drum periphery; hence each tool take the same depth of cut and the number of active picks in a given cut sector area is mostly constant at an angular interval of $2\pi/n$, where n is the number of tools on the drum. This was considered to provide a consistent variation of torque fluctuations; the corner cutting situation is neglected in this analysis. The sample drum was assumed to cut a rock block without the need for corner cutting. Furthermore, it was also found that the total number of cutters being divisible by 4 easily fits this sort of cutting pattern.

This situation is clearly illustrated in Figures 22 to 24, where a drum is fitted with 12 and 10 tools both at the same line spacing and having the same over lapping pattern. When the order of pick cutting positions is considered, it may then be seen that the depth taken by each cutting sequence appears to be different. In the



Tool layout on a simple drum.



Breakout pattern at mid drum level

Fig. 22 Tool lacing pattern of a simple drum with one tool per line.

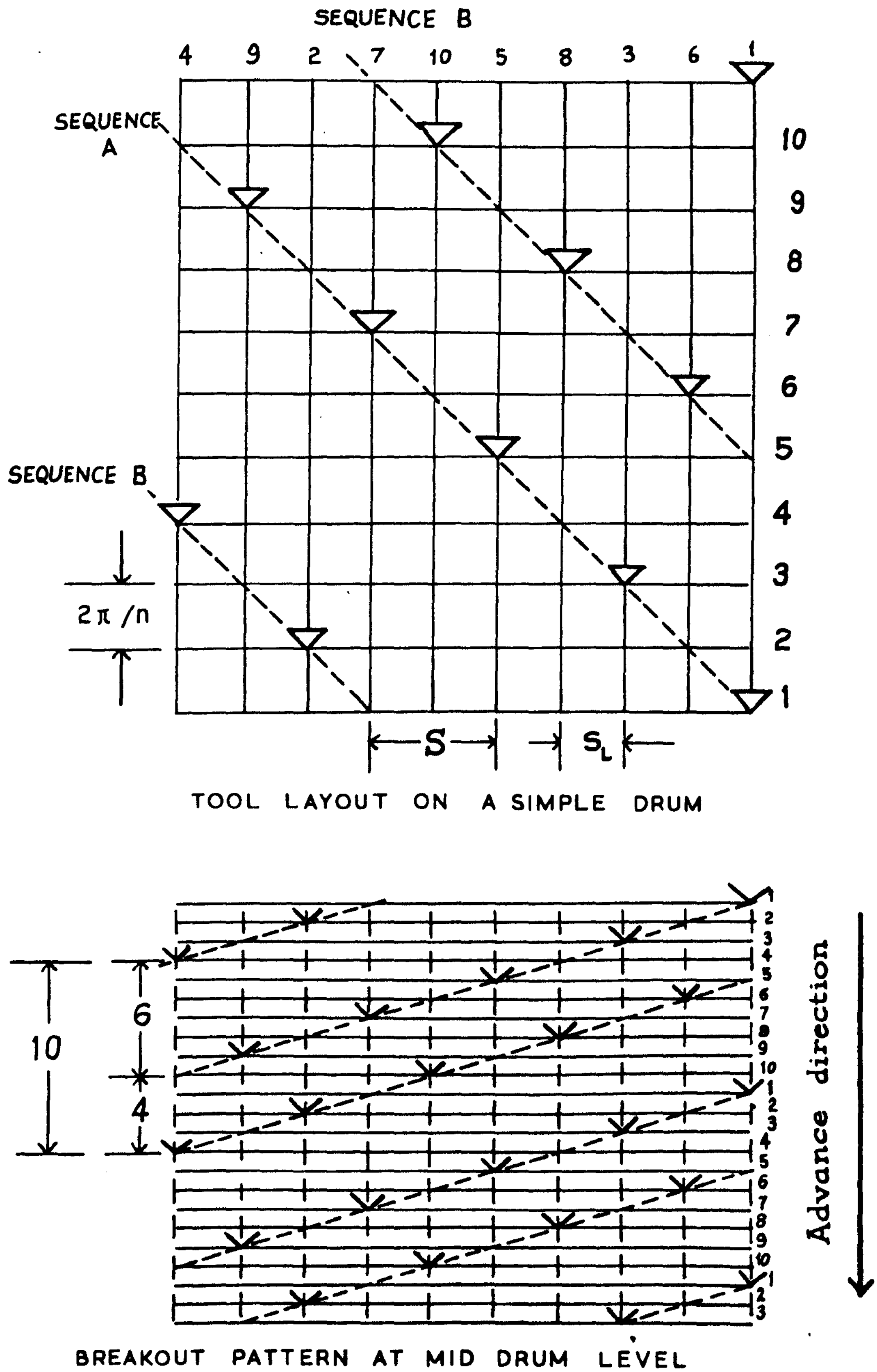
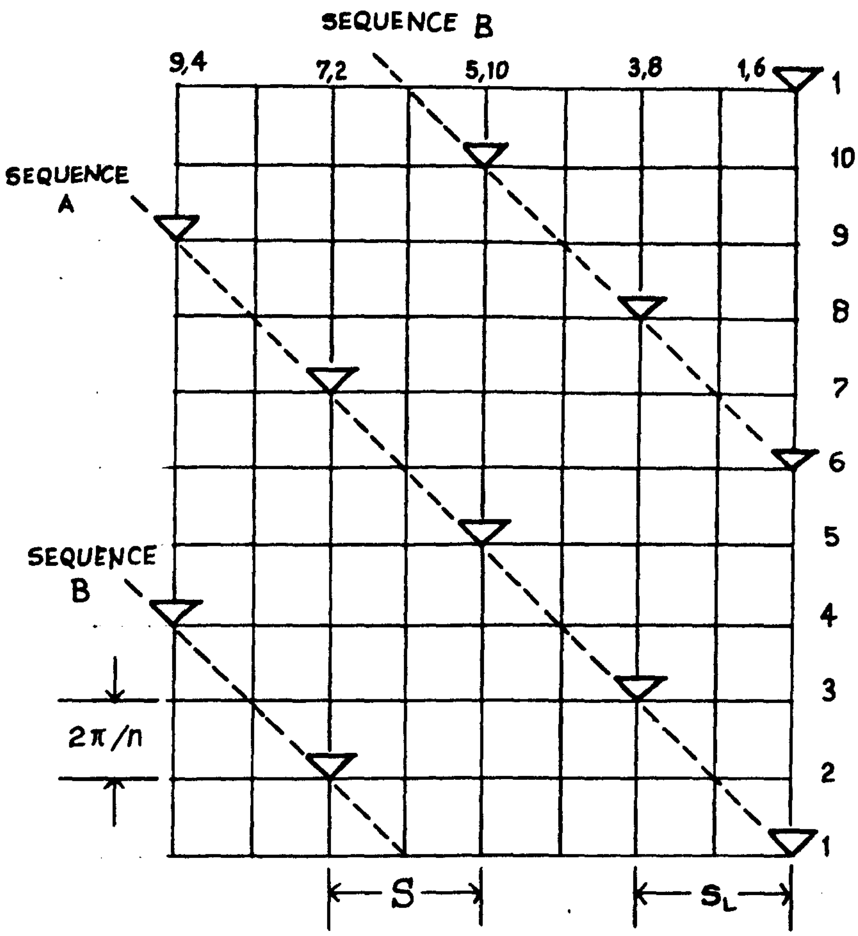
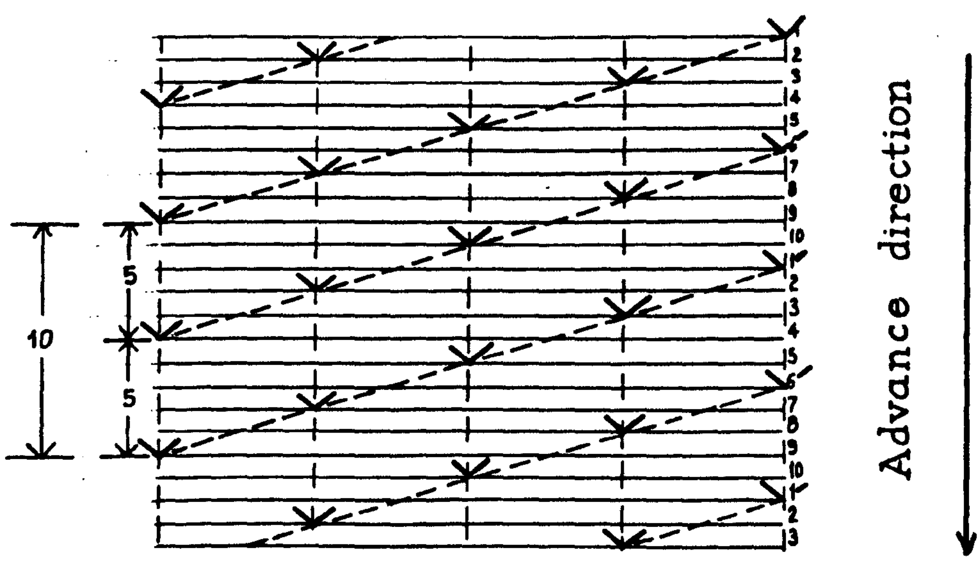


Fig. 23 Tool lacing pattern of a simple drum with one tool per line.

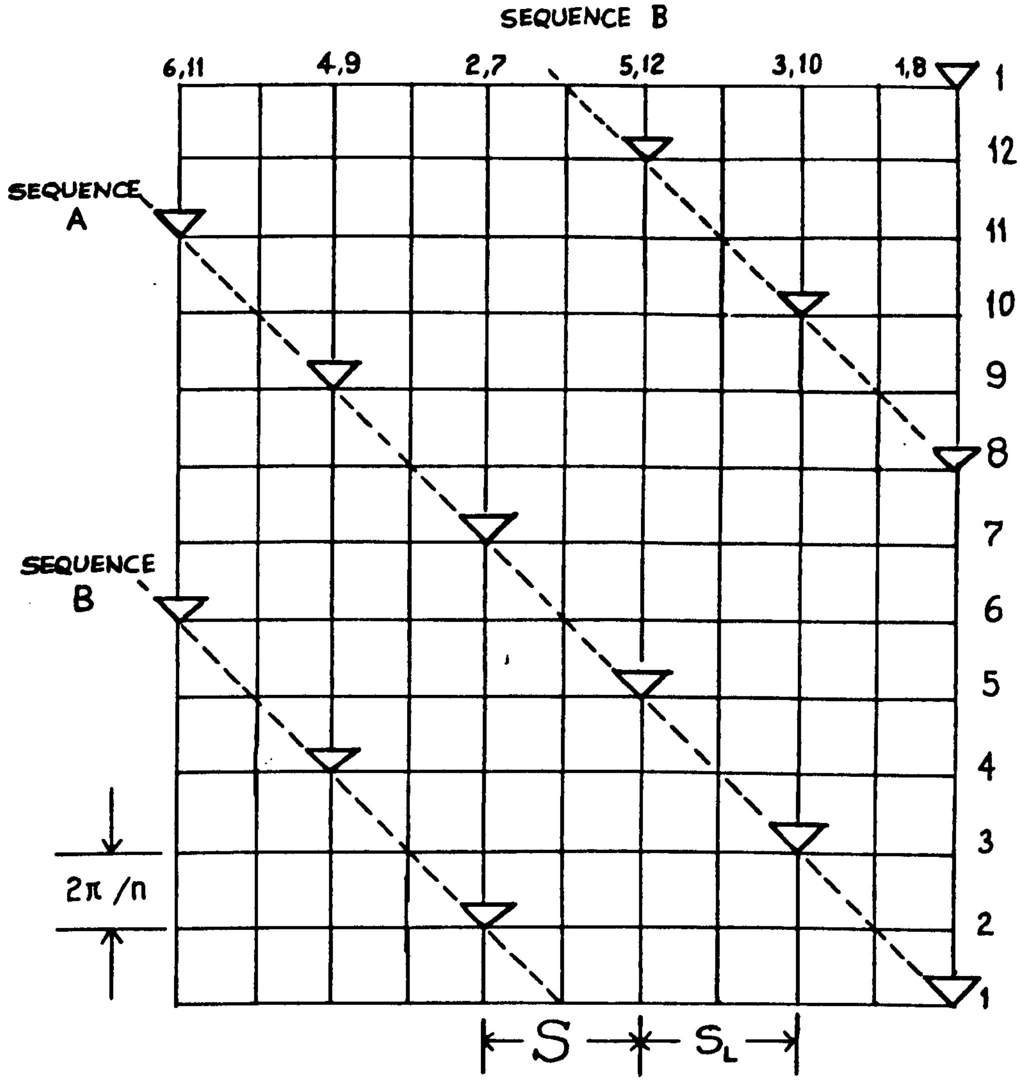


A SIMPLE TOOL LAYOUT

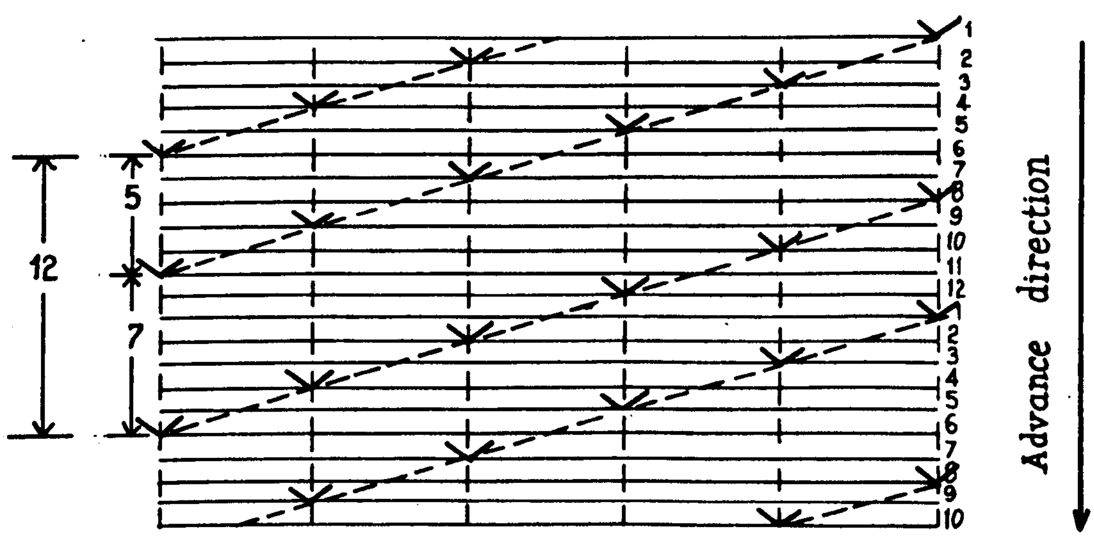


BREAKOUT PATTERN AT MID DRUM LEVEL

Fig. 24 Tool lacing pattern of a simple drum with two tools per line.



A SIMPLE TOOL LAYOUT



BREAKOUT PATTERN AT MID DRUM LEVEL

Fig. 25 Tool lacing pattern of a simple drum with two tools per line.

12-tool pattern, each sequence takes the same depth of cut and thus agrees with the equation (advance/rev)/number of cutting sequences. But this is not the case with the pattern having a total of 10 picks, where the depth taken by each cutting sequence becomes different hence each sequence appears to have different cutting duties.

If, as an example, 12 tools are fitted on the drum shell with two starts, the sequences may be as follows:

1,3,5,7,9,11 ... first sequence

2,4,6,8,10,12 ... second sequence

This situation is illustrated in Figure 22.

The cut positions of the tools and the subsequent pattern of rock breakage at the mid-drum level, where the maximum depth of cut is taken, are assumed to be the criteria for all cutting patterns, and this is shown in Figure 22. A straight line passing through the tips of picks in a sequence, may be drawn and the cutting pattern then appears to be more comprehensive. It can be seen that adjacent cuts of each sequence occur along a slope and the gradient of this slope can be expressed as:

$$\beta = \tan^{-1}\left[\frac{\text{Advance/revolution}}{S_L\ n}\right] \qquad \text{..... (8.1)}$$

where S_L = Line spacing

n = Total number of tools.

By definition, provided the dimensions of the drum and S_L are constant, β varies with 'advance/revolution'. This situation implies that for given diameter and width of drum and β, different values of S_L could be employed. All these definitions are relevant to tool lacing and are important for later parts of this work on roadheader cutting heads.

8.3 Experimental technique and procedures

It appears from previous definitions that the sequential cuts may be simulated in a laboratory condition by forming parallel grooving cuts of equal depth increments. If the exact order of cutting action (e.g. 1,2,3, ..., 11,12) is followed, then a slope on the rock surface will be produced (Figure 26a). But this is not convenient laboratory procedure as each cut requires a change in the depth set on the cutting rig.

In some cases, the successive cuts may not interact with each other. For instance, in Figure 22, cutting pattern cut 6 is not affected by the actions of tool 7 and tool 9, owing to their distance away from cut 6. This situation indicates that during the laboratory testing programme the order of cuts does not need to follow the drum cutting sequence to simulate the field situation and a more convenient test procedure may be adopted.

Utilisation of the experimental machine's rotatable cutting head proved to be the best alternative to the formation of a slope on the rock block (Figure 26b) thus avoiding the need to reset the depth after each cut.

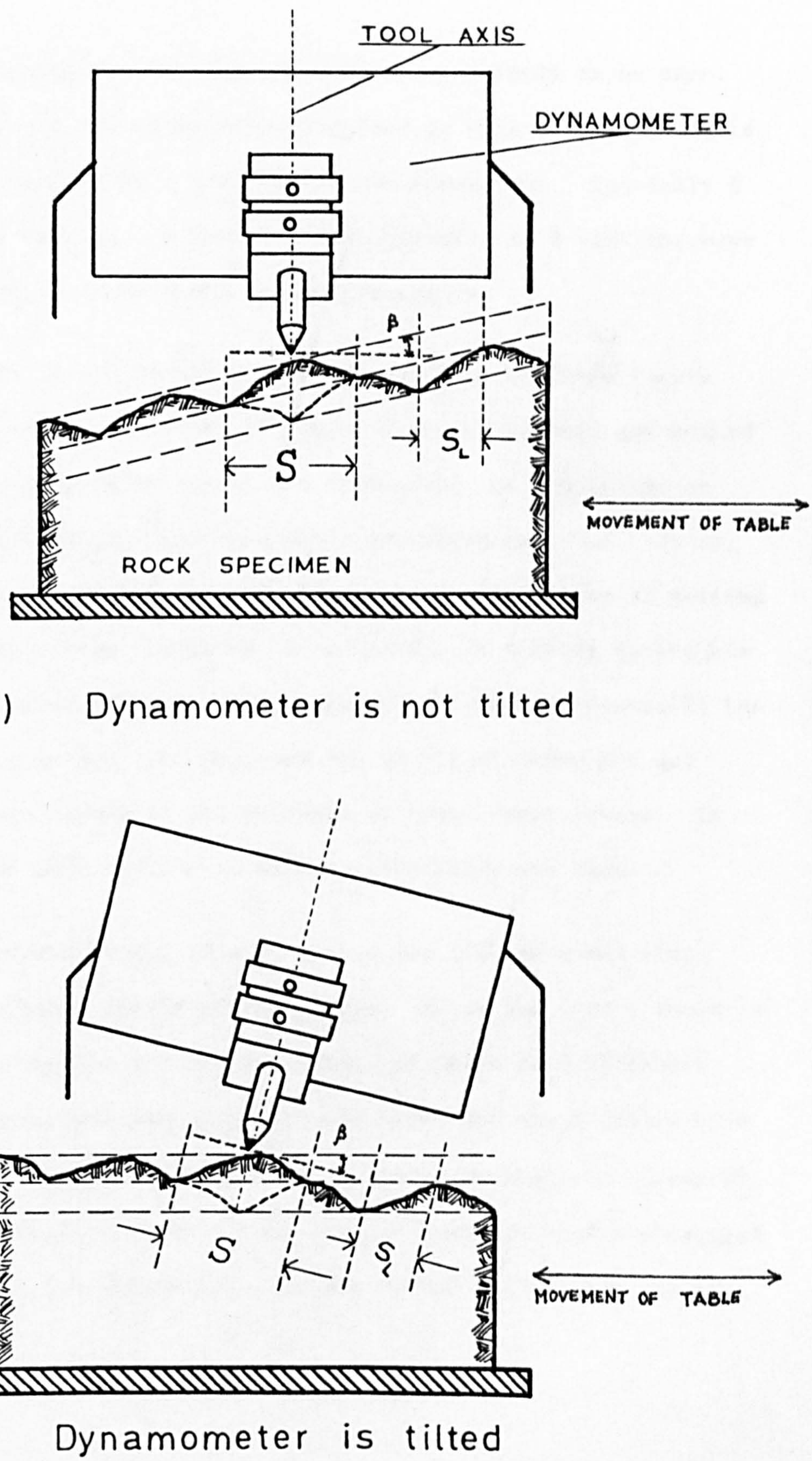
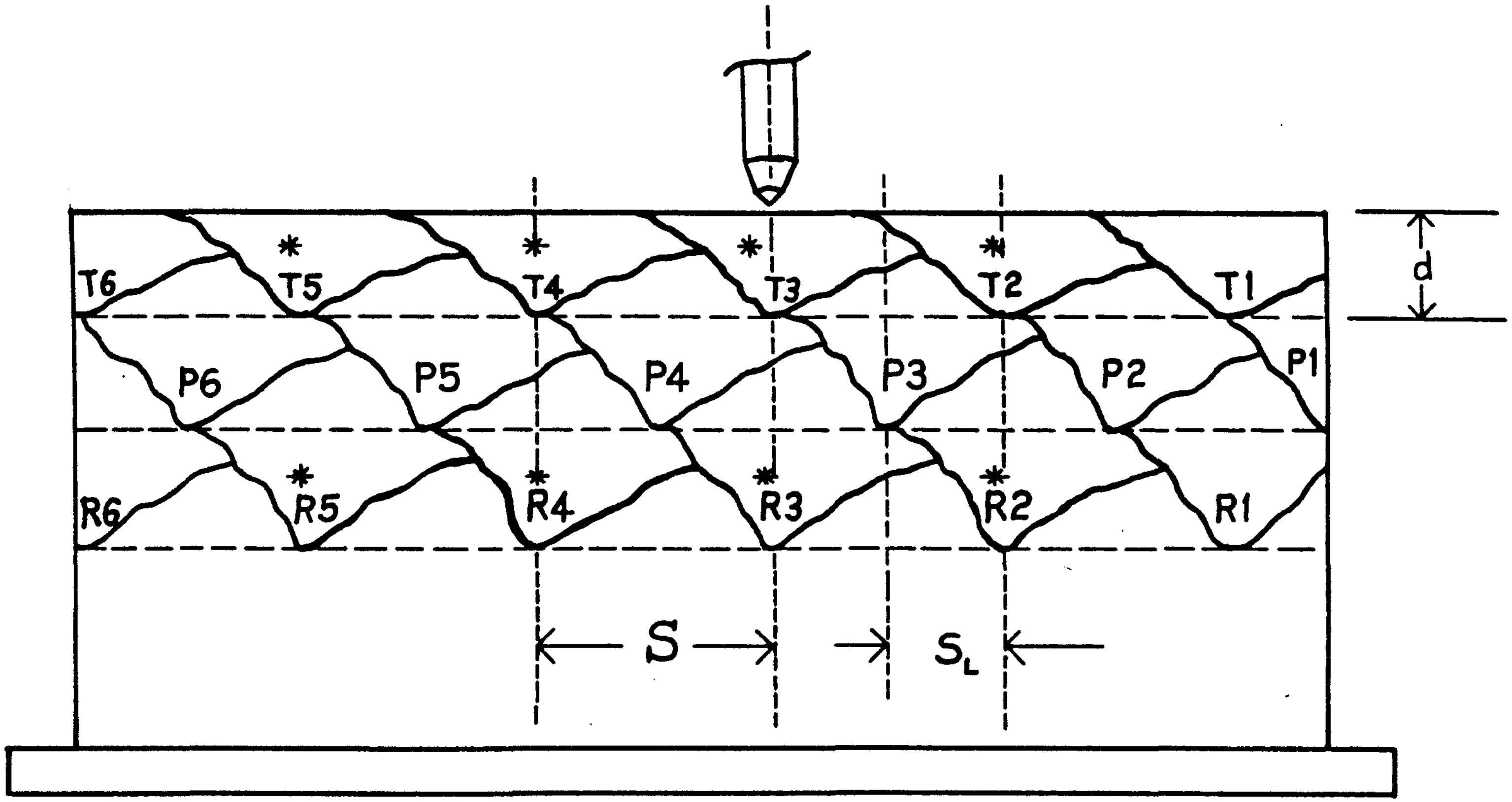


Fig. 26 Utilization of the cutting head of the shaping machine.

In a practical drum the value of β is unlikely to be zero. since the cutters are relatively staggered in this pattern and β is obviously determined by a drum with known dimensions. Initially β is assumed to be zero. A detailed investigation of β with the case of roadheaders is to be given in Chapter Eleven.

Figures 27 and 28 illustrate the way that the experiments were carried out. Initially, the rock block was trimmed and coated with paint so as to distinguish the stabilised cutting regime at which the practical machine constantly excavated the rock. It is, therefore, very important to note that with the exception of cutting carried out on trimmed surfaces, no recording of cutting forces was made until this stabilised cutting regime was reached. Generally the levels of preparatory cuts required two levels at lower S/d and while at higher values of S/d this was at least three levels. In all cases four replications of each cut condition was made.

The breakout angle of each groove was also measured after each cut by using a simple profile gauge. Since the groove shape is not uniform along the cutting direction, at least four different measures from representative parts were taken and the profiles were then traced on paper and analysed in a manner as shown in Figure 29. It should be noted that the values for the breakout angles presented in this section are approximate, as the method applied was simple.



T: Trimmed surface cuts P: Preparatory cuts

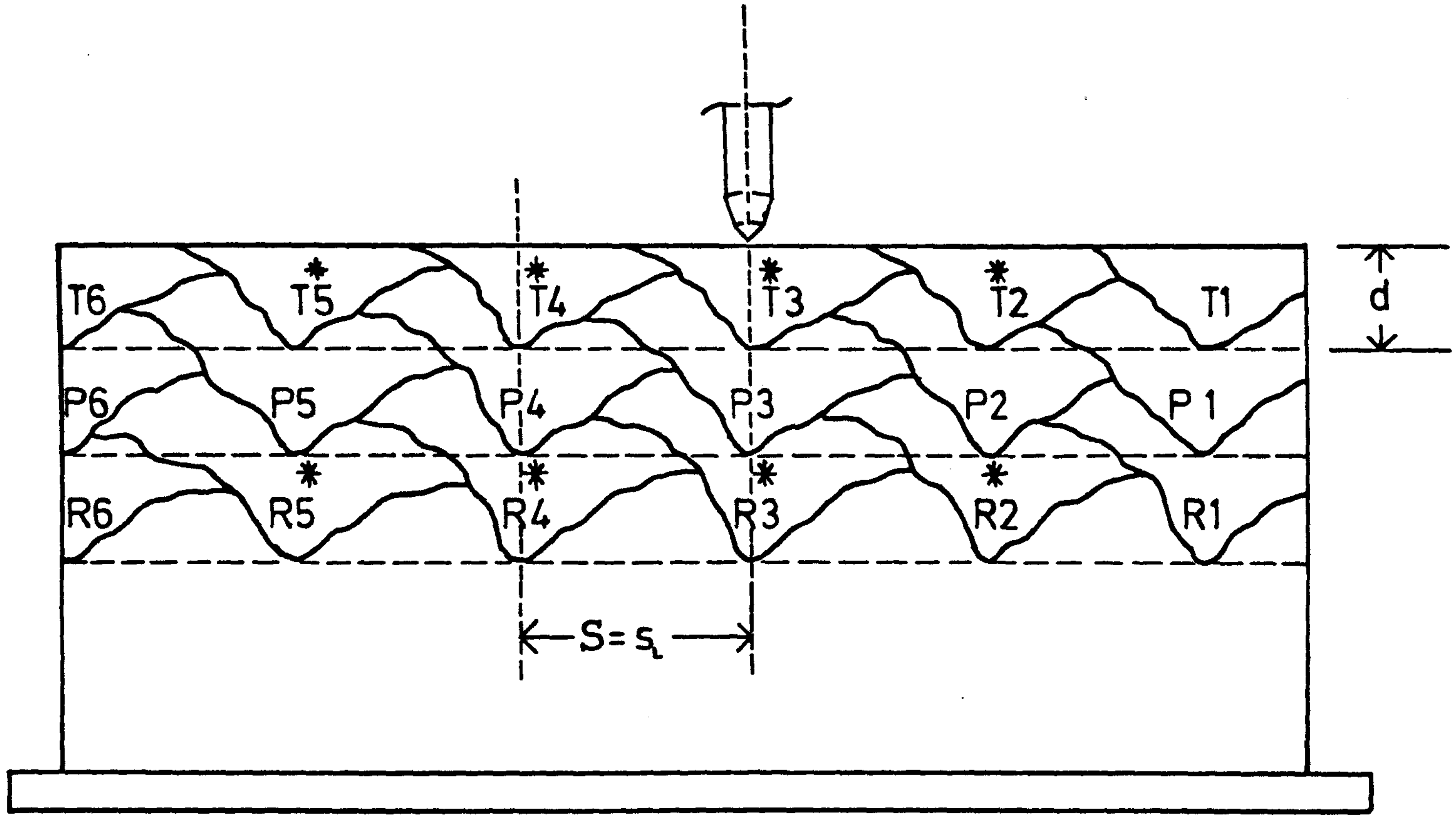
R: Representative cuts (When stabilized cutting regime was reached)

S: Cut spacing , s_L : Line spacing ($S_L = S/2$, one tool per line)

*: Instrumented cuts (Numbers indicate order of cutting)

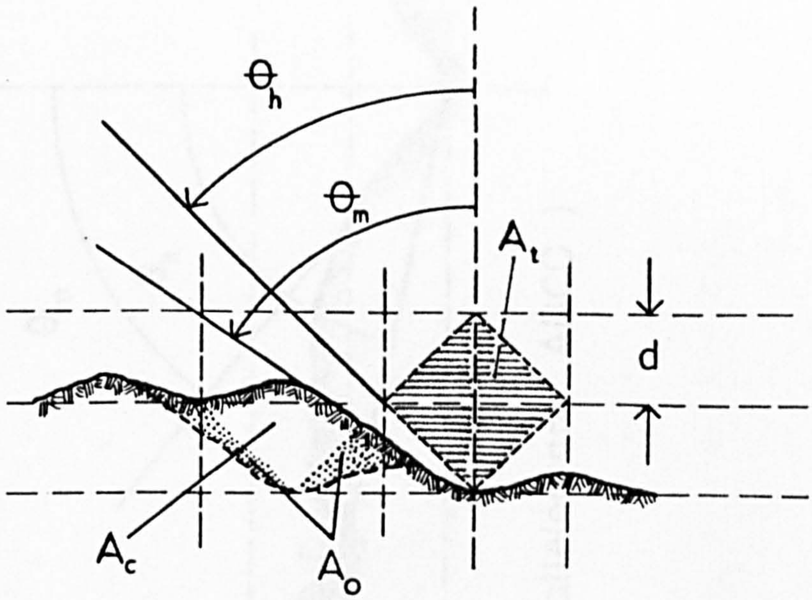
d: Depth of cut ((Advance / Revolution) / Number of starts)

Fig. 27 Notation of Relief Cut Experiments



$S = s_l$, Two tools per line

Fig. 28 Notation of Groove Deepening Experiments



θ_h : Hypothetical breakout angle

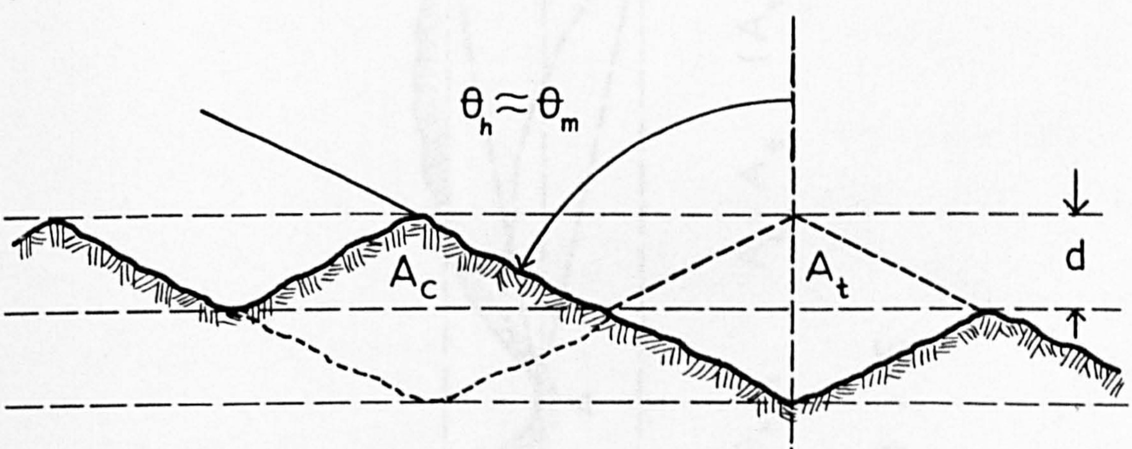
θ_m : Measured breakout angle, $\theta_m > \theta_h$

A_t : Theoretical cross-sectional area cut.

A_c : Cross-sectional cut area (Includes overlapping area), $A_c = A_t$

A_o : Overlapped area (Dotted area)

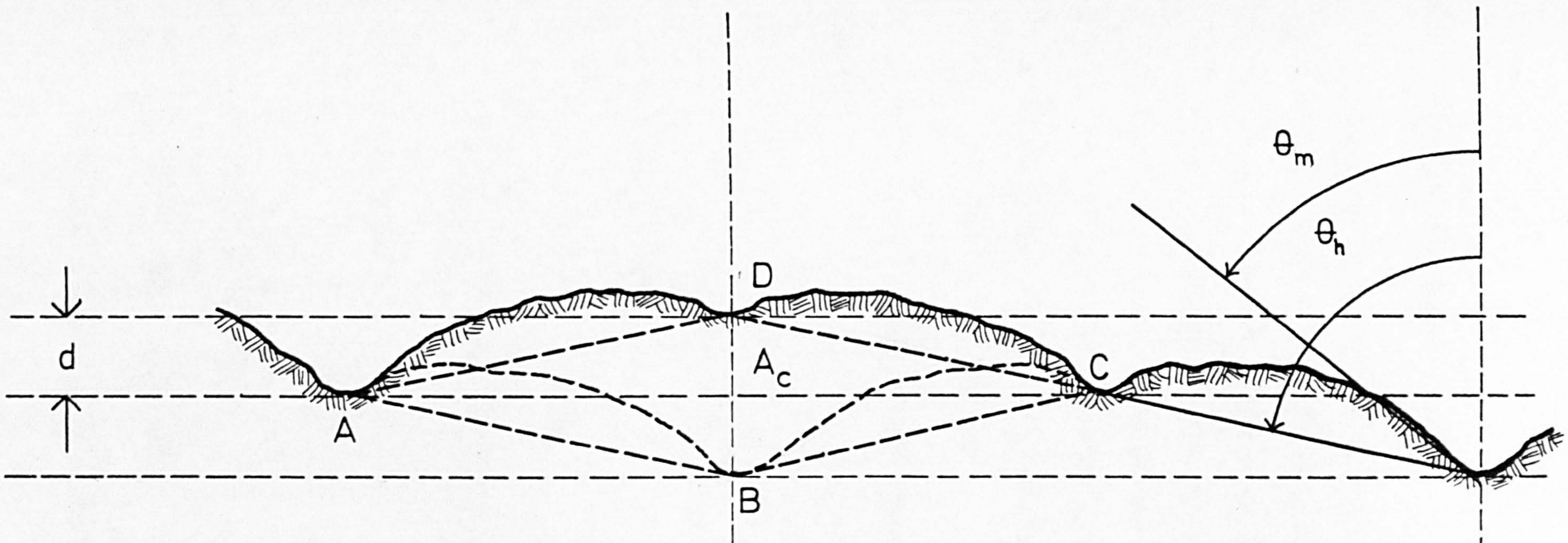
a) $s/d < 5$



$\theta_m \approx \theta_h$ $\quad A_c = A_t$

b) $s/d \approx 5$

Fig. 29 Breakouts Produced in Relief Cut Experiments



$\theta_m < \theta_h$, $A_c = A_t$ (A_t = The area of parallelogram ABCD)

c) s/d > 5

Fig. 29

8.4 Experimental Plan

The major variables were spacing, number of tools per line and tool type. Advance per revolution and cutting speed were constant and offset angle of point attack tools was zero. Due to the fact that in such simulated experiments higher forces are likely to be generated, the levels of the parameters to be investigated were limited. Thus a series of preliminary experiments were carried out and depth increments of 6mm, corresponding to an advance per revolution of 12mm, were found to be suitable.

The variable levels for the experimental programme are as follows:

Variable	Level	Description
Number of tools per line	2	One tool/line (S_L = S/2)
Cut spacing (S)	5	12mm, 24mm, 36mm, 48mm, 60mm.
Pick type	2	Radial tool, Point attack tool
Cutting mode	2	Trimmed surface trials Stabilised surface trials
Replications	4	
Rock	1	Springwell sandstone.

8.5 Presentation of Results

8.5.1 Experiments with radial tools

The results are tabulated in Appendices 4A1-4A3 and 4B1-4B3.

8.5.1.1 Trimmed Surface Results

On Forces

The forces varied with S/d in such a manner that they first increased gradually and then levelled out (Figures 30a and b).

On Yield

A gradual increase up to S/d of 4 and 6 was followed by a rapid decrease and levelled out (Figure 31).

On Specific Energy

Specific energy values showed gradual increase towards the high spacing values and then levelled out (Figure 31).

8.5.1.2 Effects of Relief Cuts (S_L = S/2 condition)

8.5.1.2.1 Forces

Forces tended to increase continually with increase in S/d ratios (Figures 30a and 30b).

8.5.1.2.2 Yield

Yield values increased linearly with S/d values. The cross-sectional area cut by a pick may be quantified as below:

$$A = S x d \qquad \ldots\ldots (8.2)$$

where A = cross-sectional area (m^2)

S = cut spacing (Figure 26)

d = (advance/rev) number of starts (m).

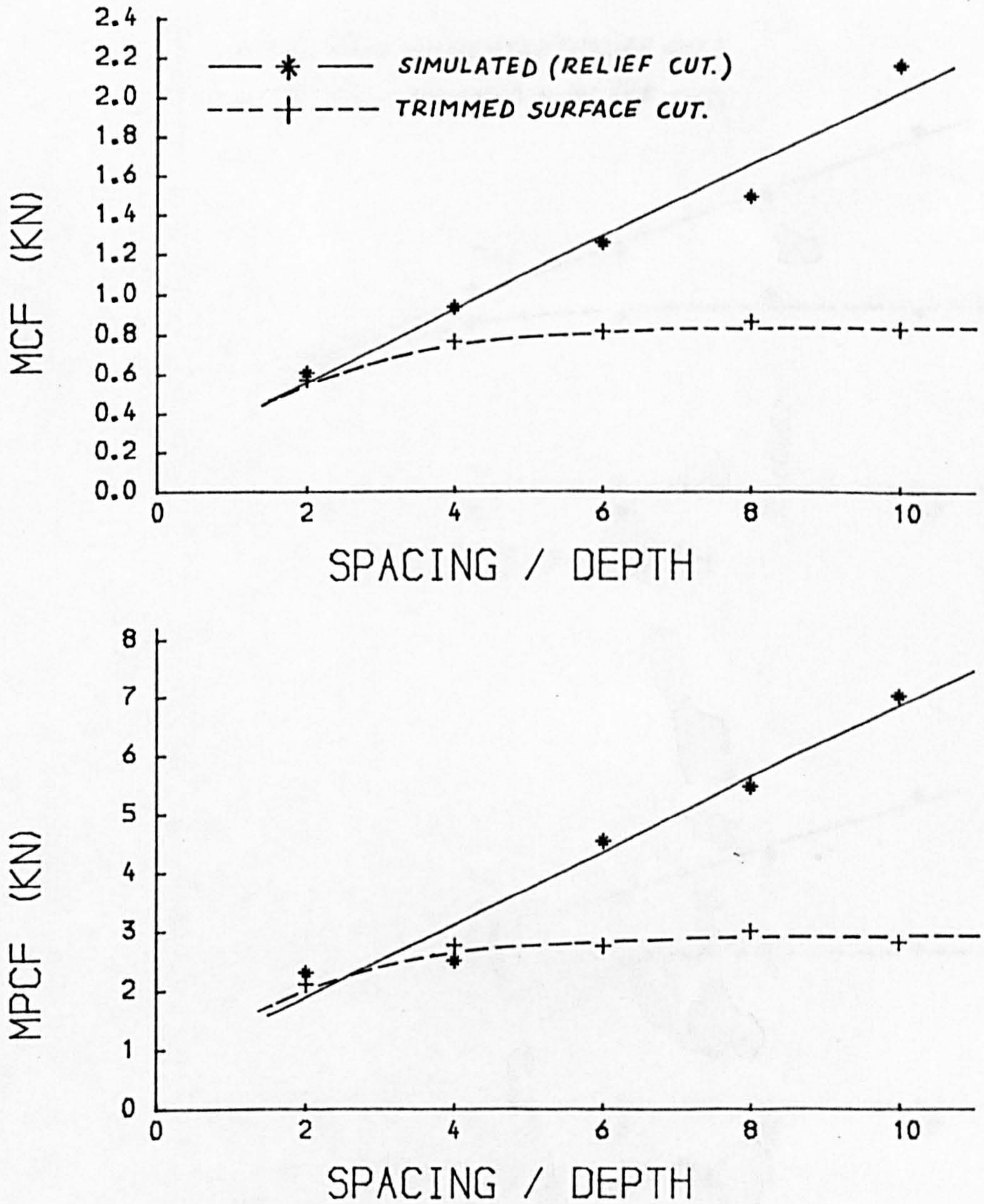


FIGURE 30a VARIATION OF CUTTING FORCES WITH S/D RATIO.
RADIAL TOOL, SIMULATED AND TRIMMED SURFACE CUTS

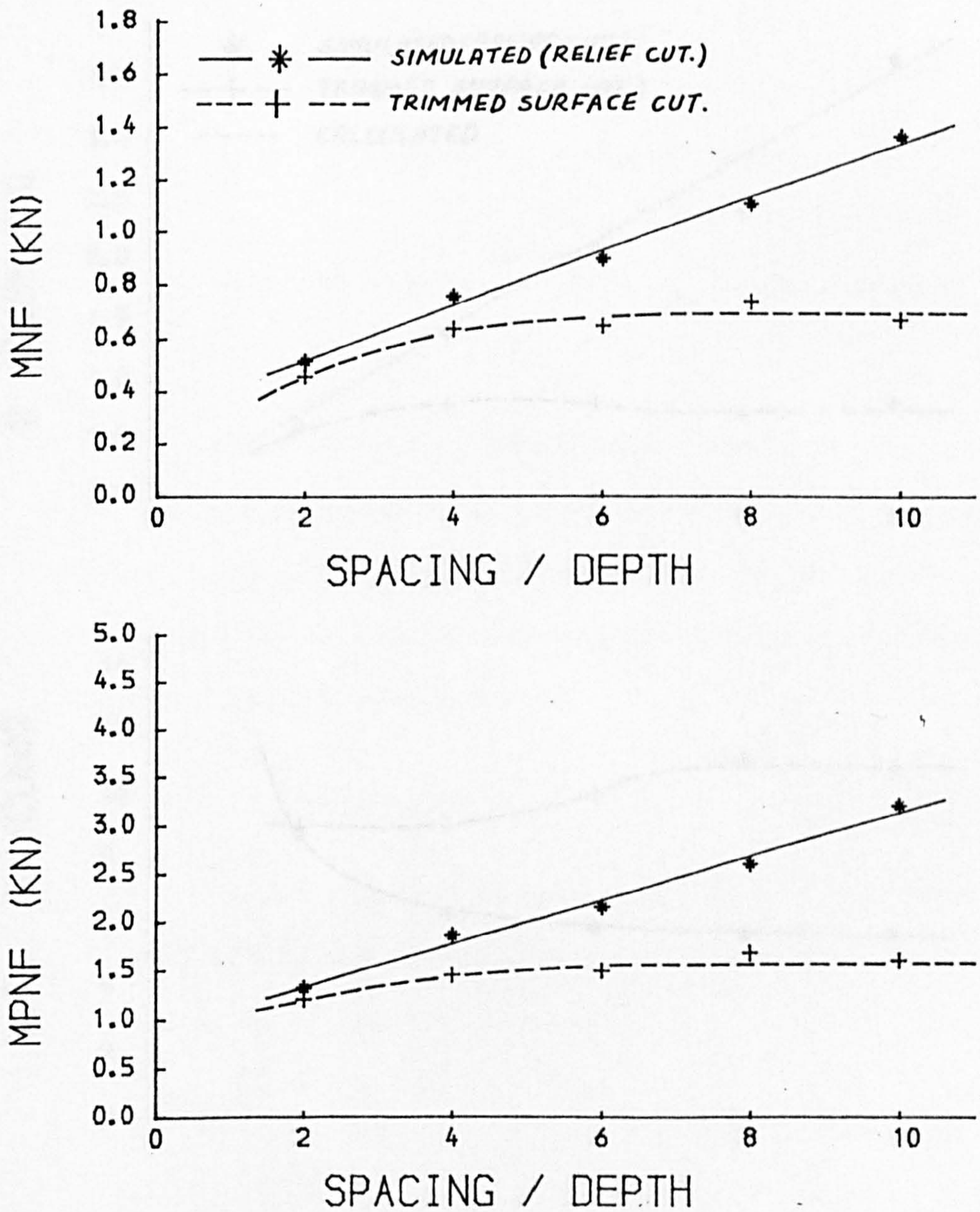


FIGURE.30b VARIATION OF NORMAL FORCES WITH S/D RATIO :
RADIAL TOOL, SIMULATED AND TRIMMED SURFACE CUTS

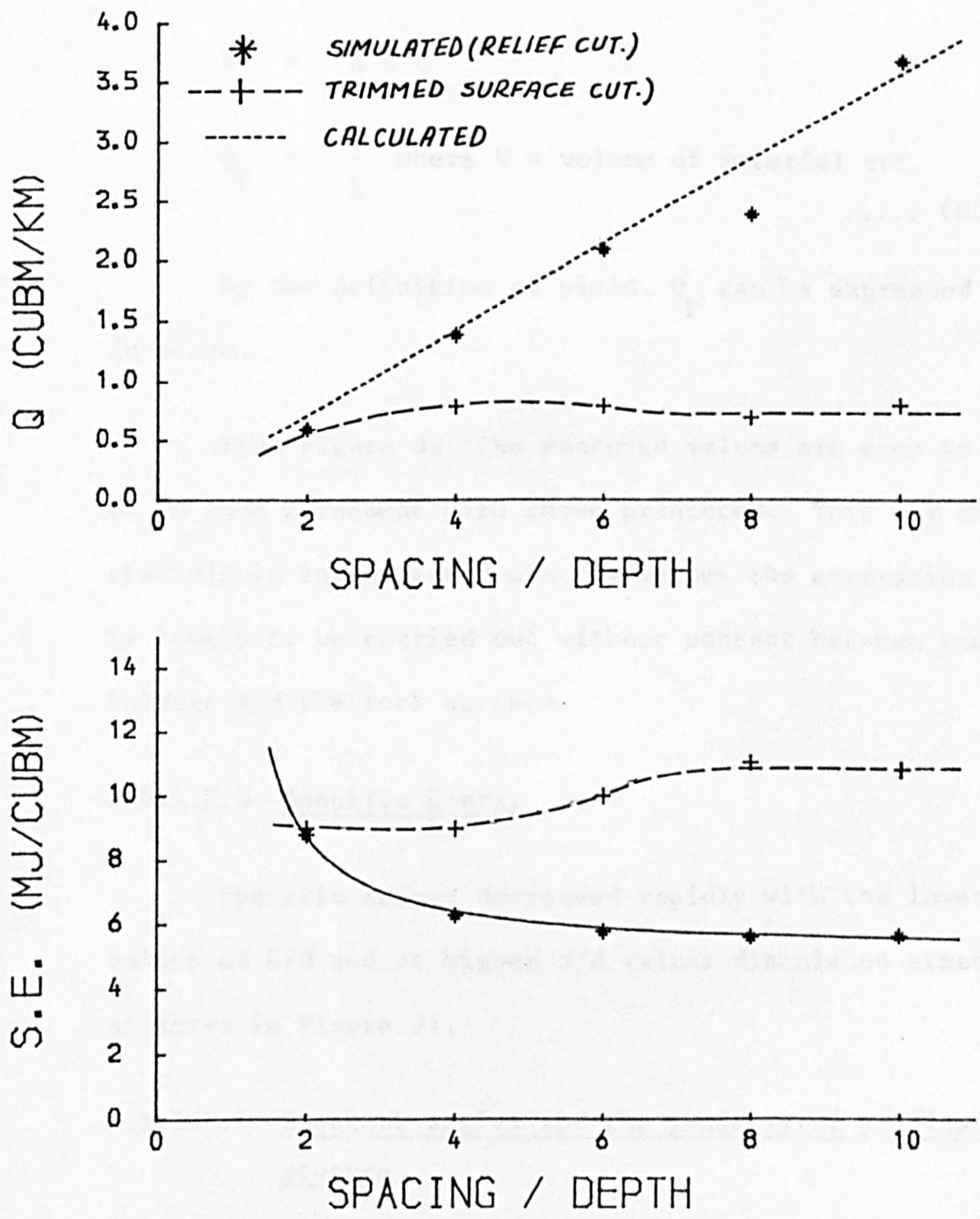


FIGURE. 31 VARIATION OF YIELD AND S.E. WITH S/D RATIO, RADIAL TOOL, SIMULATED AND TRIMMED SURFACE CUTS

For a given length (L) of a cut groove in a laboratory condition, a predicted yield equation can be developed thus:

$$V = A \times L$$

$$Q_p = \frac{V}{L} \text{ where } V = \text{volume of material cut.} \qquad \ldots\ldots (8.3)$$

By the definition of yield, Q_p can be expressed in m^3/km.

From Figure 31 the measured values are seen to be in good agreement with those predicted. This may indicate that within the measured spacing values the excavation process is likely to be carried out without contact between tool holders and the rock surface.

8.5.1.2.3 Specific Energy

Specific energy decreased rapidly with the lower values of S/d and at higher S/d values diminished steadily as shown in Figure 31.

8.5.1.2.4 Breakout angles and the geometry of profiled grooves

Breakout angles which were measured along grooves of equal line spacings varied with S/d values.

A hypothetical relation which proved to be useful to this concept was developed. At a certain spacing, if a pick is assumed to remove a ridge within the sectional cut area, the hypothetical breakout angle may be written as:

$$\theta_h = \tan^{-1}\left[\frac{S_L}{d}\right] \qquad \ldots\ldots (8.4)$$

where $S_L = S/2$

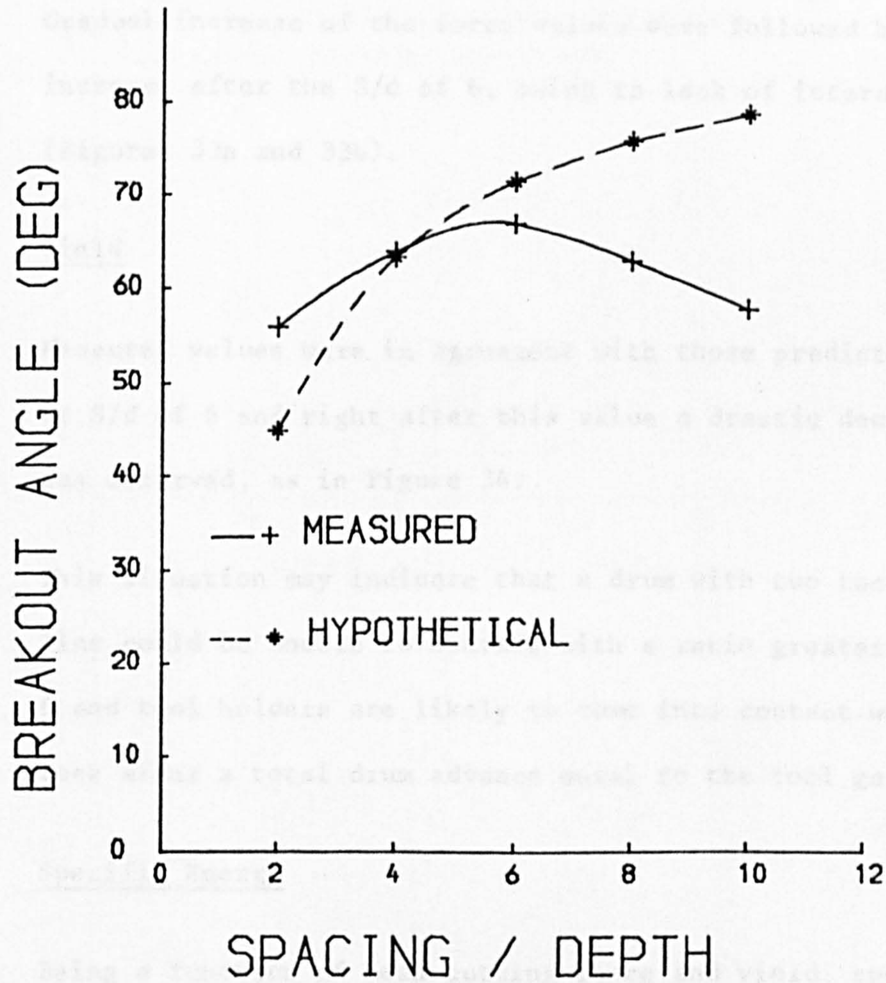
The hypothetical values of θ_h increased gradually with S/d whilst the measured values first increase and having reached a maximum, exhibit a rapid decrease. An intersection point tends to occur between S/d of 4 and 6 (Figure 32).

The observed cross-sectional profiles for the cut grooves are illustrated in Figure 29. At lower S/d values the profile geometry is approximately in the form of a regular 'V'-section. Towards the higher values of S/d these slopes become convex, as illustrated in Figure 29c.

8.5.1.5 Groove deepening cuts (S_L = S condition)

The measured variables included in this cutting mode were approximately similar to those obtained from the S_L = S/2 case, up to a spacing/depth ratio where no interaction between the grooves cut on trimmed surface occurred. As the parallel grooves ceased to interact, at S/d of 8, the cutting procedure developed into a rock coring state (Plate 25).

Plate 25



VARIATIONS OF BREAKOUT ANGLES, HYPOTHETICAL AND MEASURED VALUES, RADIAL TOOLS, RELIEF CUTS.

Fig. 32

The results are as follows:

Forces

Gradual increase of the force values were followed by a drastic increase after the S/d of 6, owing to lack of interaction (Figures 33a and 33b).

Yield

Measured values were in agreement with those predicted, up to S/d of 6 and right after this value a drastic decrease was observed, as in Figure 34.

This situation may indicate that a drum with two tools per line could be unable to operate with a ratio greater than 6 and tool holders are likely to come into contact with the rock after a total drum advance equal to the tool gauge.

Specific Energy

Being a function of mean cutting force and yield, specific energy showed a sharp increase after a gradual decrease (Figure 34). This is discussed later.

Breakout angles and groove profile

The values of the breakout angles and the shape of the grooves towards the higher values of S/d were observed to be noticably different from those previously obtained. The grooves appeared

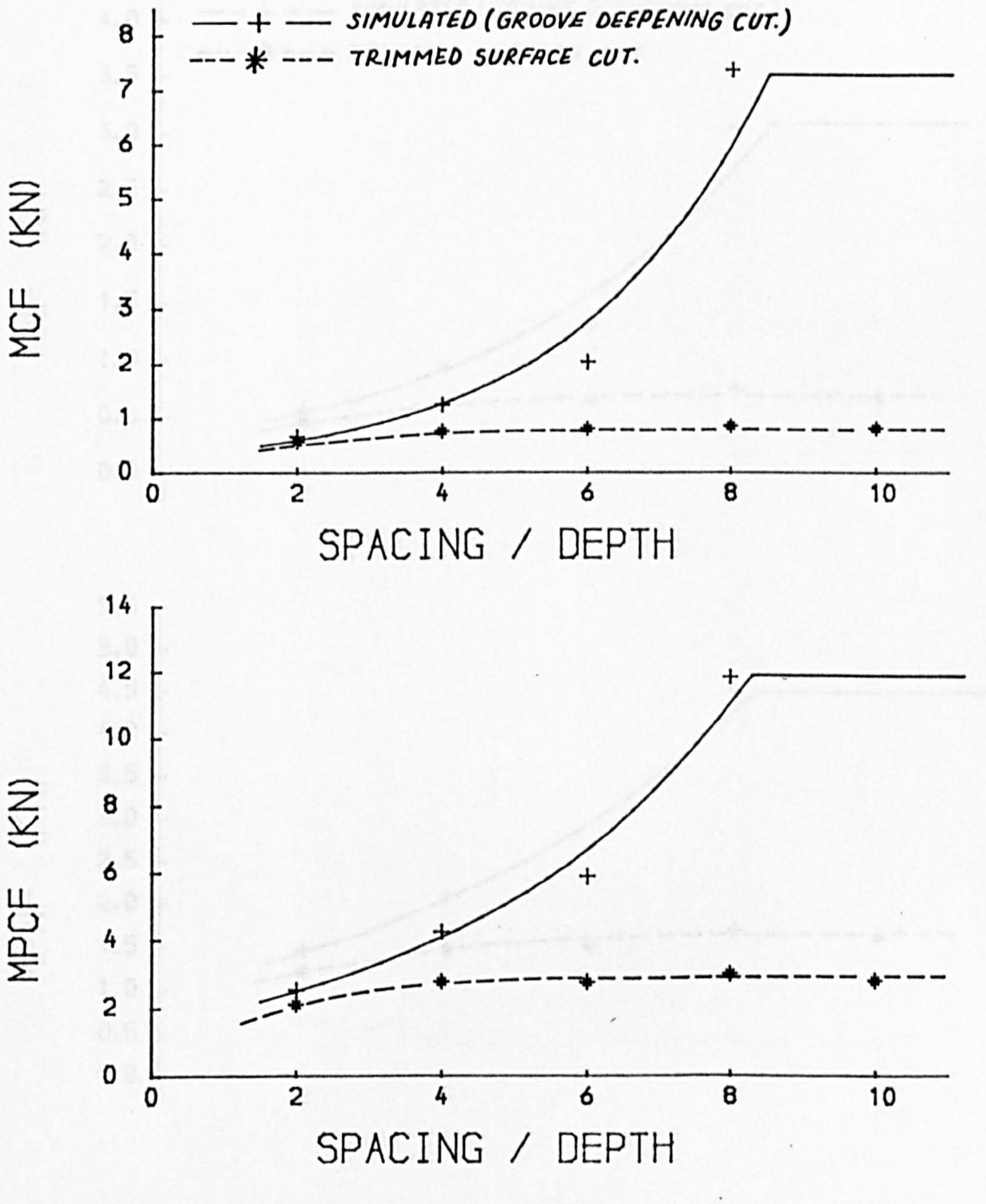


FIG.33a VARIATION OF CUTTING FORCES WITH S/D RATIO, RADIAL TOOL, SIMULATED AND TRIMMED SURFACE CUTS

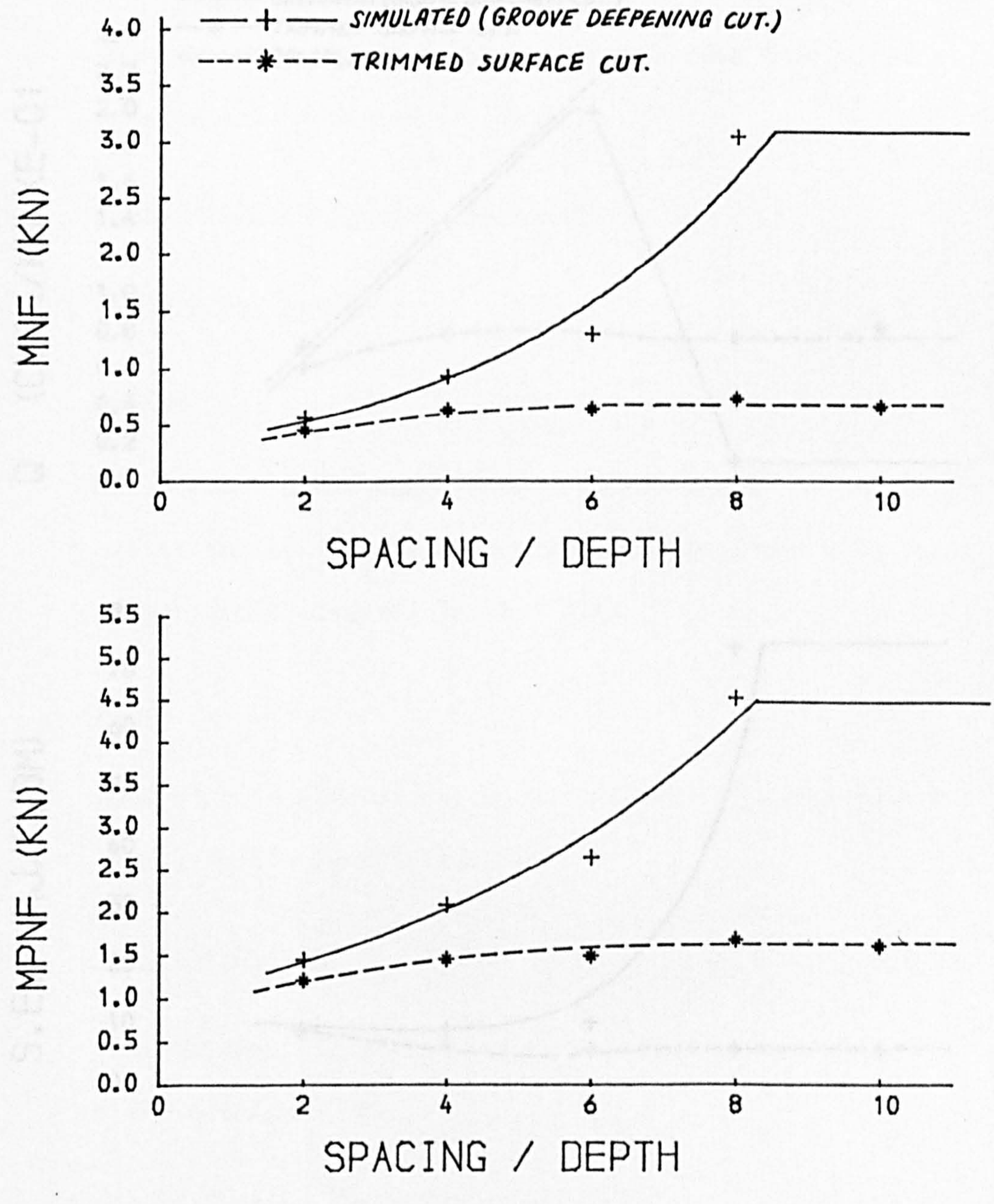


FIG. 33b VARIATION OF NORMAL FORCES WITH S/D RATIO, RADIAL TOOL, SIMULATED AND TRIMMED SURFACE CUTS

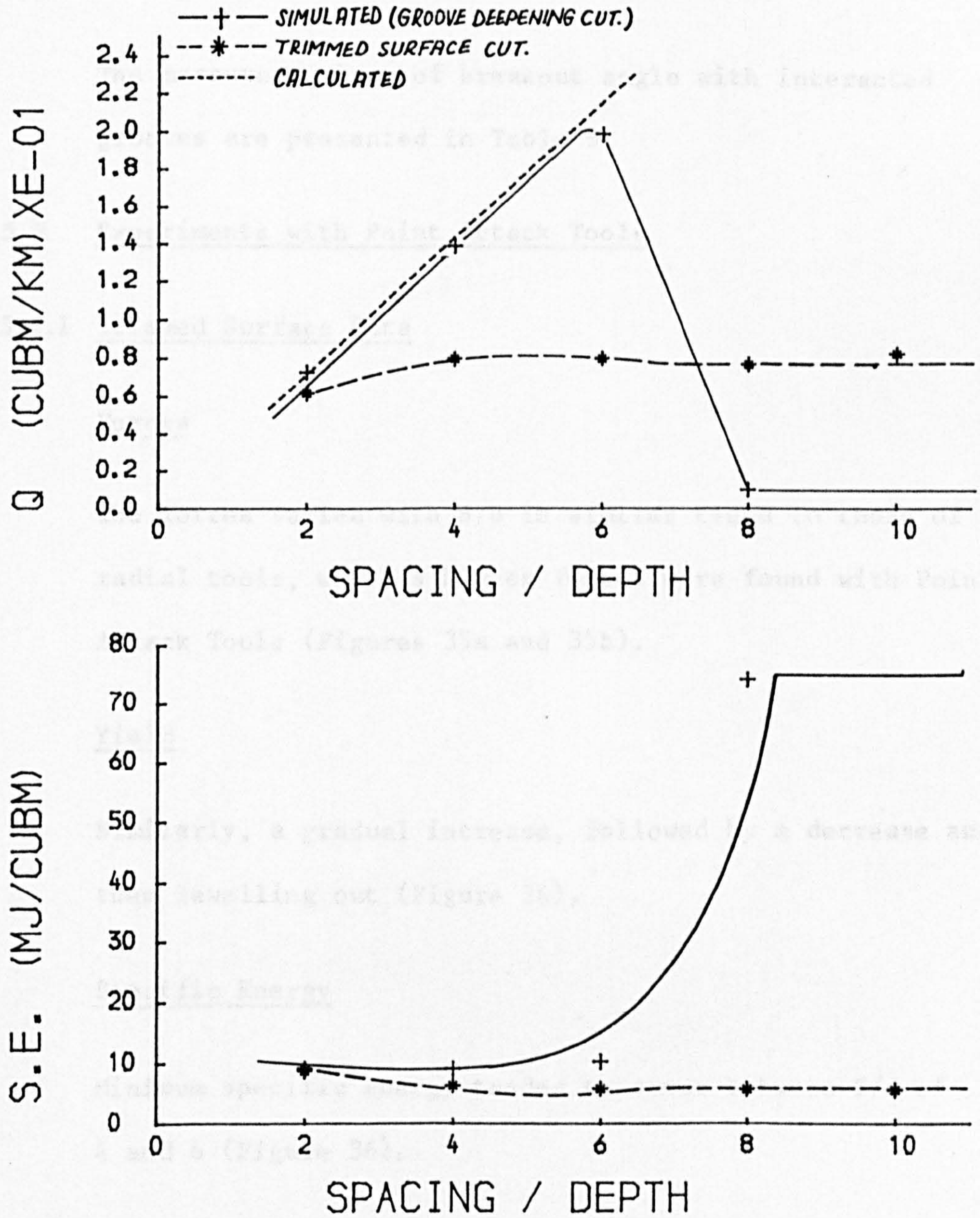


FIG. 34 VARIATION OF YIELD AND S.E. WITH S/D RATIO, RADIAL TOOL, SIMULATED AND TRIMMED SURFACE CUTS

to be more convex. At an S/d ratio of 8 the profile of the grooves was the same as the cutting tool tip due to over-deepening of the grooves with no interaction (Plate 25).

The measured values of breakout angle with interacted grooves are presented in Table 9.

8.5.2 Experiments with Point Attack Tools

8.5.2.1 Trimmed Surface Cuts

Forces

The forces varied with S/d in similar trend to those of radial tools, whereas higher forces were found with Point Attack Tools (Figures 35a and 35b).

Yield

Similarly, a gradual increase, followed by a decrease and then levelling out (Figure 36).

Specific Energy

Minimum specific energy tended to occur between S/d of 4 and 6 (Figure 36).

8.5.2 2 Relief Cutting (S_L = S/2 condition)

8.5.2.2.1 Forces

The values of the forces became higher as S/d increased; the forces showed higher magnitudes than in the radial tool experiments (Figures 35a and 35b).

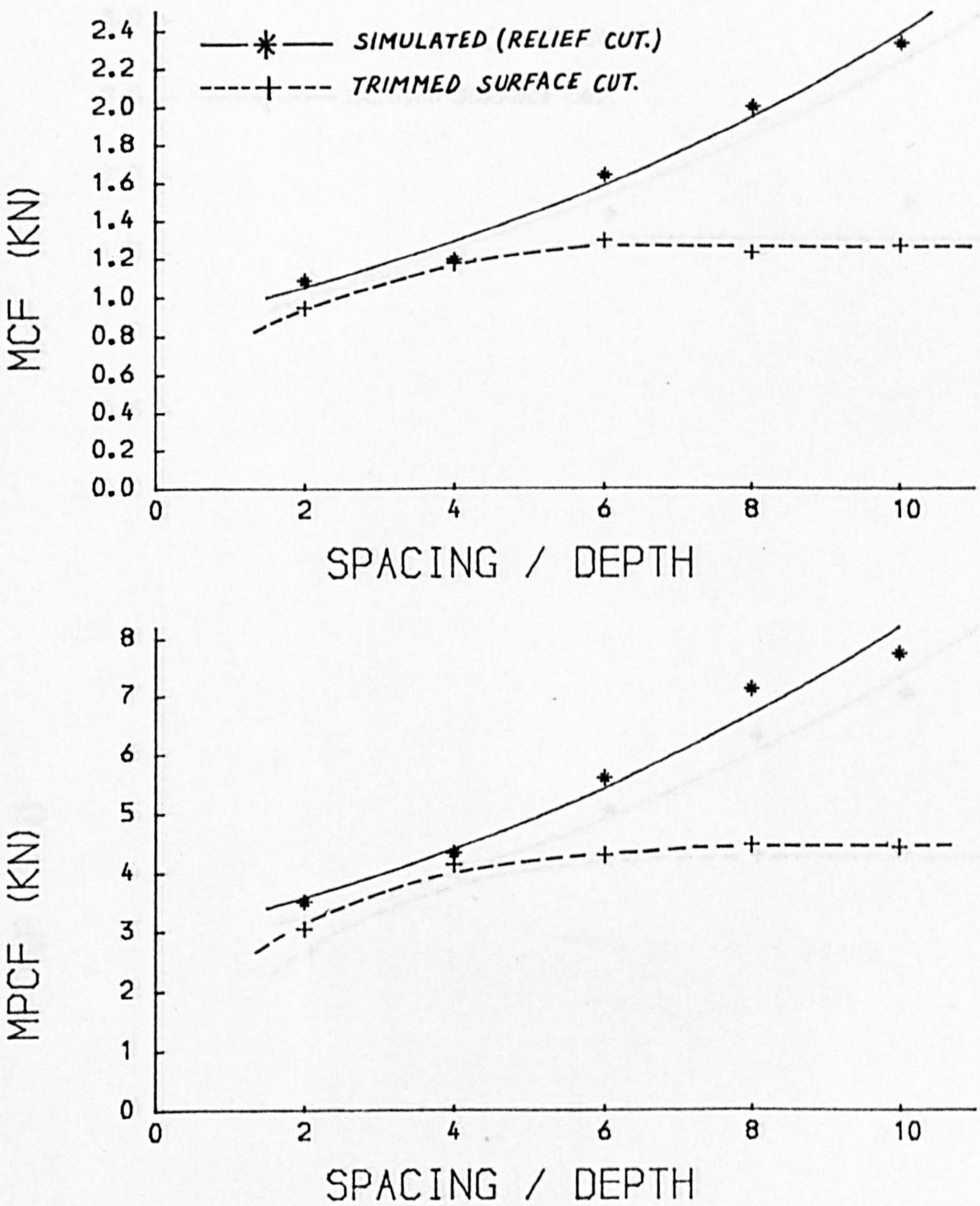


FIGURE. 35a VARIATION OF CUTTING FORCES WITH S/D RATIO. POINT ATTACK TOOL, SIMULATED AND TRIMMED SURFACE CUTS

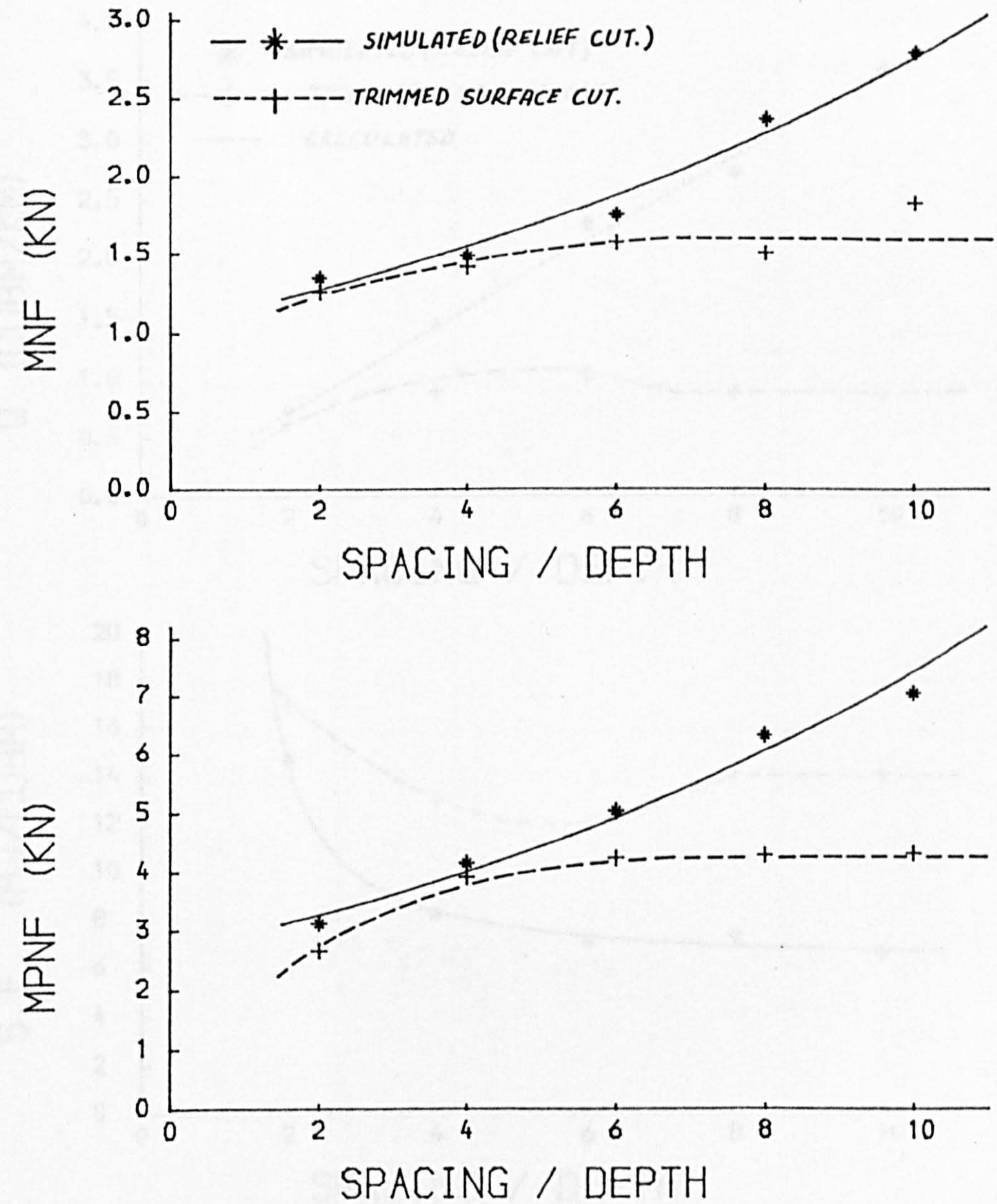


FIGURE. 35b VARIATION OF NORMAL FORCES WITH S/D RATIO, POINT ATTACK TOOL, SIMULATED AND TRIMMED SURFACE CUTS

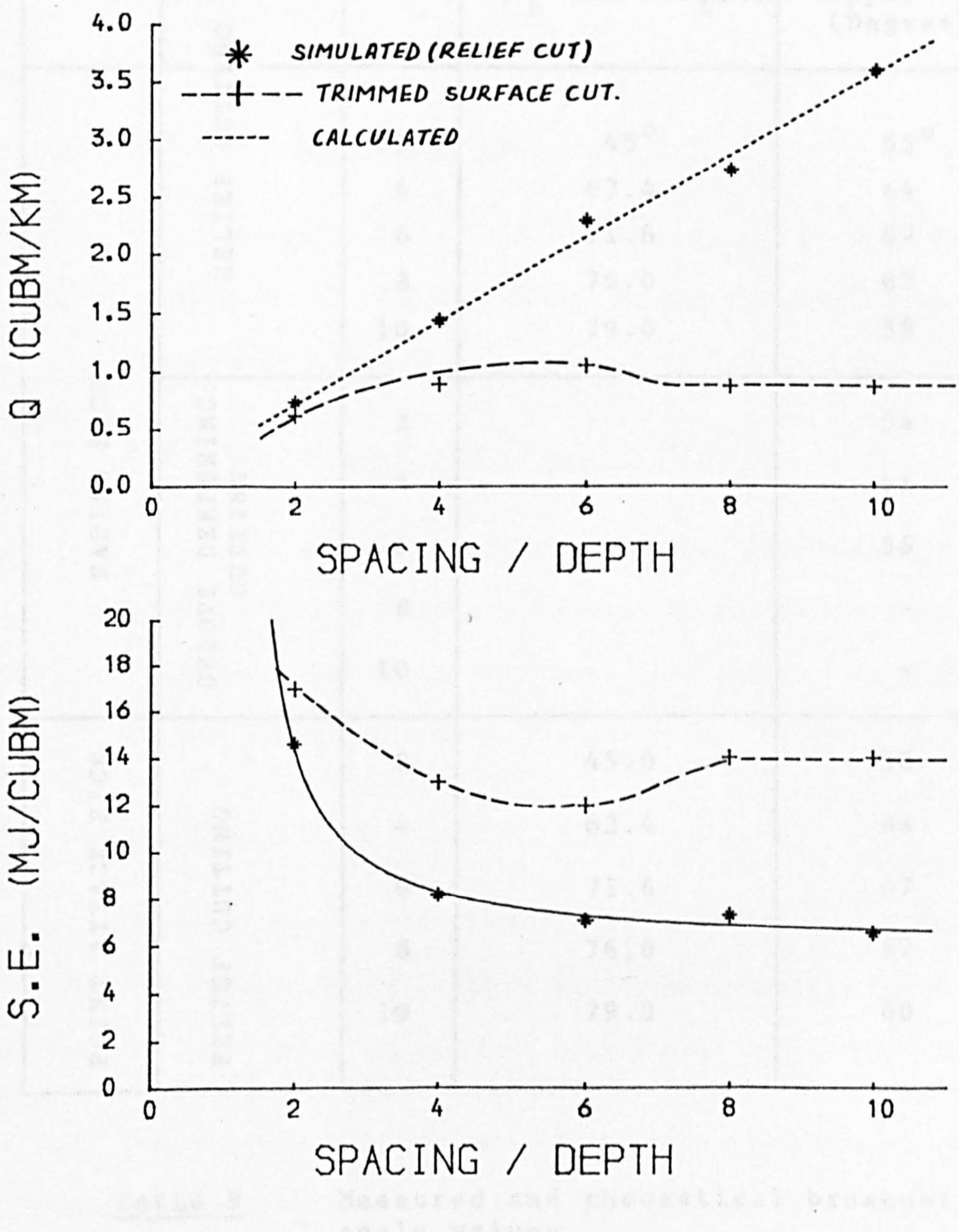


FIGURE. 36 VARIATION OF YIELD AND S.E. WITH S/D RATIO, POINT ATTACK TOOL, SIMULATED AND TRIMMED SURFACE CUTS

Tool Type	Cutting Mode	S/d	Hypothetical Values (deg.) $\theta_h = \tan^{-1}(S_L/d)$	Measured Values, approximately (Degree)
RADIAL PICK	RELIEF CUTTING	2	45°	55°
		4	63.4	64
		6	71.6	67
		8	76.0	63
		10	79.0	58
	GROOVE DEEPENING CUTTING	2		54
		4		61
		6		56
		8		-
		10		-
POINT ATTACK PICK	RELIEF CUTTING	2	45.0	58
		4	63.4	68
		6	71.6	67
		8	76.0	62
		10	79.0	60

TABLE 9   Measured and theoretical breakout angle values

8.5.2.2.2 Yield

The variation of the yield was in a linear form and the measured values were in good agreement with those predicted (Figure 36).

8.5.2.2.3 Specific Energy

Specific energy first decreased rapidly and after a value between S/d of 4 and 6, tended to show a slow decrease (Figure 36).

8.5.2.2.4 Breakout angles and profiles

The value of breakout angles was generally similar to that of radial tools and these are set out in Table 1. The profiles of the grooves were also varied in a similar manner, as illustrated in Figure 29.

8.5.2.3 Groove Deepening

Groove deepening experiments with Point Attack tools were found to be unsuitable due to the high forces generated and stalling of the shaping machine (as had been experienced in previous tests).

The experiments which were planned for point attack tools in the groove deepening mode were, therefore abandoned.

8.6 Discussion

8.6.1 Effects of cutting mode

Laboratory spacing experiments have repeatedly shown that the variation of such parameters as tool forces, rock yield and specific energy is due mainly to the state of interaction between adjacent grooves and a constant level is reached when no interaction takes place.

Experiments previously carried out at the University of Newcastle upon Tyne also showed that in a groove deepening cutting mode a constant level of force and yield values were obtained after a spacing where the grooves no longer interacted. The results of similar experiments presented in this research work confirm the findings of previous researchers (Hewit 1975). The constant level for the cutting parameters was attained for spacing values greater than 48mm at a 6mm depth of cut where at this point there was no significant interaction in both trimmed surface and groove deepening cutting trials. Hence cuts at any spacing greater than 48mm result in inefficient slot deepening.

This similarity is not present for the 'relief cutting' mode as the measured parameters continuously varied for spacings greater than 48mm. The main reason for this may be attributed to the nature of this cutting mode, being different from the groove deepening mode where the tool cuts midway between the tool grooves of the preceding sequence. Hence the position of the tip of the pick or the initial application point is closer to the free surface and less confined. Absence of interaction which occurs on a trimmed surface does not have an immediate effect on the progress of the cutting action up to a certain spacing level. This is probably due to the fact that successive cut increments create new grooves and thus prevent an occurrence of possible ridges which tend to isolate the grooves from each other, as is the situation in the groove deepening mode.

The continuous breakout of successive grooves will, however, be interrupted at some wider spacing and under these conditions, slot deepening mode will occur. Thus, although no interactions occur during the initial sequence on the flat prepared surface interaction will be experienced in the relieved cutting mode which more closely simulates field conditions.

For the above conditions the relieved cutting mode will form the basis of the discussions made throughout this work.

8.6.2 Effects of Tool Type

The relative merits of point attack and radial tools have been established by other investigators (15,66,70,89).

The measured breakout angles and geometry of groove profiles of each tool type exhibited no substantial differences and the values were found to be approximately similar; hence this may indicate that each tool follows similar trends when cutting a groove. However, forces were found to be higher in the case of point attack tools.

8.6.3 Optimum pick spacing

Considerations of optimum pick spacing have, so far, been defined on the criterion of cutting systems relevant to some practical conditions and the laboratory data required for these definitions are of cutting trials based on a flat rock surface.

In the laboratory, if the cutting action of a roadheader is simulated in such a way that each tool is cutting midway between the tools of a preceding sequence, as explained in previous sections, then specific energy achieves a wide range of efficient spacing values. As reported by Hurt and Evans (67), under these circumstances, a compromise must be provided between optimum cutting efficiency and the forces.

Unlike the yield, forces exhibit a continuous increase, particularly when cutting with point attack tools; thus the sharp decrease in specific energy tends to be rapidly converted into a slow decrease. The breakout angle and the geometry of each groove may also appear to contribute an insight to this nature of specific energy variation.

As illustrated in Figure 29, at lower spacings, the measured breakout angles being larger than hypothetical values, indicate that altitude of the relief to be cut is reduced and the effective cut area is overlapping neighbouring grooves in order to compensate the quantity of theoretical area. The geometry of cut grooves is in the form of approximately a regular 'V'-section. In this situation lower specific energy values may indicate that the tool excavates the rock material below its potential and this existing potential could well be utilised by taking some wider spacings. At the spacing between 24mm and 36mm, the breakout angle may correspond to that hypothetical angle without any overlapping. However, this is simply based on intuition and has not yet been substantiated by any experimental data.

It is interesting also to note that, at a spacing of 36mm, the breakout angle showed a slight change and at spacing values greater than 36mm the breakout angle was found to reduce. Under these conditions, specific energy began toshow a slight decrease, and the geometric profiles were altered in such a way that a convex profile was formed, as shown in Figures 29, 31, 36.

At moderate spacing (S/d ratios between 4 and 6) the groove profile was formed approximately along a line radiating from the tip of the pick towards the cut positions of the tools of the preceding sequence (Figure 29a). These straight profiles were, however, observed to change to a 'curved' shape at the higher spacing values (Figure 29c). This condition might be due to the increase of the spacing distance causing an upward breakout, creation of grooves with higher cross-sectional area, and low breakout angle, hence the successive tool may become more confined and so higher forces could be generated. Specific energy, regarding this phenomenon, tended to show a slow decrease somewhere between the spacings of 24 and 36mm (Figs. 31, 36) and after this spacing, the groove shape became more curved and the pick encountered larger sectional cut areas (Figure 29c).

From the above discussion, it is not beneficial to increase the spacing between the tools (in this case, wider than 36mm) since no significant decrease in specific energy occurs, and the forces at these levels are high and may be detrimental to the tools and machine components.

The tool spacing on a cutting drum physically determines the total number of tools that can fit on a given drum. Obviously, the wider the tool spacing the less number of tools that can be positioned on the drum. Important practical considerations are that for a wider tool spacing the greater the torque fluctuations and the magnitude of the torque changes.

In order to establish the relationship between the tool spacing torque and torque fluctuations, the experimental results may be applied to a simple shearer drum with arbitrarily chosen dimensions. The amount of material excavated per drum revolution was kept constant irrespective of tool spacing. The total number of tools was simply determined from dividing the drum width by tool spacing. The total number of tools calculated for an S/d of 10 (S = 6cm) was in the form of a fractional number for all drum widths chosen; hence this value of spacing was not considered. The results are presented in Table 10.

As can be seen from the table, specific energy decreases with increased S/d ratio, but the fluctuation in torque shown by the standard deviation for a complete revolution of the head increases with increased S/d ratio.

S/d	Total numbers of picks fitted	90° Cut Sector				180° Cut Sector			
		Mean Torque (kN)	Standard Deviation (Torque Fluctuation NM)	Volume of Cut material /(Adv./rev) (m^3)	Specific Energy (MJ/m^3)	Mean Torque (NM)	Deviation (Torque Fluctu-ation (NM)	Volume of Cut material /(Adv_3/rev) (m^3)	Specific Energy (MJ/m^3)
2	48	2.509	± 0.087	0.0010368	15.20	4.997	± 0.003	0.0020736	15.14
4	24	1.387	± 0.103	"	8.40	2.750	± 0.007	"	8.33
6	16	1.263	± 0.140	"	7.65	2.522	± 0.014	"	7.64
8	12	1.162	± 0.174	"	7.04	2.303	± 0.024	"	6.98

Drum dimensions = R = 0.30m W = 0.288m

Advance per revolution = 0.012m, Frequency = $sec.^{-1}$

TABLE 10 Evaluation of the linear cutting results on a simple shearer drum for kinematic and energetic purposes

8.7 Conclusions

(1) The measured parameters were dependent on spacing up to a certain level where no interaction between the adjacent grooves occurred; after this level a constant state was found to exist.

Groove deepening cuts were significantly affected by the absence of interaction on trimmed surface, whereas relief cuts showed no such dependencies for the measurable levels.

(2) Designing the tools on a cutting head with one tool per line is more beneficial and provides a wider range of efficient spacing values than that with two tools per line.

(3) Specific energy tends to show a slow decrease approximately after $S = 2d \tan\theta$ and in practice, an efficient excavation may not be obtained at a spacing wider than this value due to high fluctuations in torque and axle forces.

* * *

9. LABORATORY SIMULATION OF ROADHEADER CUTTING HEADS

9.1 Introduction

The use of a full-scale boom tunnelling machine is preferable to laboratory trials in an effort to develop the performance of roadheader cutting heads. However, when a specific aspect of a head design is to be investigated, laboratory simulation experiments may present certain advantages. For instance, there is no need to design a number of cutting heads with varying geometries and tool tilt angles. Furthermore, it may require less expensive cutting equipment and rock specimens. Finally, by establishing reasonable assumptions and relationships, data collected from the action of an individual pick may be used to provide an insight into the performance of the head investigated.

A detailed review of roadheaders and their corresponding cutting head design was given in Chapter Three. As mentioned, in practice, roadheader cutting heads can have a geometry which is conical, spherical and a combination of these two geometries. The cutting position of tools fitted on a head with one of these geometries may vary and this could possibly affect the duty of each cutter. The tool axis is also orientated according to the mode of operation of the roadheader.

All these explanations indicate that, in practice, roadheader cutting heads have standard design features.

As it was obviously impossible to simulate every different head design, the following considerations were borne in mind:

(1) The cutting head should bear some standard design features and provide investigations of their associated practical difficulties.

(2) As much data as possible should be obtained from experiments carried out due to the fact that this sort of laboratory experiment is time-consuming and very laborious.

Under these considerations the general specification of a head to be investigated may be determined.

9.2 Selection of a roadheader cutting head for laboratory simulation experiments

9.2.1 Determination of operational parameters

The effects of operational variables such as depth of cut taken by each tool and the lateral tool spacing have been studied in both the laboratory and field (Roxborough 1982; Hurt, McAndrew, 1981), whereas parameters such as head geometry, gauge tools and corner cutting tools have not yet been fully investigated. It was for this reason that experiments were concentrated particularly on the effects of changing the tilt of the tools and the cutting head geometry in the performance of roadheaders.

Advance/rev. and tool spacing were kept constant throughout the simulation experiments.

Due to the limitations of the experimental machine, the advance per revolution of the head was set at 12mm for small cutting heads. This would be, in practice, around 20mm (Hurt, 1980).

The value of S_L relied upon the results of previous experiments and it was decided that values of between S_L/d of 2 and 3 would be suitable.

The smaller S_L/d values would result in higher tool numbers and this is undesirable since more laboratory experiments would be required. The highest possible value of S_L/d of 3 (18mm) had to be chosen and it was thought that the differences between S_L/d of 2 and 3 would not substantially affect the scope of this investigation.

9.2.2 Disposition and cut positions of picks

A two-start array of tools was arranged in helical configuration on the head and an overlapping design was adopted with one tool per line. In each sequence, the cut starts from the machine side and progressively continues towards the nose. In practice, however, many cutting heads are designed to start from the nose towards the machine side, probably to satisfy the requirements for loading.

The tool axis was assumed to be perpendicular to the cone surface (for conical heads) or perpendicular to the tangent of the point where the tool is positioned (for spherical heads).

To avoid some complex cutting patterns, the angle of skew for the tool was taken to be zero.

9.2.3 Selection of the head geometry

As it was essential to obtain as much data as possible from a small number of simulation experiments, the geometry of the cutting head emerges as extremely important.

On a conical head, each tool is located at the same tilt angle equal to the cone angle of the cutting head; thus there are a number of cuts under the same conditions (i.e. successive cuts with a constant tilt angle).

A head with spherical geometry is more likely to be selected for a laboratory simulation roadheader cutting head trial. The experiments with the spherical head might possibly yield some results which can be related to aspects of cutting heads with conical and combined geometries.

9.2.4 The dimensions of the head

In practice there are numerous sizes of roadheader cutting heads available; the smallest head has a diameter of approximately 50cm (measured from the tip of the picks, for a Dosco MK2A type) (29).

The instrumented shaping machine allowed a maximum diameter of 44cm and beyond this size it was not possible to rotate the cutting head of the shaping machine to simulate tilt angles greater than 20^o. As the experiments were aimed at investigating tilt angles much greater than 20^o a maximum diameter of cutting head of 44cm had to be used.

9.2.5 Determination of total number of traversing and gauge picks

This was also one of the significant parameters to be considered since tool numbers influence the level of torque and torque fluctuations. Although the effect of pick numbers was investigated under a specific condition, in later chapters of this work, for the majority of the simulation experiments, the number of tools were kept constant in order to study various head models with the same number of tools.

The total number of picks fitted on a small head (for example on a Dosco MK2A type head is around 21 and 27 (Hurt, 29) including the number of sumping tools).

A head fitted with a total of 16 traversing and gauge tools of the point attack type was found to be suitable for the purposes of these investigations.

9.2.6 Aspects of sumping and loading

Sumping and loading duties which are an integral part of a cutting head's function could not be investigated within the scope of this experimental programme. A cutting head with helical tool arrays does provide a loading action by arranging the tool holders in spiral arrays around the head.

9.2.7 Mode of operation of the cutting head

The cutting head was assumed to traverse the face of the rock following a straight path normal to the axis of rotation, as illustrated in Figure 37. Laboratory simulation of roadheader cutting heads in the arcing mode of operation was found to be difficult to simulate since the roadheader cuts an arc of a circle which differs from a purely traversing action. However, this will be studied in further chapters.

9.3 Specification of the cutting heads for the simulation experiments

A total number of 9 cutting heads with different tilt angles were planned to be simulated and design characteristics were based on the principles explained so far.

Details of tool layouts are illustrated in Figure 38 and general specifications are also set out in Appendix 6A1.

Some common aspects may be as follows:

(a) Each head is fitted with a total of 16 point attack picks and the value of tilt angle of the last tool, together with the others, varies for each head.

(b) The line spacing which is half of the cut spacing (S) was kept constant around the cutting head periphery and corresponded to a sector area of 4.63^{o} for each head.

(c) The distance around the cutting head periphery between the first tool at the machine side and the last tool at the nose was assumed to be constant for all the

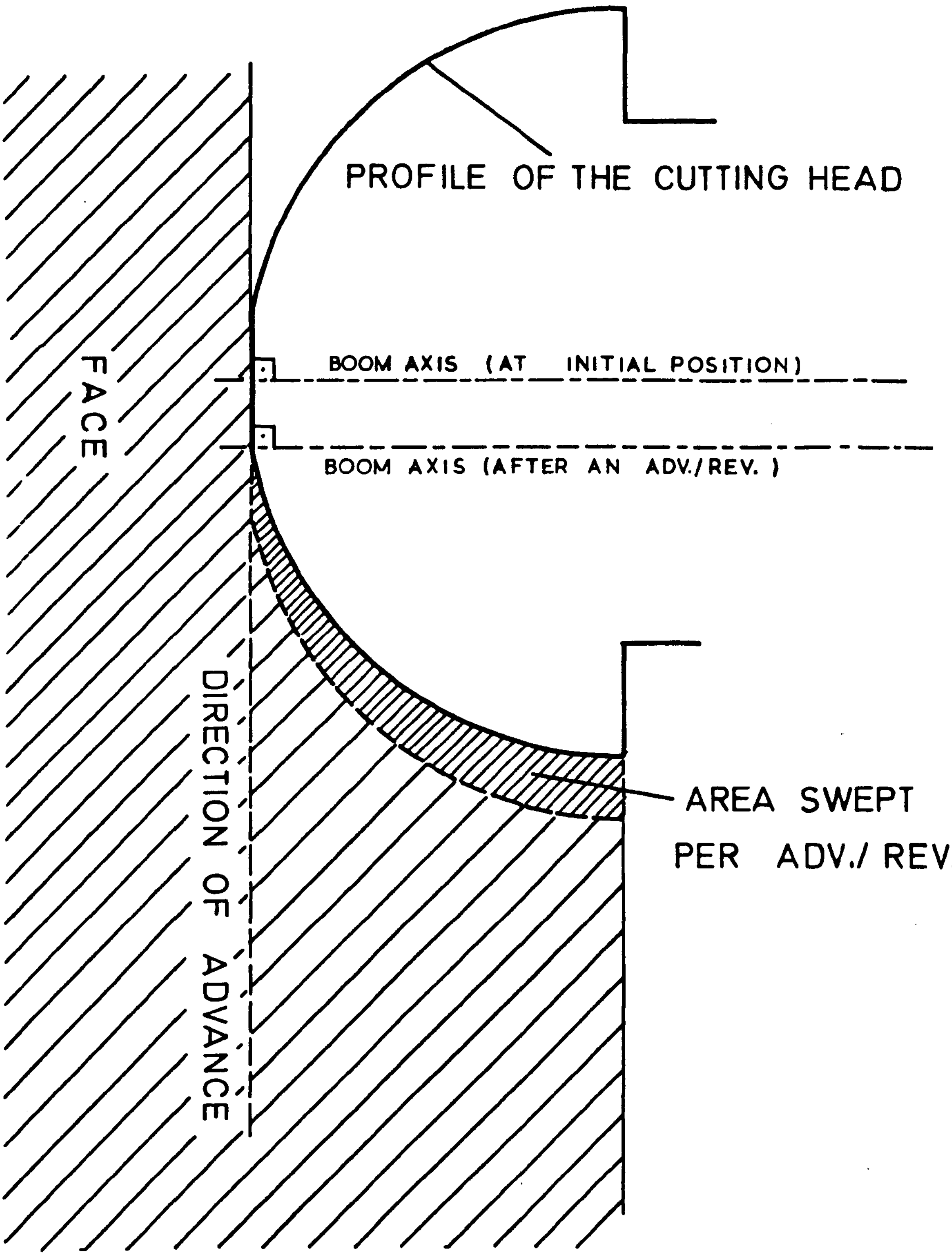
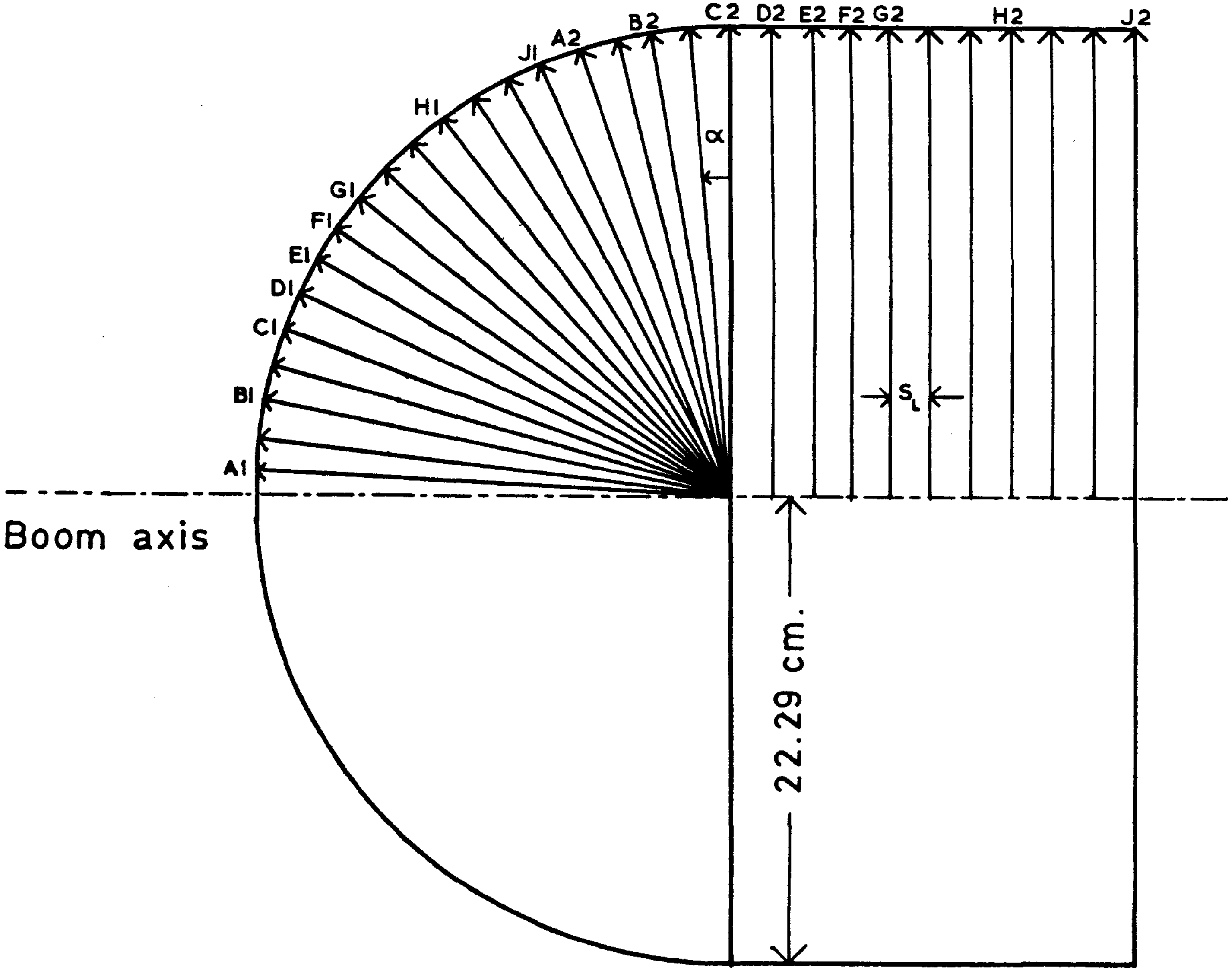


Fig. 37 Cutting Action of a Roadheader in Traversing Mode



CUTTING HEAD NO.	CUTTING HEAD PERIPHERY	
1	A1	A2
2	B1	B2
3	C1	C2
4	D1	D2
5	E1	E2
6	F1	F2
7	G1	G2
8	H1	H2
9	J1	J2

Cutting periphery which is given by '$s_L \times (n-1)$' is constant for the all heads.

The numbers in front of the letters refer to the pick cutting positions, e.g.
2 indicates the first tool,
1 shows the corner cutting (last) tool.

Fig. 38a Details of the Cutting Heads Investigated

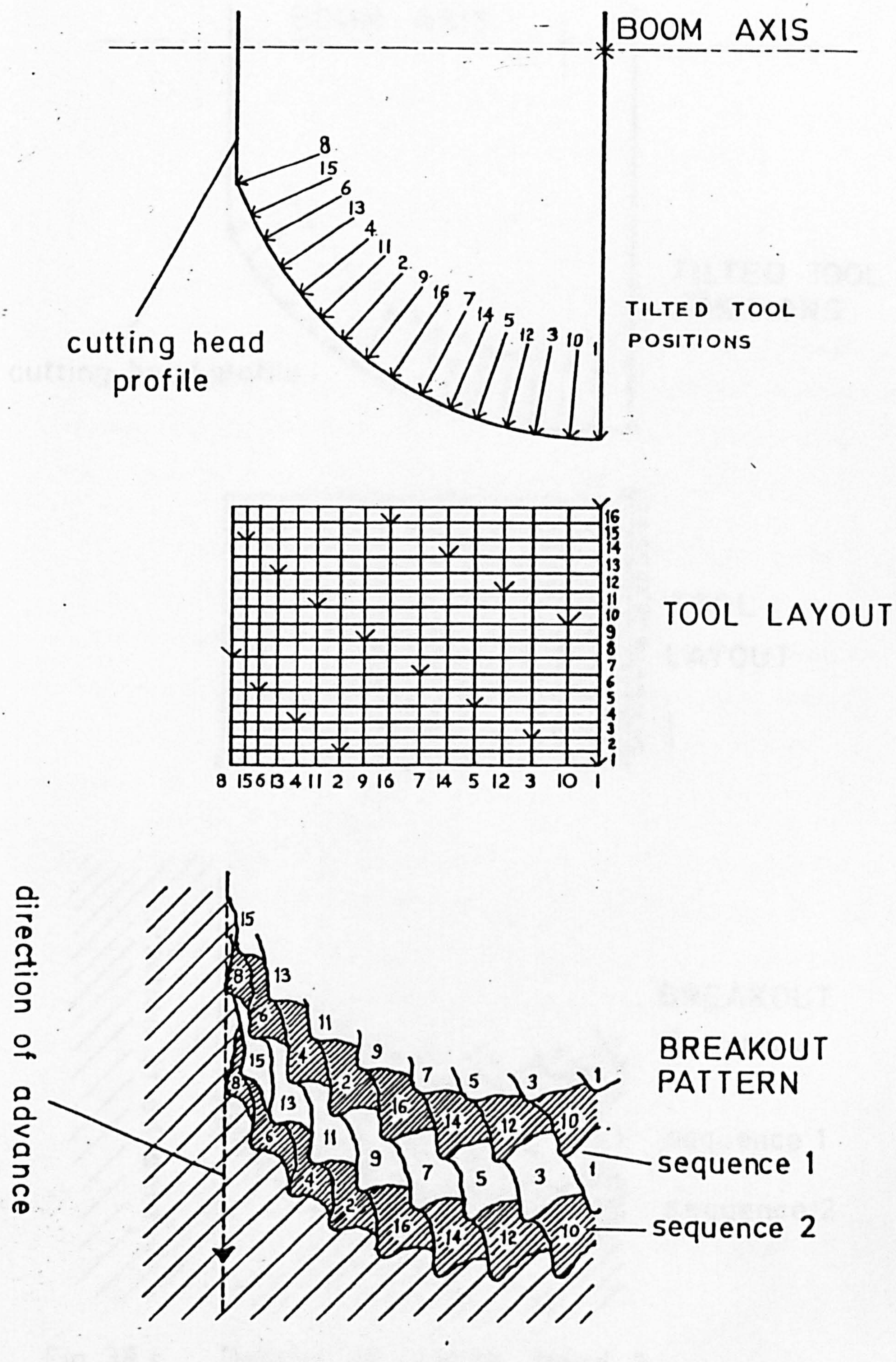


Fig. 38 b Details of Cutting Head 1

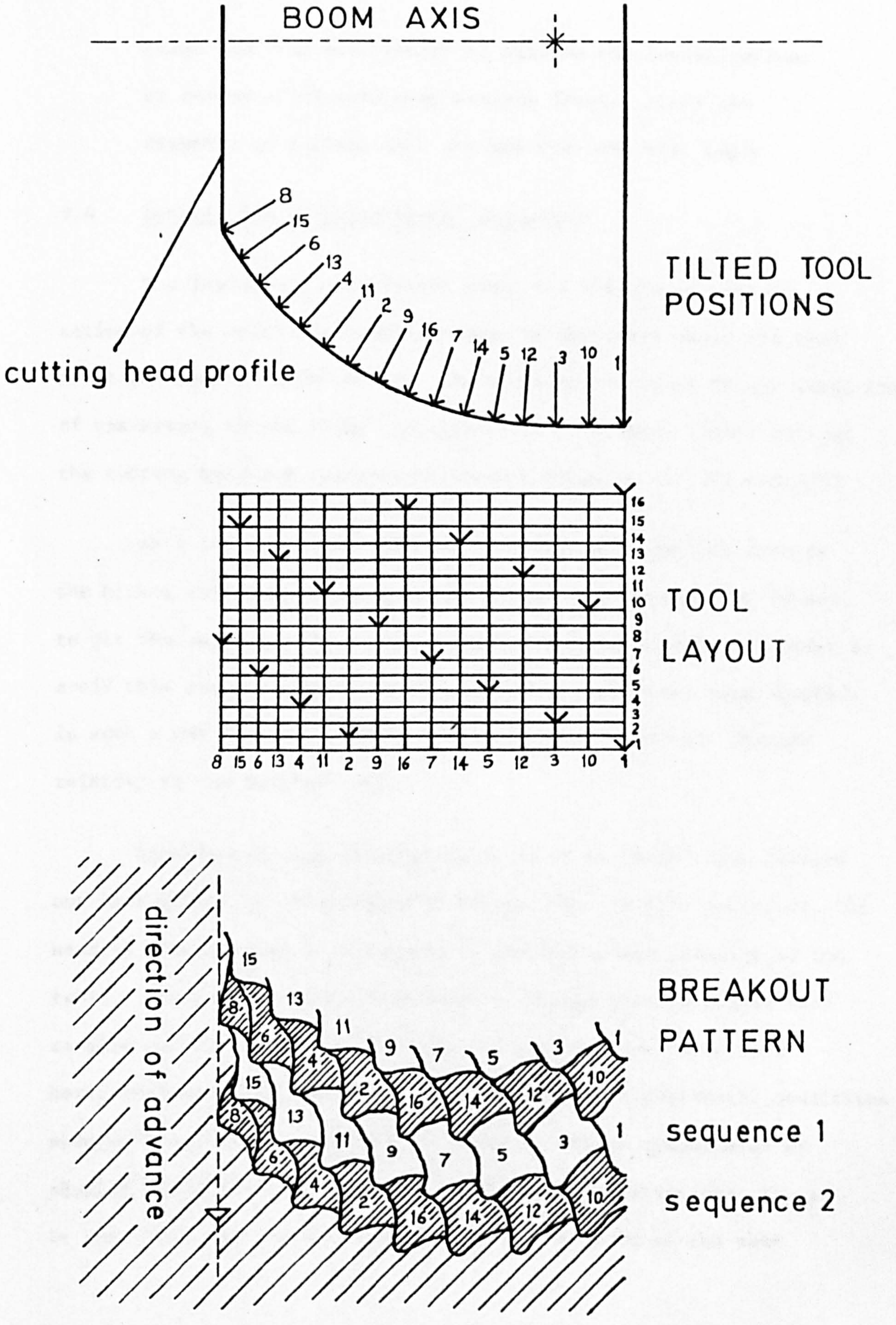


Fig. 38 c Details of Cutting Head 2

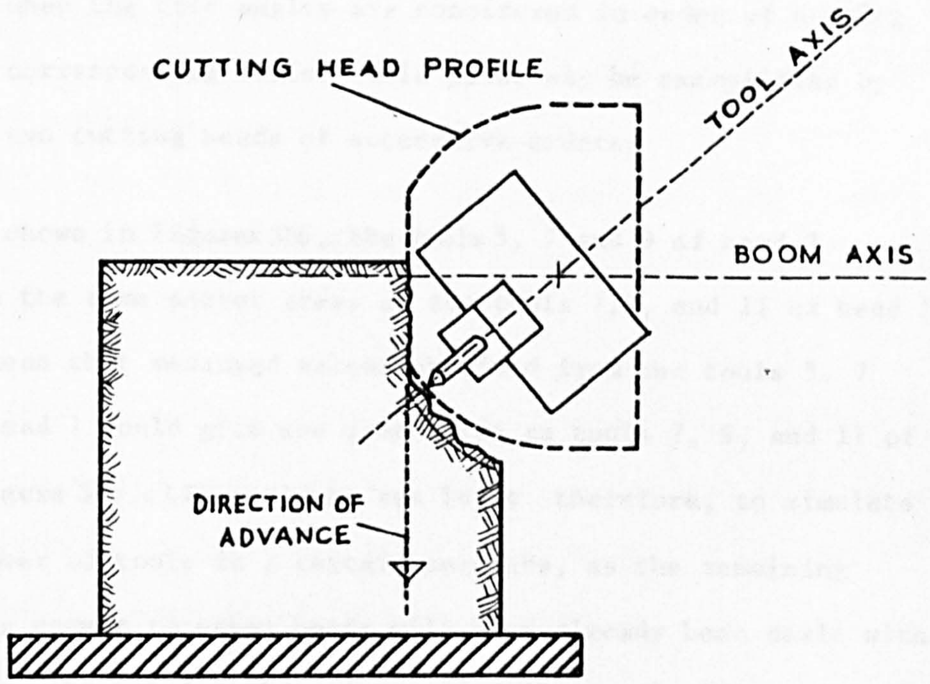
heads and this was thought to provide the investigations of torque fluctuations at various levels, since the diameter of a given tool changes with the tilt angle.

9.4 Description of experimental procedure

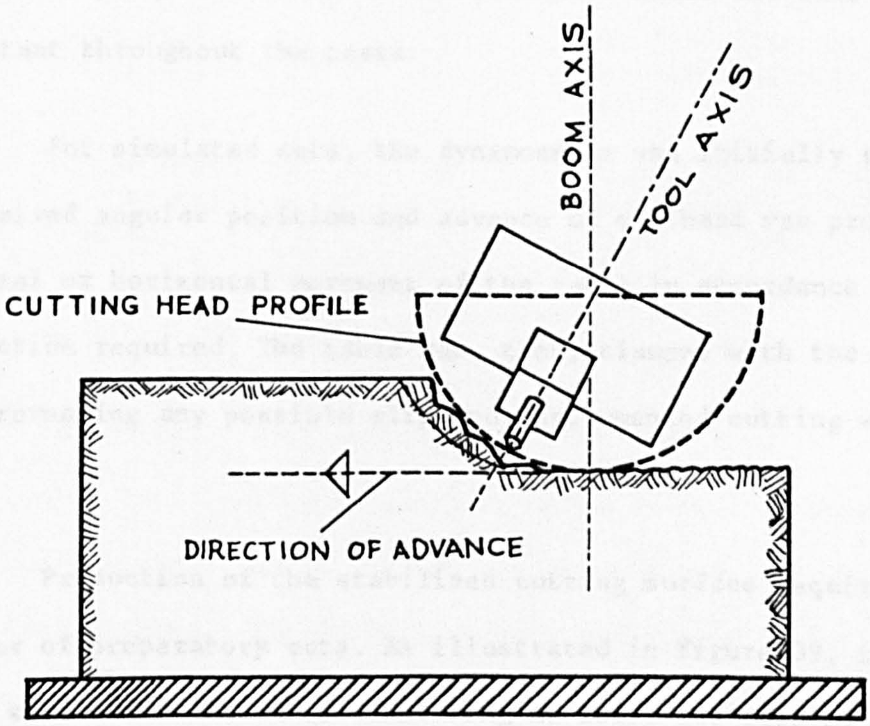
The laboratory experiments simulated the actual cutting action of the roadheader cutting heads at the point where the tool is at its maximum depth of cut. This situation occurs in the direction of traversing in the plane containing the rotational (boom) axis of the cutting head and the line of advance (Figures no. 39a and 39b).

As a result of some initial tentative observations towards the higher tilt angles, it was noticed that the dynamometer tended to hit the rock specimen together with the cutting tool. In order to avoid this problem two different simulation procedures were adopted, in such a way that the advance direction of the head was changed relative to the machine table.

Experiments with tilting angles of up to 50.90° were carried out in a manner as illustrated in Figure 39a. In this procedure, the head is simulated as it advanced on a vertical plane relative to the table. Simulations of cutting heads at higher tilting angles were carried out such that the direction of advance took place on a horizontal plane (Figure 39b). In this way the experimental conditions were safe and the possibility of damage to either dynamometer or shaping machine was unlikely. From the head illustrations, it can be seen that each cutting head includes some tools at the same



a) Tilt angle (α) ≤ 50°



b) Tilt angle (α) ≥ 50°

Fig. 39 Description of Laboratory Simulation Experiments positions when the tilt angles are considered in order of cutting action of corresponding tools. This point may be exemplified by comparing two cutting heads of successive orders.

As shown in Figures 38b,c the tools 5, 7 and 9 of head 1 operate in the same sector areas as the tools 7,9, and 11 of head 2. This may mean that measured values obtained from the tools 5, 7 and 9 of head 1 could give the same value as tools 7, 9, and 11 of head 2 (Figure 38b,c). It would be realistic, therefore, to simulate only a number of tools in a certain sequence, as the remaining tools being common to other heads will have already been dealt with. In this way, the total number of experiments was significantly reduced.

The radius resulting from the rotation of the entire dynamometer was exactly equal to that of the simulated heads and this was kept constant throughout the tests.

For simulated cuts, the dynamometer was initially brought to a desired angular position and advance of the head was provided by lateral or horizontal movement of the table in accordance with the direction required. The table was, then, clamped with the intention of preventing any possible slip and instrumented cutting was carried out.

Production of the stabilised cutting surface required a high number of preparatory cuts. As illustrated in Figure 39, instrumented cuts were commenced after completing at least two cutting sequences which required all gauge and corner tools.

9.5 Experimental plan

The predominant variable between different cutting heads was the tilt angle. This alone may cause variation in the level of forces on each tool, thus changing the diameter of the heads which, in turn, influences the torque and torque fluctuations.

In order to differentiate between tool positions, the last pick at the nose will be referred to as 'corner cutting tool' (since it always operates in the corner) and the remainder of the tilted picks termed as 'gauge tools' for convenience.

The planned experimental variables are as follows:

Variable	Level	Description
Gauge tool position (degree)	5	The last five tools at the nose for each cutting head.
Corner cutting tool positions (degree)	9	23.14°, 37.02°, 50.90°, 55.53°, 60.16°, 64.79°, 69.42°, 78.68°, 87.94°.
Replications	4	

The actual number of gauge tools on each head is 16, but due to some common tool positions for all the heads at least eight tools were actively included in cutting experiments and only six of these were instrumented. The details of each pick position included in the heads are presented in Appendix 6A1.

It should be noted that hundreds of unrecorded preparatory cuts were required for these experiments.

9.6 Results of the experiments (tabulated in Appendices 5A1,5A2,5B1)

9.6.1 Effects of tilt angles on forces

Forces decreased as the tilt angle increased in both gauge and corner cutting tools (Figures 40-43).

The forces tended to diminish first slowly and later showed a rapid decrease.

The influence of tilting was small up to 40° then a rapid decrease in forces was noted (due to the smaller amount of rock removed).

The trend for corner cutting conditions was different. The sharp decrease in forces at low tilt angles continued and the value of gauge tools at an angle between 60° and 70° coincided and, after this point, it tended to behave as a gauge tool.

9.6.2 Effects of the tilt angles on yield

The yield values decreased with the tilt angles in a manner as shown in Figure 44.

With a similar trend to the forces, the yield diminished slowly at first and towards higher tilt angle values they decreased rapidly. In corner cutting the yield initially increased and then decreased in a similar manner to the gauge tools.

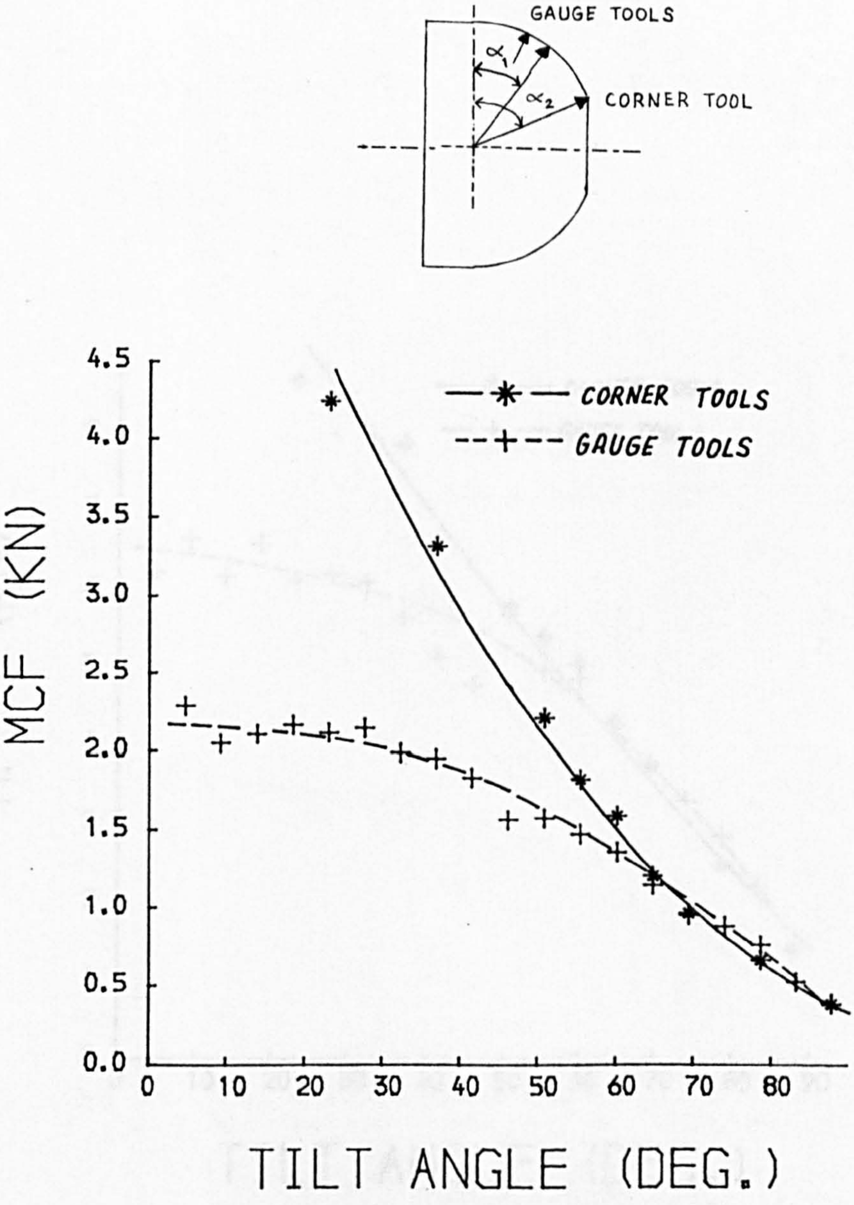


FIG.40 VARIATION OF MEAN CUTTING FORCE WITH TILT ANGLE ,TOTAL PICK NO:16.

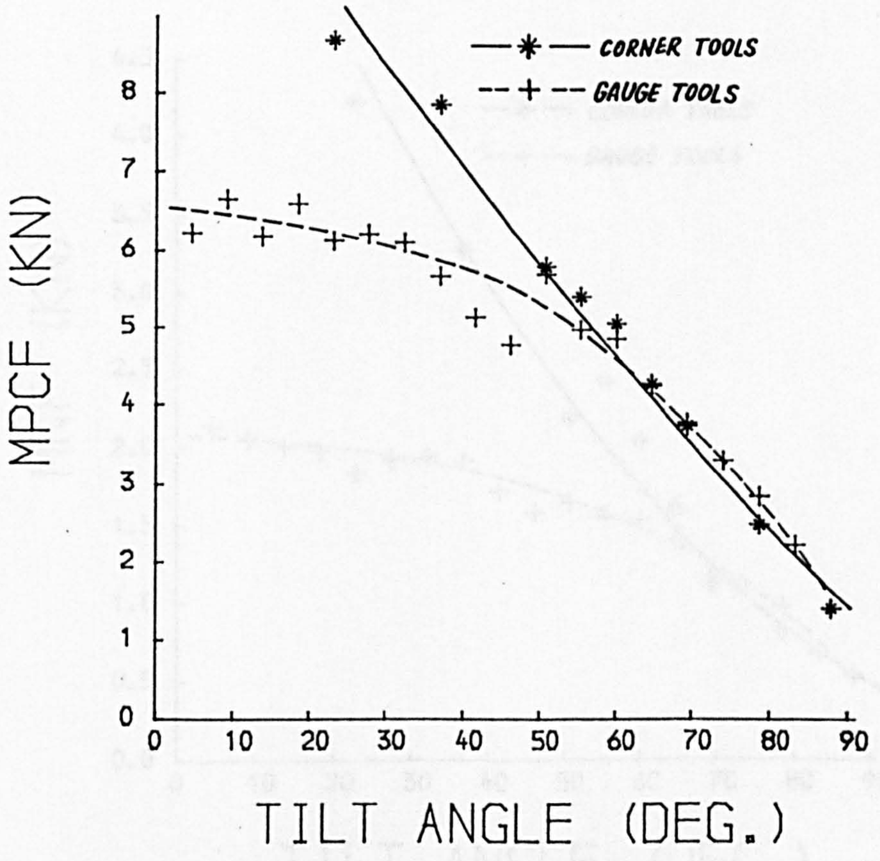


FIG.41 VARIATION OF MEAN PEAK CUTTING FORCE WITH TILT ANGLE, TOTAL PICK NO:16.

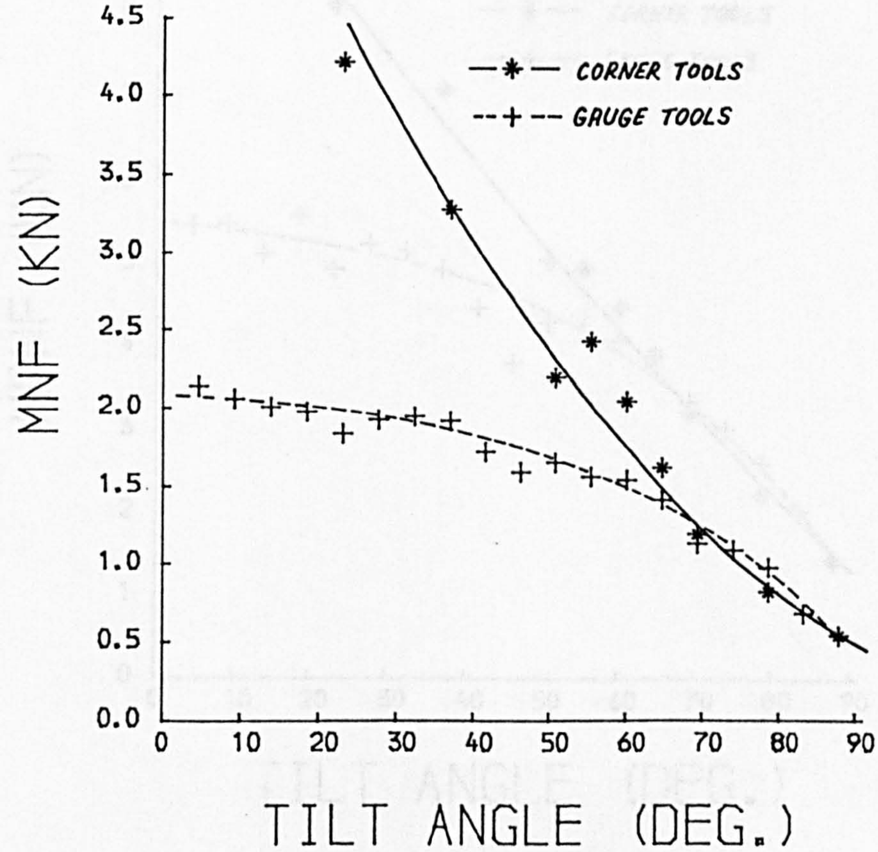


FIG.42 VARIATION OF MEAN NORMAL FORCE WITH TILT ANGLE; TOTAL PICK NO:16.

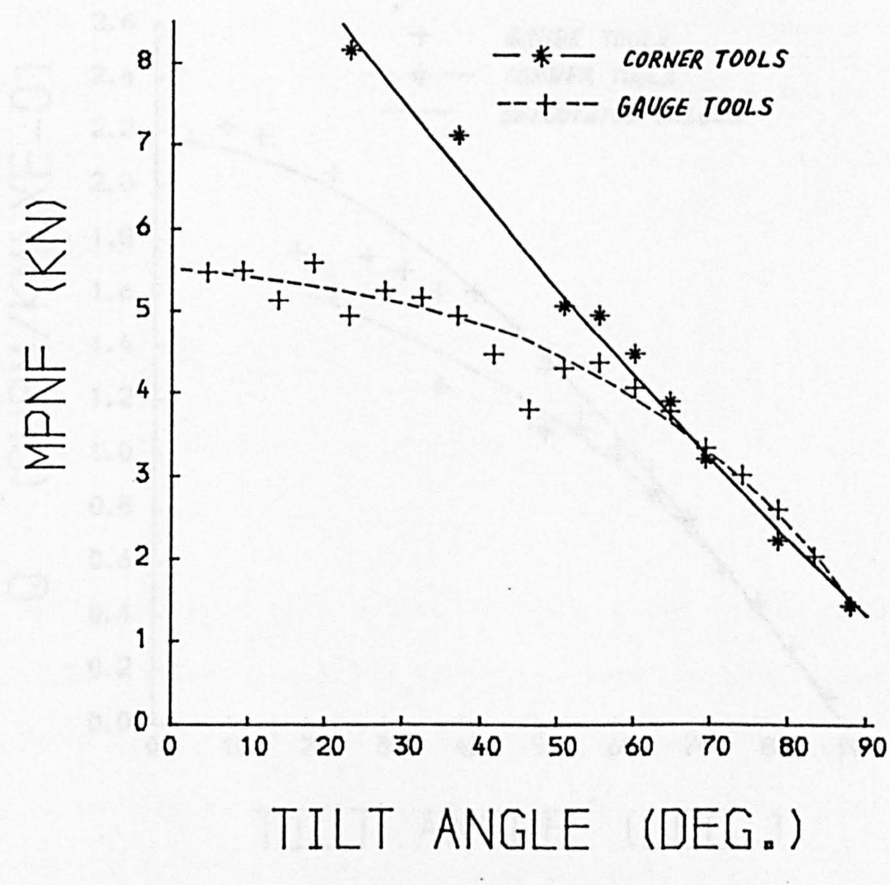


FIG.43 VARIATION OF MEAN PEAK NORMAL FORCE WITH TILT ANGLE, TOTAL PICK NO.16.

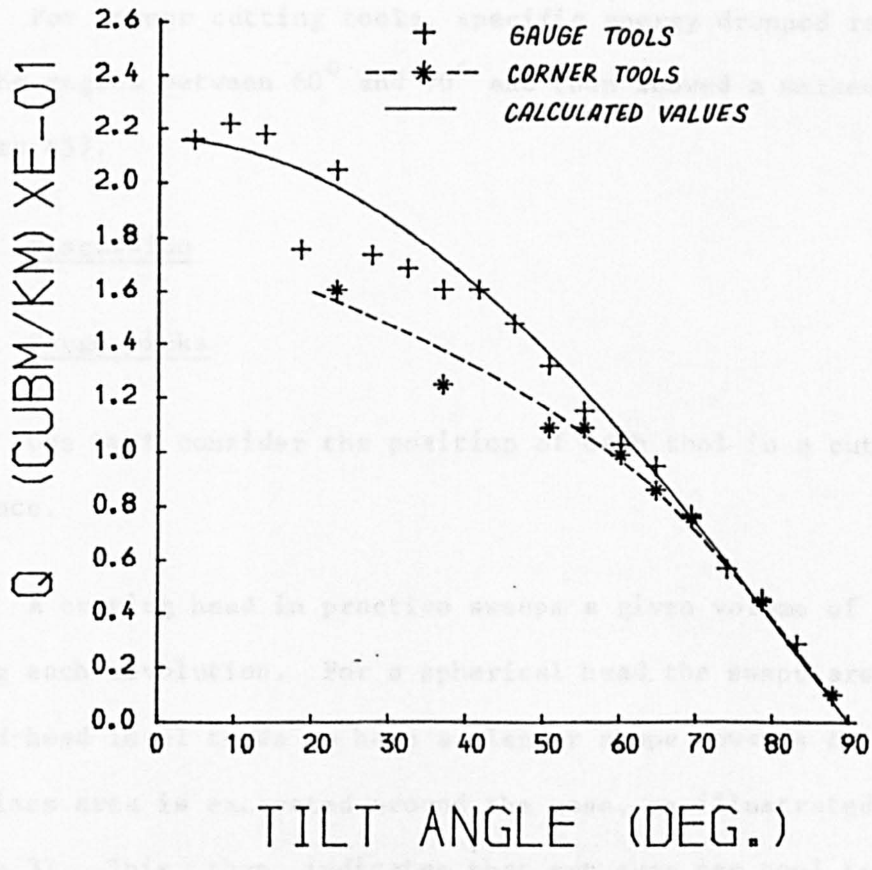


FIG. 44 VARIATION OF MEASURED AND PREDICTED YIELD WITH TILT ANGLE, TOTAL PICK NO. 16.

9.6.3 Effect of tilting angle on specific energy

Specific energy showed a very slow increase for the majority of tilt angles changing, however towards the nose when a sudden rise was observed (Figure 45).

For corner cutting tools, specific energy dropped rapidly for the angles between 60^{o} and 70^{o} and then showed a marked increase (Figure 45).

9.7 Discussion

9.7.1 Gauge picks

One must consider the position of each tool in a cutting sequence.

A cutting head in practice sweeps a given volume of rock during each revolution. For a spherical head the swept area observed at mid-head level tends to have a slender shape towards the nose; thus less area is excavated around the nose, as illustrated in Figure 37. This, then, indicates that cut area per tool is not uniformly distributed around the cutting head periphery.

The cutting action of a pick on the head varies with angular and spatial positions of picks and mode of cut.

The duty of each tool may be defined by illustrating the order of cutting action within the cutting pattern adopted, as shown in Figure 46. From this figure, it may be seen that the perimeter formed by a cutting sequence no longer concurs with the profile of the head geometry, i.e. the curve passing through the tip

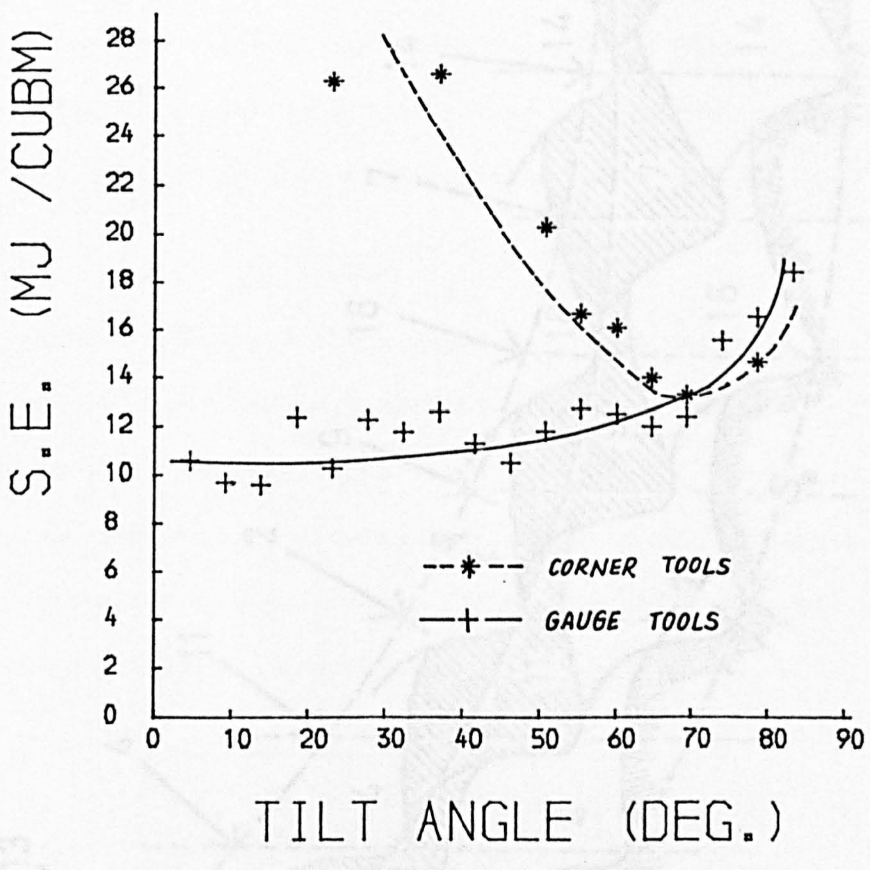


FIG.45 VARIATION OF SPECIFIC ENERGY VALUES WITH TILT ANGLE, TOTAL PICK NO:16.

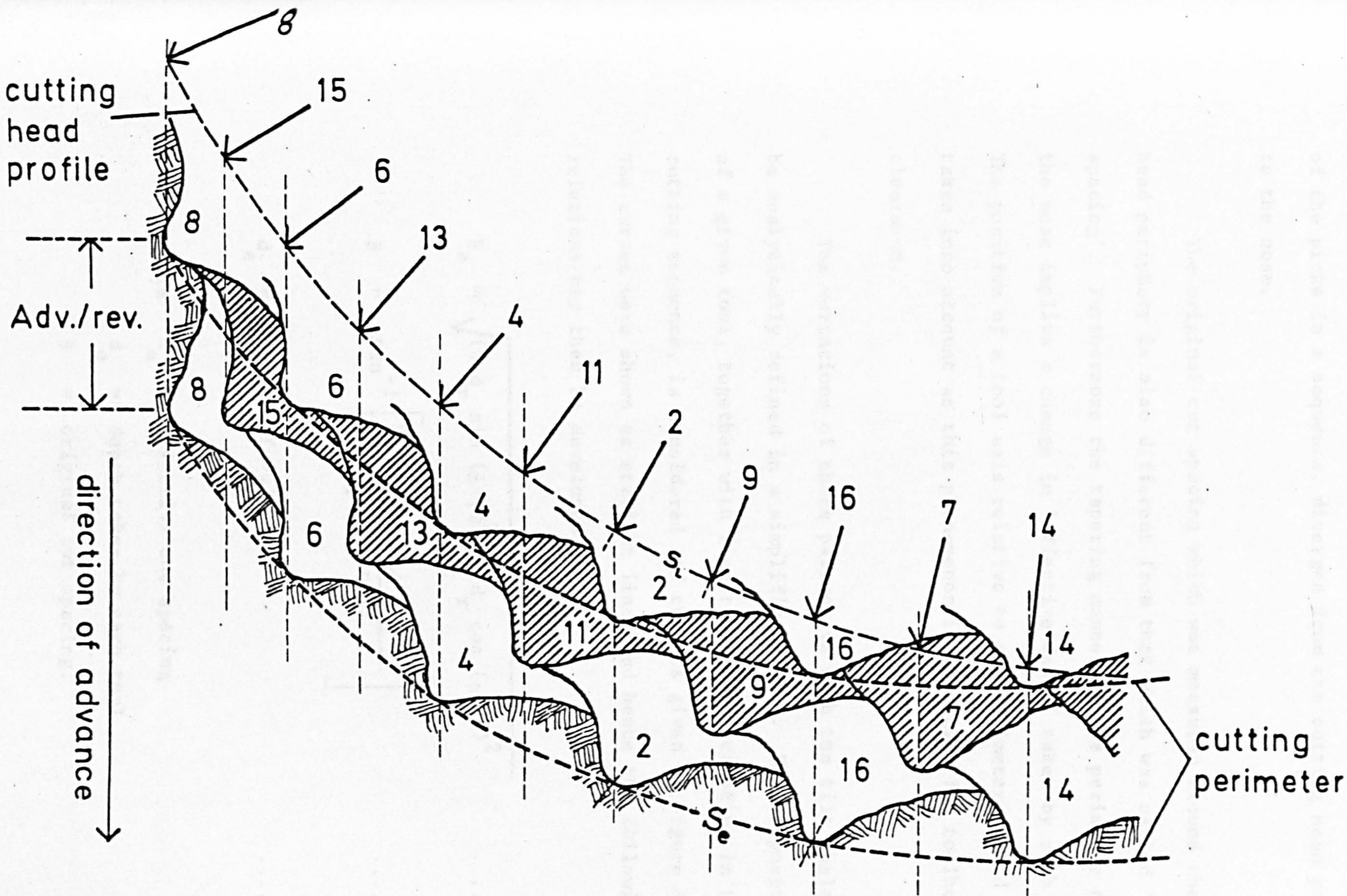


Fig.46 Illustration of a Cutting Pattern

of the picks in a sequence, diverges from the cutting head profile to the nose.

The original cut spacing which was measured around the cutting head periphery is also different from that which was called 'effective spacing'. Furthermore the tapering manner of the perimeter towards the nose implies a change in 'effective depth' taken by each tool. The position of a tool axis relative to the perimeter should be taken into account as this phenomenon is important for toolholder clearance.

The variations of these parameters with the tilt angles can be analytically defined in a simplified manner. Thus a position of a given tool, together with a preceding tool existing in the same cutting sequence, is considered and this is given in Figure 47. The curves were shown as straight lines and hence the following relations may then be developed:

$$S_e = \sqrt{(S-d_r \sin(\alpha-\gamma))^2 + (d_r \cos(\alpha-\gamma))^2} \quad \ldots\ldots (9.1)$$

$$\beta = \tan^{-1}\left[\frac{d_r \cos(\alpha-\gamma)}{S - d_r \sin(\alpha-\gamma)}\right] \quad \ldots\ldots (9.2)$$

$$d_e = d \cos((\alpha-\gamma) - \beta) \quad \ldots\ldots (9.3)$$

where S_e = Effective cut spacing

d_e = depth taken by each tool

S = original cut spacing.

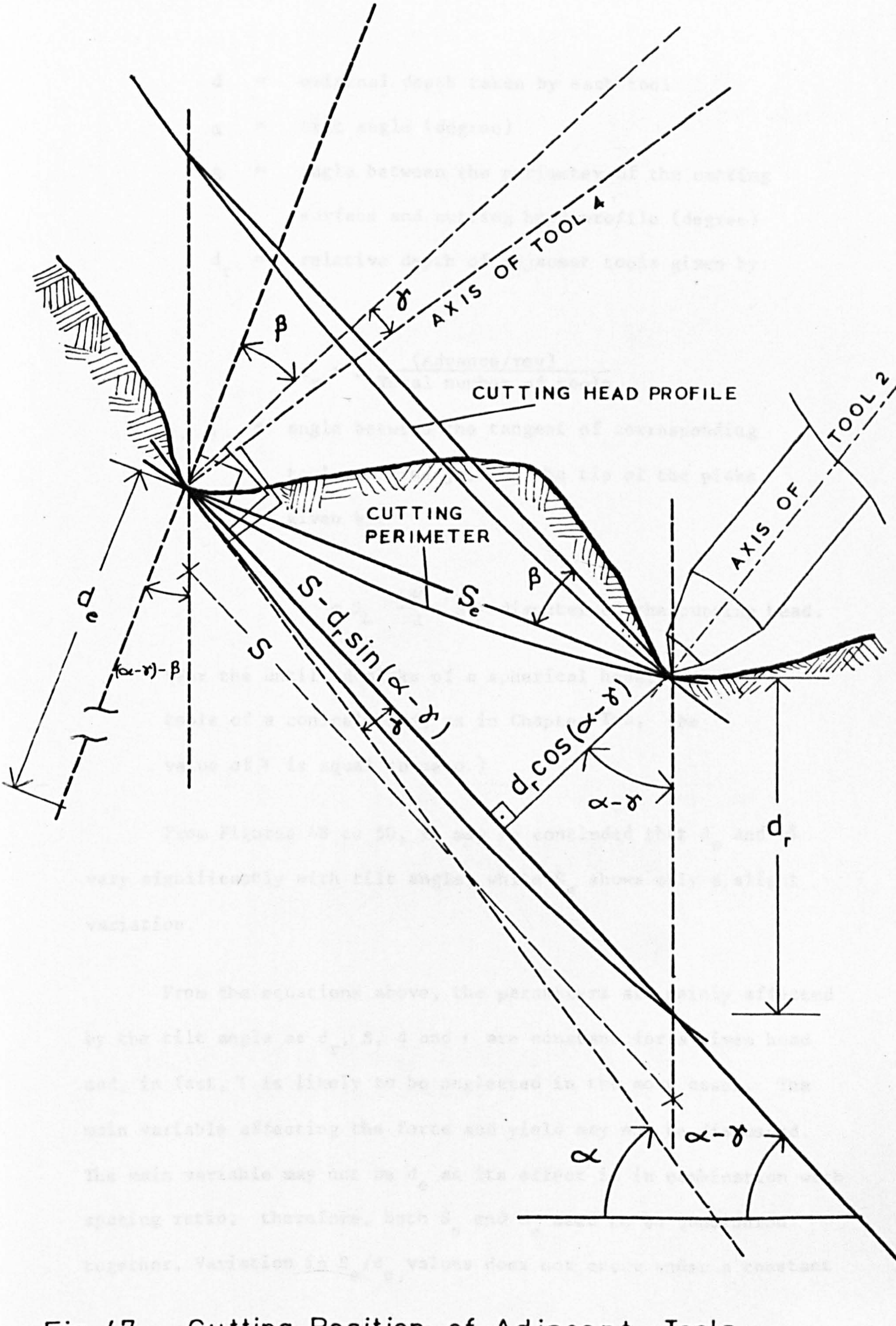


Fig.47 Cutting Position of Adjacent Tools

d = original depth taken by each tool

α = tilt angle (degree)

β = angle between the perimeter of the cutting surface and cutting head profile (degree)

d_r = relative depth of adjacent tools given by:

$$d_r = 2 \frac{(\text{Advance/rev})}{\text{Total number of tools}}$$

γ = angle between the tangent of corresponding tool and line joining the tip of the picks, given by:

$$= S_L \frac{180}{\pi R} \quad R = \text{diameter of the cutting head.}$$

(For the untilted picks of a spherical head, and all tools of a conical head, as in Chapter Ten, the value of γ is equal to zero.)

From Figures 48 to 50, it may be concluded that d_e and β vary significantly with tilt angle, while S_e shows only a slight variation.

From the equations above, the parameters are mainly affected by the tilt angle as d_r, S, d and γ are constant for a given head and, in fact, γ is likely to be neglected in the most cases. The main variable affecting the force and yield may now be discussed. The main variable may not be d_e as its effect is in combination with spacing ratio; therefore, both S_e and d_e need to be considered together. Variation in S_e/d_e values does not occur under a constant

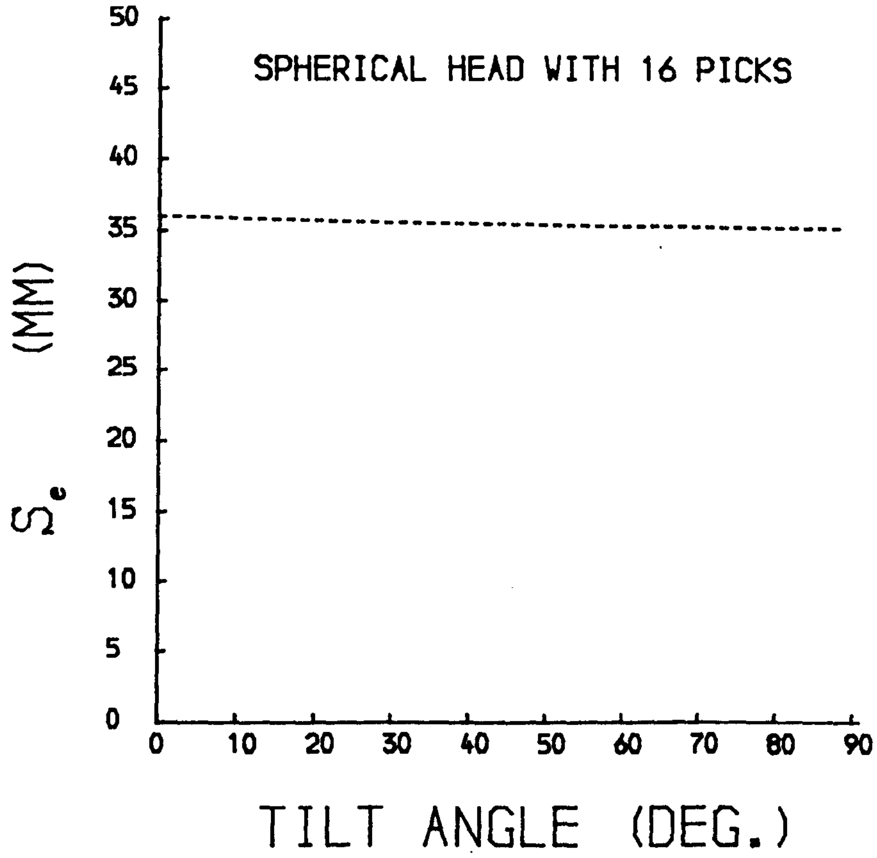


FIG.48 VARIATION OF EFFECTIVE CUT SPACING WITH TILT ANGLES .

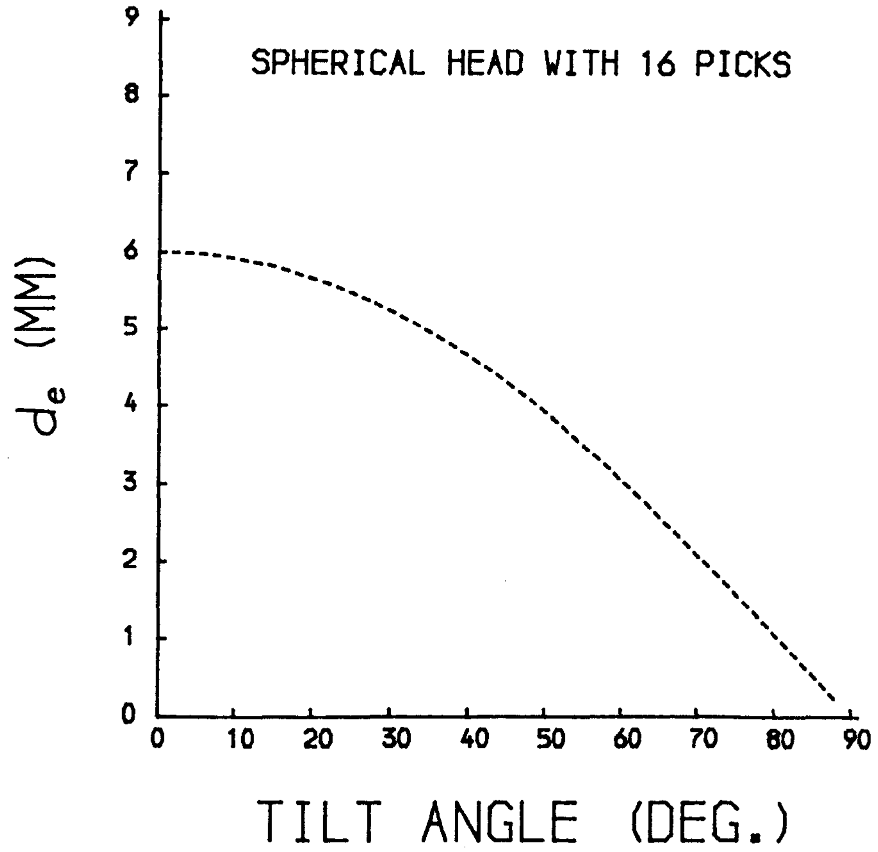


FIG. 49 VARIATION OF EFFECTIVE DEPTH WITH TILT ANGLES.

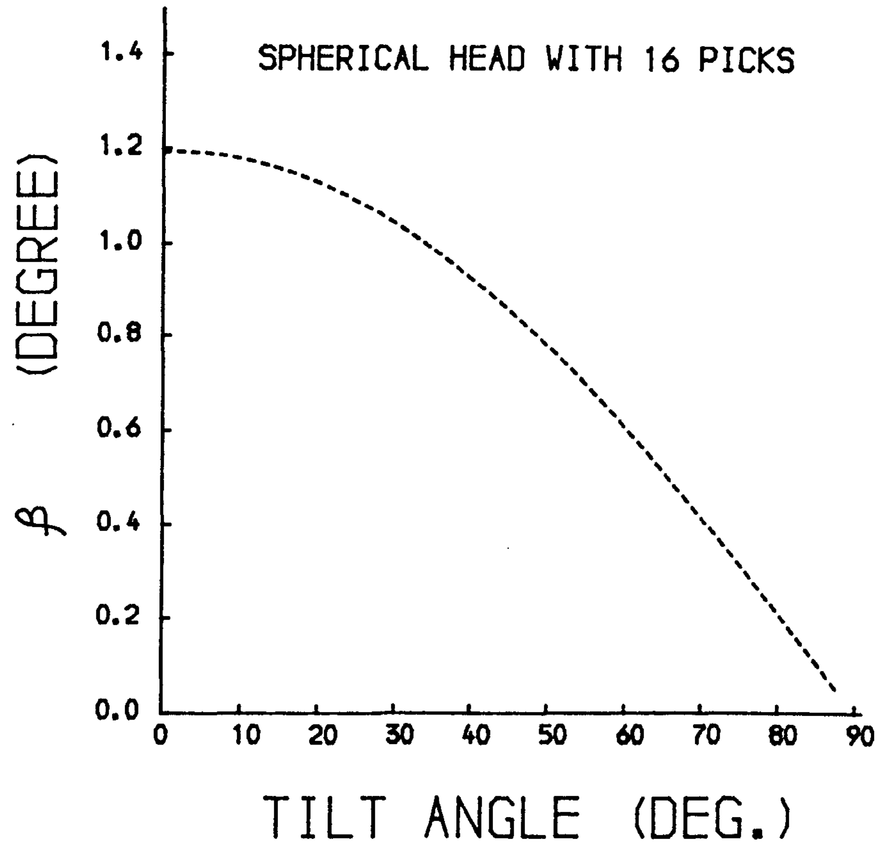


FIG. 50 VARIATION OF THE ANGLE OF TOOL AXIS WITH TILT ANGLES .

tool position, since β which determines the tool position relative to the cutting perimeter, also varies with tilt angle.

As previously mentioned, d_e, S_e and β are functions of the tilt angle for a given d_r value. Hence a definition of a common factor including the effect of all these parameters would provide an insight into this aspect and a cross-sectional area cut by each pick may be considered.

As illustrated in Figure 51, the tool shown operates within a certain area which is the sum of ABCD/2 and BEDF/2. As the difference between the values of ABCD and BEDF is not significant and may be assumed to be negligible, the sectional area is then expressed as follows:

$$A_\alpha = BEDF$$

$$= S_L . 2d. \cos (\alpha - \frac{\gamma}{2}) \quad ..... (9.4)$$

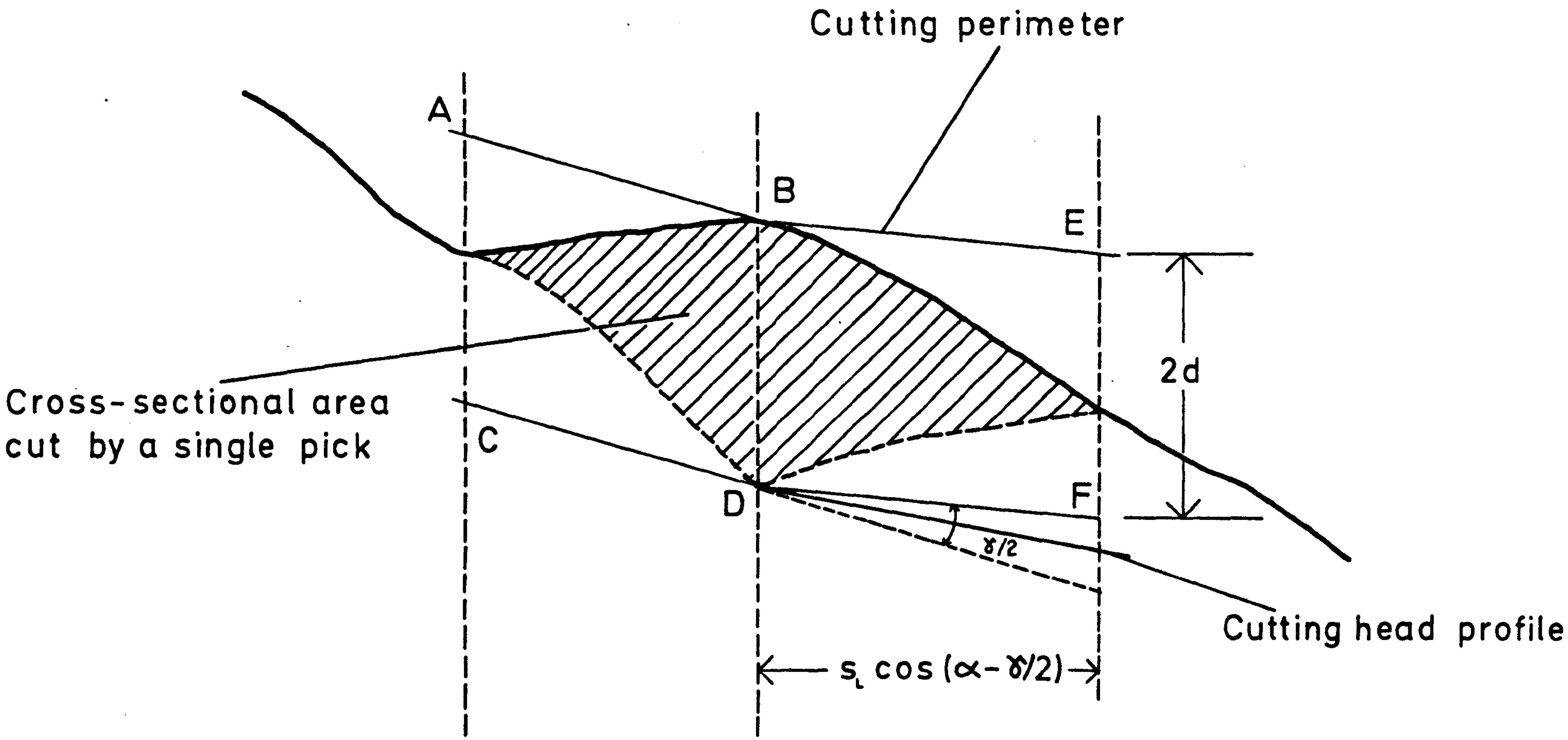
where A_α = the cross-sectional area cut by a pick of given tilt angle, due to the fact that $\frac{\gamma}{2}$ is very small the expression can be reduced to:

$$A_\alpha = S_L . 2d \cos (\alpha) \quad ..... (9.5)$$

$$= S_e \times d_e \quad ..... (9.6)$$

Furthermore, the equations(8.2)(8.3) for yield may be developed as follows:

$$Q_p = \frac{A\alpha}{L} \quad ..... (9.7)$$



(THE CURVES CORRESPONDING TO CUTTING PERIMETER AND CUTTING HEAD PROFILE ARE SHOWN AS STRAIGHT LINES)

Fig. 51 Definition of Cross-sectional Area Cut by a Gauge Tool

Figures 52 and 53 show that a linear relationship exists between the measured force values and calculated sectional cut areas. A_S, S_L and d are constant for a given cutting head. It may be said that the forces vary linearly with $\cos\alpha$.

Furthermore, measured yield values presented a good agreement with those predicted (Figure 45) thus confirming the phenomenon of the cross-sectional cut area per pick.

The reason for the gradual rise of specific energy around the nose region may be attributed to the decreasing values of the effective depth. At such shallow depths the point attack tool mostly rubs the surface, rather than presenting efficient cuts.

Accordingly, the performance of the gauge cutters were significantly affected by the tilt angle and this effect may be indirectly be expressed by the definition of a sectional area cut by the corresponding pick.

9.7.2 Corner cutting tools

Experimental results showed that the tilt angle played a significant role in the aspect of corner cutting.

The observed cutting action of the corner pick at various tilt angles is illustrated in Figure 54 and it seems that the angle between the corner wall and the cutting perimeter is the prime factor which is closely associated with the performance of the corner pick since the confinement of the pick is predominantly controlled by the value of this angle.

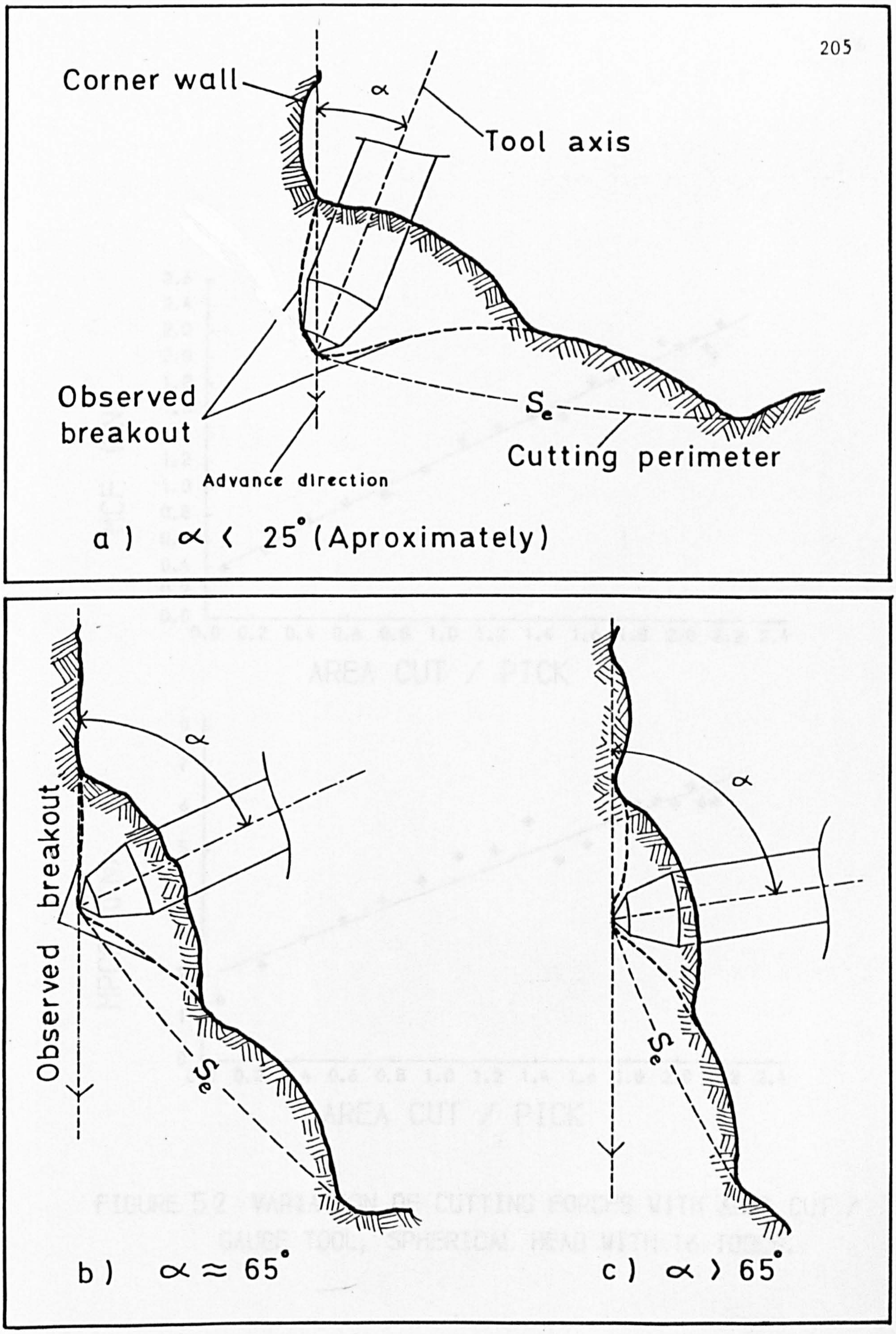


Fig. 54 Observed Cutting Position of Corner Tools

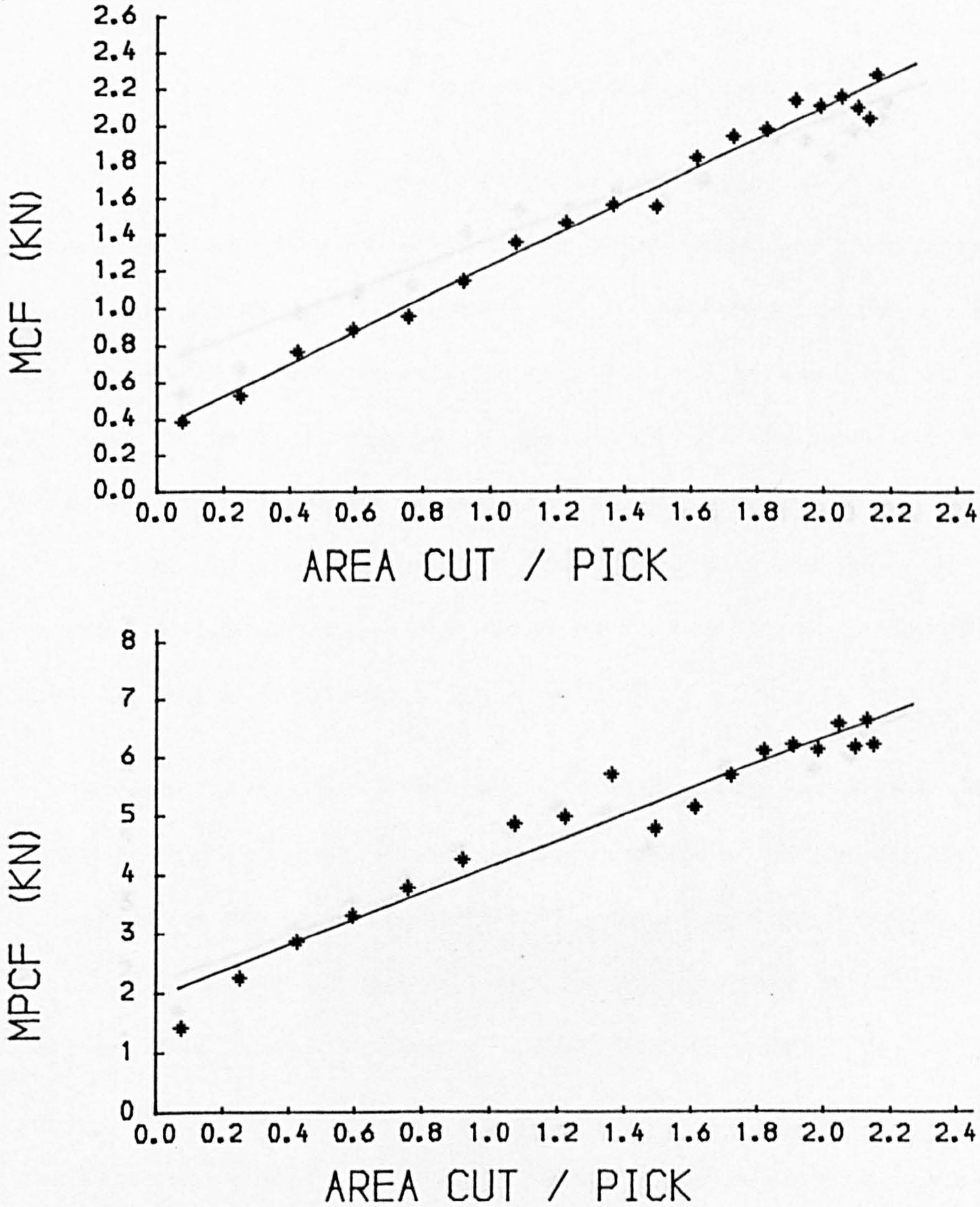


FIGURE 52 VARIATION OF CUTTING FORCES WITH AREA CUT / GAUGE TOOL, SPHERICAL HEAD WITH 16 TOOLS.

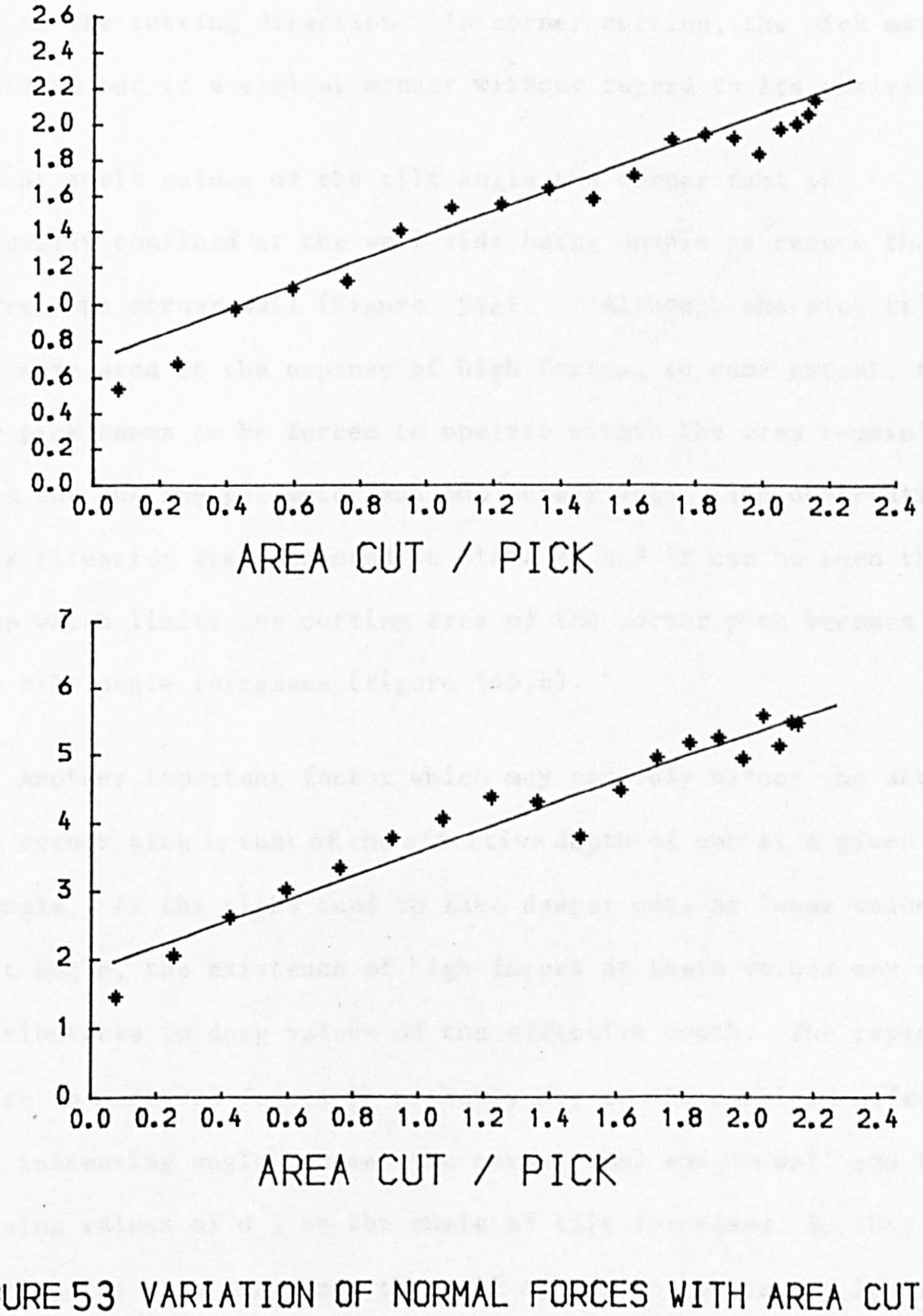


FIGURE 53 VARIATION OF NORMAL FORCES WITH AREA CUT / GAUGE TOOL, SPHERICAL HEAD WITH 16 TOOLS.

In relieved cutting condition, the point attack tool, as explained previously, usually tends to break rock by forming a V section of a certain breakout angle when viewed on a plane perpendicular to the cutting direction. In corner cutting, the pick may be expected to cut in a similar manner without regard to its position.

At small values of the tilt angle the corner tool is particularly confined at the wall side being unable to remove the area from the corner wall (Figure 54a). Although the pick tries to cut more area at the expense of high forces, to some extent, the corner pick seems to be forced to operate within the area remaining between the cutting perimeter and the corner wall. The observations of this situation are presented in Plate 27 and it can be seen that the gap which limits the cutting area of the corner pick becomes larger as the tilt angle increases (Figure 54b,c).

Another important factor which may possibly affect the action of the corner pick is that of the effective depth of cut at a given tilt angle. As the picks tend to take deeper cuts at lower values of tilt angle, the existence of high forces at these values may also be attributable to deep values of the effective depth. The rapid decrease in measured forces is probably due to the combined effects of the increasing angle between the corner tool and the wall and the decreasing values of d_e, as the angle of tilt increases. In this way, the tool gains more area from the wall to cut by generating lower forces. It is for this reason also that specific energy diminishes until a certain value is reached.

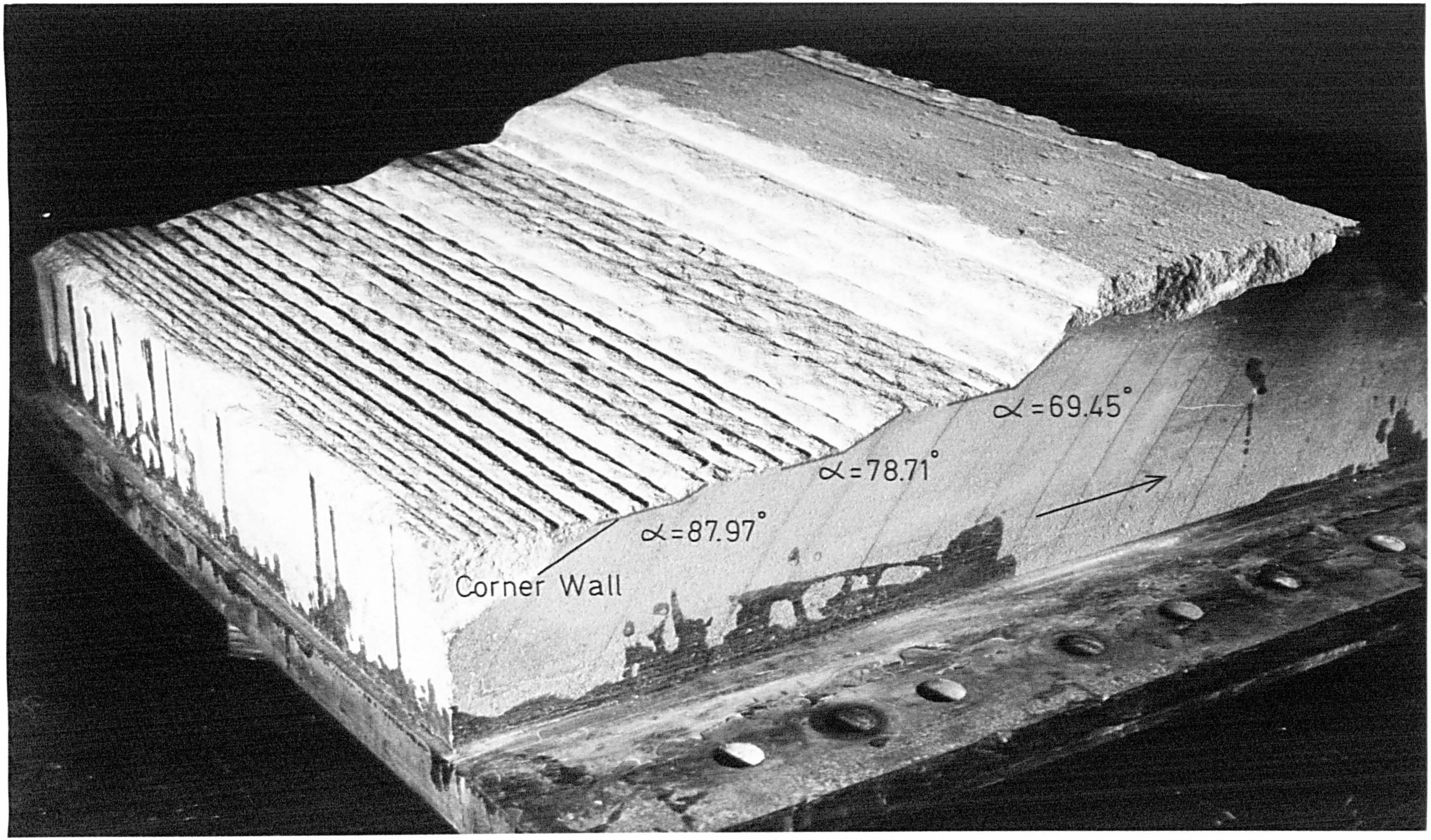


Plate 26

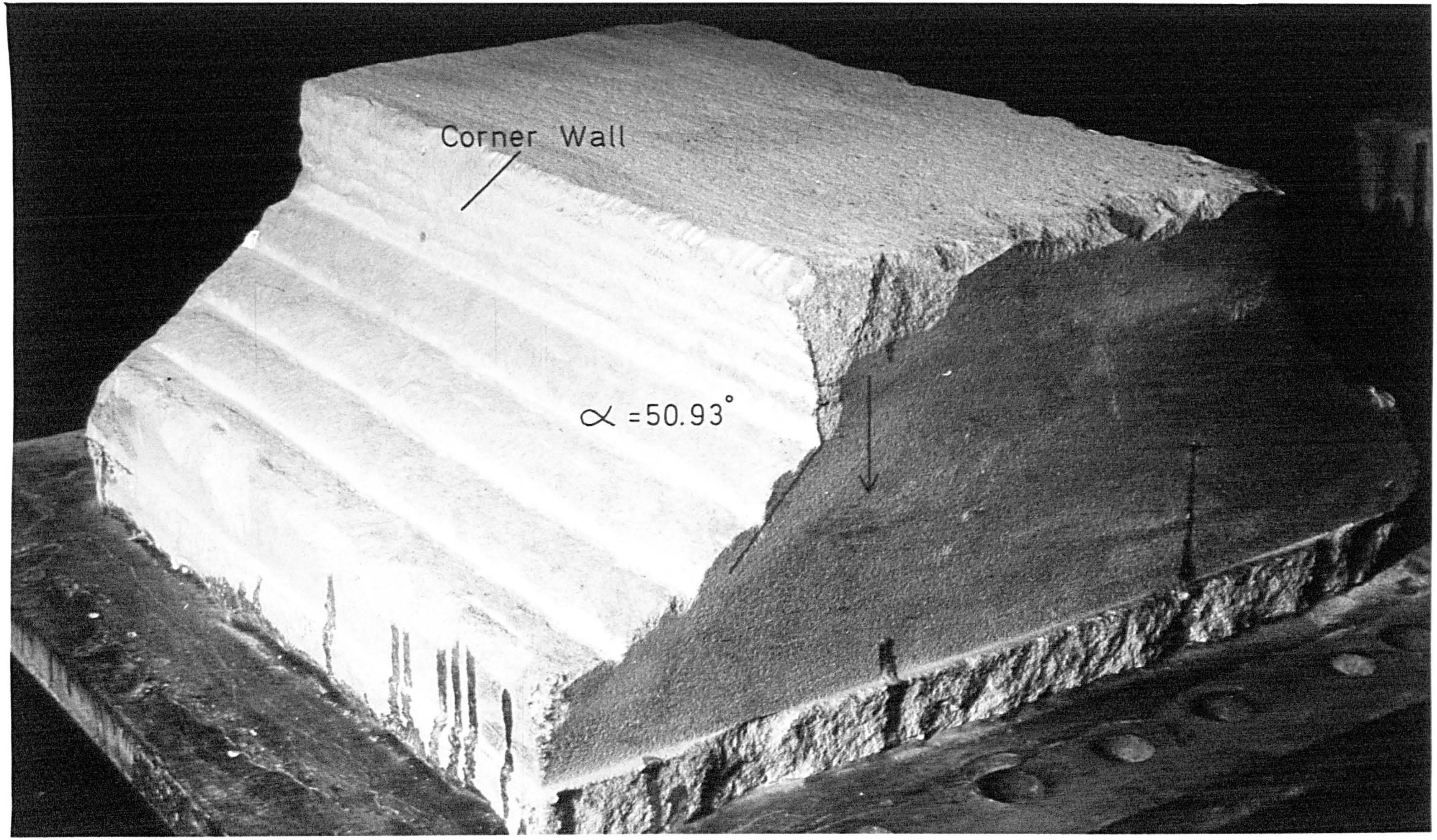


Plate 26

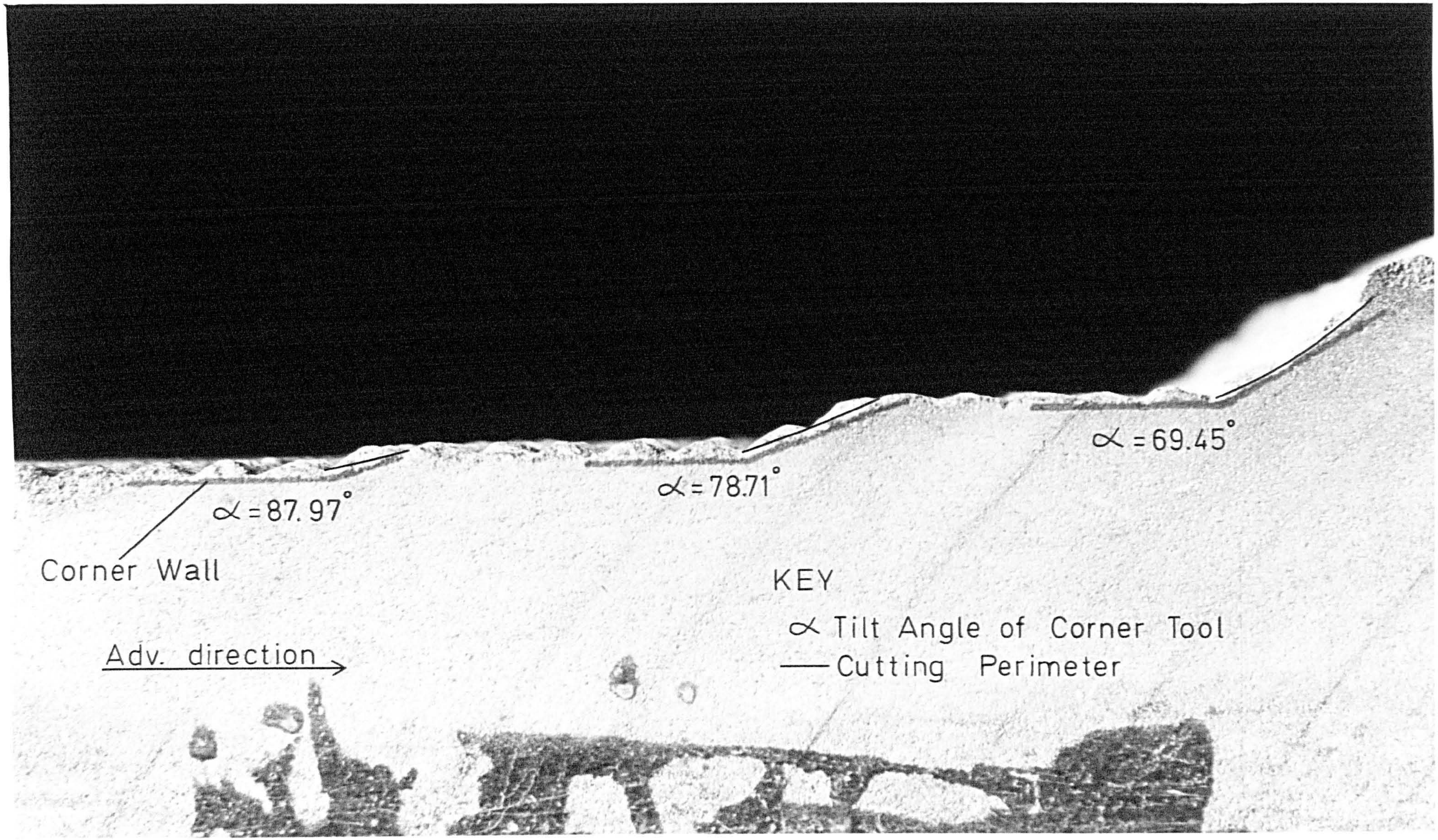

α = 87.97°
α = 78.71°
α = 69.45°
Corner Wall
KEY
α Tilt Angle of Corner Tool
—— Cutting Perimeter
Adv. direction

Plate 27

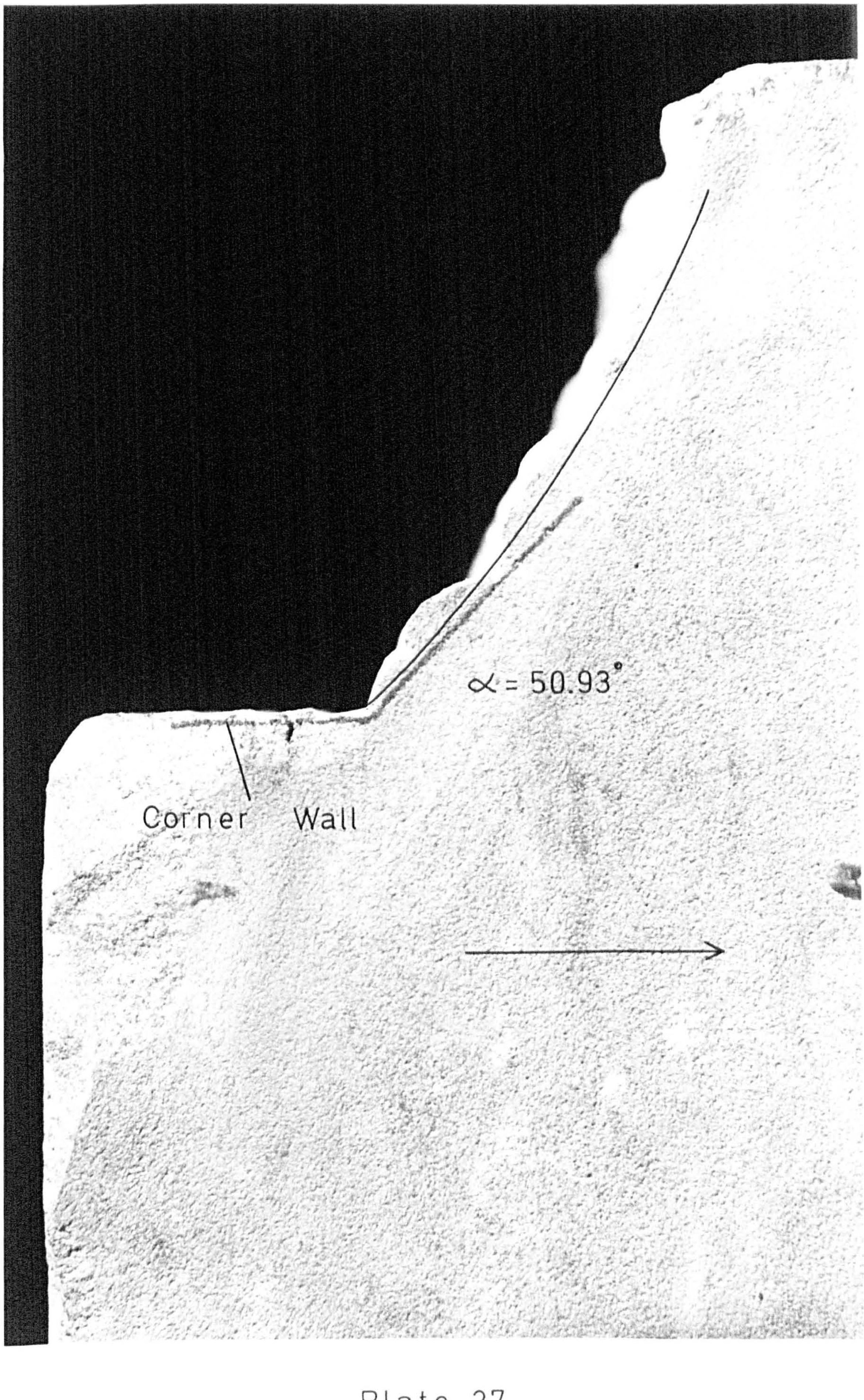


Plate 27

The force values become similar to those of the gauge tools and continue to decrease with a similar trend at values between 60° and 70° tilt angle. This may indicate that the corner pick is no longer cutting in semi-isolated conditions in low angles of tilt. It is also interesting to note here that the value of tilt angle is approximately equal to that of breakout angle for an unrelieved groove cut using the point attack pick which, when measured, was found to be around 66° under flat surface cutting conditions.

As can be seen From Plate 26, when this value of tilt angle was used, the surface of the corner wall presented serrated reliefs, whereas a smooth shape existed below this value. This situation may be attributed to the value of the corner angle exceeding that of breakout angle of the pick, since the tool tends only to cut the area within the boundary of this breakout angle.

9.8 Conclusions

In accordance with the cutting heads and their design and operational features which have been described, the following conclusions may be drawn:

(1) Effective depth taken by each tool at a given angular position, continually decreases with increased value of tilt angle, whilst the effective spacing shows a slight decrease. The tool position is also continuously changed.

(2) Forces and yield in gauge cutting tools continuously decrease with tilt angle and the cuts become less efficient around the nose area.

(3) Corner cutting tools were greatly affected by the increasing values of tilt angle and the corner pick starts to behave as a gauge pick at a value of tilt angle approximately equal to the breakout angle of the pick under a normal relieved cutting condition, i.e. 65^{o}.

(4) A linear relationship exists between the forces on each gauge tool and its corresponding cross-sectional cut area.

* * *

10. INFLUENCE OF CUTTING HEAD GEOMETRY ON THE PERFORMANCE OF ROADHEADERS OPERATING IN TRAVERSING MODE

10.1 Introduction

The results from the previous chapter show that tilt position of cutting tools on a cutting head significantly affects the individual tool forces and hence the performance of the machine. The geometry of a cutting head appears to reflect the tool position and, therefore, different head geometries could result in variation of some cutting parameters, i.e. level of torque and torque fluctuations, slewing force and volumetric rate of excavated material.

In tunnelling practice, a smooth roof and wall surface is desirable to provide good support and to avoid the need to fill the voids behind the lining which may increase the cost of tunnelling operations. The geometry of cutting heads emerges to play an important role in producing a smooth surface.

There is no detailed information available either from field or laboratory investigations on the selection of cutting head geometry, though there are many variations of spherical and conical geometries found in practice.

In this chapter, the effects of cutting head geometry on the performance of roadheaders are investigated in terms of their relative kinematic and energetic characteristics. The torque and slewing force values were calculated by a computer program and the required input data was obtained from the results presented in the previous chapter.

10.2 Designing of Cutting Heads with Different Geometries

Although the geometry of roadheader cutting heads vary, in practice the most common types are of spherical, conical or a combination of these two geometries. The picks positions can vary on these heads.

As emphasised earlier, in order to study a particular cutting head, a certain number of laboratory tests is required to generate the necessary data and this is a time-consuming and tedious procedure. With the intention of utilising the data from previous trials, the spherical heads which have already been investigated were assumed to be the prototype heads. The conical and combined heads were, therefore, derived from these spherical heads.

The cutting heads were classified into three groups with respect to their geometries; namely, spherical, conical and combined (a cutting head consists of spherical and conical shapes). The tilt angles were the main criterion for the comparisons made throughout this chapter.

10.2.1 Cutting heads with spherical geometry

In this type all the picks appear to have different tilt angles and thus different force values and cutting radii. These heads have already been mentioned previously.

Since the main objective was the cutting head geometry and the geometry of such spherical heads would be influenced by varying the tool positions, the only variable was, therefore, the tilt angles and tool numbers, advance per revolution, and the head dimensions were kept constant.

The variables for the investigation of spherical heads are shown as follows:

Tilt angle of first tool (at the machine side)	Tilt angle of corner tool (last tool)
0^{o}	64.82^{o}
0^{o}	69.45^{o}
4.63^{o}	74.08^{o}
9.25^{o}	78.71^{o}
13.88^{o}	83.84^{o}
18.21^{o}	87.97^{o}

The reason for choosing the corner tool starting from the angle of 64.82^{o} is that the forces acting on the corner tool become small, which is desirable and the corner tool acts as a gauge tool from this value, as was shown in Figures 40 to 43.

10.2.2 Conical Heads

Being different from the spherical heads, all the tools are disposed on a conical surface and thus, the tilt angles were the same for the gauge and corner cutting tools. Although such conical heads are not very common in practice, it is worthwhile to take them into account when comparing cutting head geometries.

As in Figure 55, a tangent line passing through a given pick position, forms the cone angle and the tools are arranged along this line at a constant distance of 1.8cm apart. Thus a conical head is derived in such a way that the cone angle is equal to the tilt angle of a given tool on a corresponding spherical head. This is the main principle of conical or combined head derivations from that for spherical heads.

In Figure 55 a line being perpendicular to the axis of tool 11 can be drawn and the adjacent picks may be arranged along this slope in a way such that their axis is perpendicular to the line which also represents the profile of the conical head.

The cutting position of pick 2 relative to pick 11 is slightly altered on the new conical surface and tends to act at a point below its former position at a distance depending upon the value for γ. The deflection from the original point on the spherical head would increase with the higher values for γ; the pick position therefore becomes different. The value for γ which was calculated had to be of 4.63^o for spherical conditions and may be small when equations (9.1),(9.2), (9.3) are considered. Furthermore, the value for γ may be lower than 4.63^o in the most practical conditions, since changes with the variation of R at a constant line spacing (S_L) and the diameter of cutting heads in practice appears to be higher than that considered in this work. Hence the γ may be neglected for the sake of convenience. Under these circumstances it might be reasonable to assume that tool 2 removes approximately the same area at the same cutting position when it could cut on a spherical head, in relation to pick 11.

It is also important to note that no change takes place in the positions of tools located after pick 4 to the nose side. Finally, it may be said that cutting condition of a tool on a spherical head is approximately the same as on a conical surface, with angle being equal to the tilt angle of the tool.

The force values for a conical head thus remain approximately the same as in the corresponding spherical heads since, according to the equations (9.2) and (9.5) the area cut and the tool position would give the same values, with the exception of γ which may be negligible.

One of the most important features of these conical heads would be the equal force distributions throughout the tools; in other words, each gauge tool on a conical head experiences the same force values in consequence of the same cutting conditions. Furthermore, the state of corner cutting tools also remains the same if the value for γ is not considered as in gauge tools. As previously mentioned, the corner tools behave as a gauge tool at about the tilt angle of 64.08^{o} and this means that after this value the force distribution is the same on gauge and corner cutting tools.

The conical heads were derived from the spherical heads by starting from the tilt angle of 64.08^{o} (Figure 56). This was due to the provision of equal force distributions and the sensitivity of the corner cutting tools which usually requires careful consideration. The selected tool position on the spherical head also corresponds to the corner tool on the conical head.

The only dependent variable thus appears to be the cone angle and these are as follows:

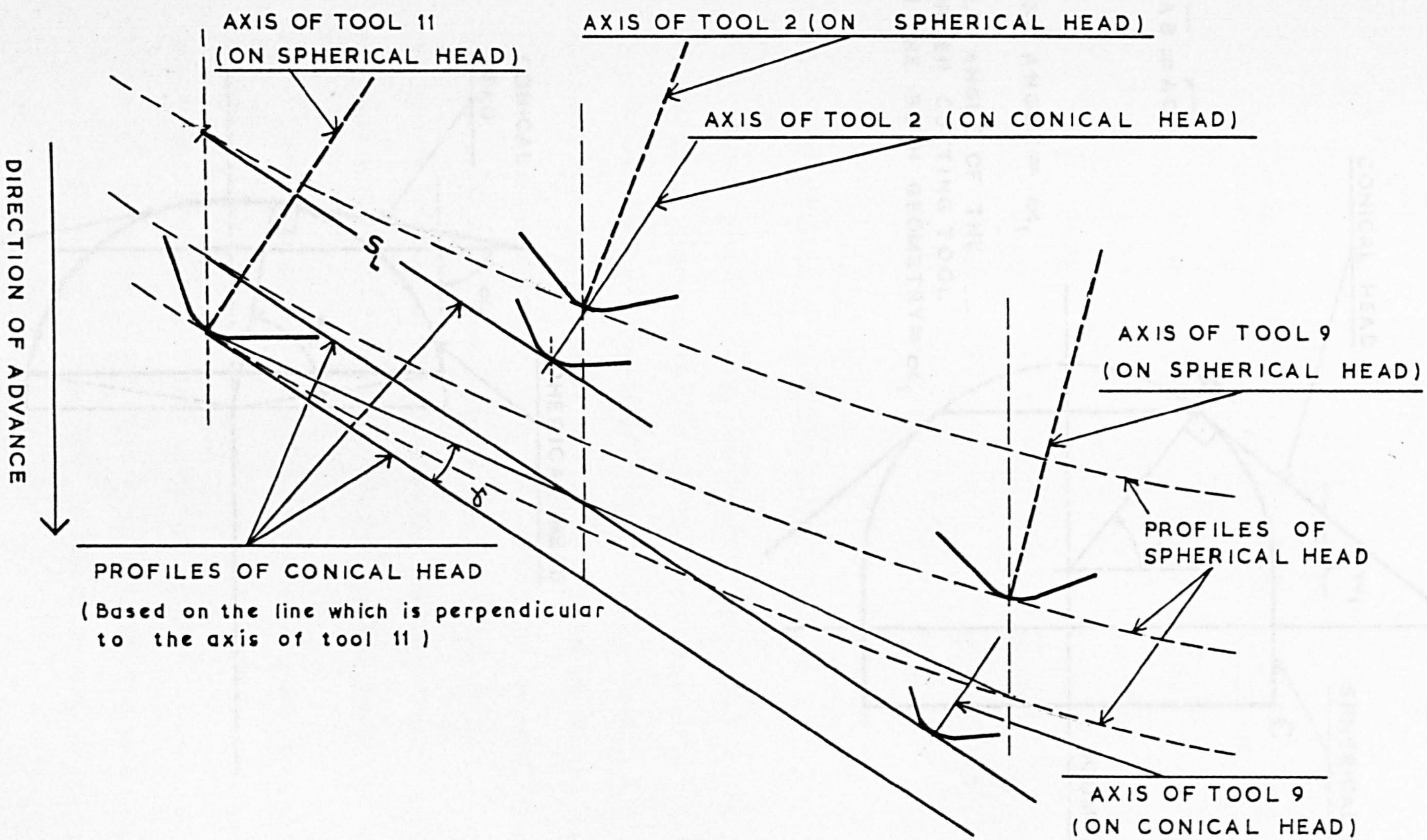


Fig.55 Relative Cutting Position of Adjacent Tools

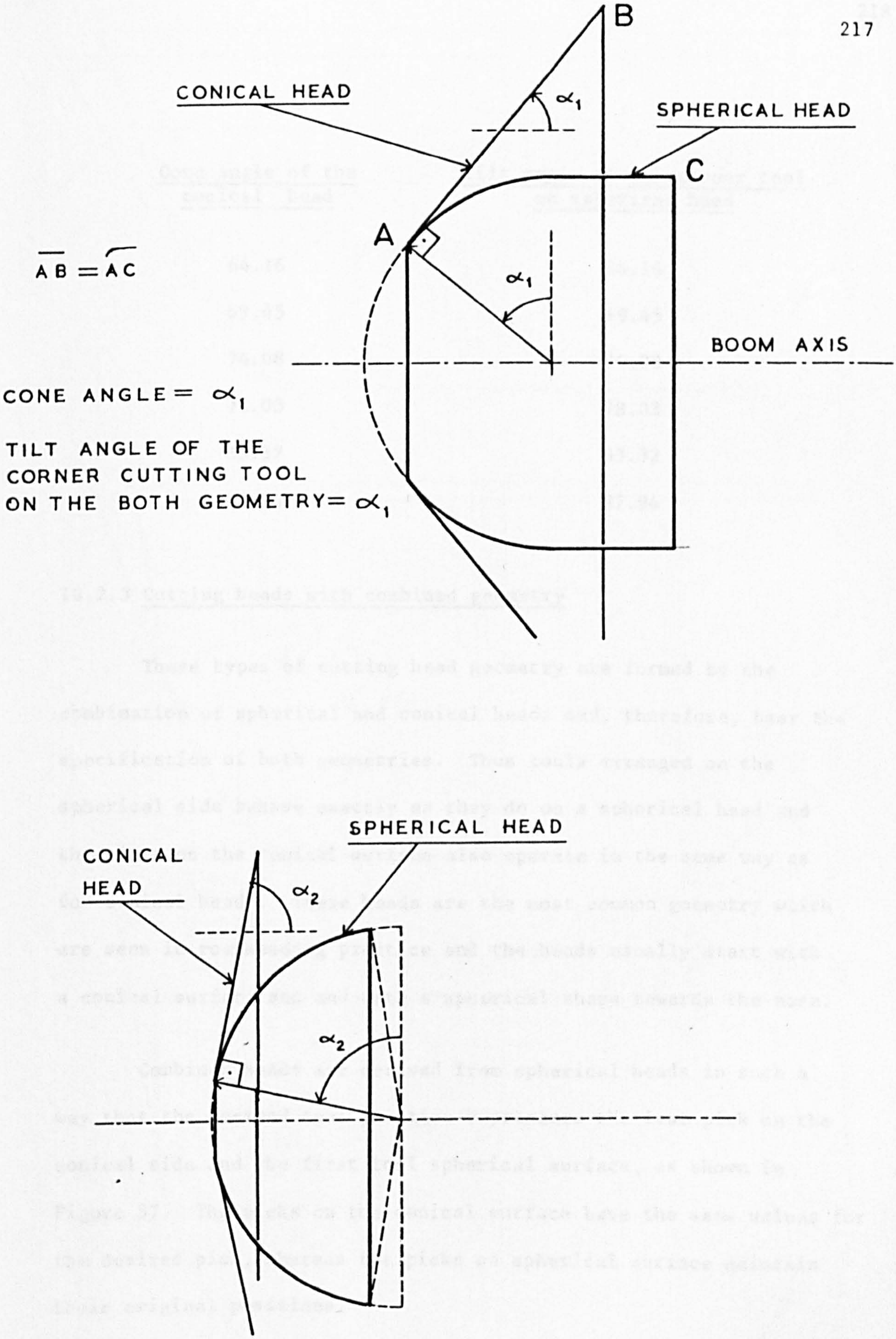


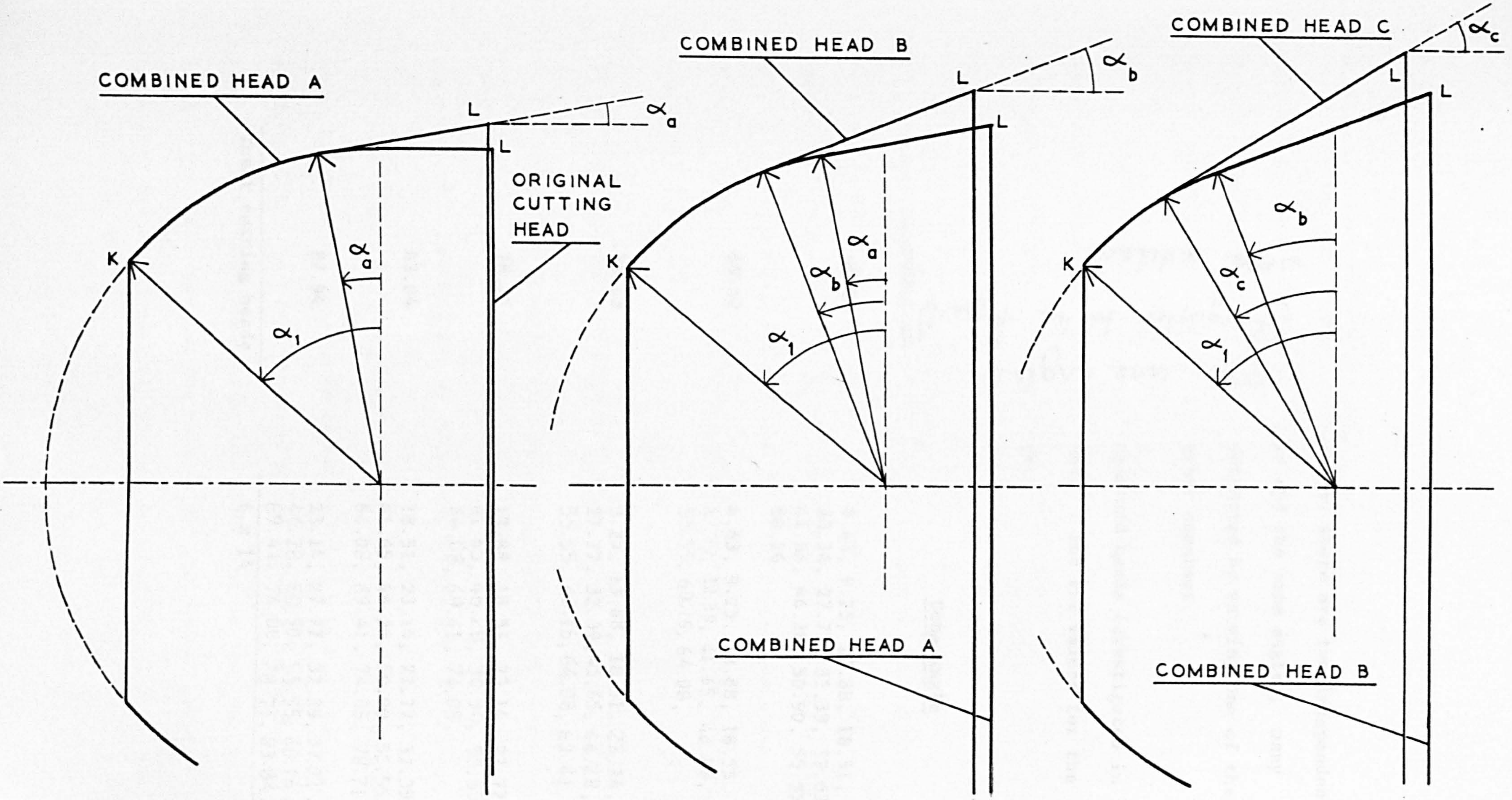
Fig.56 Derivation of Conical Heads

Cone angle of the conical head	Tilt angle of the corner tool on spherical head
64.16	64.16
69.45	69.45
74.08	74.08
78.03	78.03
83.32	83.32
87.94	87.94

10.2.3 Cutting heads with combined geometry

These types of cutting head geometry are formed by the combination of spherical and conical heads and, therefore, bear the specification of both geometries. Thus tools arranged on the spherical side behave exactly as they do on a spherical head and the picks on the conical surface also operate in the same way as for conical heads. These heads are the most common goemetry which are seen in roadheading practice and the heads usually start with a conical surface and end with a spherical shape towards the nose.

Combined heads are derived from spherical heads in such a way that the desired tool position represents the last pick on the conical side and the first tool spherical surface, as shown in Figure 57. The picks on the conical surface have the same values for the desired pick, whereas the picks on spherical surface maintain their original positions.



((α_1) TILT ANGLE OF THE CORNER CUTTING TOOL AND THE CUTTING HEAD LENGTH (KL) ARE KEPT CONSTANT)

Fig. 57) Derivation of combined heads from a spherical head.

Unlike the other two geometries, there are two independent variables; namely, the corner tools and the cone angles; many possible configurations can be constructed by varying one of these two variables, while keeping the other constant.

The specifications of the combined heads investigated in this work are given in Appendix 6A3, and the values for the tilt and cone angles are as follows:

Tilt angle of the corner cutting tool	Cone angle
64.08	4.63, 9.25, 13.88, 18.51, 23.14, 27.77, 32.39, 37.02, 41.65, 46.28, 50.90, 55.55, 60.16.
69.42	4.63, 9.25, 13.88, 18.55, 23.14 27.77, 32.39, 41.65, 46.28, 50.90, 55.55, 60.16, 64.08,
74.05	9.25, 13.88, 18.51, 23.14, 27.77, 32.39, 41.65, 46.28, 50.90, 55.55, 60.16, 64.08, 69.41,
78.71	13.88, 18.51, 23.14, 27.77, 32.39, 41.65, 46.28, 50.90, 55.55, 60.16, 64.08, 69.41, 74.05,
83.84	18.51, 23.14, 27.77, 32.39, 37.02, 41.65, 46.28, 50.90, 55.55, 60.16, 64.08, 69.41, 74.05, 78.71,
87.94	23.14, 27.77, 32.39, 37.02, 41.65, 46.28, 50.90, 55.55, 60.16, 64.08, 69.41, 74.08, 78.71, 83.84,
Total cutting heads	6 x 14

10.3 Parameters considered for comparison of cutting heads with different geometries

In view of the definitions of the cutting heads it is apparent that the level of forces will change by varying the head geometries and the dependent variables such as cutting torque, slewing force, volume of material swept per advance/revolution, are also expected to vary for a particular head.

10.3.1 Cutting torque

Details of cutting torque and the method for calculations were explained earlier. Torque and torque fluctuations are of importance in cutting head design since the level of fluctuations affects the balance of the head and the high fluctuations are detrimental to the cutting picks, gears and other mechanical components.

10.3.2 Slewing force (horizontal thrust)

Forces acting on the boom axis are of very great importance since the advance rate of the roadheaders is also affected by the magnitude of horizontal thrust, depending on the mode of cutting.

In climb-milling cutting, the vertical thrust is generally higher than that in horizontal direction, thus a higher advance rate may be achieved, provided the boom has an adequate resistance to the vertical reactions. However, as the picks tend to take the maximum depth of cut when entering the rock in 90^{o} cut sector, severe vibrations and rapid tool wear are likely to occur. This is not the case in upmilling mode where the tool does not necessarily take the full depth and, therefore, the upmilling cutting mode seems to be more practical as outlined in Chapter Three.

For the cutting heads in this discussion, the upmilling cutting mode was adopted and vertical thrust was not calculated as in this mode they are usually of small magnitude.

10.3.3 Volume of material swept per advance/revolution

This is worth consideration when determining the cutting efficiency.

The volume swept is expressed in terms of the cutting head geometry, as shown in Figure 58a,b,c.

The amount of rock material swept per advance/revolution of the cutting heads with different geometries are as follows:

(a) Spherical heads:

$$V_S = d_a R^2 \left[\frac{n(\alpha_2 - \alpha_1)}{360} + \frac{\sin 2\alpha_2' - \sin 2\alpha_1}{4} \right] \quad \text{..... (10.1)}$$

(b) Conical heads:

$$V_c = d_a S \cos\alpha \left[R_L + \frac{S \sin\alpha}{2} \right] \quad \text{..... (10.2)}$$

(c) Combined heads:

$$V_c = V_S + V_c \quad \text{..... (10.3)}$$

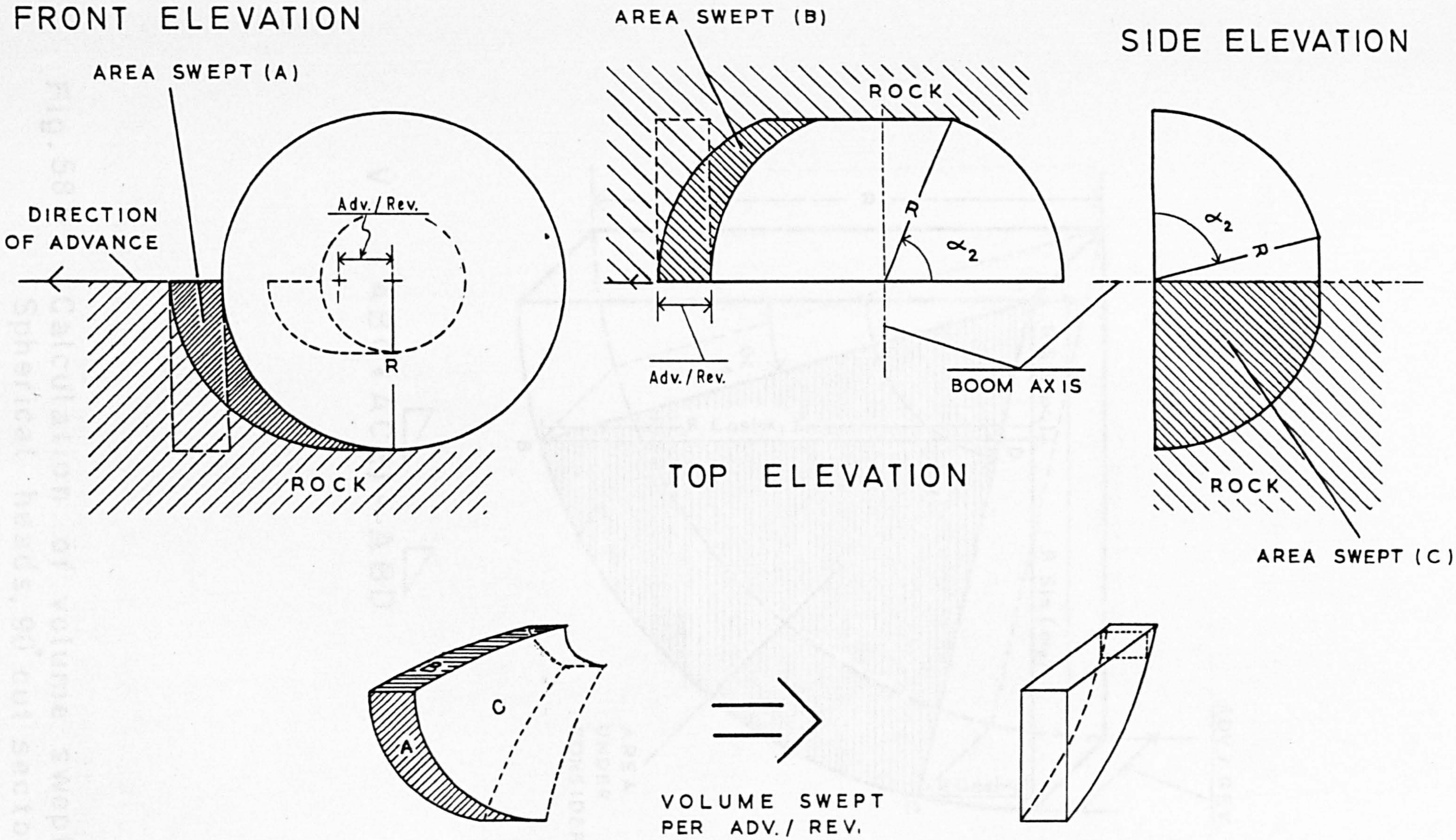
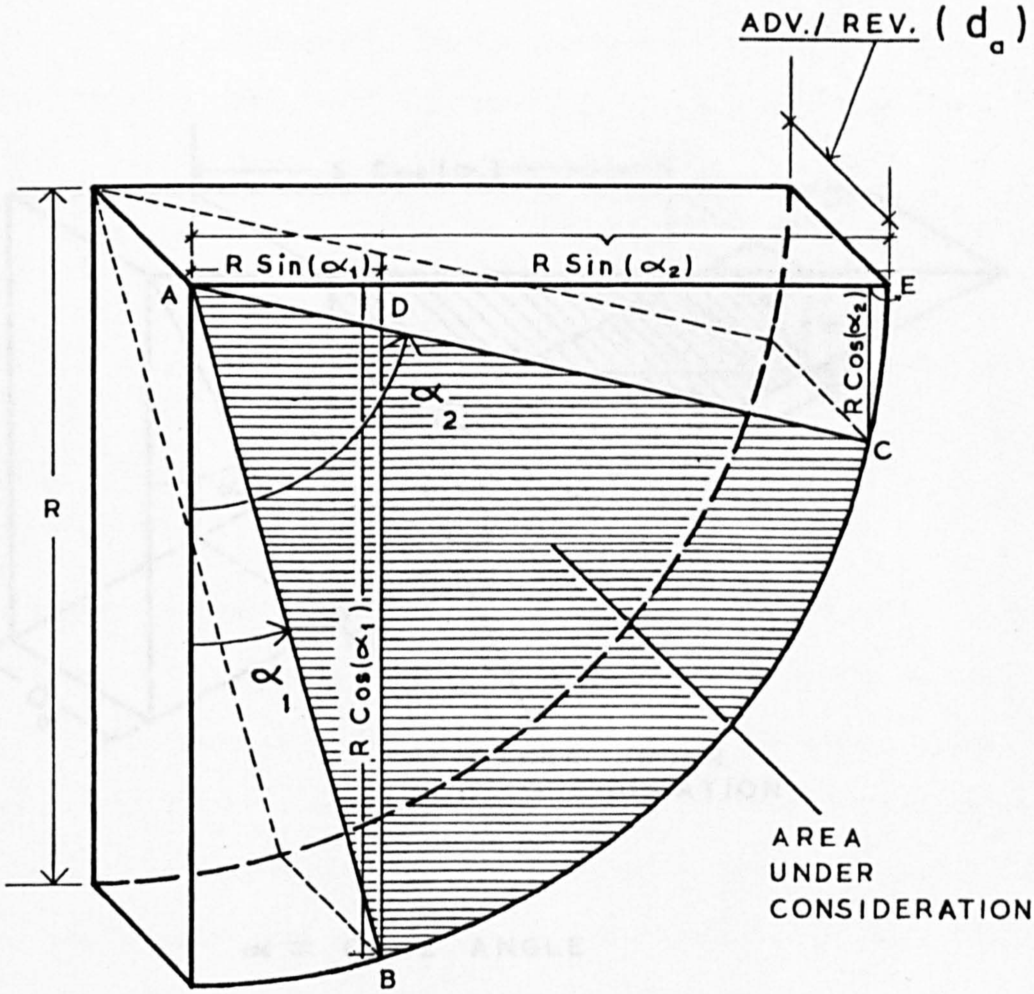


Fig.58a) Notation of volume swept by a spherical head.



$$\dot{V} = (\triangle ABC + \triangle ACE) - \triangle ABD$$

Fig. 58 b) Calculation of volume swept; Spherical heads, 90° cut sector.

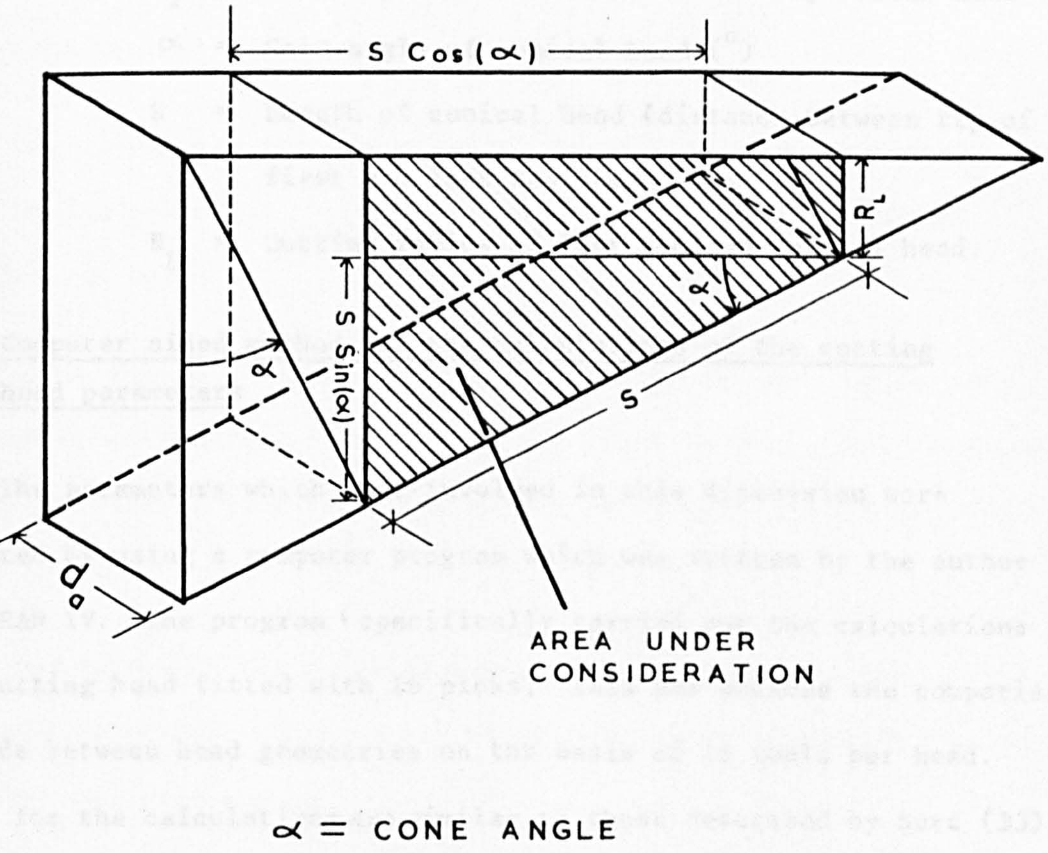


Fig. 58c Calculation of volume swept; Conical heads, 90° cut sector.

where d_a = Advance per revolution (m)

R = Maximum diameter of spherical head (m)

α_2 = Tilt angle of the last tool on spherical head (^{o})

α_1 = Tilt angle of the first tool on spherical head (^{o})

α = Cone angle of conical head (^{o})

S = Length of conical head (distance between tip of first and last tool)(m)

R_L = Cutting radius of last tool on conical head.

10.4 Computer aided method for the calculations of the cutting head parameters

The parameters which were involved in this discussion were calculated by using a computer program which was written by the author in FORTRAN IV. The program specifically carried out the calculations for a cutting head fitted with 16 picks; this was because the comparisons were made between head geometries on the basis of 16 tools per head. Methods for the calculations are similar to those described by Hurt (33).

A number of assumptions were necessary in order to simplify the analysis. The mean cutting force for each tool was related to the depth of penetration of the tool at any point (p) by the formula $F_c = F_m p/D$, where F_m is the cutting force value measured in the laboratory for a particular tool at the maximum depth of penetration and the value of P was determined from $p = D\sin\theta$, where D = Advance/revolution of the cutting head and θ = Angular cutting position from point of entry into cut. This approximation is justified on the understanding that D is much smaller than the radius of cutting.

Only mean force components are used in the analysis. The large force variations experienced by each tool when cutting were ignored since the object of the analysis is to compare the cutting heads rather than to construct a complete mathematical model of their cutting action.

The torque was the summation of the product of F_c and the corresponding radius of cutting for all the active tools within a specified cut sector.

As in Figure 59, for tilted tools on a given head the normal force component no longer acts within the plane of horizontal reaction. For the calculations the effective normal force component is expressed as $F_N \times \cos \alpha$.

The volume of the material swept per advance/revolution is also included amongst these calculations in order to determine the values for specific energy.

Accordingly, the program calculates the torque, slewing force for a given cutting head, at one degree increment of a rotation; also, it gives the mean values and standard deviations of these parameters and prints out the volume swept and specific energy values for one revolution of the head.

The computer program is given in Appendix 8A in detail.

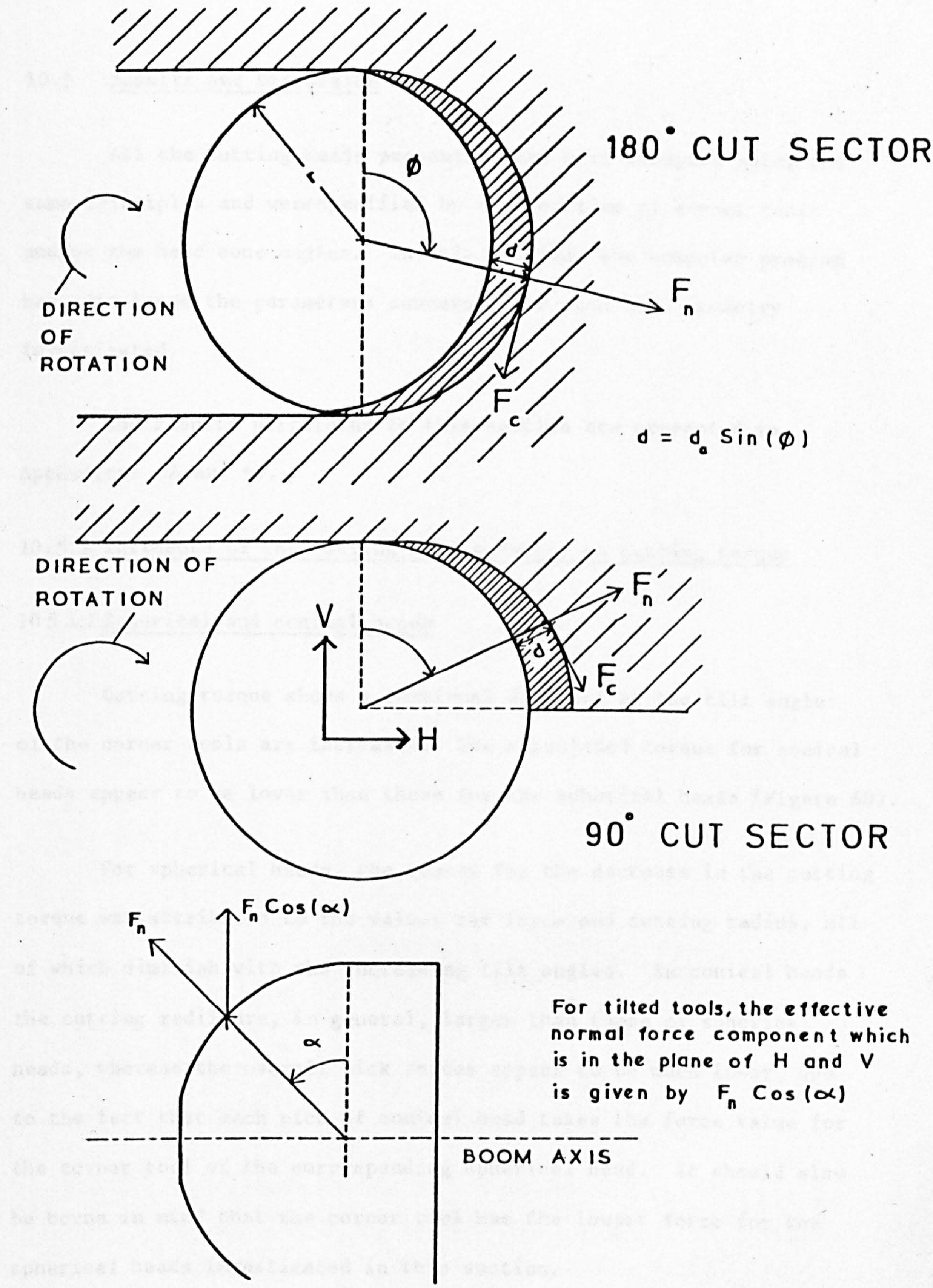


Fig. 59 Illustration of cutting head parameters included in the computer program.

10.5 Results and Discussion

All the cutting heads presented here were designed using the same principles and werespecified by the position of corner tools and/or the head cone angles. In this section, the computer program has calculated the parameters concerned for each head geometry investigated.

The results pertaining to this section are presented in Appendices 6A and 6B.

10.5.1 Influence of the cutting head geometry on cutting torque

10.5.1.1 Spherical and conical heads

Cutting torque shows a continual decrease as the tilt angles of the corner tools are increased. The calculated torque for conical heads appear to be lower than those for the spherical heads (Figure 60).

For spherical heads, the reason for the decrease in the cutting torque was attributed to the values for force and cutting radius, all of which diminish with the increasing tilt angles. In conical heads the cutting radii are, in general, larger than those of spherical heads, whereas the overall pick forces appear to be much lower, due to the fact that each pick of conical head takes the force value for the corner tool of the corresponding spherical head. It should also be borne in mind that the corner tool has the lowest force for the spherical heads investigated in this section.

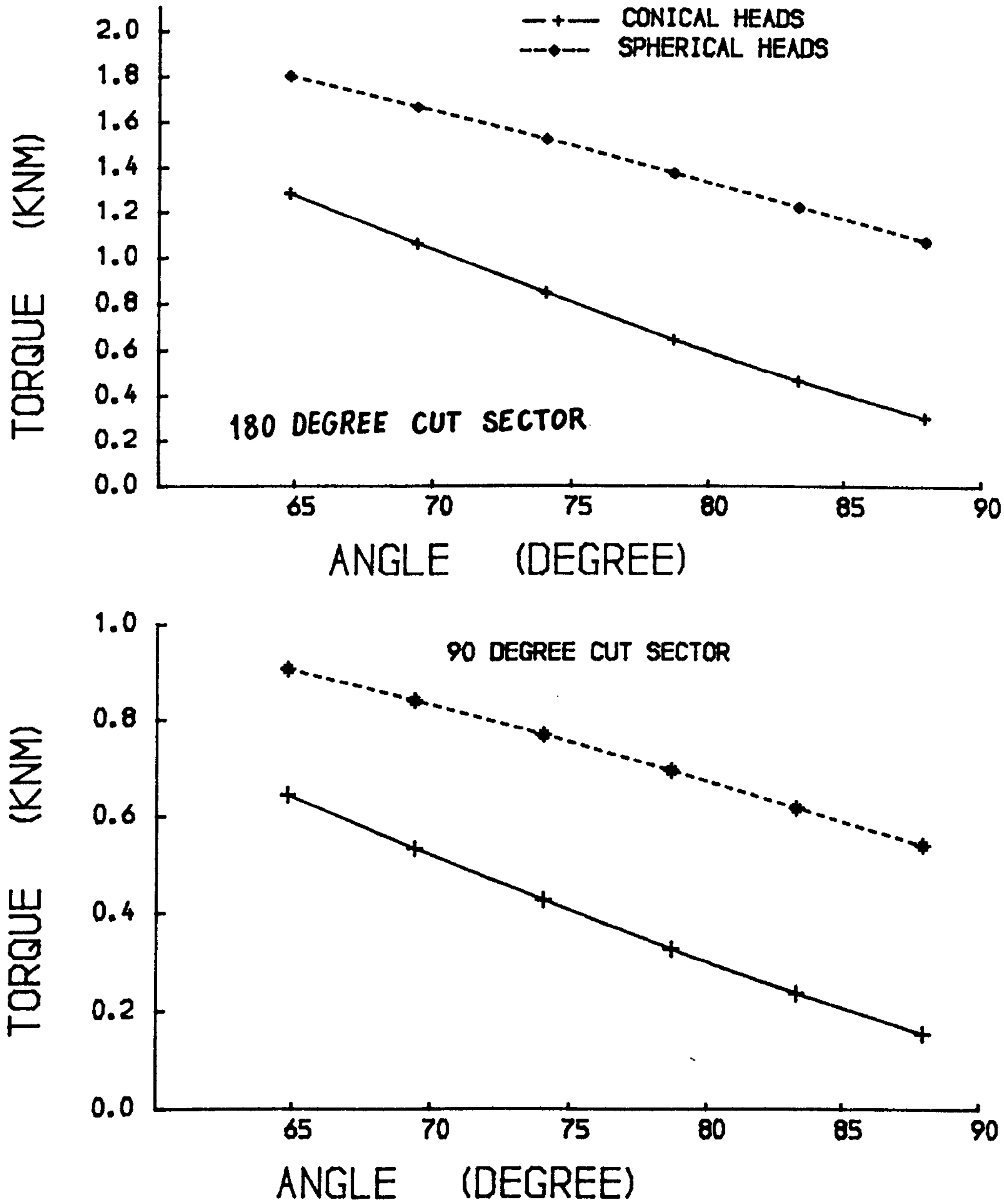


FIG. 60 VARIATION OF THE TORQUE VALUES WITH THE TILT ANGLE OF THE CORNER CUTTING TOOL , SPHERICAL AND CONICAL HEADS WITH 16 PICKS

10.5.1.2 Combined heads

For a given spherical head the torque decreases with cone angle; in other words, as the conical part of a combined head dominates the entire geometry the torque diminishes. Also, torque values become lower with decreasing tilt angles of corner cutting tools (Figure 61).

All these trends may be ascribed to the combined effects of both conical and spherical geometry and the variations in pick forces and cutting radius as described in 10.6.1.1.

10.5.2 Effects of head geometry on slewing force

10.5.2.1 Spherical and conical heads

Horizontal reactions decreased with the increasing values for corner cutting tools and the degree of reduction seems to be more rapid in the case of conical heads (Figure 62).

The variations of slewing forces may only be related to the individual pick forces, since on a given cutting head, the slewing forces are affected by the tool forces. The rapid falls in the case of conical heads is probably due to the force levels being lower than those of spherical heads.

10.5.2.2 Combined Heads

The slewing force reduces with the increase of cone angle and the tilt angles of corner cutting tools, being the quotient of

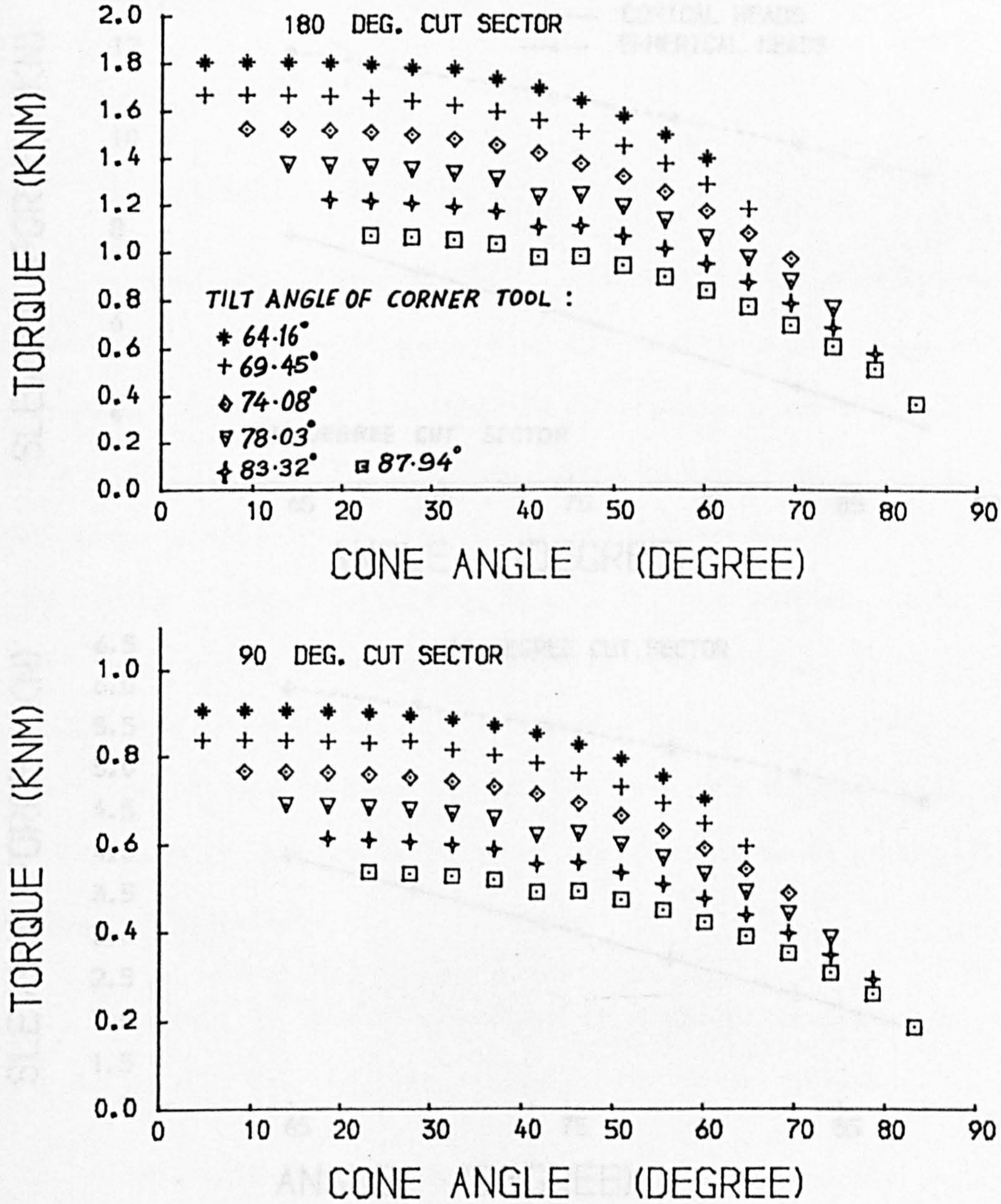


FIG. 61 VARIATIONS OF TORQUE VALUES WITH THE CONE ANGLE OF THE CUTTING HEADS WITH DIFFERENT CORNER CUTTING TOOL POSITIONS.

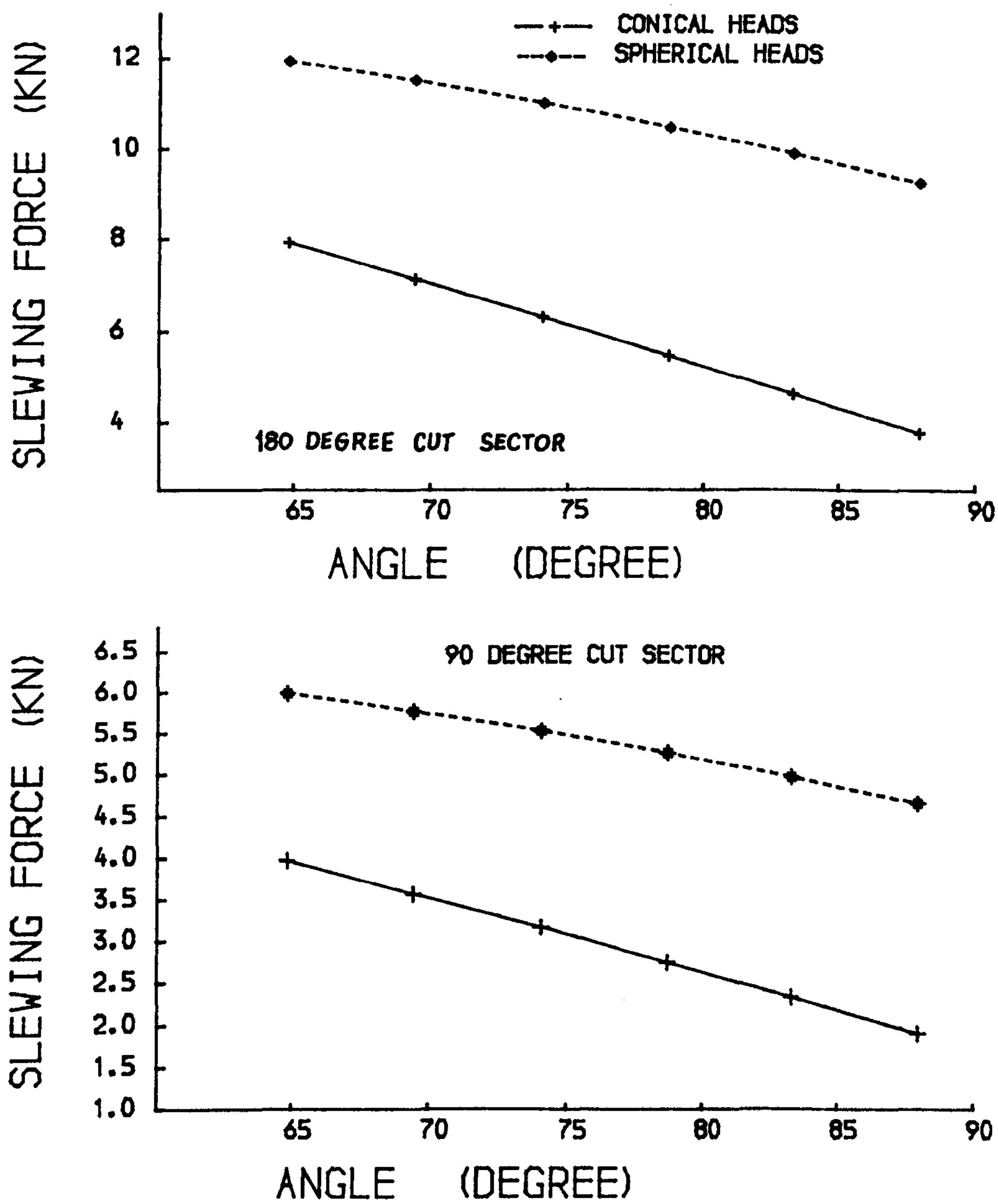


FIG. 62 VARIATION OF SLEWING FORCE VALUES WITH THE TILT ANGLE OF THE CORNER CUTTING TOOL, SPHERICAL AND CONICAL HEADS WITH 16 PICKS

the combined effects of the two head geometries, as expained above (Figure 63).

10.5.3 Fluctuations in torque and slewing force

10.5.3.1 Spherical heads

(a) Fluctuations in slewing force

As outlined in Chapter Three, force or torque fluctuations are due to the presence of gross disparities between the tool duties, i.e. when magnitude of the forces and torque experienced by each tool becomes different. If the standard deviations of slewing force or torque for a revolution of a cutting head is assumed to be the criterion for comparing a number of cutting heads, the fluctuations would then be influenced by the magnitude of overall tool forces; in other words, the higher the tool forces, the larger the standard deviation or fluctuations. This situation may be seen from the figures which are given in Appendix 6B1 and showing the torque and force fluctuation per advance/revolution.

In Figure 64 the fluctuations in slewing force present a steady decrease, with the tilt angles of the corner tools.

As the tilt angles increased the number of tools in the nose region would rise and thus the tool duties changed, due to the rapid decrease of forces in this region. If Figures 40 and 42 are considered, it may be seen that the variations in tool forces are slow up to the

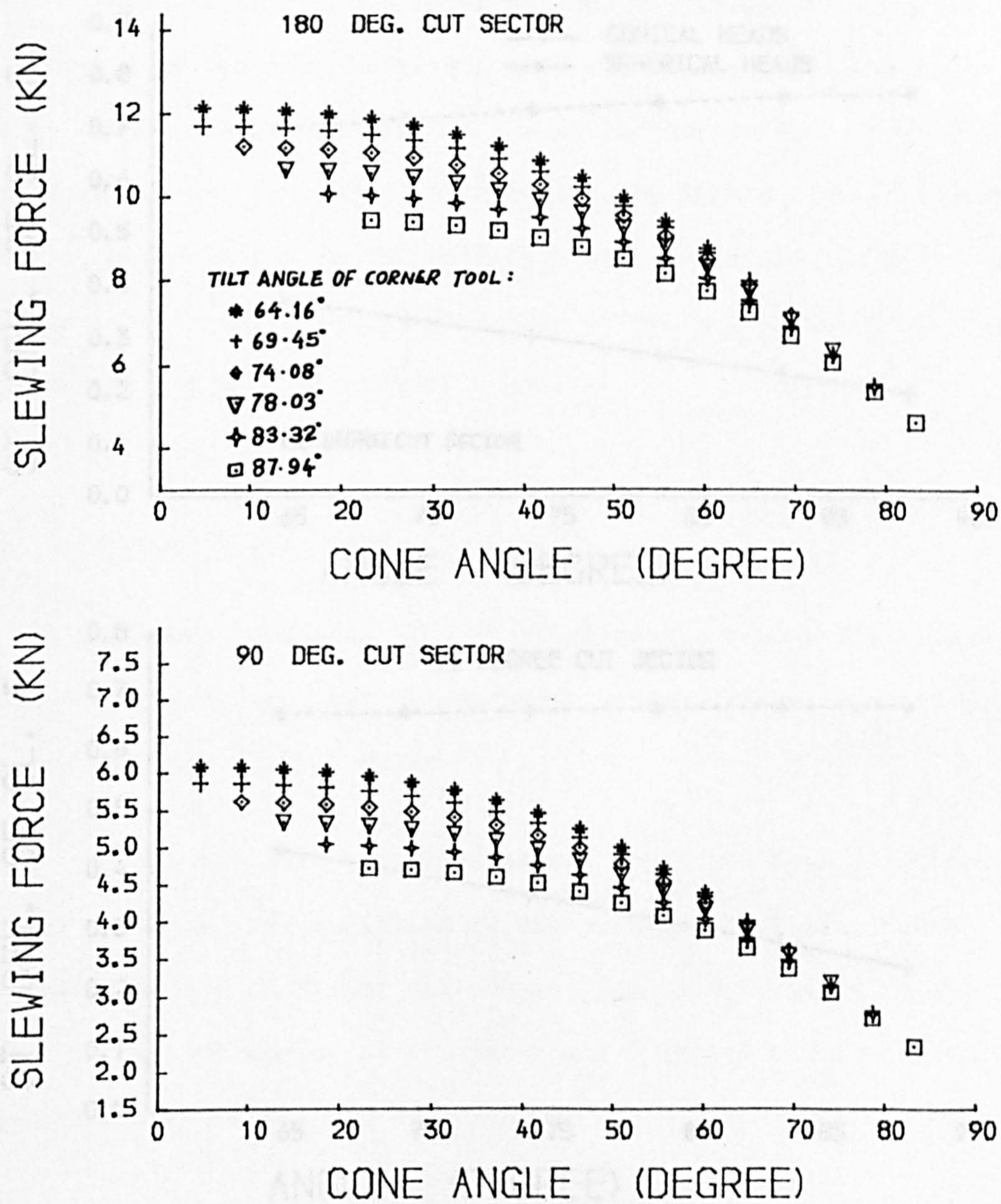


FIG. 63 VARIATIONS OF SLEWING FORCE VALUES WITH CONE ANGLE OF THE CUTTING HEADS WITH DIFFERENT CORNER CUTTING TOOL POSITIONS .

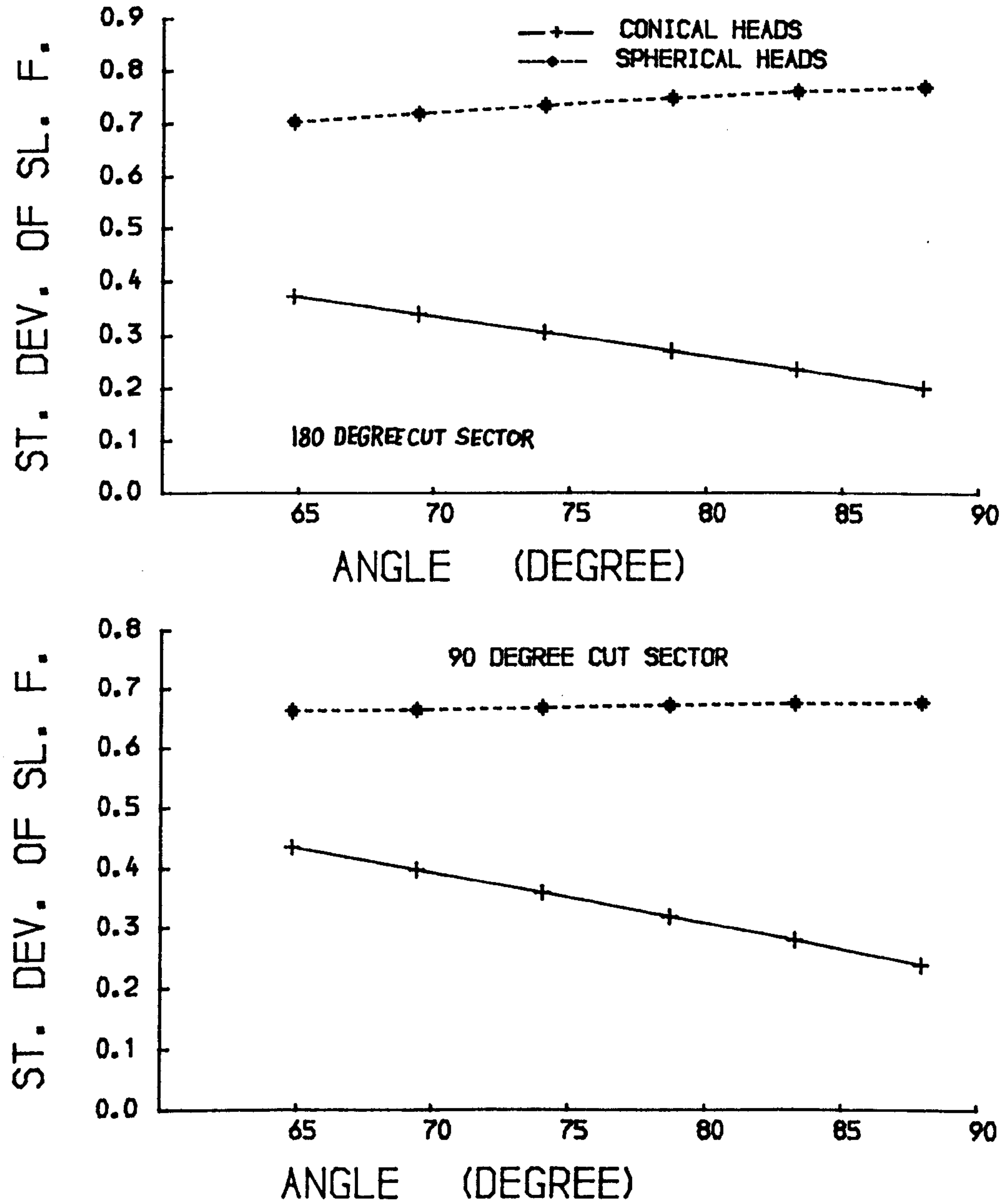


FIG. 64 VARIATION IN ST. DEV. OF SLEVING FORCE VALUES WITH THE TILT ANGLE OF THE CORNER CUTTING TOOL, SPHERICAL AND CONICAL HEADS WITH 16 PICKS

tilt angle (about 50°) and below this value forces remain constant compared with the forces at tilt angles higher than 50°.

The majority of the tools are usually situated below this value for many cutting heads and this may mean the overall tool forces do not change significantly when the corner tools have the higher values of tilt angle. Therefore, the steady rise in slewing force is probably due to the different tool duties in the nose region. Fluctuations in the slewing force are, however, not significant when compared with those for conical heads.

(b.) Torque fluctuations

As shown in Figure 65 fluctuations in torque first show a steady increase and, having reached a minimum value, tend to fall towards the higher tilt angles.

At low tilt angles, fluctuations in torque seem to follow a similar trend to that explained in the previous section. However, the decreasing manner at higher tilt angles may be attributed to the effect of cutting radius of the picks which causes the torque values to become smaller towards the nose region.

Torque fluctuations for spherical heads did not show a significant variation compared with those for conical heads, and these are given in Appendix 6B1.

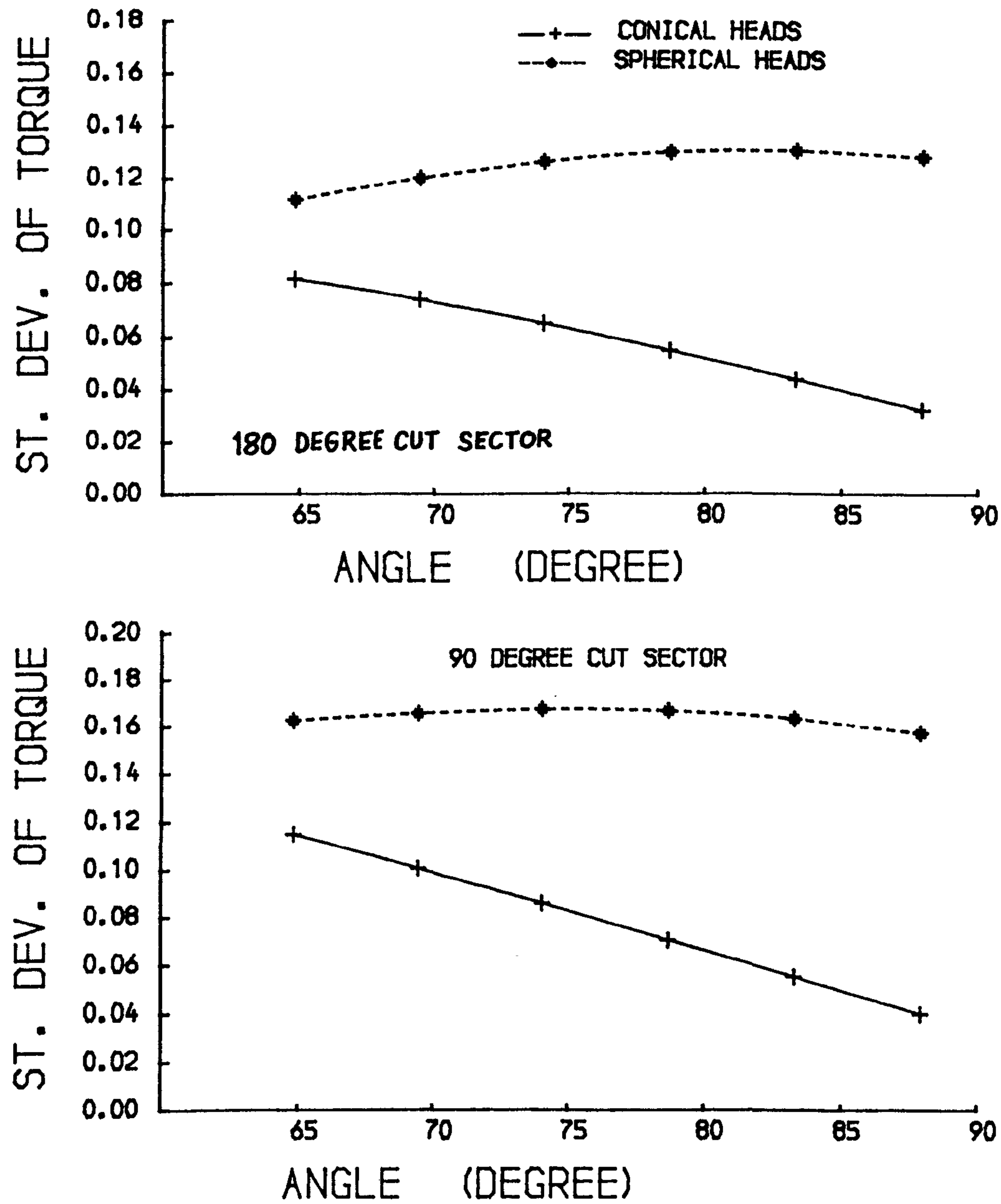


FIG. 65 VARIATION IN STANDARD DEVIATION OF TORQUE VALUES WITH THE TILT ANGLE OF THE CORNER CUTTING TOOL, SPHERICAL AND CONICAL HEADS WITH 16 PICKS

10.5.3.2 Conical heads

Fluctuations in slewing forces and torque show a rapid decrease with tilt or cone angles and the magnitudes are much smaller than those of spherical heads, due to the low pick forces (Figures 64 and 65).

Being different from spherical heads, the pick forces on a conical head are constant and at the higher cone angles the differences in these forces are generally high and, therefore, this results in a rapid decrease of fluctuations in torque and slewing force.

Fluctuations in torque and slewing force values per advance/revolution are shown in Appendix 6B2.

10.5.3.3 Combined heads

Being the quotient of spherical and conical heads, the fluctuations in torque and slewing force significantly reduce as the cone angle and the tilt angle of corner cutting tools become higher (Figures 66 and 67).

Fluctuations in torque and slewing force values per advance/revolution are shown in Appendix 6B3.

10.5.4 Volume of the material swept per advance/revolution of a cutting head

The volume of material excavated per advance/revolution of a given head decreases with the increasing tilt or cone angle. It would

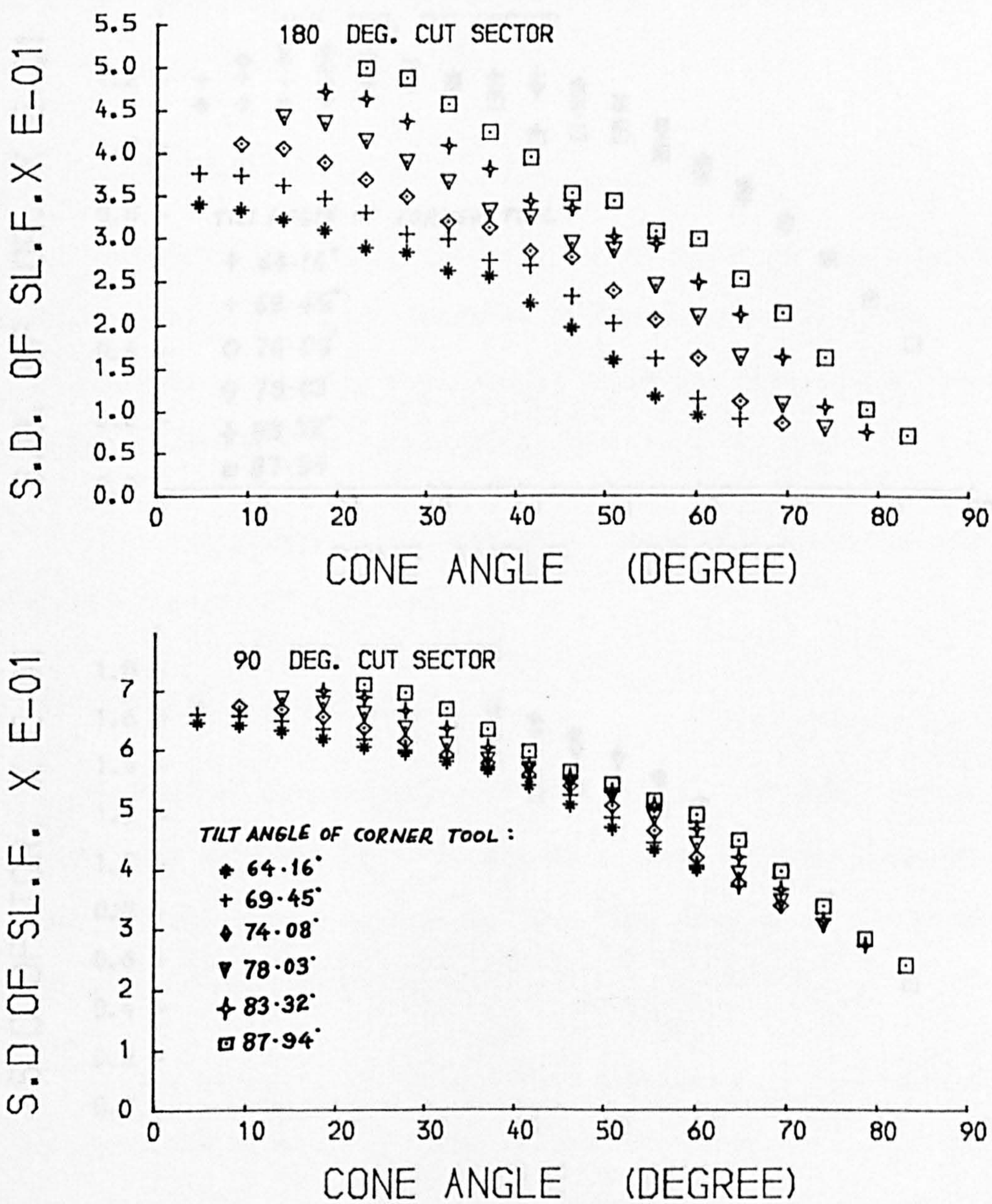


FIG. 66 VARIATIONS IN ST. DEV. OF SLEWING FORCE VALUES WITH CONE ANGLE OF THE CUTTING HEADS WITH DIFFERENT CORNER CUTTING TOOL POSITIONS .

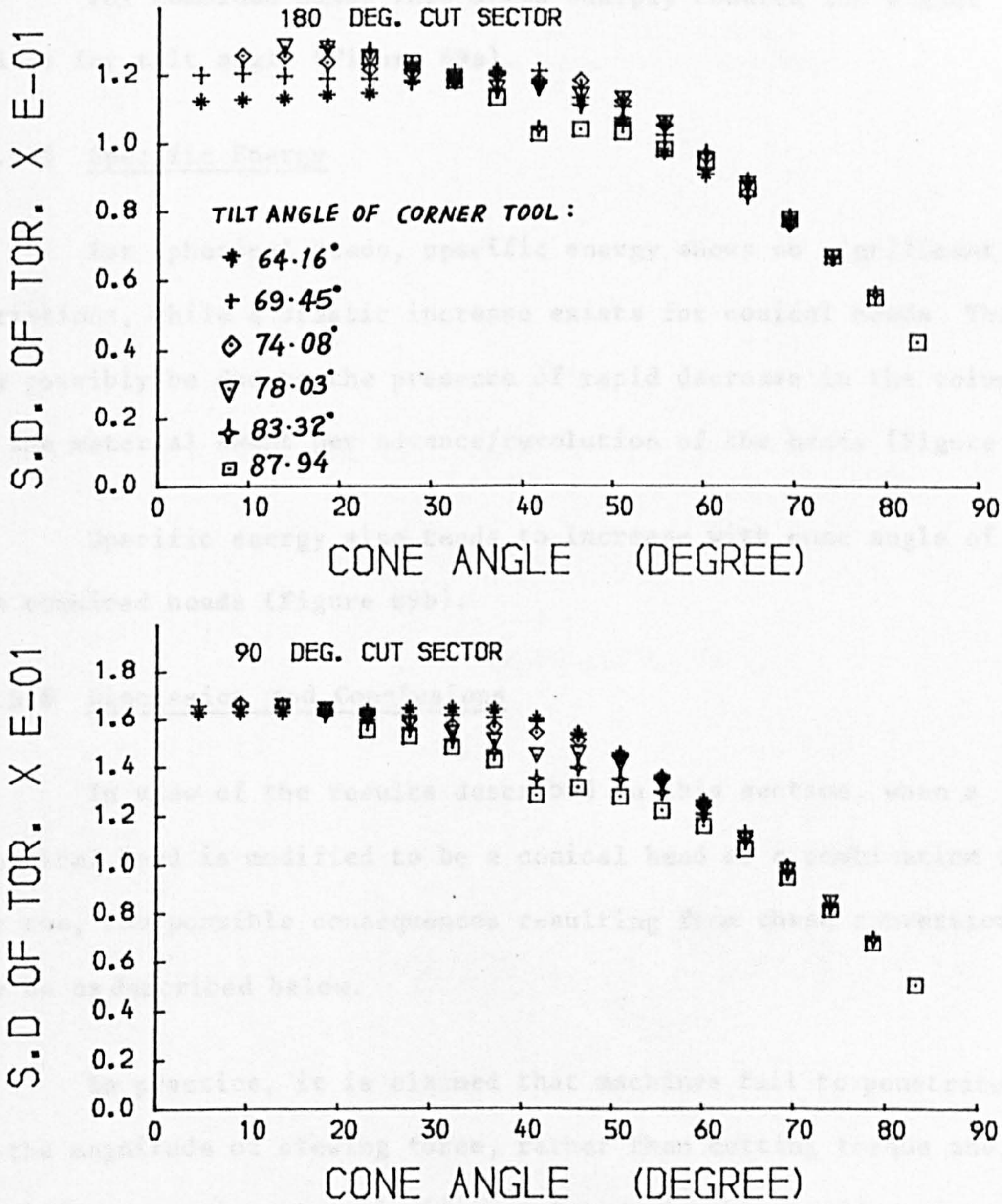


FIG. 67 VARIATIONS IN ST. DEV. OF TORQUE VALUES WITH CONE ANGLE OF THE CUTTING HEADS WITH DIFFERENT CORNER CUTTING TOOL POSITIONS .

seem that spherical heads sweep more material than the conical heads (Figure 68).

For combined heads this drops sharply towards the higher values for tilt angle (Figure 69a).

10.5.5 Specific Energy

For spherical heads, specific energy shows no significant variations, while a drastic increase exists for conical heads. This may possibly be due to the presence of rapid decrease in the volume of the material swept per advance/revolution of the heads (Figure 70).

Specific energy also tends to increase with cone angle of the combined heads (Figure 69b).

10.5.6 Discussion and Conclusions

In view of the results described in this section, when a spherical head is modified to be a conical head or a combination of the two, the possible consequences resulting from these conversions may be as described below.

In practice, it is claimed that machines fail to penetrate because of the magnitude of slewing force, rather than cutting torque and specific energy is not a significant factor in the consideration of machine design but is, however, of value for machine operations. The magnitude of the pick forces on a cutting head are shown to be of importance, since the parameters affecting the performance of a tunnelling machine are also greatly controlled by individual tool forces.

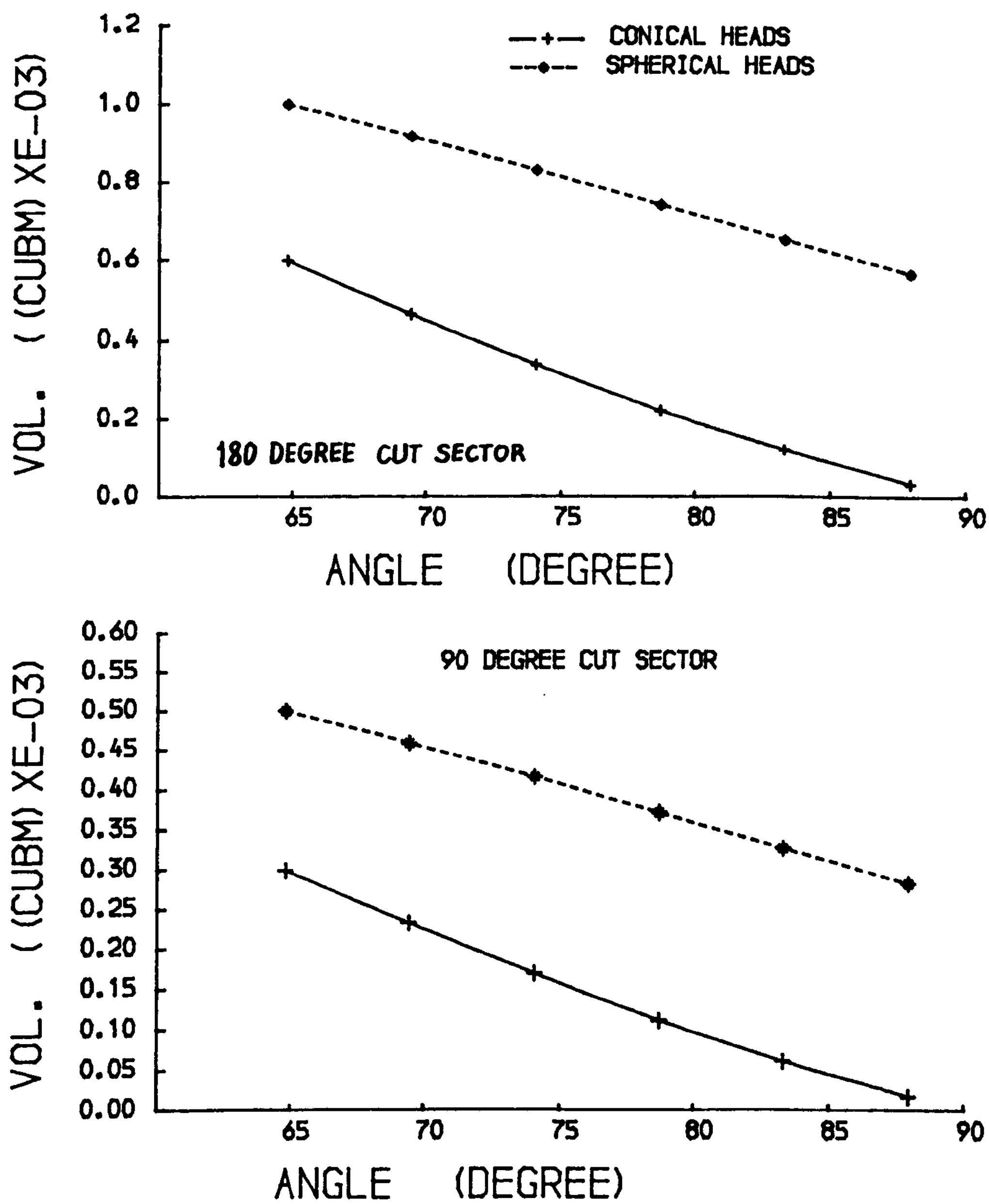
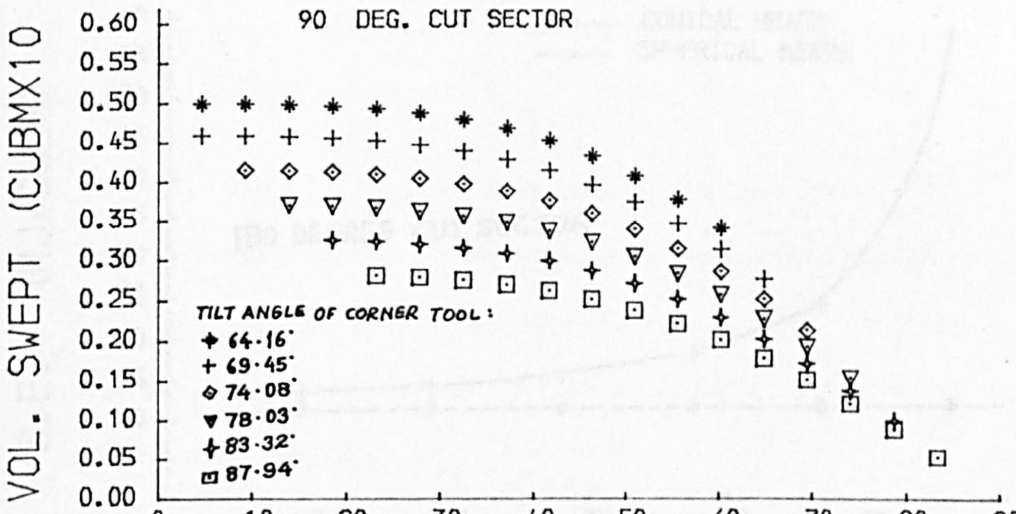


FIG. 68 VARIATION OF VOLUME SWEPT PER ADVANCE/REVOLUTION WITH THE TILT ANGLE OF THE CORNER CUTTING TOOL, SPHERICAL AND CONICAL HEADS WITH 16 PICKS

a)



b)

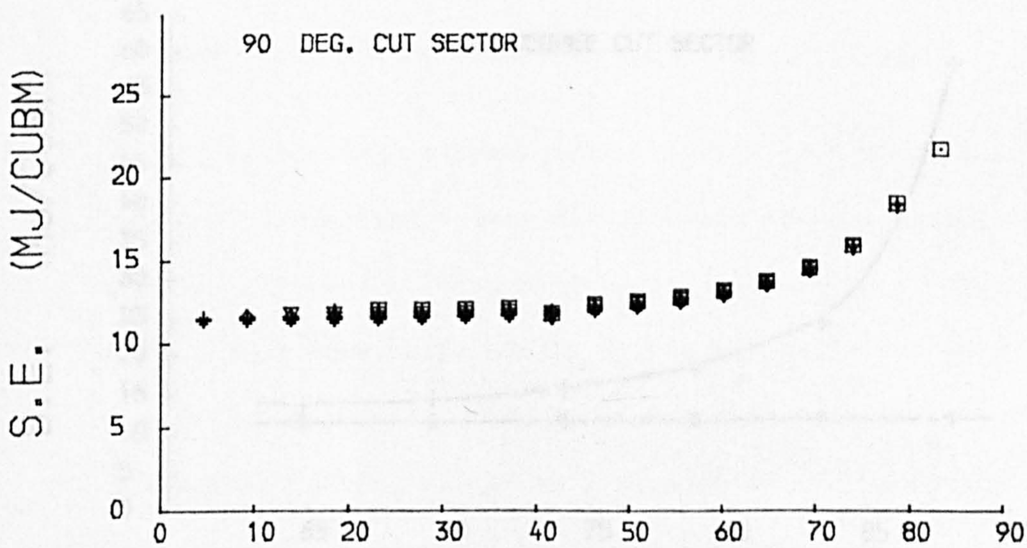


FIG. 69 VARIATIONS OF VOLUME SWEPT AND S.E. VALUES WITH CONE ANGLE OF THE CUTTING HEADS WITH DIFFERENT CORNER CUTTING TOOL POSITIONS .

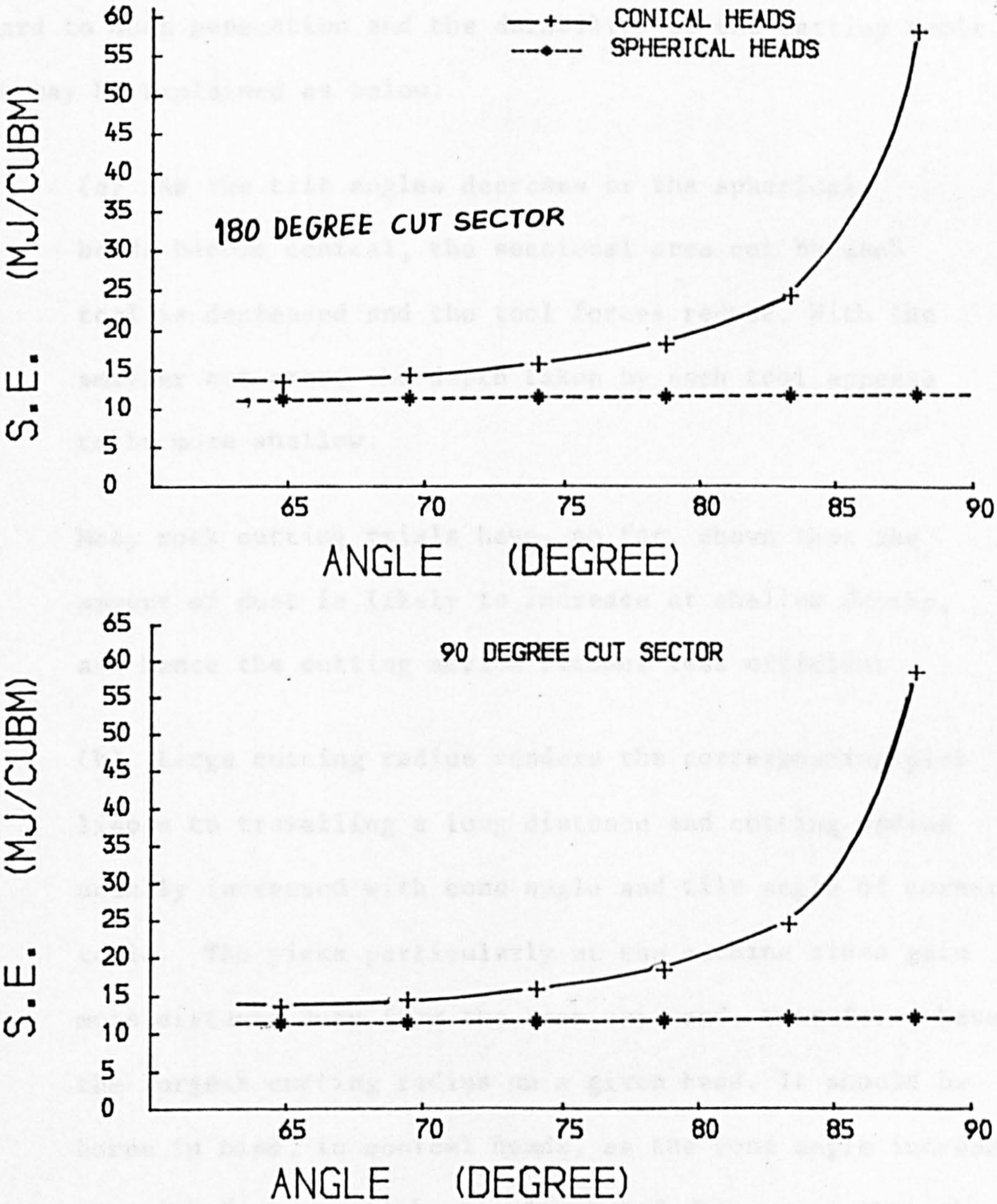


FIG. 70 VARIATION OF SPECIFIC ENERGY VALUES WITH THE TILT ANGLE OF THE CORNER CUTTING TOOL, SPHERICAL AND CONICAL HEADS WITH 16 PICKS

To some extent for the above reasons the conical heads seem to be better than spherical heads. But there appear to be some disadvantages to conical heads over the spherical heads with regard to dust generation and the durability of the cutting tools. This may be explained as below:

(a) As the tilt angles decrease or the spherical heads become conical, the sectional area cut by each tool is decreased and the tool forces reduce. With the smaller cut area, the depth taken by each tool appears to be more shallow.

Many rock cutting trials have, so far, shown that the amount of dust is likely to increase at shallow depths, and hence the cutting action becomes less efficient.

(b) Large cutting radius renders the corresponding pick liable to travelling a long distance and cutting radius usually increased with cone angle and tilt angle of corner tools. The picks particularly at the machine sides gain more distance duty from the boom axis and, therefore, have the largest cutting radius on a given head. It should be borne in mind, in conical heads, as the cone angle increases the pick forces will become lower and this means that the pick is travelling long distances whereas it has lower forces.

Although tool wear is influenced by deeper cuts, investigations have emphasised that the tool wear mainly increases with travelling distance (90, 91).

Accordingly, the extreme values for cone and tilt angles may not bring many advantages and from the results and explanations, it would seem that benefits might be gained through the selection of moderate cone and tilt angles for all of the cutting heads investigated in this section.

It should be noted that the variation in force and torque fluctuations referred to in this chapter apply only to the head conditions used. Normally torque fluctuations are dominated by the lacing pattern employed.

*   *   *

11. ASPECTS OF CUTTING HEAD DESIGN

11.1 Introduction

For each roadheader there are a number of geometries and sizes of cutting head available. For a given head, the total number of picks can be changed by varying the tool spacing between adjacent tools keeping the other dimensions constant. This situation was discussed in Chapter Eight, and it was shown that the measured parameters presented a significant variation with changing spacing.

In Chapter Nine it was shown that tool duties for a given cutting head were affected by tilt angle, advance/revolution and total number of picks fitted on the head, and the tilt angle was the only variable studied. The effect of total number of picks at a constant advance/revolution will be investigated in this chapter.

In practice, on most cutting heads, the cutting sequences start from the nose and progress towards the machine side of the head. It has been shown that (Pomeroy and Robinson, 28) the tool forces become higher when cutting in this mode; the aspects of corner cutting tools in this mode of operation has also been included in this chapter.

11.2 Cutting heads with different numbers of tools

In order to avoid a large number of cutting experiments, only one cutting head type has been considered for these investigations.

A cutting head with spherical geometry was chosen due to the applicability of the measured parameters to the other type of geometry, as detailed in Chapter Nine.

A typical cutting head design for this investigation is shown in Figure 71. As can be seen from the figure, the length of cutting head is extended without altering the spacing between adjacent tools. Cutting head 1 has a total of eight picks which are disposed around a periphery from A to B. The next cutting head is derived from the former one in such a way that the additional picks are arranged from the Point B to C at the same spacing. Cutting heads 3 and 4 are obtained in a similar way (Figure 71).

11.3 Experimental Design

In view of the explanations given in the previous section, four cutting heads were planned for the experiments. All cutting heads were simulated under identical conditions and thus the only variable was the total pick number on each head.

The cutting heads are illustrated in Figure 71 and they are described as follows:

(a) Cutting Head 1 : has a total of 8 tools and the corner cutting tool has a tilt angle of $50\text{-}90^{\circ}$. The tilt angle of the first gauge tool is $18\text{-}51^{\circ}$.

(b) Cutting Head 2 : Total pick number 16. This head already includes eight tools of cutting head 1. The

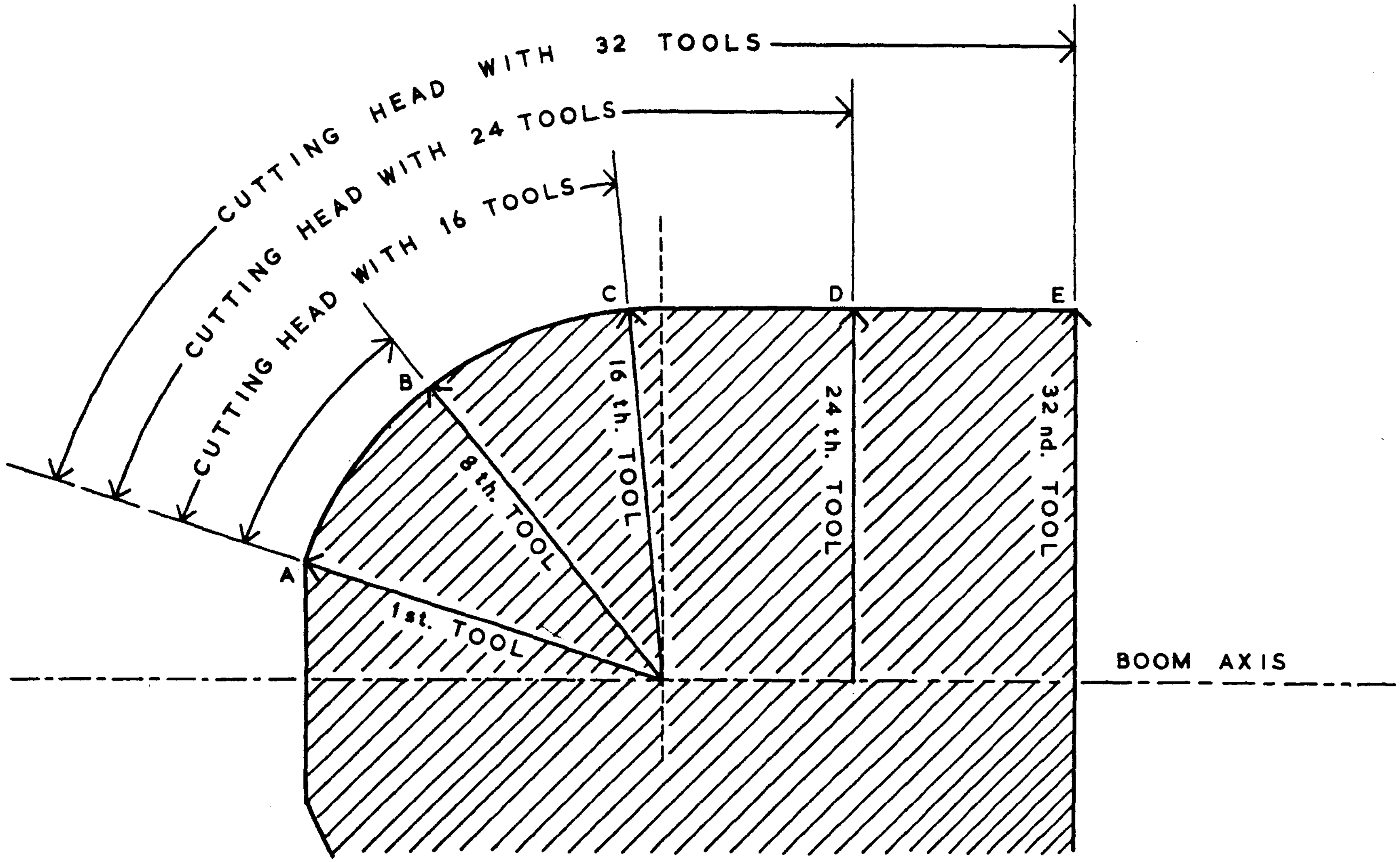


Fig. 71 Notation of cutting heads with different tool numbers.

remaining 8 tools are, therefore, arranged from the first tool of the head 1 towards the machine side.

(c) Cutting Head 3 : There are 24 tools arranged on this cutting head and thus heads 1 and 2 are included in this head.

(d) Cutting Head 4 : This head has the largest tool number and covers the tool positions of the cutting heads 1, 2 and 3.

Corner cutting tools were investigated at only one level of cutting position, since such simulation experiments are laborious and time-consuming. The tilt angle of the corner cutting tool for all the cutting heads was taken at 50.91^{o}. As previously shown, at higher tilt angles, because of the reduced cross-sectional cut area, the tool forces were usually of low magnitude and, therefore, any possible differences in force values for all the cutting heads may not be sensitive and distinguishable. It was for this reason that tilt angles were taken at low values.

The experimental variables for this investigation are as follows:

Factor	Level	Description
Tilt angle of corner cutting tools	1	50-93^{o}
Tilt angle of gauge tools	7	46.30, 42.67, 37.04 32.41, 27.78, 23.15 18.52
Number of cutting heads	4	Head 1 : with 32 tools Head 2 : with 24 tools Head 3 : with 16 tools Head 4 : with 8 tools
Replications	3	
Total:	112	instrumented cuts (including all tilt angles of cutting head 4.

All the experiments were carried out in the same way as that described in Chapter Nine.

11.4 Results and Discussion

11.4.1 Effects of Tool Numbers

The results for these experiments are tabulated in Appendices 5A3, 5A4 and 5B2.

11.4.1.1 Forces

As can be seen in Figure 72a,b,c,d,e, and f, the number of tools has no significant influence on the gauge tools within the measured levels. However, with respect to corner cutting tools, the

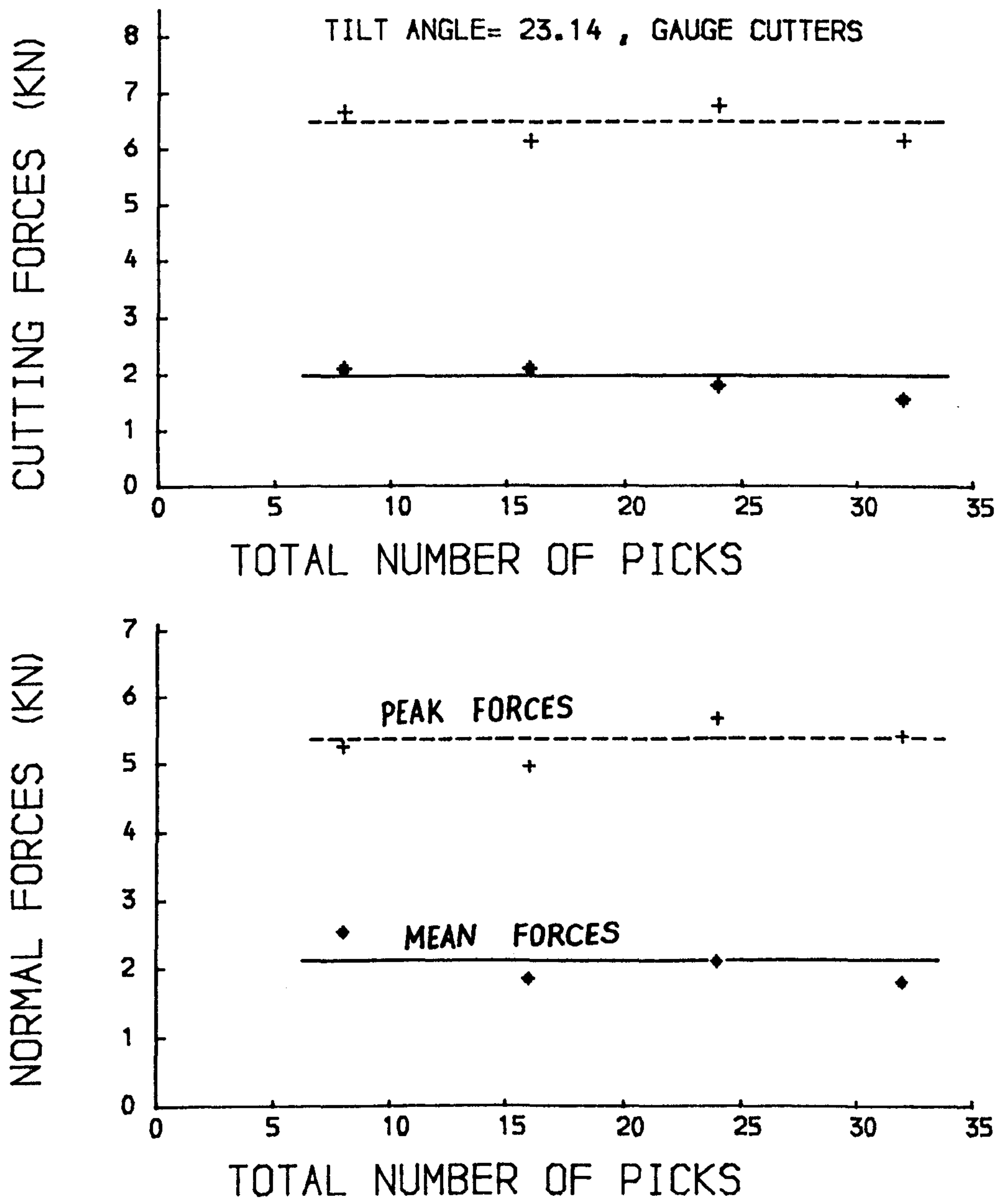


FIGURE.72a VARIATION OF PICK FORCES WITH CUTTING HEADS HAVING DIFFERENT NUMBER OF CUTTING TOOLS.

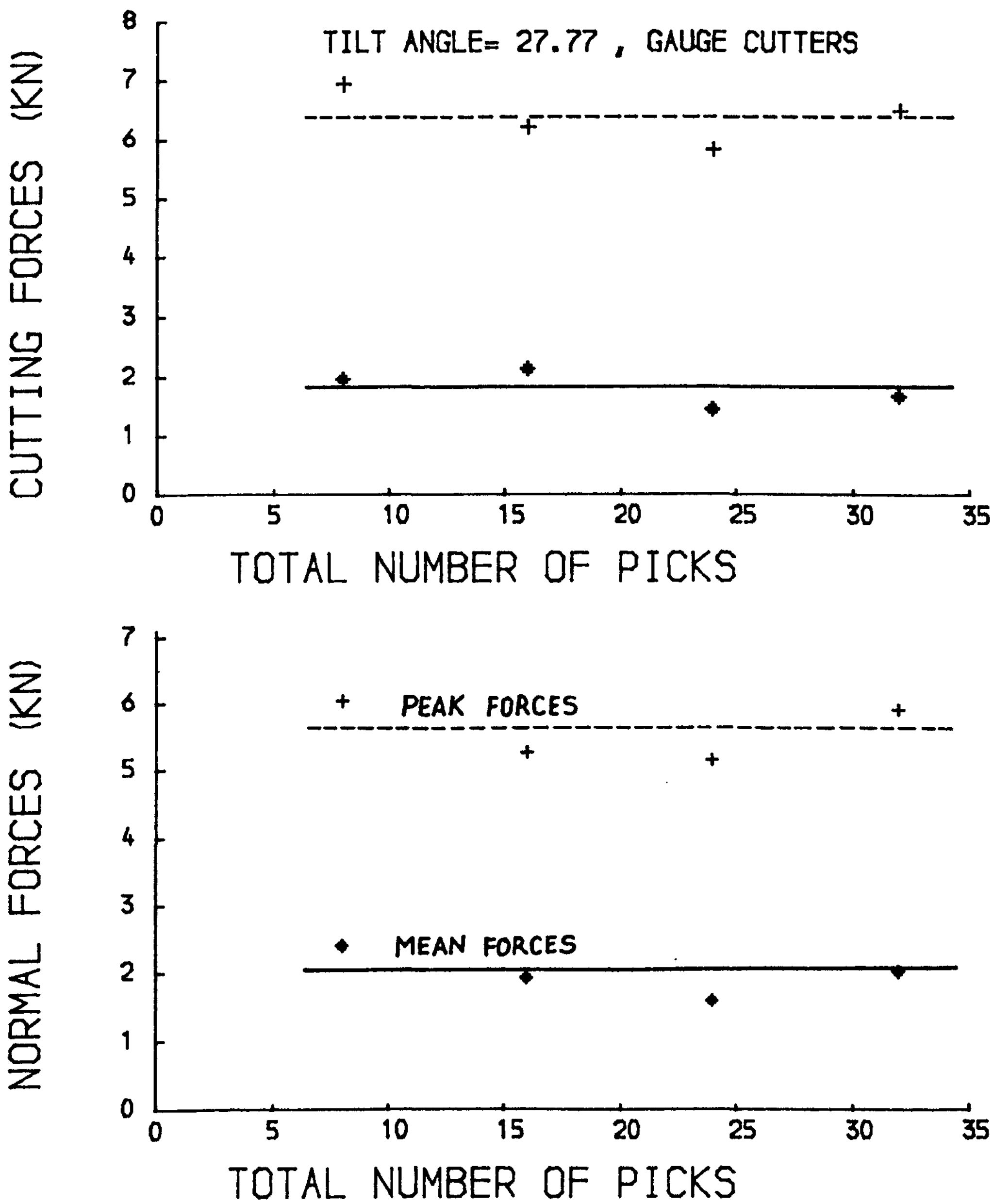


FIGURE.72b VARIATION OF PICK FORCES WITH CUTTING HEADS HAVING DIFFERENT NUMBER OF CUTTING TOOLS.

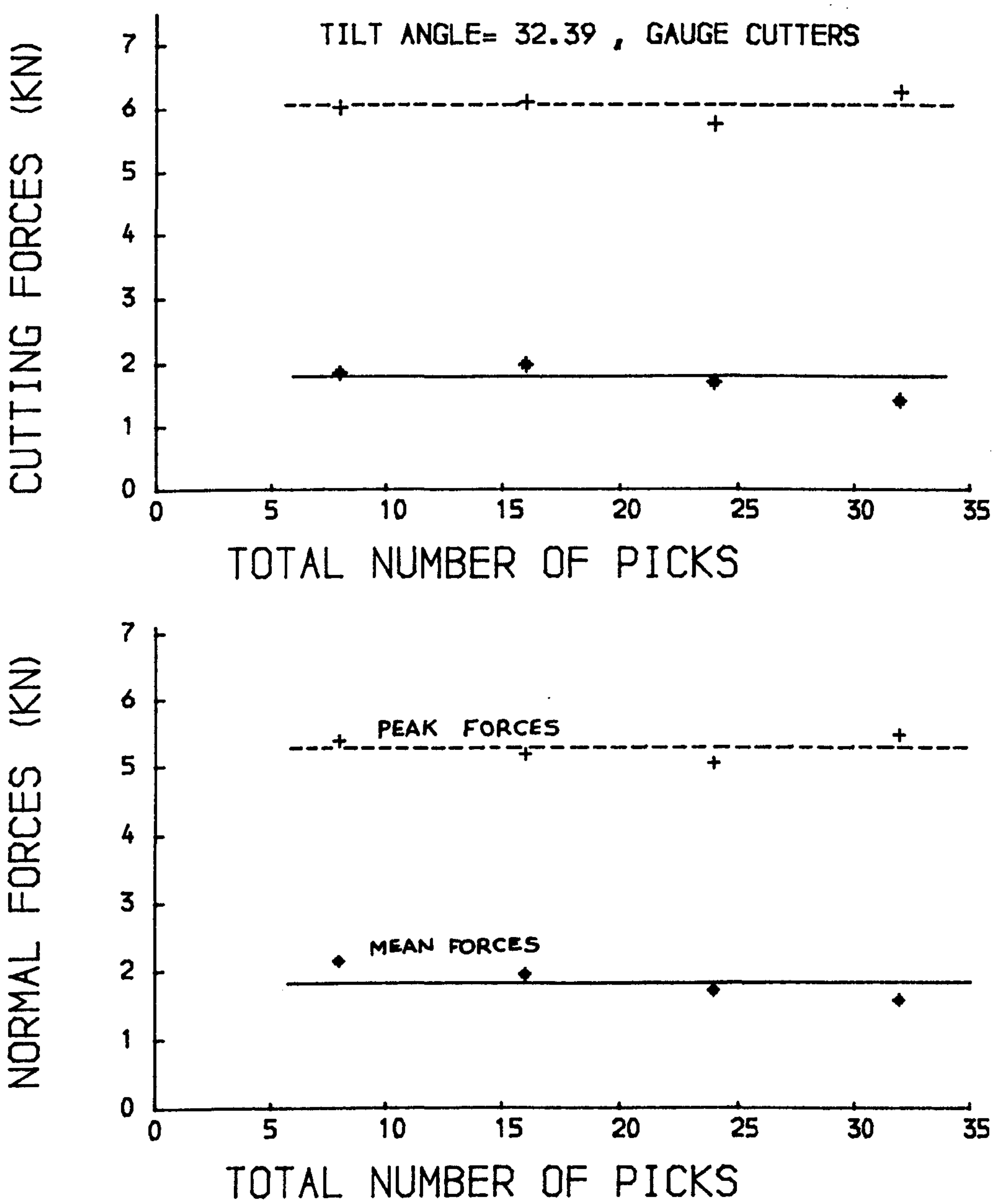


FIGURE.72c VARIATION OF PICK FORCES WITH CUTTING HEADS HAVING DIFFERENT NUMBER OF CUTTING TOOLS.

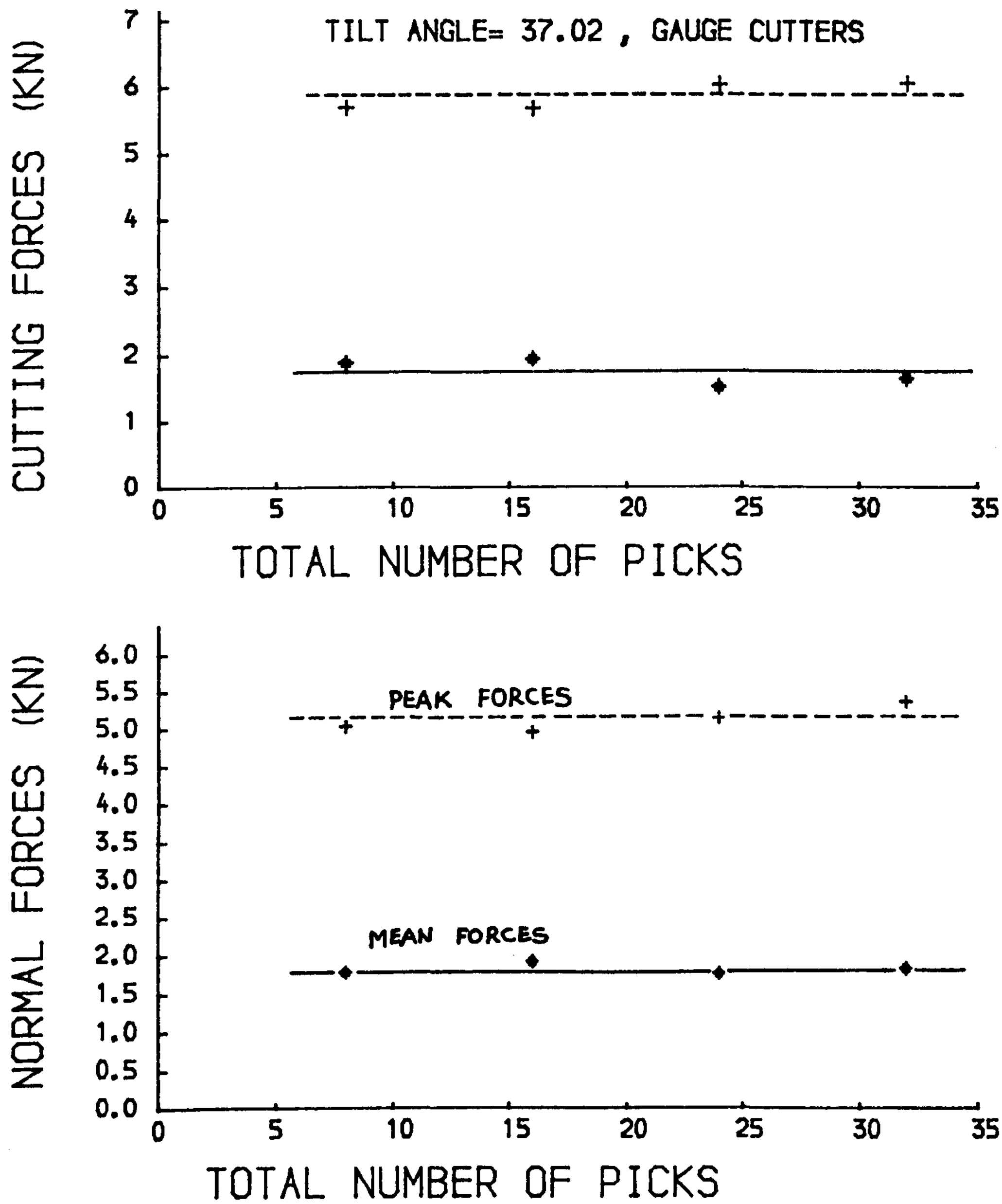


FIGURE.72d VARIATION OF PICK FORCES WITH CUTTING HEADS HAVING DIFFERENT NUMBER OF CUTTING TOOLS.

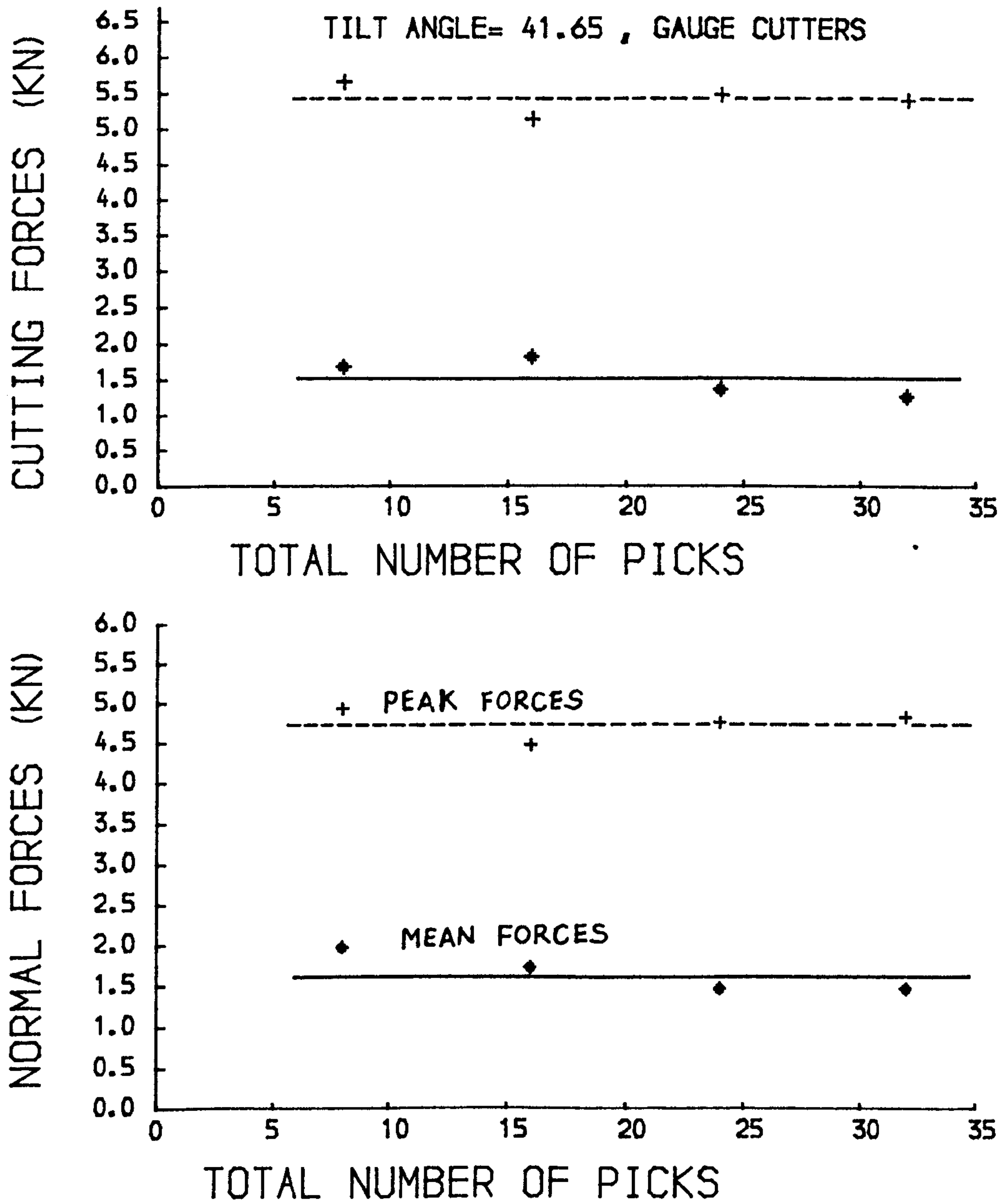


FIGURE.72e VARIATION OF PICK FORCES WITH CUTTING HEADS HAVING DIFFERENT NUMBER OF CUTTING TOOLS.

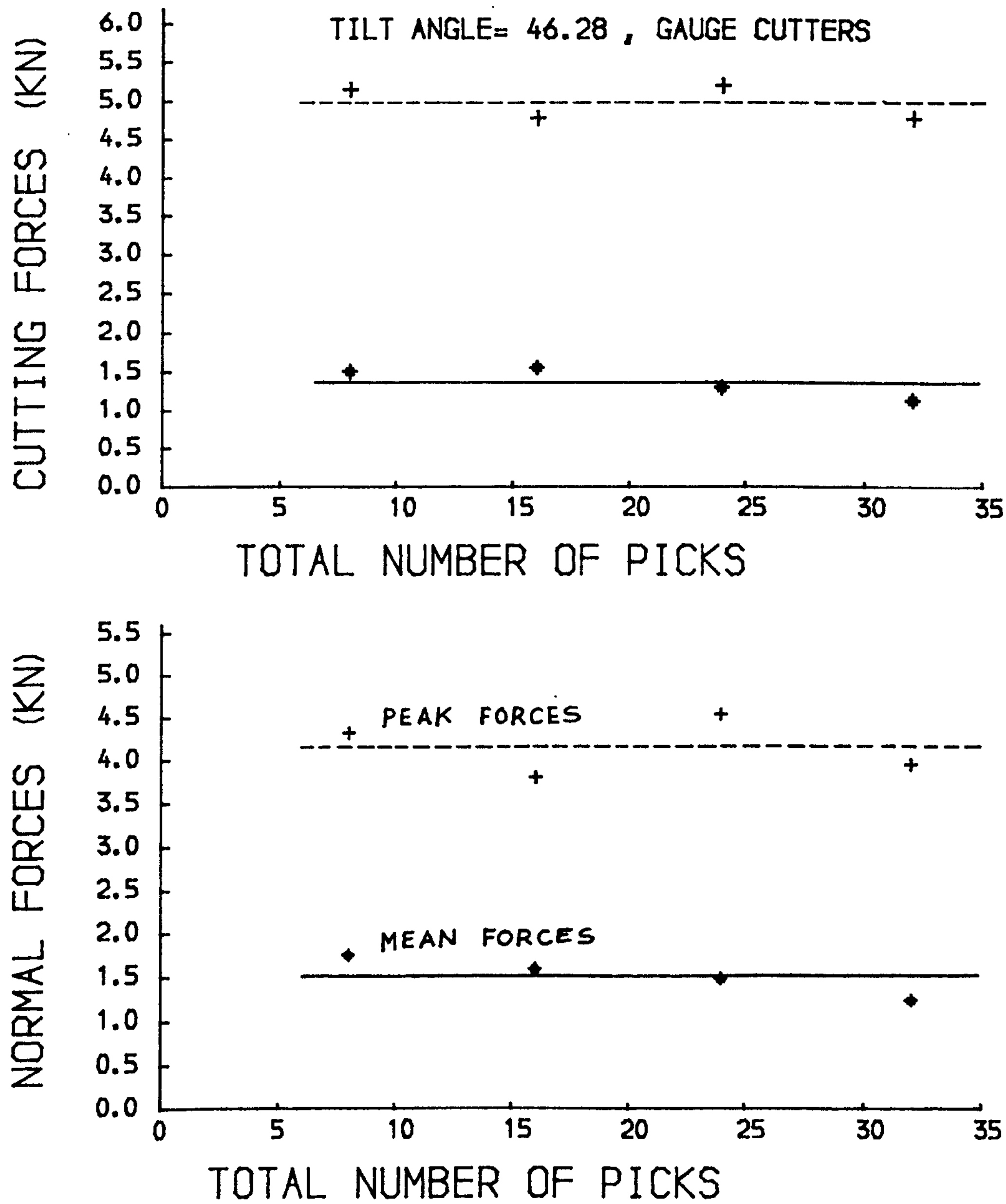


FIGURE.72f VARIATION OF PICK FORCES WITH CUTTING HEADS HAVING DIFFERENT NUMBER OF CUTTING TOOLS.

trend was different where the tool forces tended to show a decrease with total pick numbers (Figure 73).

11.4.1.2 Yield

The yield values for individual picks were measured at a tilt angle of 32.41° and are shown in Figure 74. The yield values did not present any variation and tended to be constant with the tool numbers.

11.4.1.3 Specific Energy

Specific energy values did not show any significant change with the tool numbers, as given in Figure 74.

11.4.2 Discussion

If the cutting action of the heads is considered in general, it can be seen that each head sweeps a certain volume of material with respect to its size (as illustrated in Figure 75). Furthermore, all cutting heads have a number of common tools (including the corner cutting tools) at the nose side; in other words, the last eight tools at the nose side are common to all cutting heads with regard to the tilt angles. The cross-sectional area cut by each tool was calculated from '$S_e \times d_e$' and remained approximately constant for all cutting heads. But values for S_e, and d_e respectively became different, as shown in Table 12 and Figures 76, 77 and 78.

Experimental results have revealed no significant differences in force values for the gauge cutters of the cutting heads. Further,

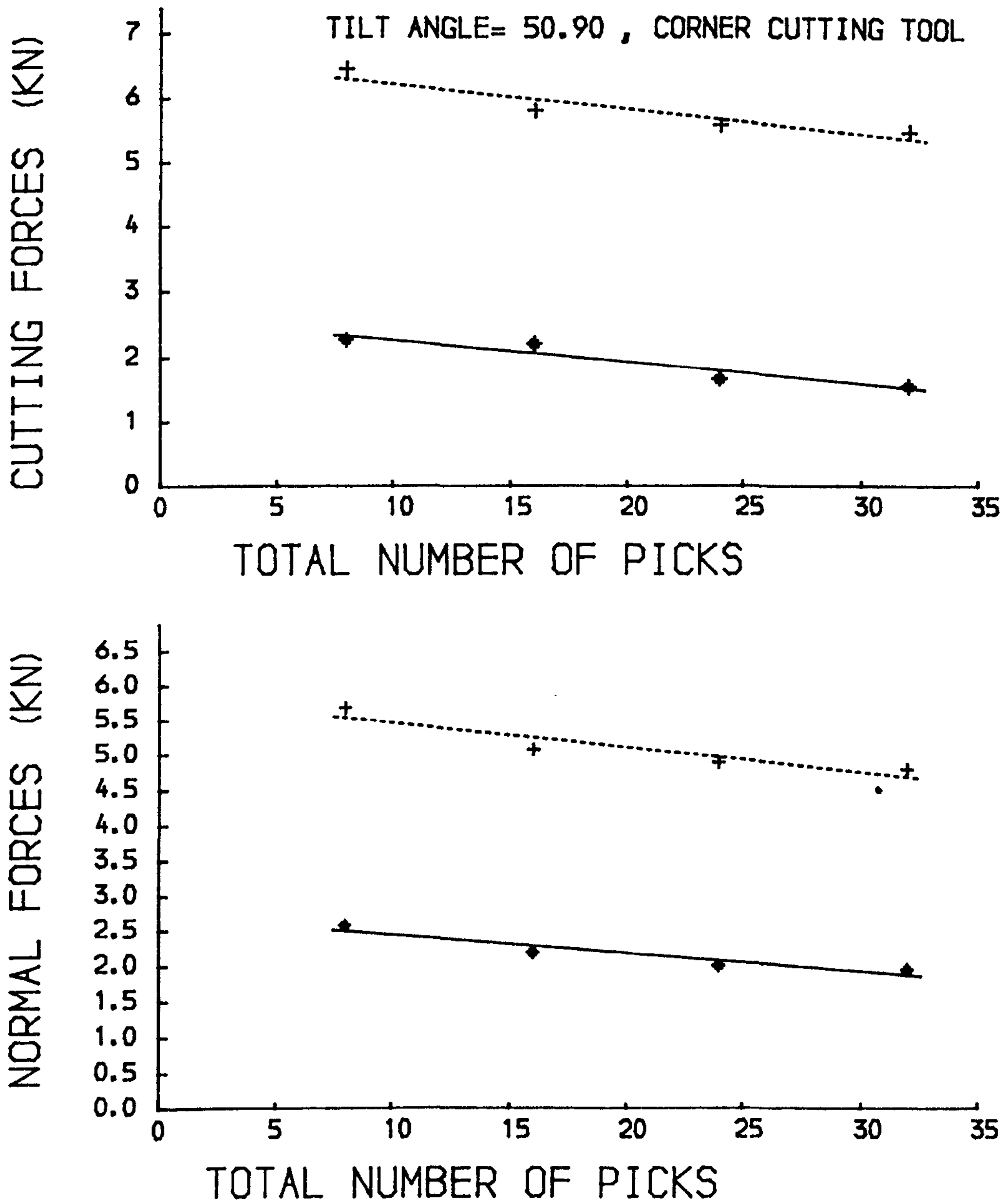


FIGURE.73 VARIATION OF PICK FORCES WITH CUTTING HEADS HAVING DIFFERENT NUMBER OF CUTTING TOOLS.

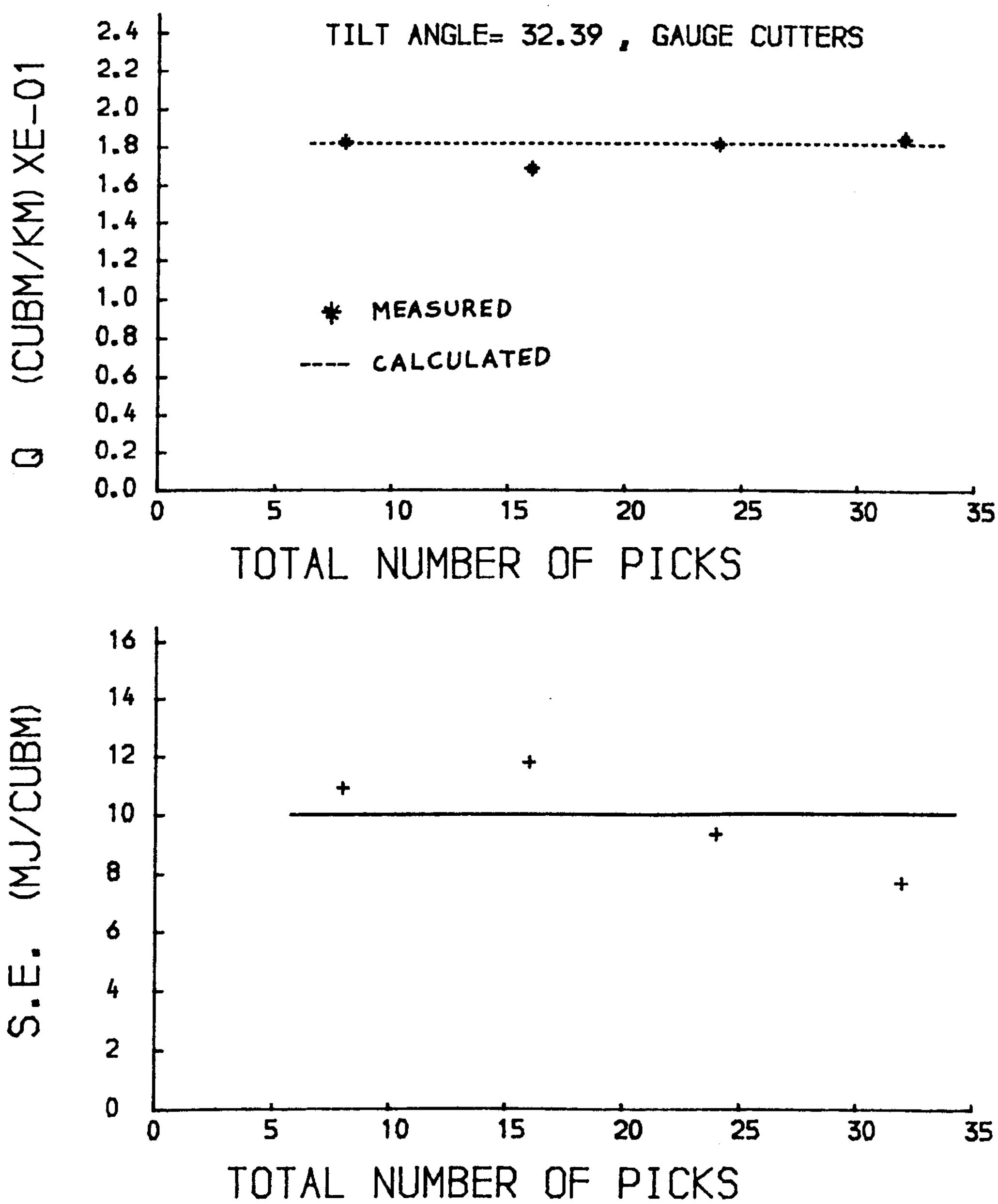


FIG. 74 VARIATION OF YIELD AND S.E. WITH CUTTING HEADS HAVING DIFFERENT NUMBER OF CUTTING TOOLS.

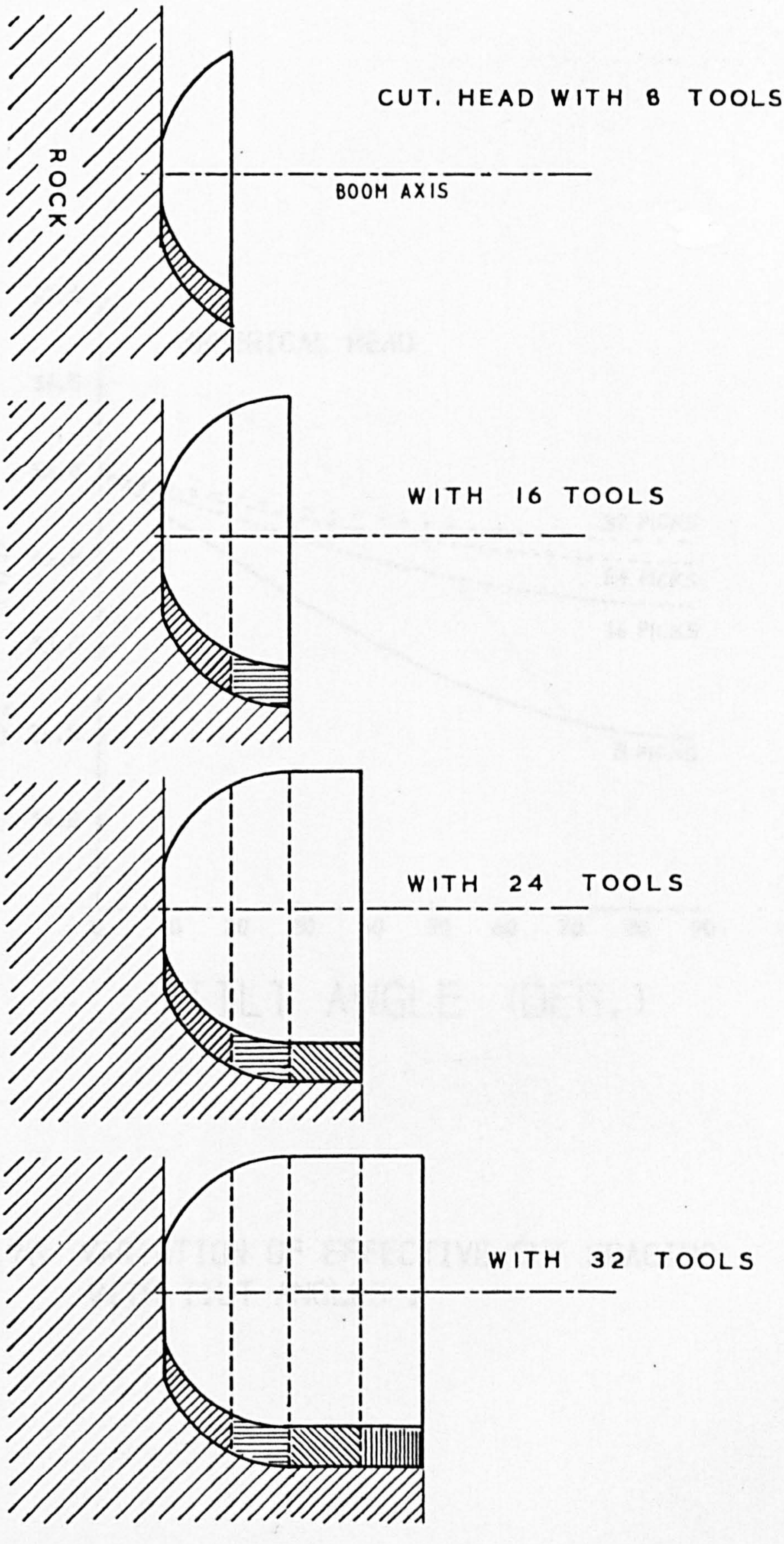


Fig. 75 Illustration of area swept;
Cutting headswith different tool numbers.

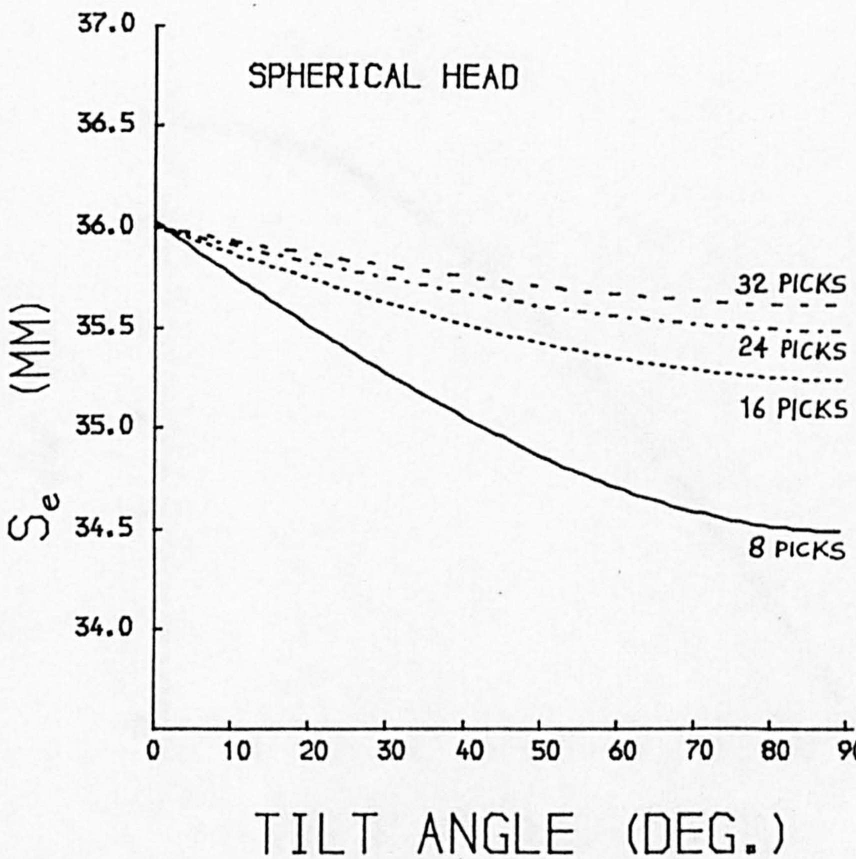


FIG. 76 VARIATION OF EFFECTIVE CUT SPACING WITH TILT ANGLES .

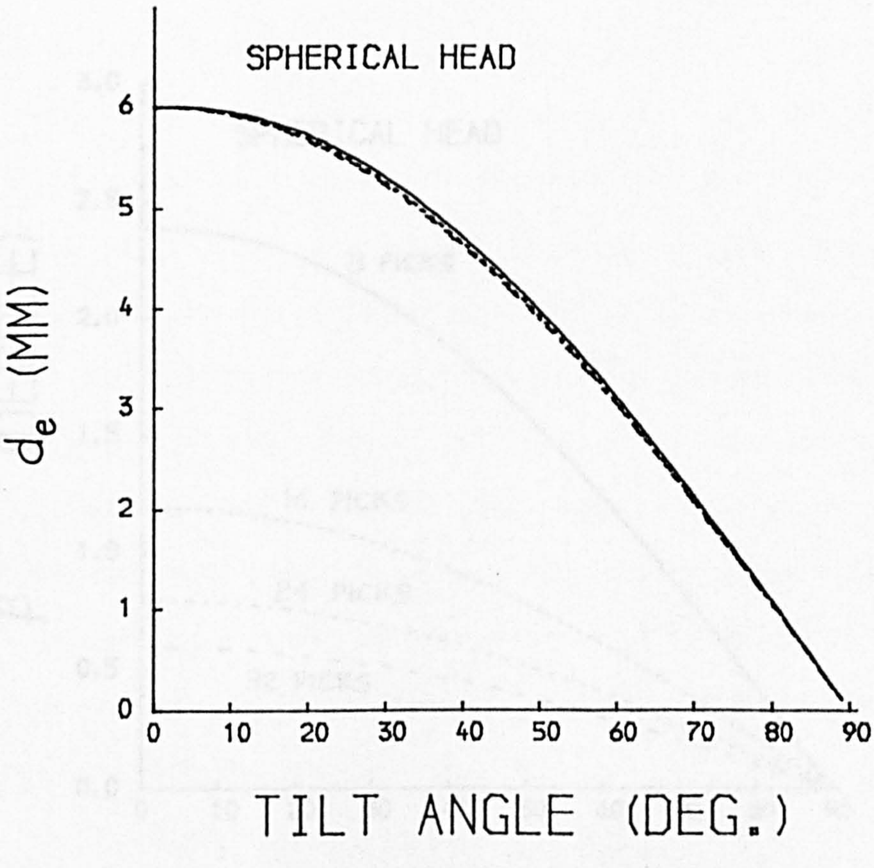


FIG.77 VARIATION OF EFFECTIVE DEPTH OF CUT WITH TILT ANGLES .

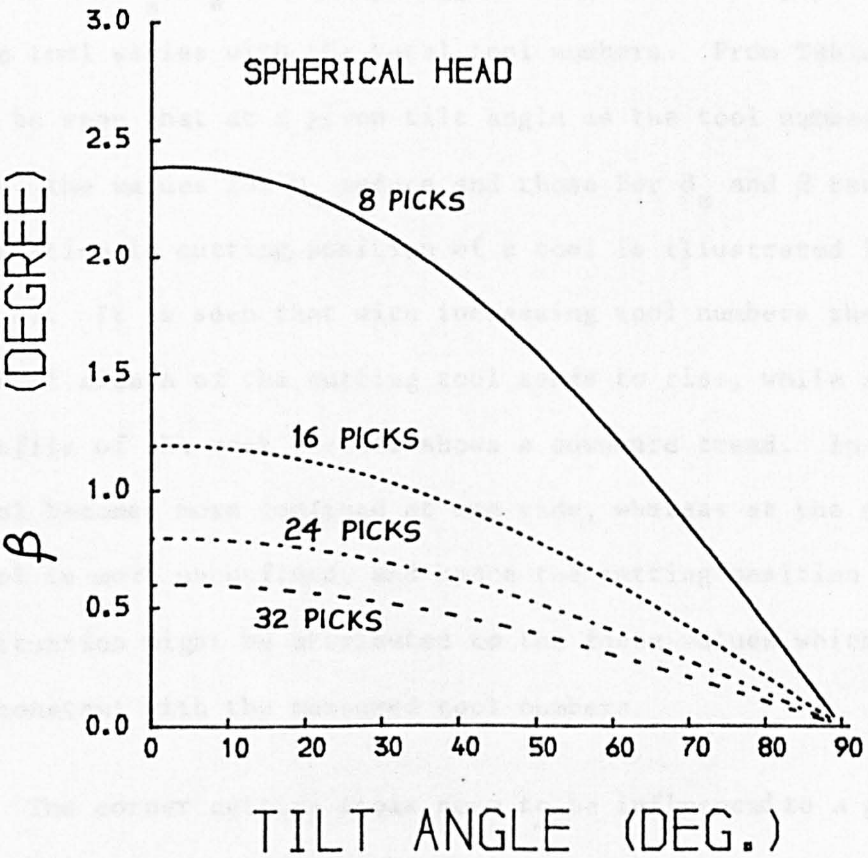


FIG. 78 VARIATION OF THE ANGLE OF TOOL AXIS (β)
WITH TILT ANGLES .

experiments on all tilt angles of the cutting head with eight tools have also given the tool forces of similar value to those previously obtained for the head with sixteen tools (Figures 79 to 84).

Although the cross-sectional areas remain constant, variation in values for S_e, d_e and may suggest that the cutting position at a given tool varies with the total tool numbers. From Table 11 it can be seen that at a given tilt angle as the tool numbers become smaller, the values for S_e reduce and those for d_e and β tend to rise. The variation in cutting position of a tool is illustrated in Figure 85. It is seen that with increasing tool numbers the cut profile at side A of the cutting tool tends to rise, while at side B, the profile of the rock surface shows a downward trend. In this way, the tool becomes more confined at one side, whereas at the other side, the tool is more unconfined, and hence the cutting position is balanced. This situation might be attributed to the force values which tended to be constant with the measured tool numbers.

The corner cutting tools seem to be influenced to a greater extent by the changes in the tool cutting positions and this situation is illustrated in Figure 86. At lower tool numbers, the profile of the rock surface moves upward, away from the corner cutting tool and, as a consequence, the tool becomes more confined. As the angle between the tool axis and the corner wall is unchanged, the cutting position is not balanced as it is in gauge cutting tools. Thus higher tool forces are likely to be generated as tool number decreases.

Tilt Angle Degree	Cutting head with 8 tools			Cutting head with 16 tools			Cutting head with 24 tools			Cutting head with 32 tools		
	S_e	β	d_e	S_e	β	d_e	S_e	β	d_e	S_e	β	d_e
0.0	3.6031	0.0416	0.6000	3.6008	0.0208	0.6000	3.6003	0.0139	0.6000	3.6002	0.0104	0.6000
4.63	3.5910	0.0416	0.5981	3.5947	0.0208	0.5981	3.5963	0.0139	0.5981	3.5972	0.0104	0.5981
9.26	3.5789	0.0414	0.5923	3.5887	0.0206	0.5922	3.5923	0.0137	0.5922	3.5942	0.0103	0.5922
13.89	3.5670	0.0408	0.5826	3.5827	0.0203	0.5825	3.5883	0.0135	0.5825	3.5912	0.0101	0.5825
18.52	3.5552	0.0400	0.5691	3.5769	0.0199	0.5690	3.5844	0.0132	0.5690	3.5883	0.0099	0.5690
23.15	3.5437	0.0389	0.5518	3.5712	0.0193	0.5518	3.5806	0.0128	0.5517	3.5854	0.0096	0.5517
27.78	3.5326	0.0376	0.5310	3.5657	0.0186	0.5309	3.5770	0.0124	0.5309	3.5827	0.0093	0.5309
32.41	3.5219	0.0360	0.5067	3.5604	0.0178	0.5066	3.5735	0.0118	0.5066	3.5800	0.0088	0.5066
37.04	3.5117	0.0341	0.4791	3.5553	0.0168	0.4790	3.5701	0.0112	0.4790	3.5775	0.0084	0.4790
41.67	3.5021	0.0320	0.4484	3.5506	0.0158	0.4483	3.5670	0.0105	0.4483	3.5752	0.0078	0.4482
46.30	3.4931	0.0297	0.4148	3.5462	0.0146	0.4146	3.5640	0.0097	0.4146	3.5730	0.0073	0.4146
50.93	3.4848	0.0271	0.3784	3.5421	0.0133	0.3783	3.5613	0.0088	0.3782	3.5710	0.0066	0.3782
55.56	3.4773	0.0244	0.3395	3.5384	0.0120	0.3394	3.5589	0.0079	0.3394	3.5691	0.0059	0.3394
60.19	3.4706	0.0215	0.2985	3.5351	0.0105	0.2984	3.5567	0.0070	0.2983	3.5675	0.0052	0.2983
64.82	3.4648	0.0184	0.2555	3.5323	0.0090	0.2554	3.5548	0.0060	0.2553	3.5661	0.0045	0.2553
69.45	3.4599	0.0152	0.2108	3.5299	0.0075	0.2107	3.5532	0.0049	0.2107	3.5649	0.0037	0.2107
74.08	3.4560	0.0119	0.1647	3.5279	0.0058	0.1646	3.5519	0.0039	0.1646	3.5640	0.0029	0.1646
78.71	3.4530	0.0085	0.1176	3.5265	0.0042	0.1175	3.5510	0.0028	0.1175	3.5632	0.0021	0.1175
83.34	3.4511	0.0050	0.0696	3.5255	0.0025	0.0696	3.5503	0.0016	0.0696	3.5628	0.0012	0.0696
87.97	3.4501	0.0015	0.0213	3.5250	0.0008	0.0213	3.5500	0.0005	0.0213	3.5625	0.0004	0.0213

Table 11 Variation of S_e, β and d_e with total number of tools at various tilt angles.

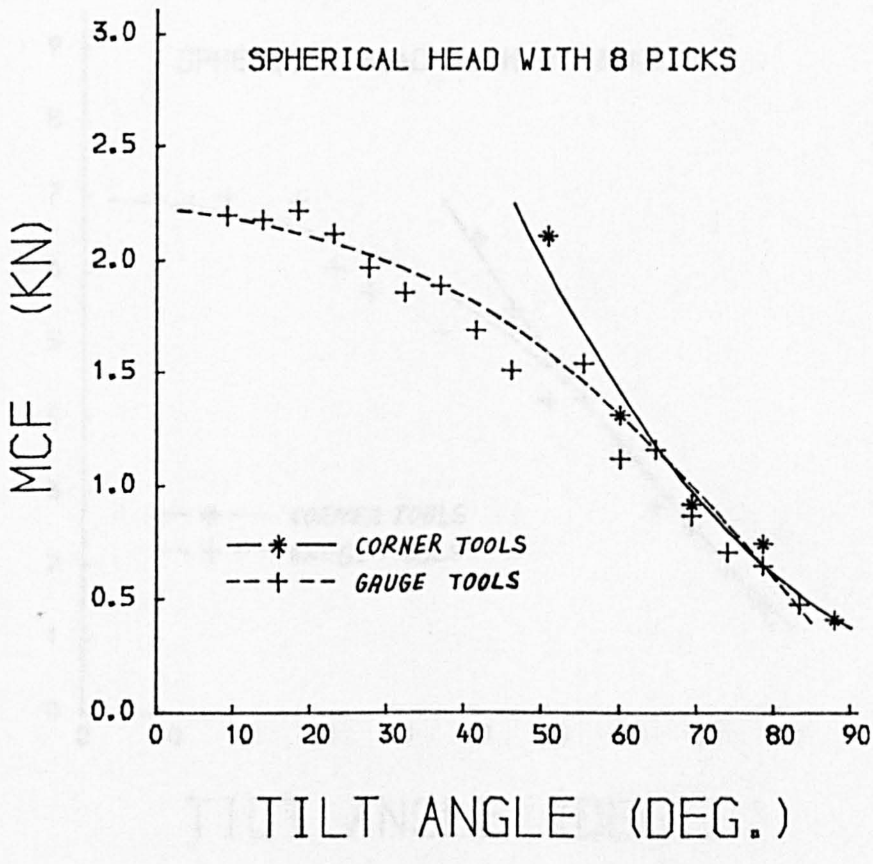


FIG. 79 VARIATION OF MEAN CUTTING FORCE VALUES WITH TILT ANGLE.

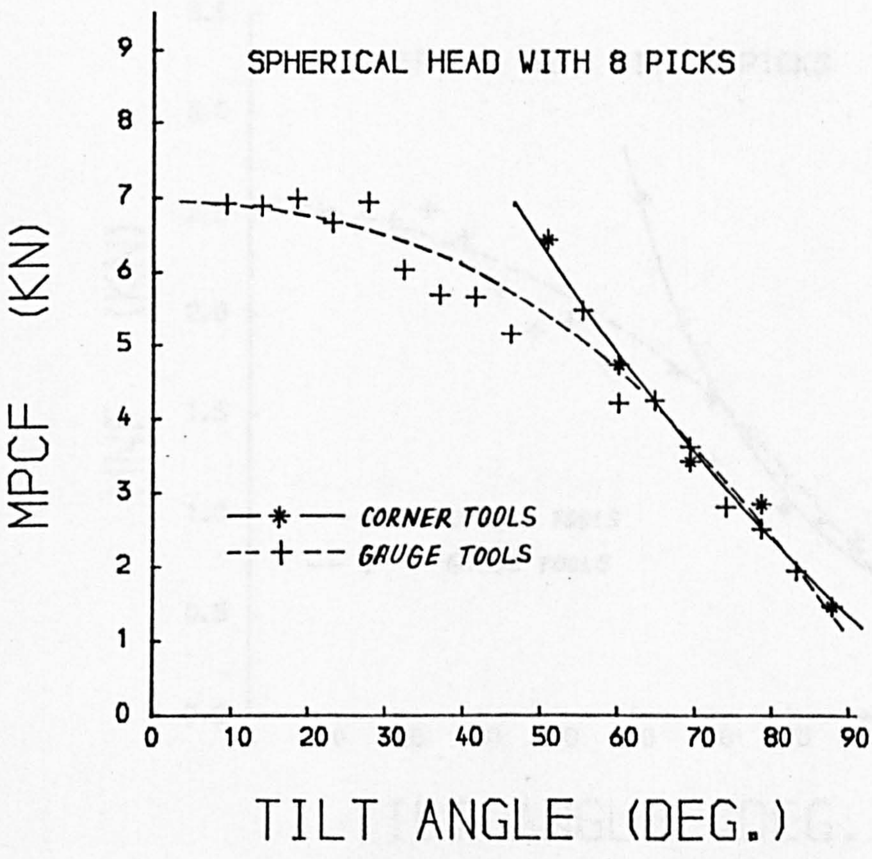


FIG.80 VARIATION OF MEAN PEAK CUTTING FORCE WITH TILT ANGLE,

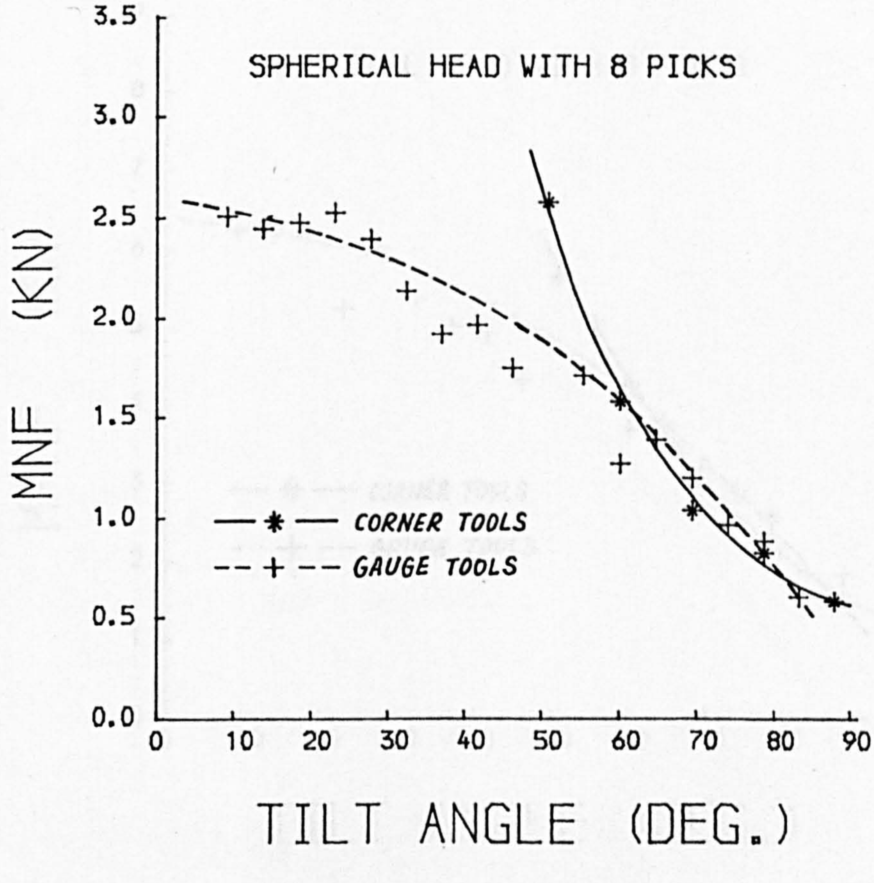


FIG. 81 VARIATION OF MEAN NORMAL FORCE VALUES WITH TILT ANGLE.

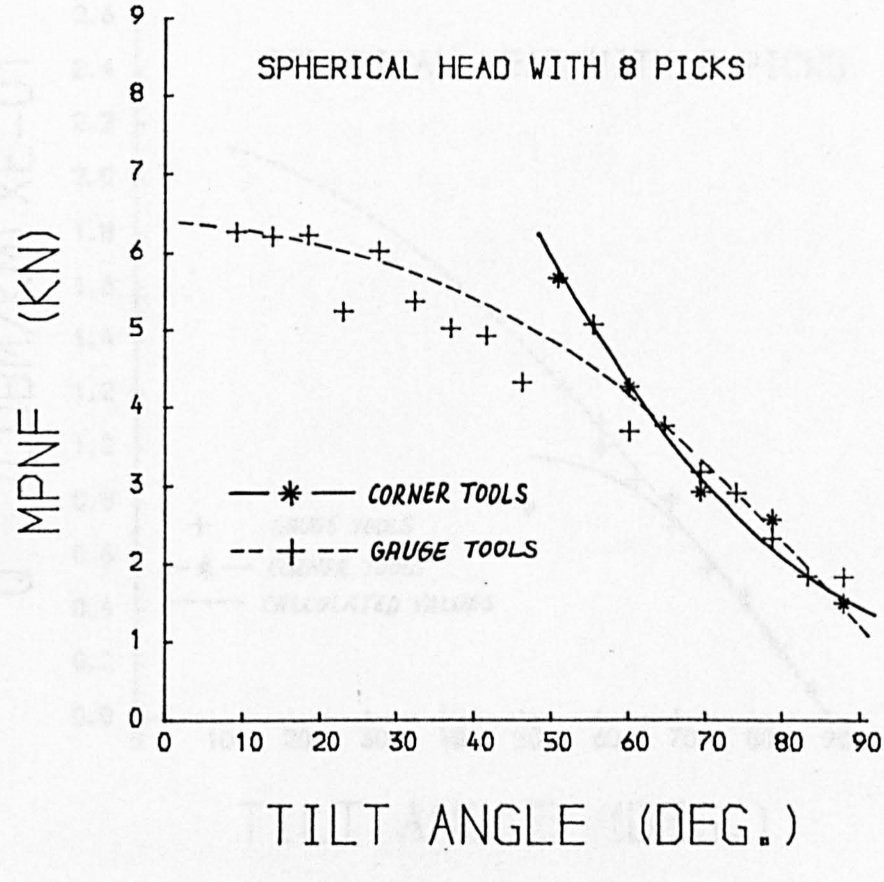


FIG.82 VARIATION OF MEAN PEAK NORMAL FORCE WITH TILT ANGLE.

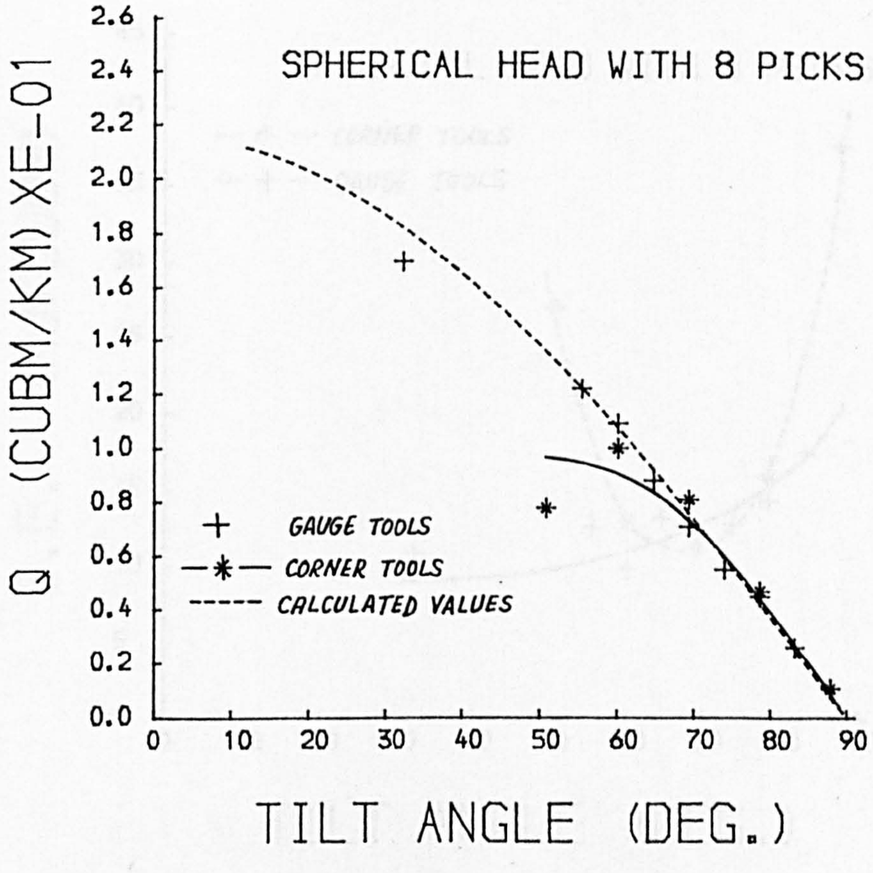


FIG.83 VARIATION OF MEASURED AND PREDICTED YIELD WITH TILT ANGLE.

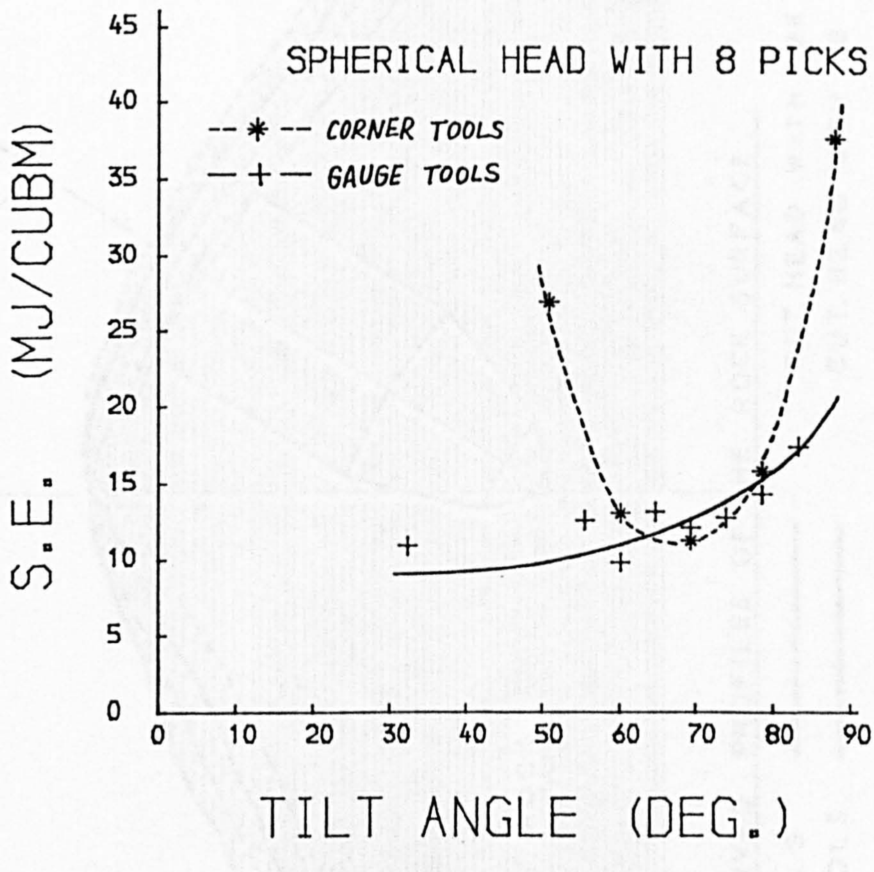


FIG.84 VARIATION OF SPECIFIC ENERGY VALUES WITH TILT ANGLE.

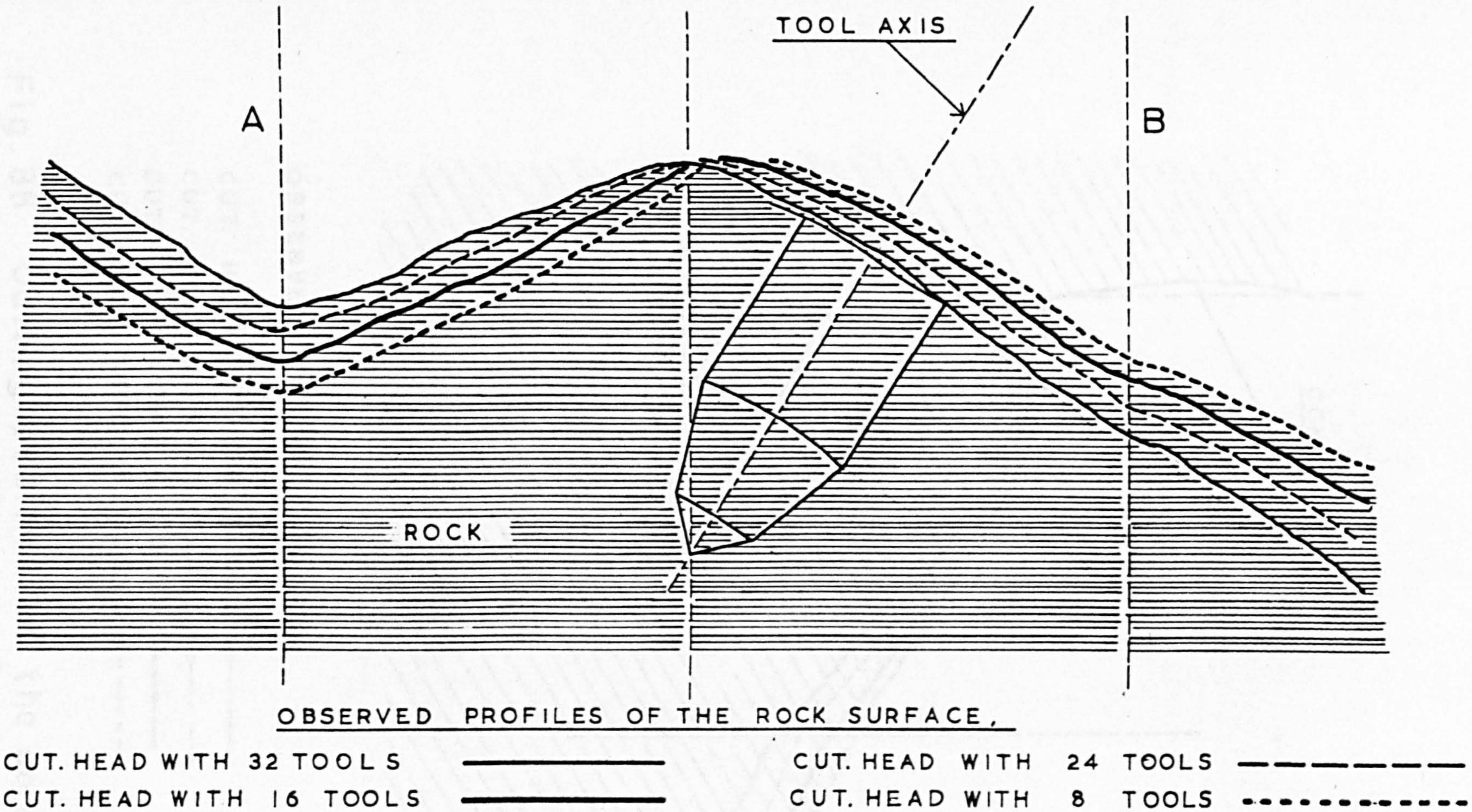


Fig. 85 Changes in the cutting position of a tool with respect to the rock surface when cutting with heads having different tool numbers.

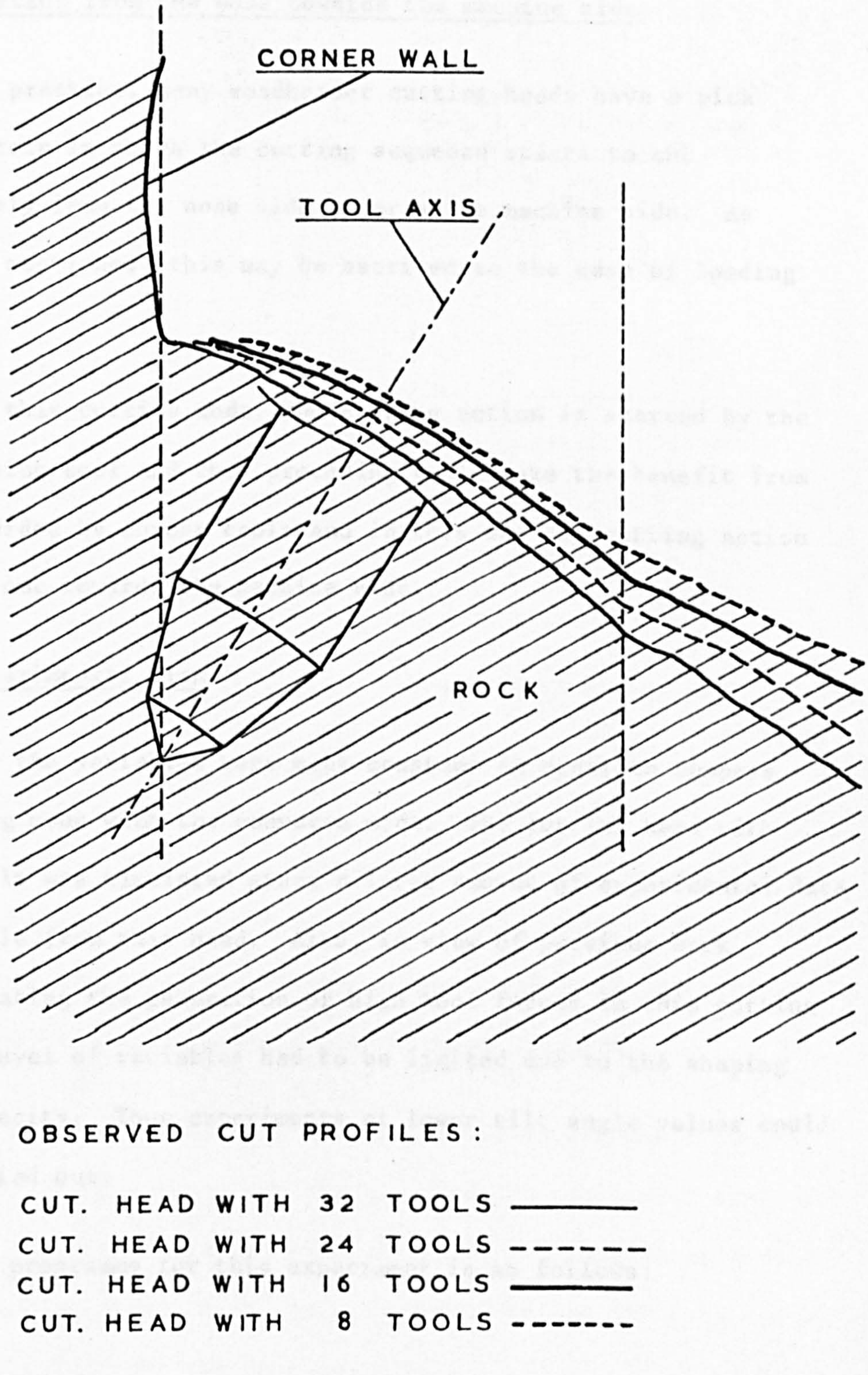


Fig. 86 Cutting position of the corner cutting tool when cutting with heads having different tool numbers.

11.5 Cutting from the nose towards the machine side

In practice, many roadheader cutting heads have a pick lacing pattern in which the cutting sequence starts to cut progressively from the nose side towards the machine side. As previously mentioned, this may be ascribed to the ease of loading action.

In this cutting mode, the cutting action is started by the corner cutting tool and thus preceding tools take the benefit from relief provided by corner tools and in this way the cutting action is carried out towards the machine side.

11.5.1 Experimental Plan

All the variables were kept constant in order to compare this cutting mode with the converse mode. The cutting head with sixteen tools was simulated since a large amount of experimental data was available from this head. Also, in view of previous work (28) indicating the generation of high tool forces in this cutting mode, the level of variables had to be limited due to thé shaping machine capacity. Thus experiments at lower tilt angle values could not be carried out.

The programme for this experiment is as follows:

Variable	Level	Description
Gauge tools	4	(1) 87.97, 83.34, 78.71 (2) 74.08, 69.45, 64.82 (3) 60.19, 55.56, 50.93 (4) 46.30, 41.67, 37.04
Corner cutting tools	5	87.91, 78.71, 69.45 60.19, 50.93
Replications	4	
Total	80	instrumented cuts

11.5.2 Results and Discussion

The results for this section are presented in Appendices 5A5,5A6.

11.5.2.1 Forces

In this cutting mode, forces exhibited higher values than those of cutting in converse mode and this may be attributed to the confinement of the tool. Variation in force values for both gauge and corner cutting picks are shown in Figures 87 to 92.

The main factor causing a rise in tool forces would be the fact that the cutting sequences start from the unrelieved side. The increase in tool forces is not high at higher tilt angles on account of the smaller cross-sectional areas. Therefore, at low tilt angles, an appreciable increase can be seen.

Furthermore the cutting position of a pick at a given tilt angle appears to differ from the previous cutting mode. The cutting

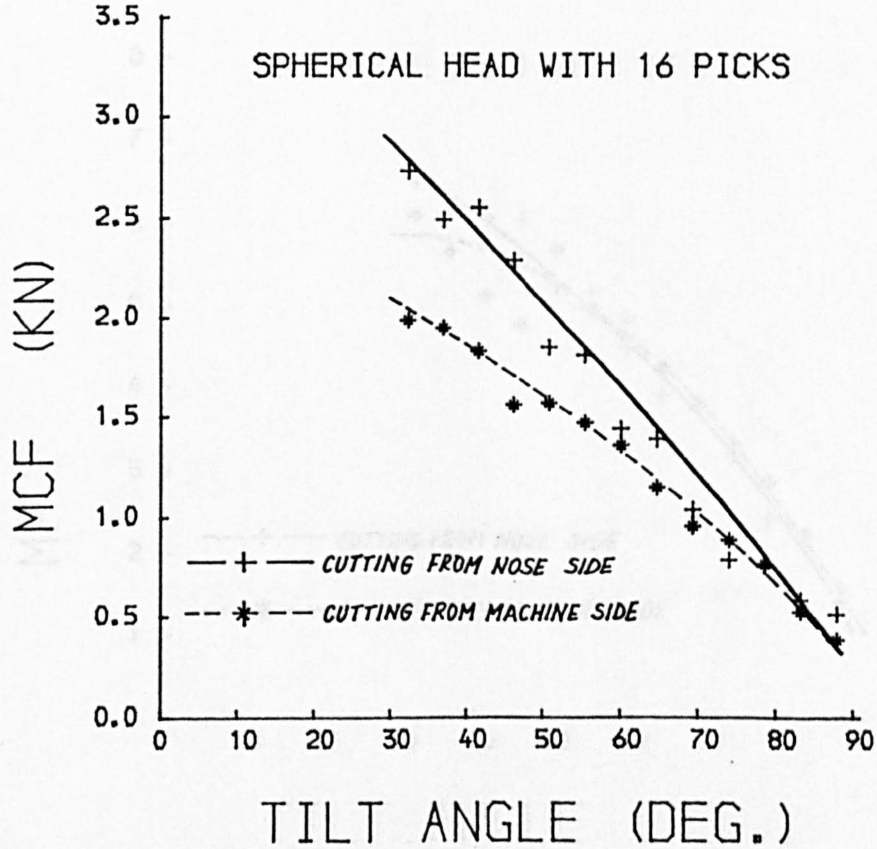


FIG. 87 VARIATION OF MCF VALUES WITH TILT ANGLES TWO DIFFERENT MODE OF CUTTING

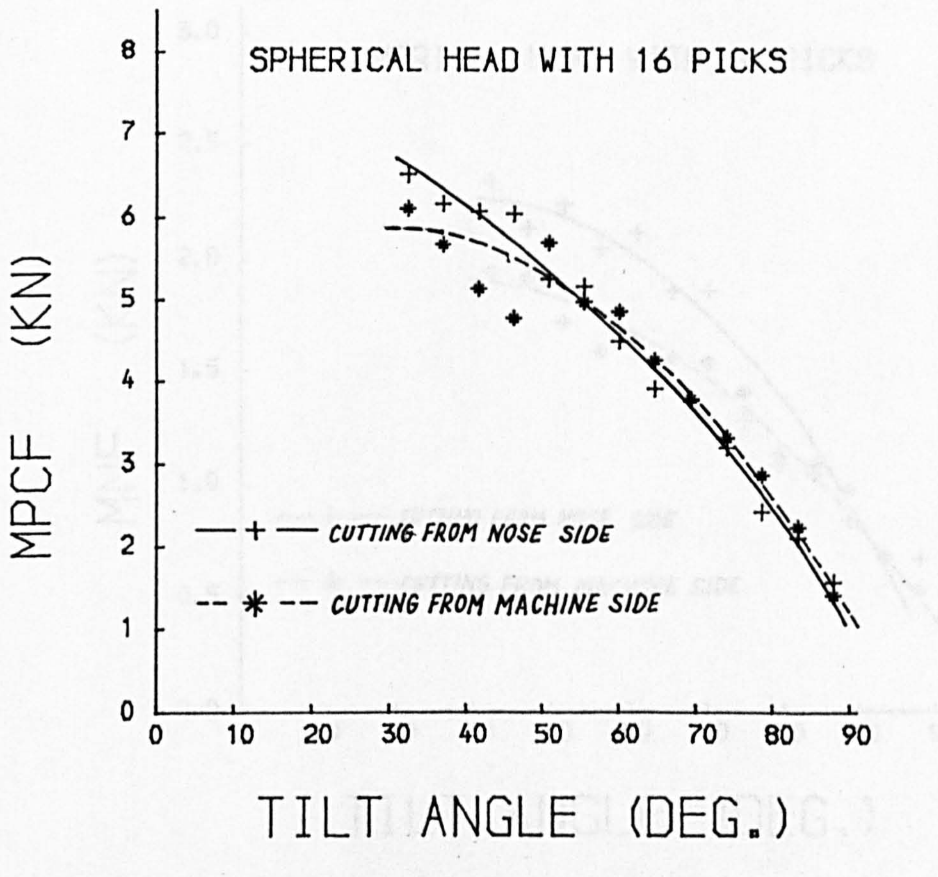


FIG.88 VARIATION OF MPCF VALUES WITH TILT ANGLES, TWO DIFFERENT MODE OF CUTTING.

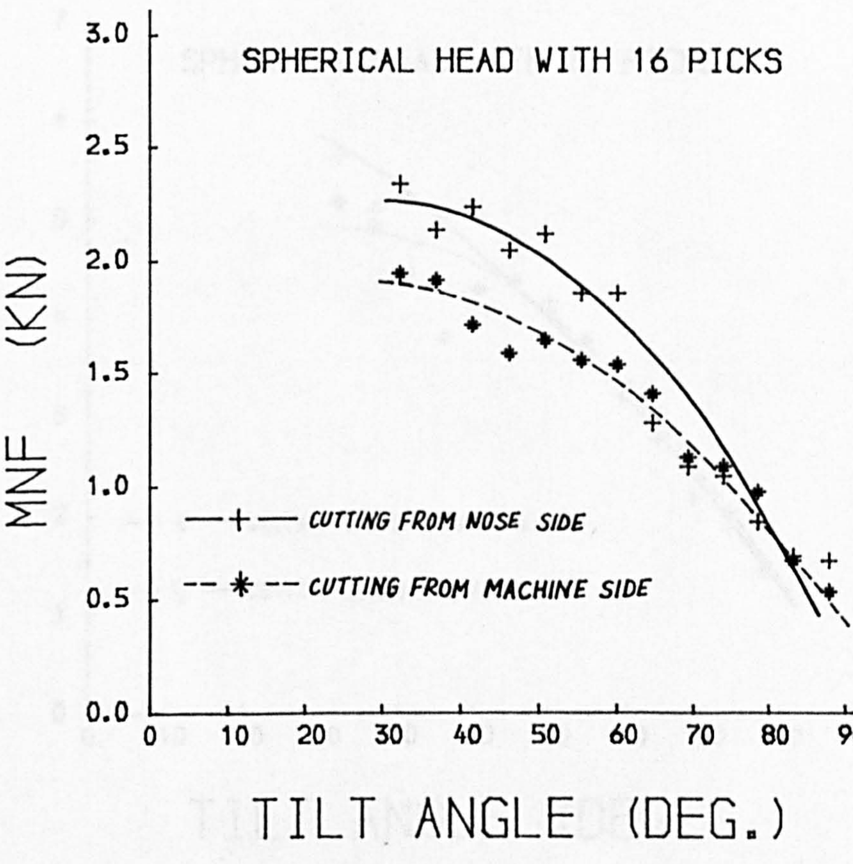


FIG.89 VARIATION OF MNF VALUES WITH TILT ANGLES, TWO DIFFERENT MODE OF CUTTING.

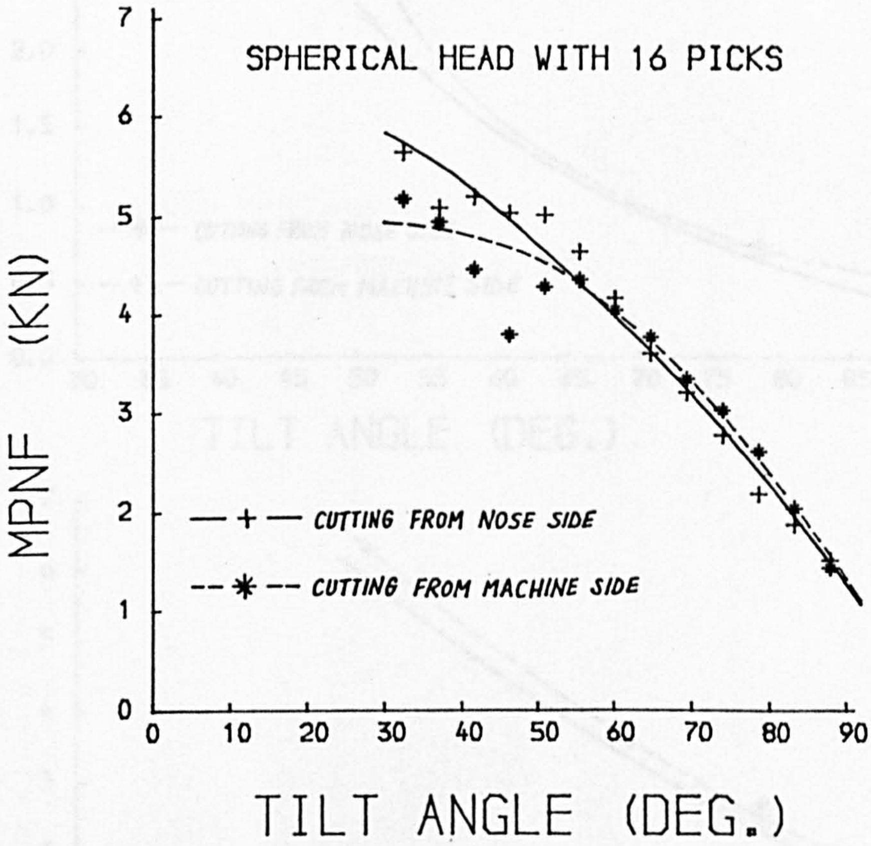


FIG.90 VARIATION OF MPNF VALUES WITH TILT ANGLES, TWO DIFFERENT MODE OF CUTTING.

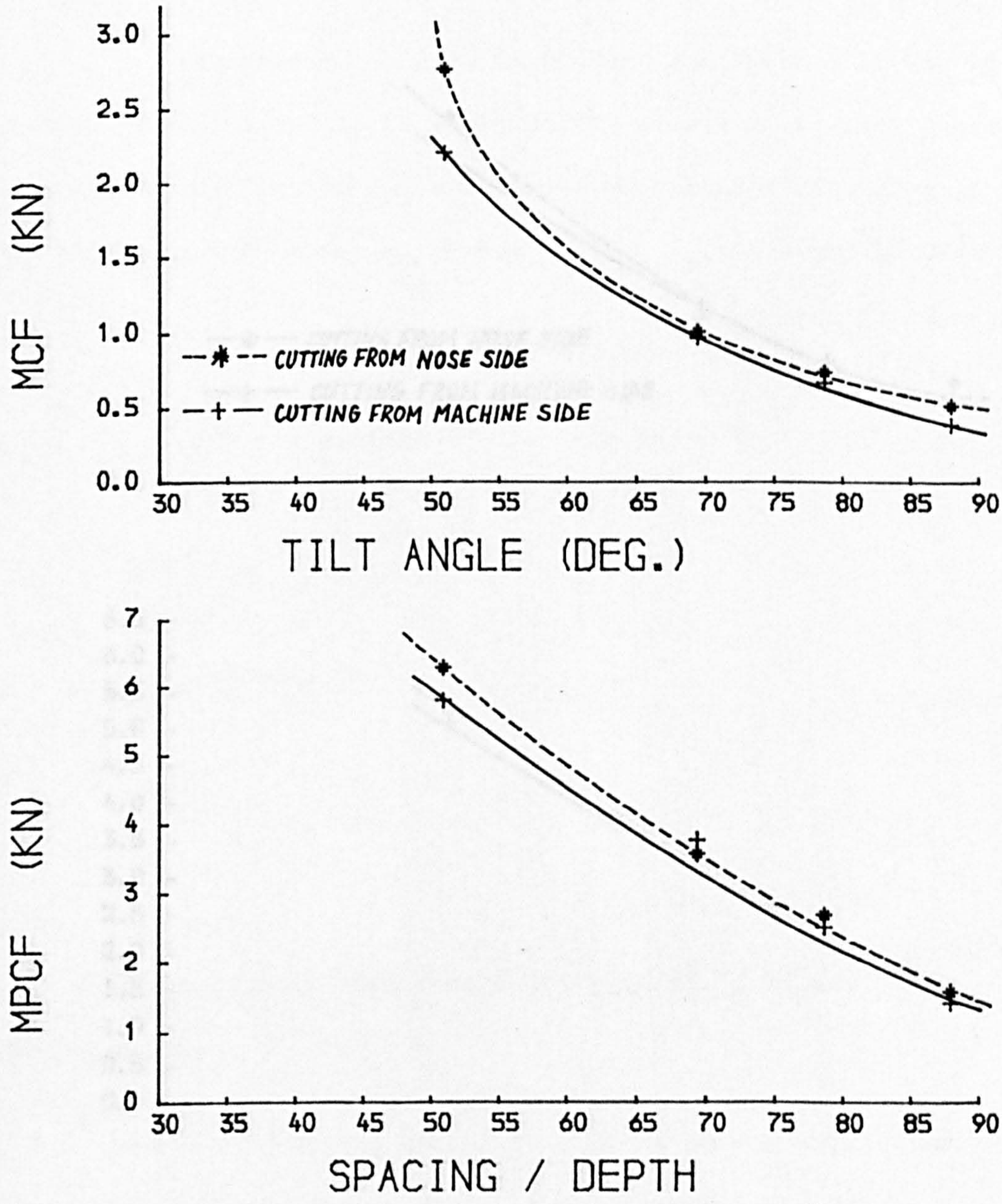


FIG.91 VARIATION OF CUTTING FORCES WITH TILT ANGLES, TWO DIFFERENT CUTTING MODE, CORNER CUTTING TOOL

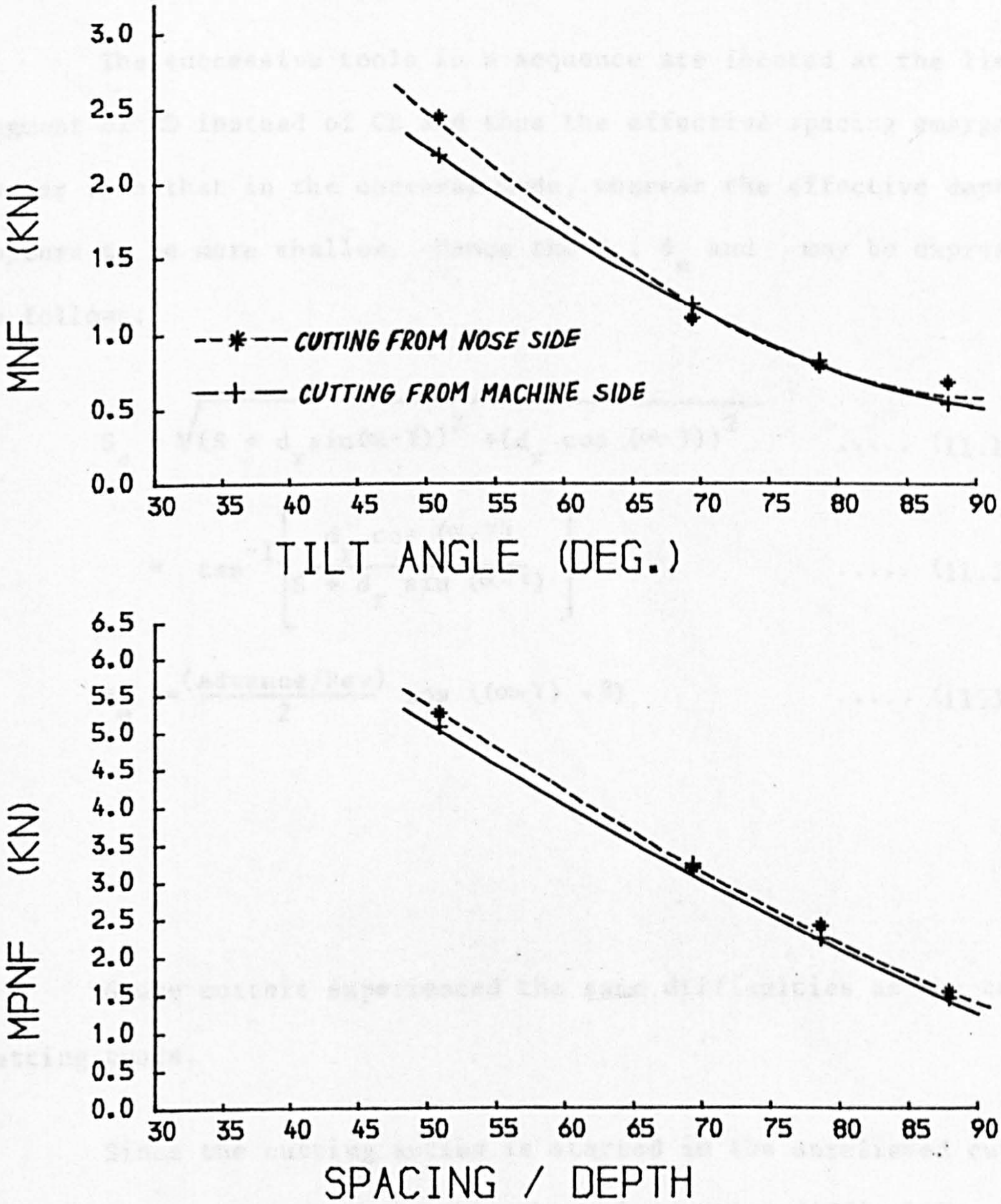


FIG. 92 VARIATION OF NORMAL FORCES WITH TILT ANGLES, TWO DIFFERENT CUTTING MODE, CORNER CUTTING TOOL

position of a tool is illustrated in Figure 93 and the tool positions were constructed in a similar way to that previously defined in Chapter Nine.

The successive tools in a sequence are located at the line segment of AD instead of CB and thus the effective spacing emerges as longer than that in the converse mode, whereas the effective depth appears to be more shallow. Hence the S_e, d_e and may be expressed as follows:

$$S_e = \sqrt{(S + d_r \sin(\alpha-\gamma))^2 + (d_r \cos(\alpha-\gamma))^2} \qquad \ldots\ldots (11.1)$$

$$= \tan^{-1}\left[\frac{d_r \cos(\alpha-\gamma)}{S + d_r \sin(\alpha-\gamma)}\right] \qquad \ldots\ldots (11.2)$$

$$d_e = \frac{(\text{Advance/Rev})}{2} \cos((\alpha-\gamma) + \beta) \qquad \ldots\ldots (11.3)$$

Gauge cutters experienced the same difficulties as the corner cutting tools.

Since the cutting action is started in the unrelieved cutting mode by the corner cutting tools, the main cutting difficulties seem to be imposed on the corner tools. Thus at low tilt angles these tools may be easily destroyed.

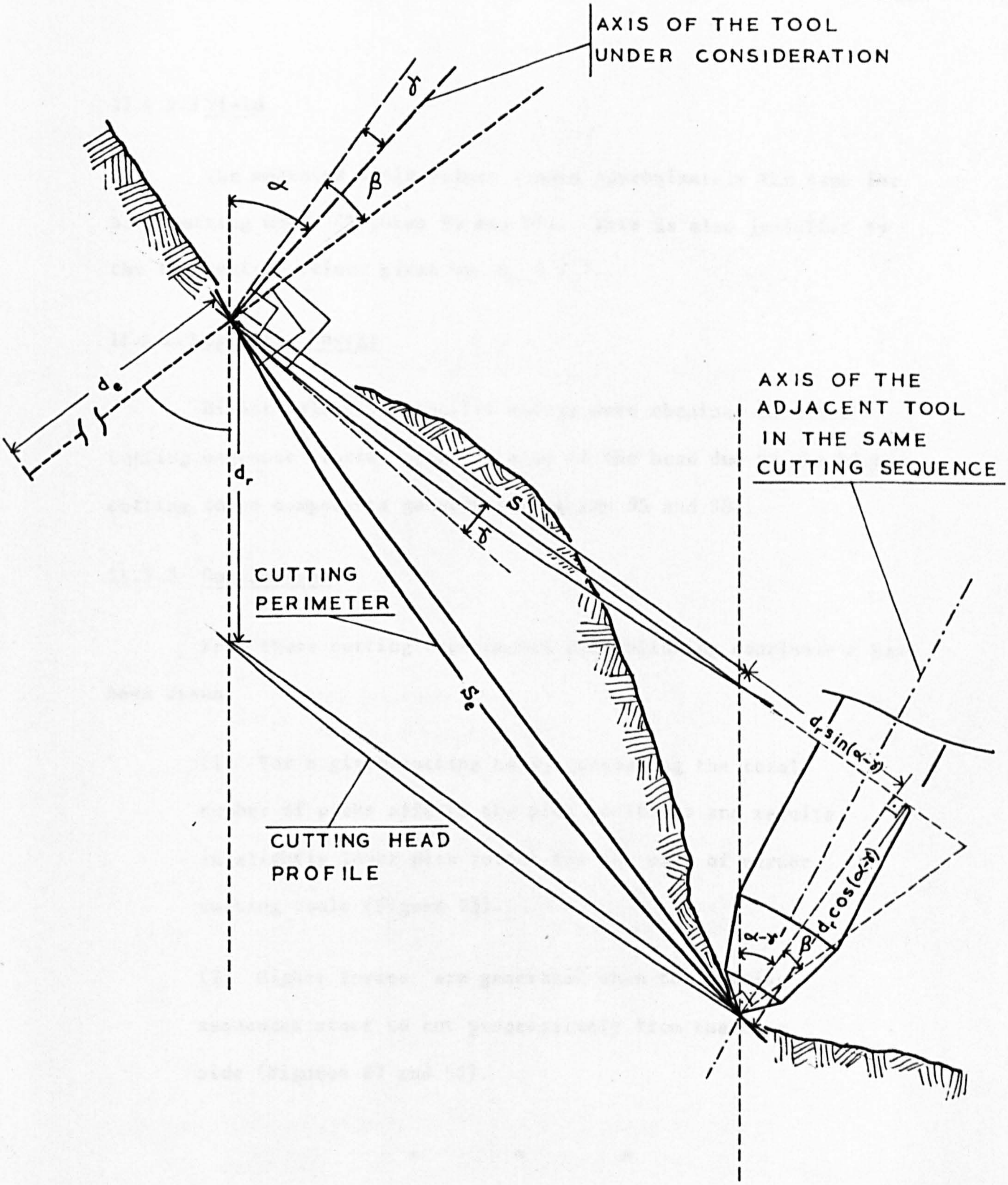


Fig.93 Cutting position of the adjacent tools when cutting away from the nose side.

11.5.2.2 Yield

The measured yield values remain approximately the same for both cutting modes (Figures 94 and 96). This is also justified by the theoretical values given by '$S_e \times d_e$'.

11.5.2.3 Specific Energy

Higher values of specific energy were obtained when the cutting sequence started from the nose of the head due to the higher cutting force components generated (Figures 95 and 96).

11.5.3 Conclusions

From these cutting experiments the following conclusions have been drawn:

(1) For a given cutting head, increasing the total number of picks affects the pick positions and results in slightly lower pick forces for the case of corner cutting tools (Figure 73).

(2) Higher forces are generated when the cutting sequences start to cut progressively from the nose side (Figures 87 and 92).

* * *

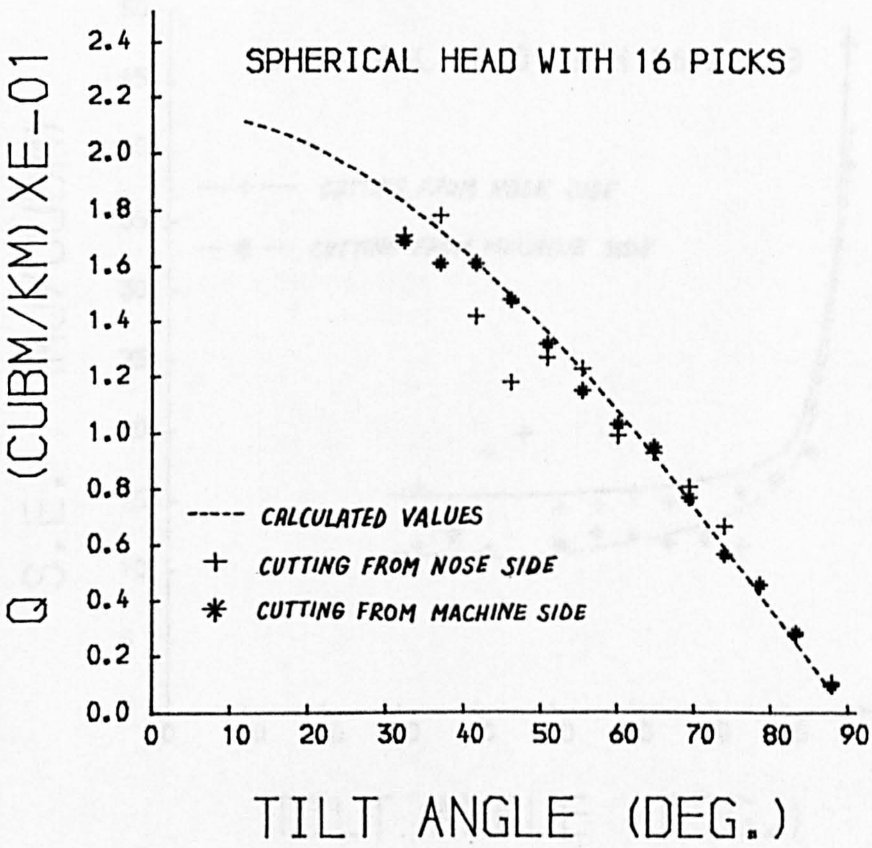


FIG.94 VARIATION OF YIELD VALUES WITH TILT ANGLES, TWO DIFFERENT MODE OF CUTTING.

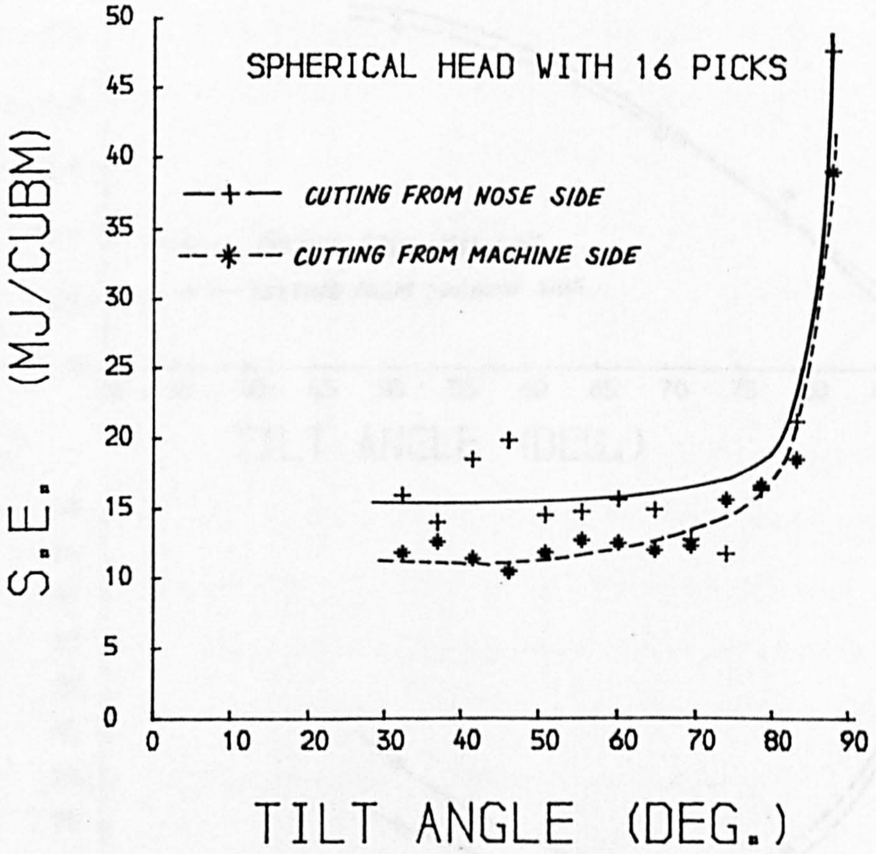


FIG.95 VARIATION OF S.E. VALUES WITH TILT ANGLES, TWO DIFFERENT MODE OF CUTTING.

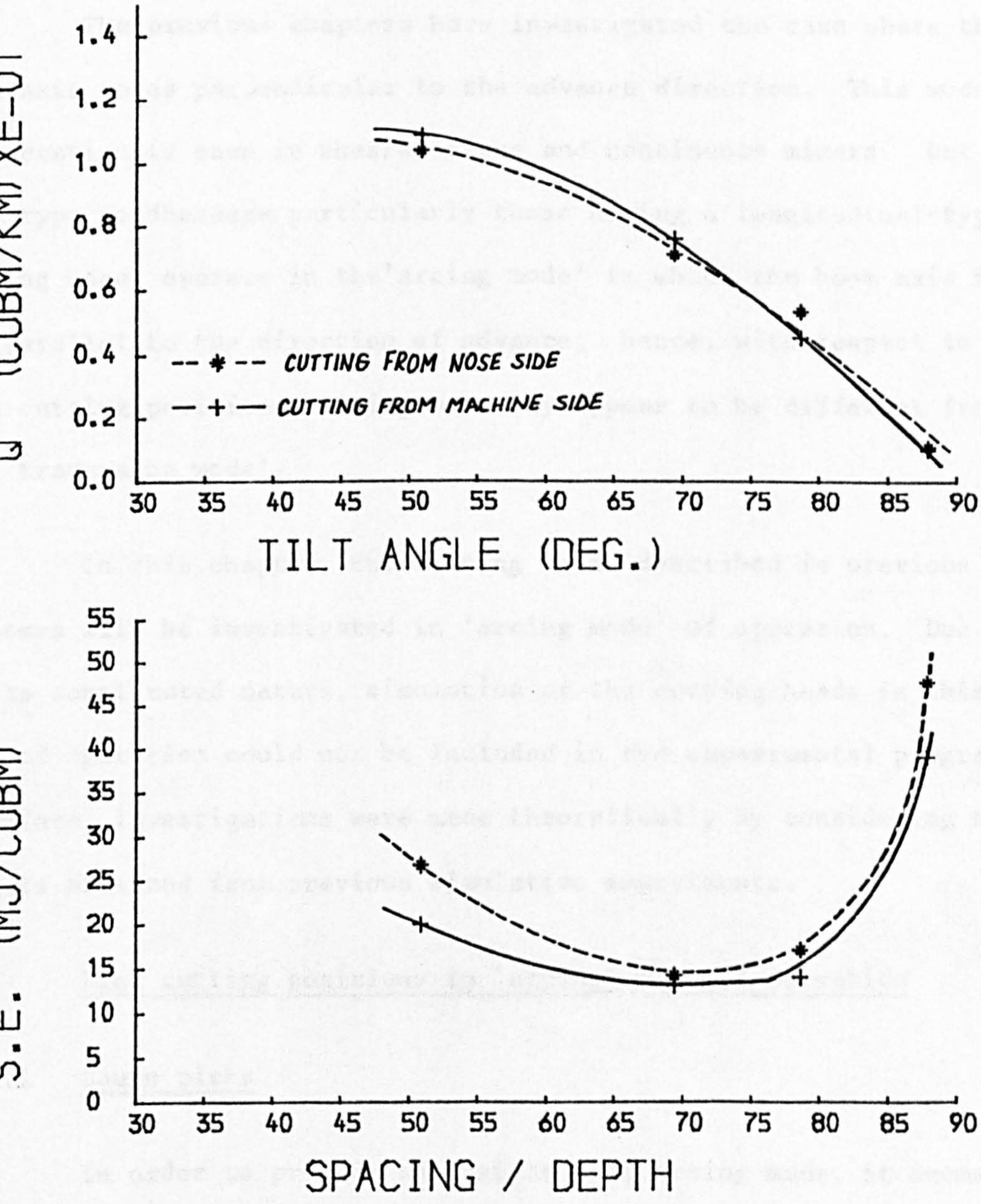


FIG. 96 VARIATION OF YIELD AND S.E. WITH TILT ANGLES, TWO DIFFERENT CUTTING MODE, CORNER CUTTING TOOL

12. ANALYSIS OF CUTTING HEAD ACTION : ARCING MODE

12.1 Introduction

The previous chapters have investigated the case where the boom axis moves perpendicular to the advance direction. This mode of operation is seen in shearer drums and continuous miners. But boom-type roadheaders particularly those having a longitudinal-type cutting head, operate in the'arcing mode' in which the boom axis is not parallel to the direction of advance; hence, with respect to the pick cutting positions, arcing mode may appear to be different from the 'traversing mode'.

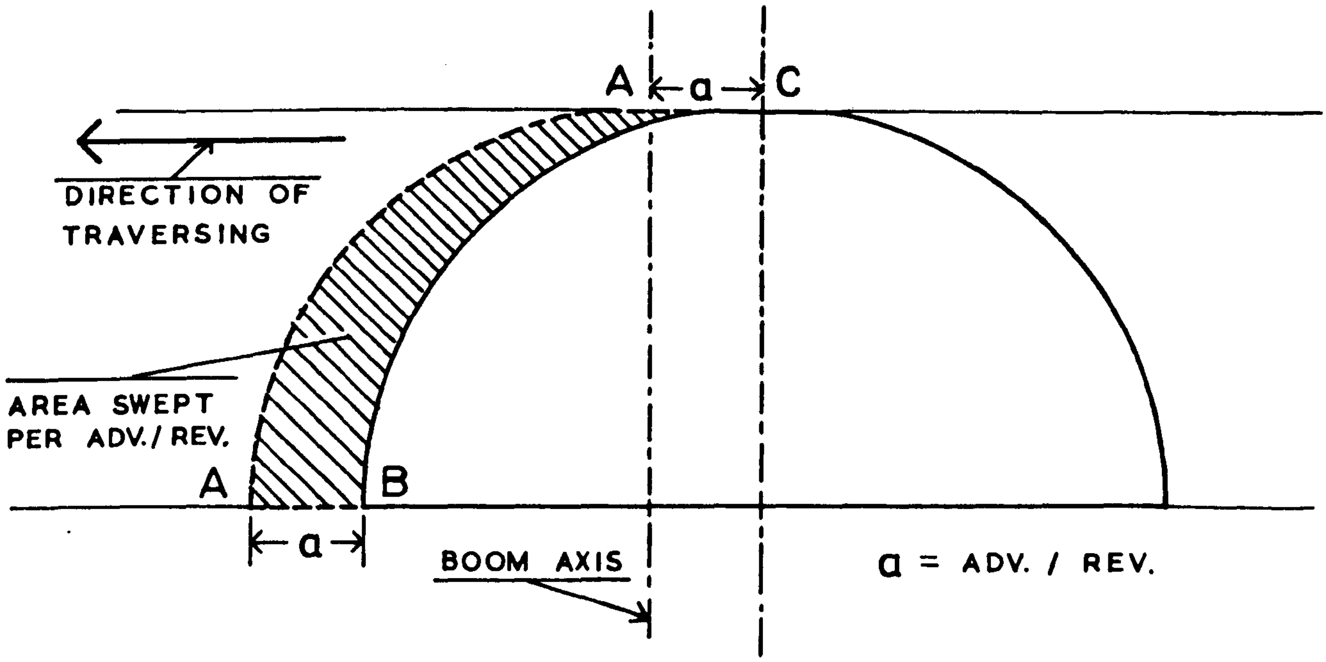
In this chapter, the cutting heads described in previous chapters will be investigated in 'arcing mode' of operation. Due to its complicated nature, simulation of the cutting heads in this mode of operation could not be included in the experimental programme. Therefore, investigations were made theoretically by considering the results obtained from previous simulation experiments.

12.2 Pick cutting positions in 'arcing' mode of operation

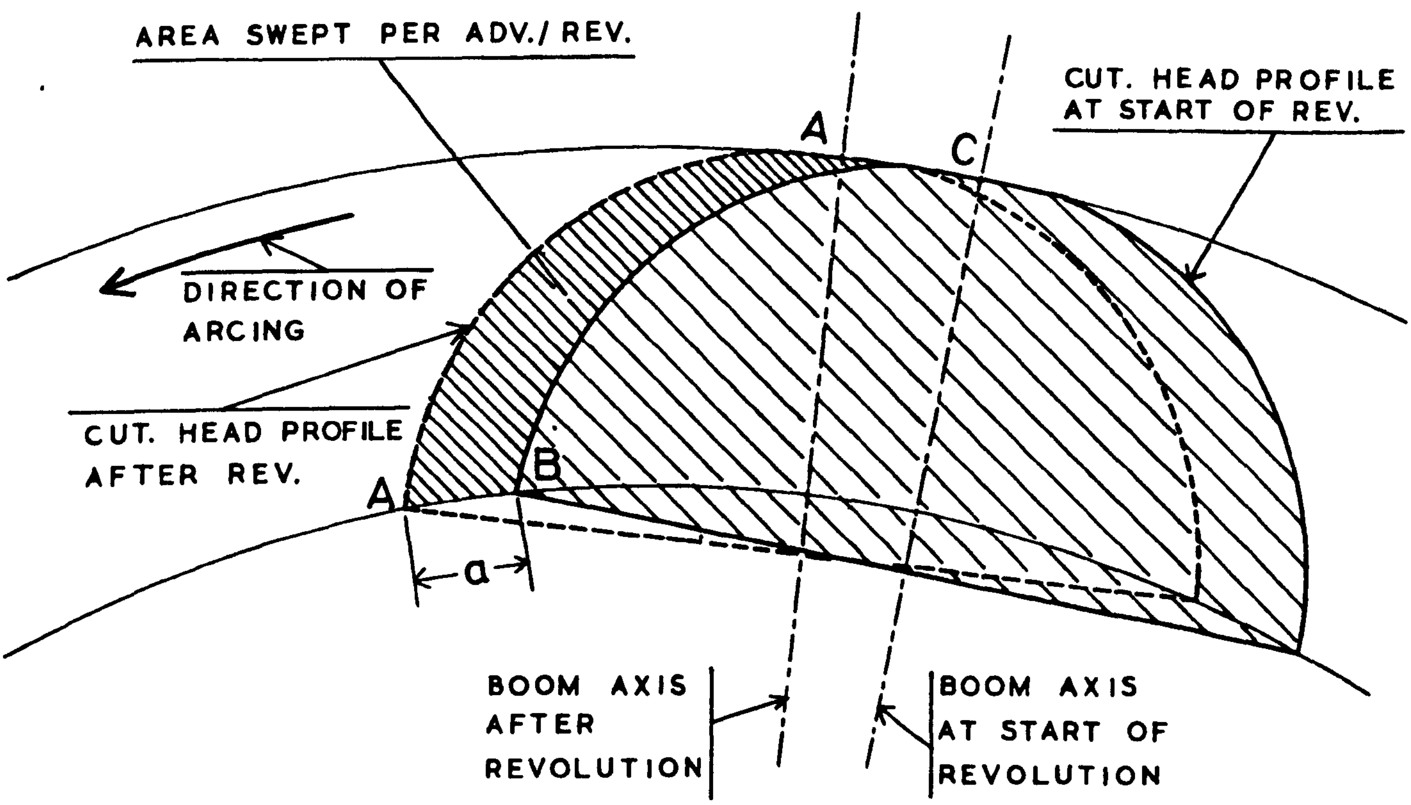
12.2.1 Gauge picks

In order to provide an insight into arcing mode, it seems worthwhile to compare it with 'traversing' cutting mode.

The pick positions on a cutting head operating in both modes of operation is simply illustrated in Figure 97. When a cutting



a) Traversing mode, AB = AC



b) Arcing mode, AB < AC

Fig.97 Notation of area swept in two different modesof operation.

head traverses, all the tools achieve the same distance for a given advance per revolution of the cutting head, i.e. as in Figure 97a, from point A to point B, the nominal distance 'a' would be the same at any pick position. If the same cutting is considered in arcing mode, as in Figure 97b, it may then be seen that each pick would no longer advance at distance 'a' but the first pick only. Furthermore, the picks travel along concentric cyclic paths and the rate of nominal advance per revolution appears to be influenced by the radii of these cycles, which are measured from the point where the boom is connected to the main machine body. Thus the length of boom seems to have an influence on the duty of the cutting tools.

It has been shown in Chapter Nine that the level of pick forces is related to the cross-sectional area cut by each pick, and this relationship may also be applicable to the aspect of arcing mode.

The cross-sectional areas may be analytically calculated by considering the relative pick positions, as shown in Figure 98. By taking the equation (9.5) into account, the corresponding cross-sectional area may be defined as the area of ABDC and also ABDC equals the area of AEFC. Thus the cross-ectional area cut by a pick may be expressed as follows:

$$A_\alpha = \frac{\pi}{360}\,\theta_{adv}\left(W_\alpha^{\,2} - (W_\alpha - S_L\cos\alpha)^2\right) \qquad \ldots\ldots (12.1)$$

where A_α = cross-sectional area cut by tool at a given angle of α (m^2)

W_α = effective boom length measured up to a given cutting tool (m).

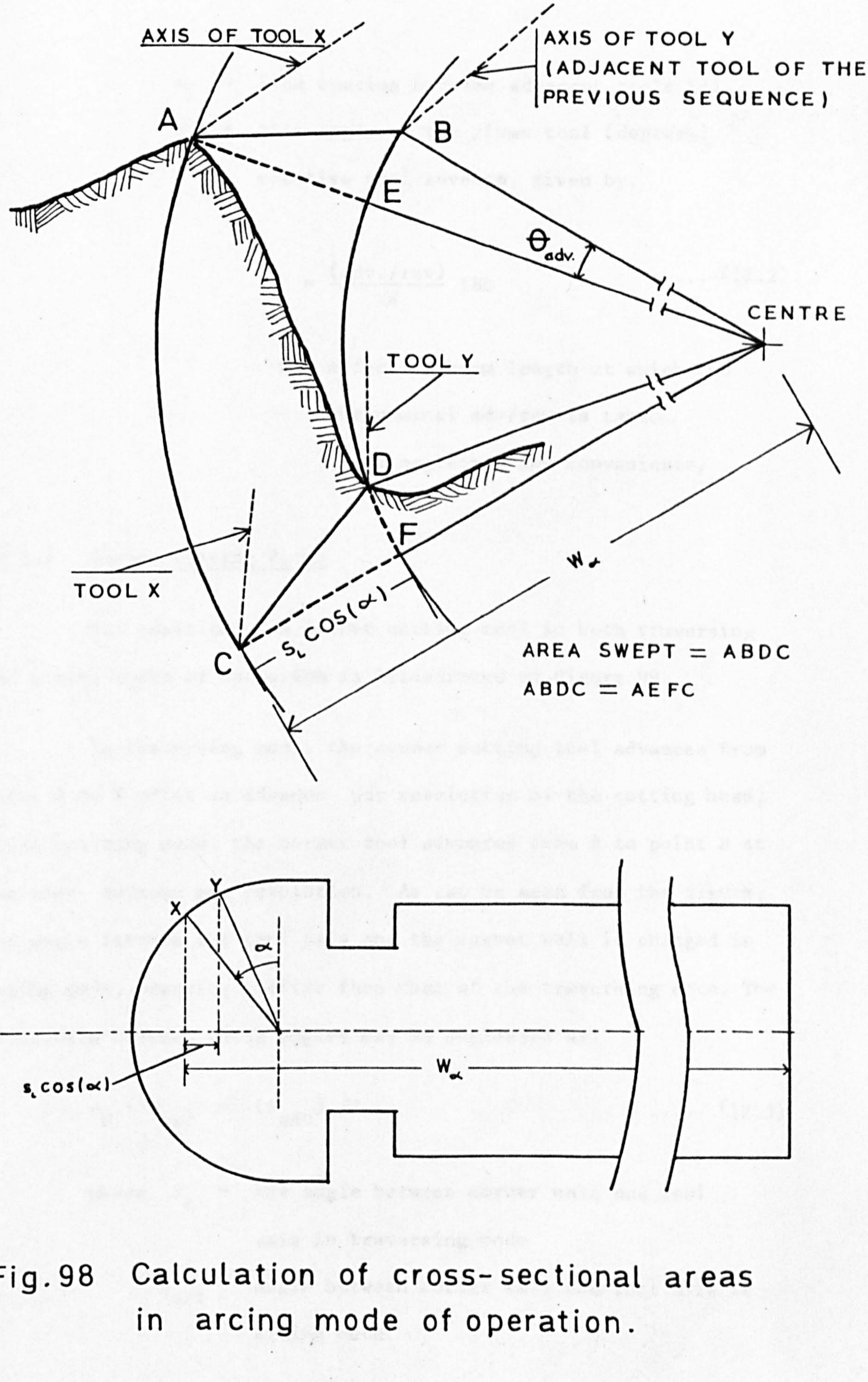


Fig.98 Calculation of cross-sectional areas in arcing mode of operation.

S_L = line spacing between adjacent tools (m)

α = tilt angle of the given tool (degrees)

θ_{adv} = relative tool advance, given by:

$$= \frac{(adv./rev)}{\pi W} 180 \qquad \text{.....(12.2)}$$

W = effective boom length at which the the nominal adv/rev is taken (γ is neglected for convenience)

12.2.2 Corner Cutting Picks

The position of a corner cutting tool in both traversing and arcing modes of operation is illustrated in Figure 99.

In traversing mode, the corner cutting tool advances from point A to B after an advance per revolution of the cutting head, while in arcing mode, the corner tool advances from A to point B at the same advance per revolution. As can be seen from the figure, the angle between the tool axis and the corner wall is changed in arcing mode, becoming smaller than that of the traversing mode. The difference between these angles may be expressed as:

$$\theta_t - \theta_{arc} = (\theta_{adv}) /2 \qquad \text{..... (12.3)}$$

where θ_t = the angle between corner wall and tool axis in traversing mode

θ_{arc} = angle between corner wall and tool axis in arcing mode.

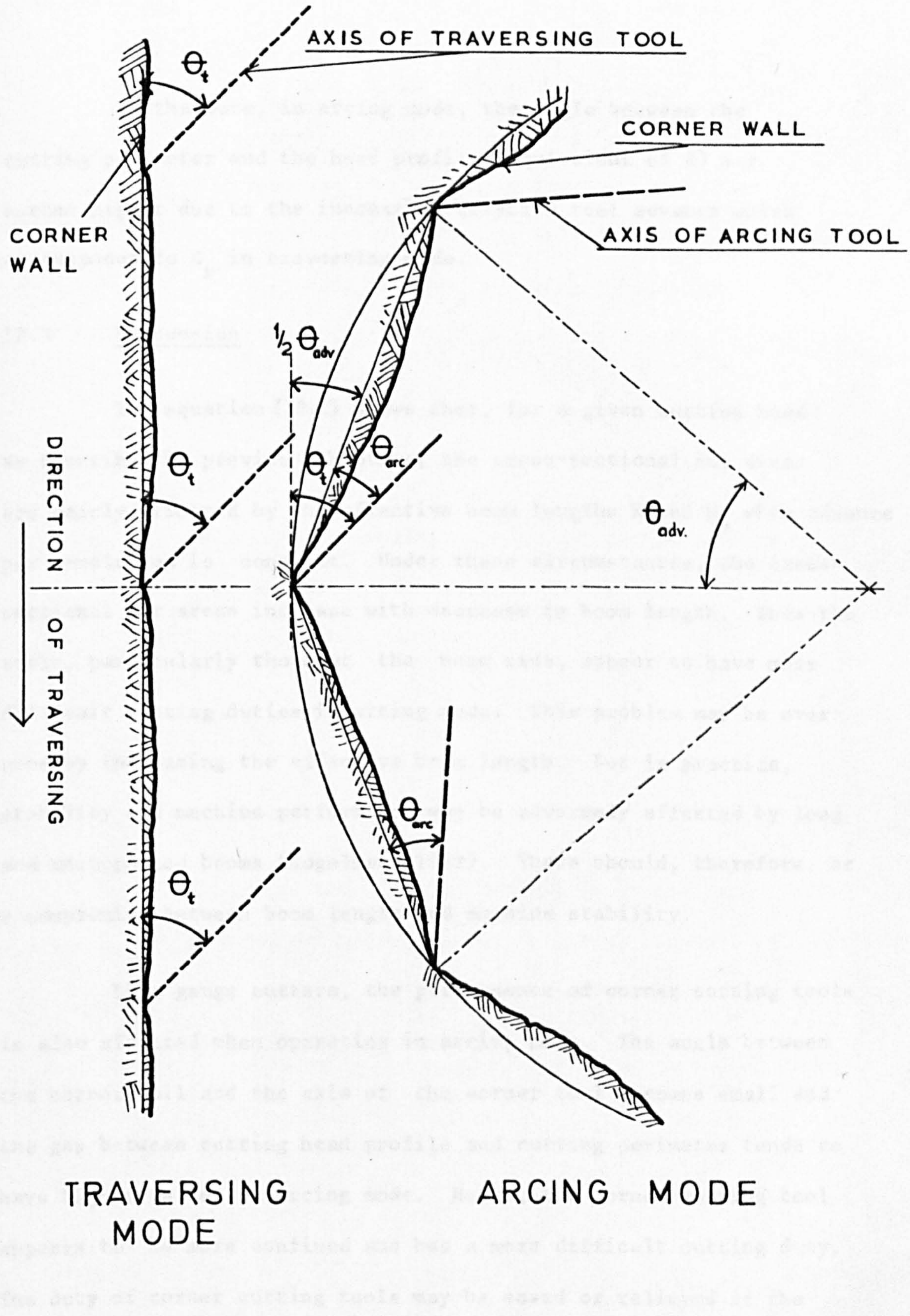


Fig. 99 Cutting position of corner cutting tools in traversing and arcing mode.

Furthermore, in arcing mode, the angle between the cutting perimeter and the head profile (equivalent of β) may become higher due to the increasing relative tool advance which corresponds to d_r in traversing mode.

12.3 Discussion

The equation (12.1) shows that, for a given cutting head as described in previous chapters, the cross-sectional cut areas are mainly affected by the effective boom lengths W and W_α when advance per revolution is constant. Under these circumstances, the cross-sectional cut areas increase with decrease in boom length. Thus the tools, particularly those at the nose side, appear to have more difficult cutting duties in arcing mode. This problem may be overcome by increasing the effective boom length. But in practice, stability and machine performance may be adversely affected by long and unsupported booms (Kogelmann 1982). There should, therefore, be a compromise between boom length and machine stability.

Like gauge cutters, the performance of corner cutting tools is also affected when operating in arcing mode. The angle between the corner wall and the axis of the corner tool becomes small and the gap between cutting head profile and cutting perimeter tends to have higher values in arcing mode. Hence, the corner cutting tool appears to be more confined and has a more difficult cutting duty. The duty of corner cutting tools may be eased or relieved if the corresponding tilt angle is increased.

12.4 Conclusion

The cutting heads which were earlier described and simulated in the previous chapters, were theoretically considered in arcing mode of operation and the following conclusions can be drawn; though the following conclusions are valid, their practical significance is very small:

(1) Cutting duties of the tools are influenced by a change in the boom length;

(2) Increasing boom length, the duty of the cutting tools may be eased, providing this is matched with stability of the machine;

(3) Under identical conditions the tools may, in arcing mode, have more difficult cutting duties than in the traversing mode of operation; and

(4) In arcing mode, corner cutting tools are more confined and by increasing tilt angle at a rate depending upon values of W and adv/rev, corner cutting conditions may be relieved.

*   *   *

13. LABORATORY DISC CUTTING CHARACTERISTICS OF ROCK SALT

13.1 Introduction

Disc cutters have found application in the excavation of hard rock formations because of their high resistance to wear. Like drag tools, laboratory experiments on the performance of disc cutters have been based mainly on cutting on a flat rock surface. However, the number of studies aimed at simulation of the practical cutting action of the discs have recently increased. All these research works have expressed the view that groove deepening mode of cutting is the most representative method for simulating the cutting action of disc cutters under field conditions.

Results of such simulation experiments have revealed that the specific energy decreases with spacing and depth, and so a pronounced minimum value does not exist at a given spacing-penetration (S/p) ratio.

It has also been shown (49) in groove deepening cutting, a complete breakthrough between the adjacent grooves is not consistent after the critical S/p value which is determined on a flat surface cutting condition. The occurrence of the complete breakout has further been reported to be in the form of a 'cyclic deepening' when the adjacent grooves are progressively cut (53).However, the results associated with this phenomenon are limited to only one type of disc and detailed information whichcovers several disc and operational parameters are not yet available.

In this chapter, the disc cutting characteristics of rock salt are described and the results are related to the performance of tunnel boring machines. The experiments were carried out in groove deepending cutting mode and two discs with different edge angles were used. Skewed cutting was also conducted in an attempt to simulate the disc performance near the centre of a full-face tunnelling machine.

13.2 Experimental Procedure

13.2.1 Groove Deepening Cutting

In this type of cutting experiment, the preparation of the rock surface is essential in order to attain a stable cutting condition where instrumented cuts are recorded.

A stable cutting regime is reached when the yield obtained from a particular groove has become equal to the calculated value (i.e. all the rock removed from the two adjacent grooves). For this reason, the rock surface was initially coated with paint and only after all the painted surface had been removed were the desired cutting conditions attained. After this stage, the measures value for yield was found to be approximately equal to that of calculated value.

Each cutting pass consisted of several cuts across the rock at the desired spacing. The successive passes were made at a constant depth increment along the path of an existing groove generated by a previous cut.

To avoid breaking away the sides of the experimental block, a number of relieved cuts at an equal spacing of 10mm were taken at the sides of the rock. The procedure for groove deepening mode of cutting is illustrated in Figure 100.

It is important also to note that in groove deepening cuts the number of uninstrumented cuts was much larger than that of instrumented cuts, as a consequence of preparation of rock surface. This may be clearly seen from Figure 105.

13.2.2 Skew Cutting Experiments

In these experiments, the cutter was skewed to the direction of cutting by a 2.5^{o} angle. In Figure 101, it is illustrated that the disc is skewed to the right of travel, as was the case in the experiments.

The skew angle was achieved by rotating the entire dynamometer. These tests were carried out on the flat surface of the rock specimen. The disc was set to the desired depth and position, and the unrelieved cuts were followed by relieved cuts.

Due to the fact that the entire dynamometer was rotated the measured rolling and sideway force component no longer corrrespond to their initial specification. As a consequence, the instantaneous values of the actual force components (designated f_r and f_o; cf. F_R and F_S for measured values) associated with a skew angle ϕ_S are given by (47):

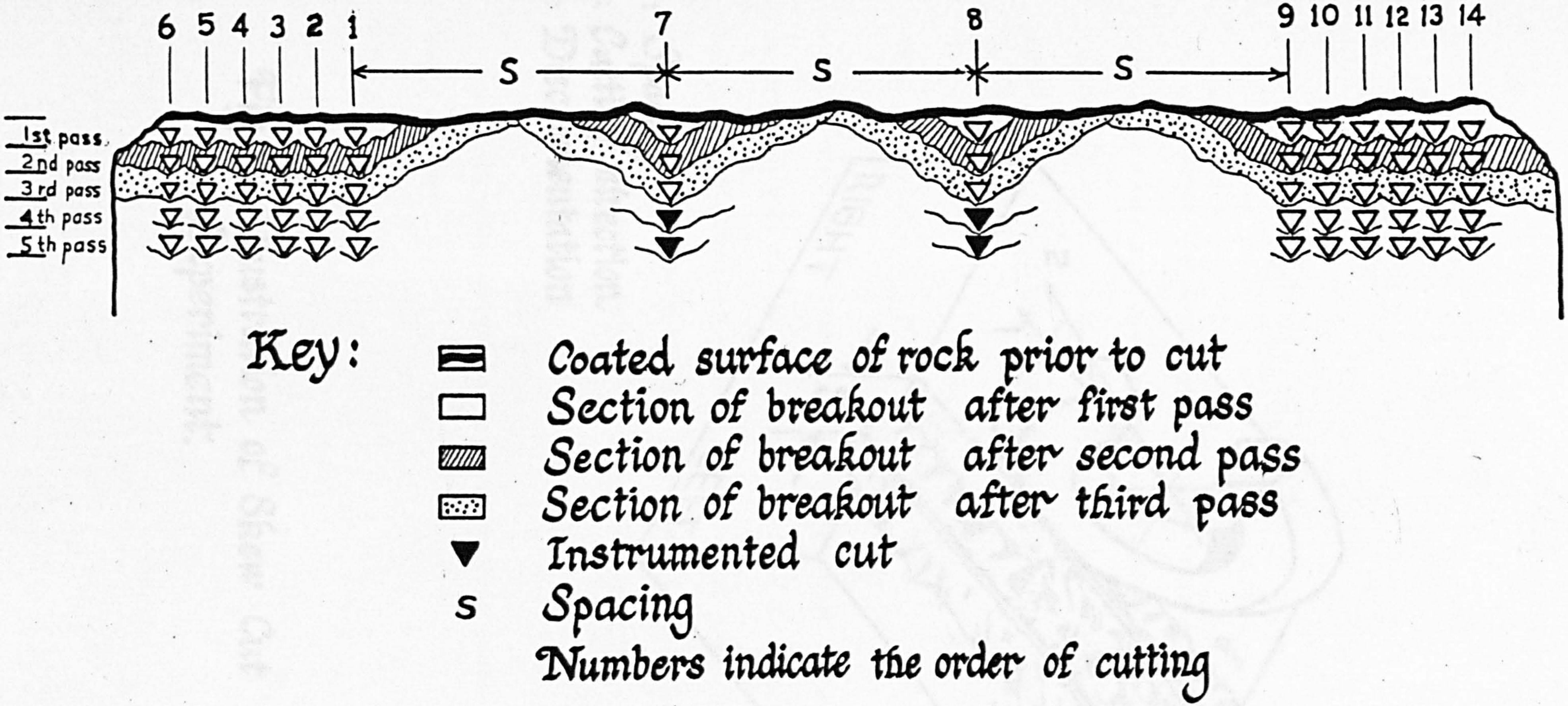
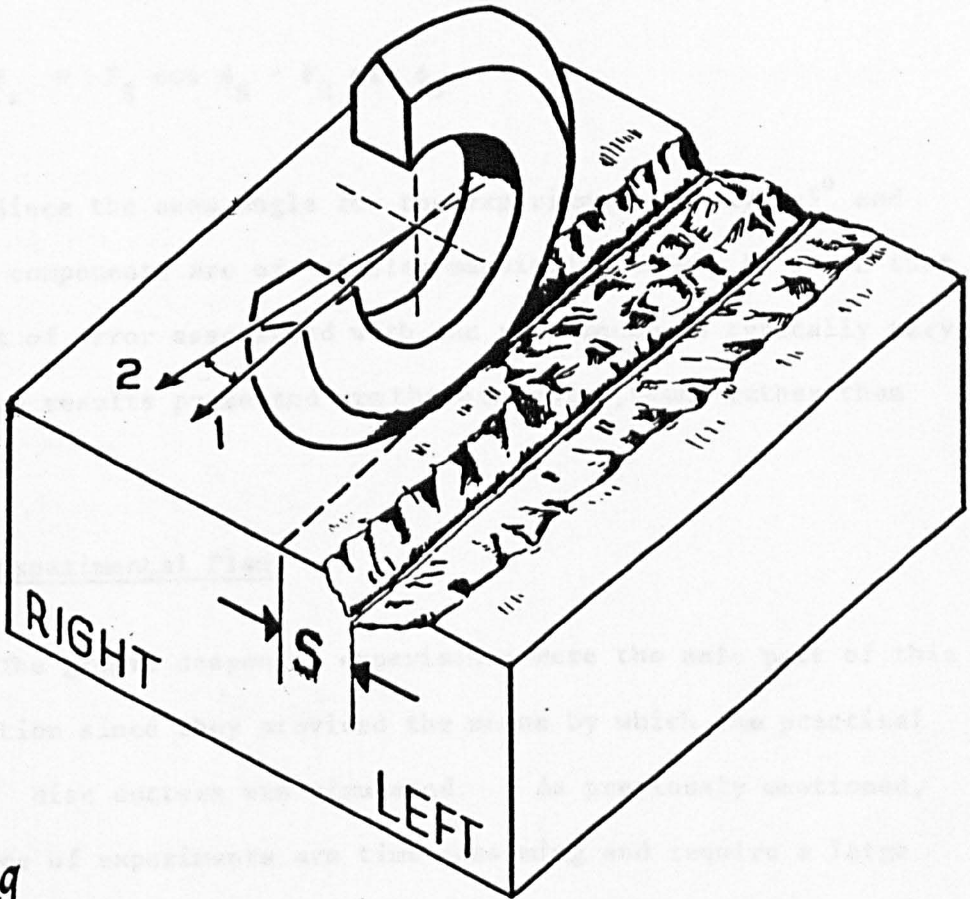


Fig.100 Description of Groove Deepening Experiments.



S : Spacing
1 : Cutting direction
2 : Disc orientation

Fig. 101 Illustration of Skew Cut Experiment.

$$f_r = F_R \cos \phi_S - F_S \sin \phi_S$$

$$f_s = F_S \cos \phi_S - F_R \sin \phi_S$$

Since the skew angle for the experiment is only 2-5^{o} and the force components are of similar magnitude, it may be shown that the amount of error associated with the phenomenon is typically very small. The results presented are those measured, then, rather than corrected.

13.3 Experimental Plan

The groove deepening experiments were the main part of this investigation since they provided the means by which the practical action of disc cutters was simulated. As previously mentioned, these types of experiments are time-consuming and require a large number of suitable blocks. As a consequence, the number of variables had to be limited.

The experimental design for the disc cutter experiments is as follows:

(a) Groove Deepening Cutting Experiments

Variable	Level	Description
Disc edge angle	2	60^{o} and 40^{o}
Penetration	2	10mm; 14mm
Spacing to penetration ratio	6	3,5,7,9,11,13
Number of successive passes	3	--
Replications	3	

(b) Skew Cut Experiments

Disc edge angle	2	60^{o} and 40^{o}
Penetration	1	10mm
Spacing	6	30mm, 50mm, 70mm, 110mm, 130mm
Replications	3	

Total: 252 instrumented cuts

13.4 Results of the Experiments

The rock salt which was the experimental rock showed a heterogeneous structure since scattered marl and various sizes of rock salt crystals were observed in the rock specimen. It was, therefore, thought at first that a wide range of scattered results was likely to be produced. However, the results obtained were reasonably consistent.

The mean value for each cutting parameter was plotted against the corresponding spacing-penetraion (S/p) values. The results of disc cutting experiments were further tabulated in Appendices 7A and 7B.

13.4.1 Groove Deepening Experiments

13.4.1.1 60^{o} Edge Angle Disc

13.4.1.1.1 Forces : In all cases the forces increased gradually and at higher S/p ratios tended to show a steady rise. No significant differences exist between mean and mean peak forces. However, for thrust forces the maximum peak forces were found to be higher (Figures 102 to 105).

13.4.1.1.2 Yield : In Figures 106 and 107 the straight dotted lines radiating from the origin indicate the predicted yield and this was obtained as follows:

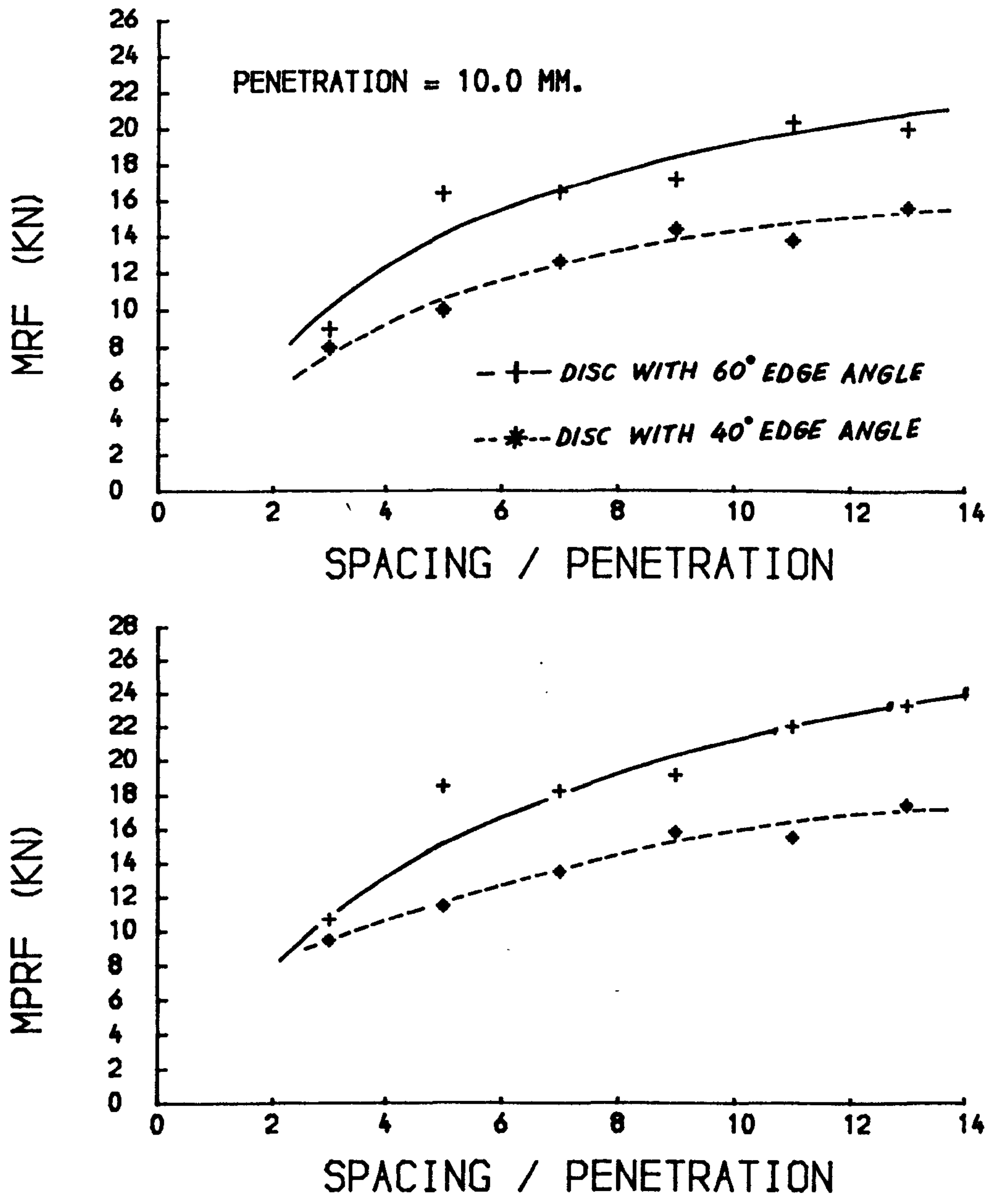


FIG.102 VARIATION OF ROLLING FORCES WITH S/P RATIO, GROOVE DEEPENING CUTTING MODE.

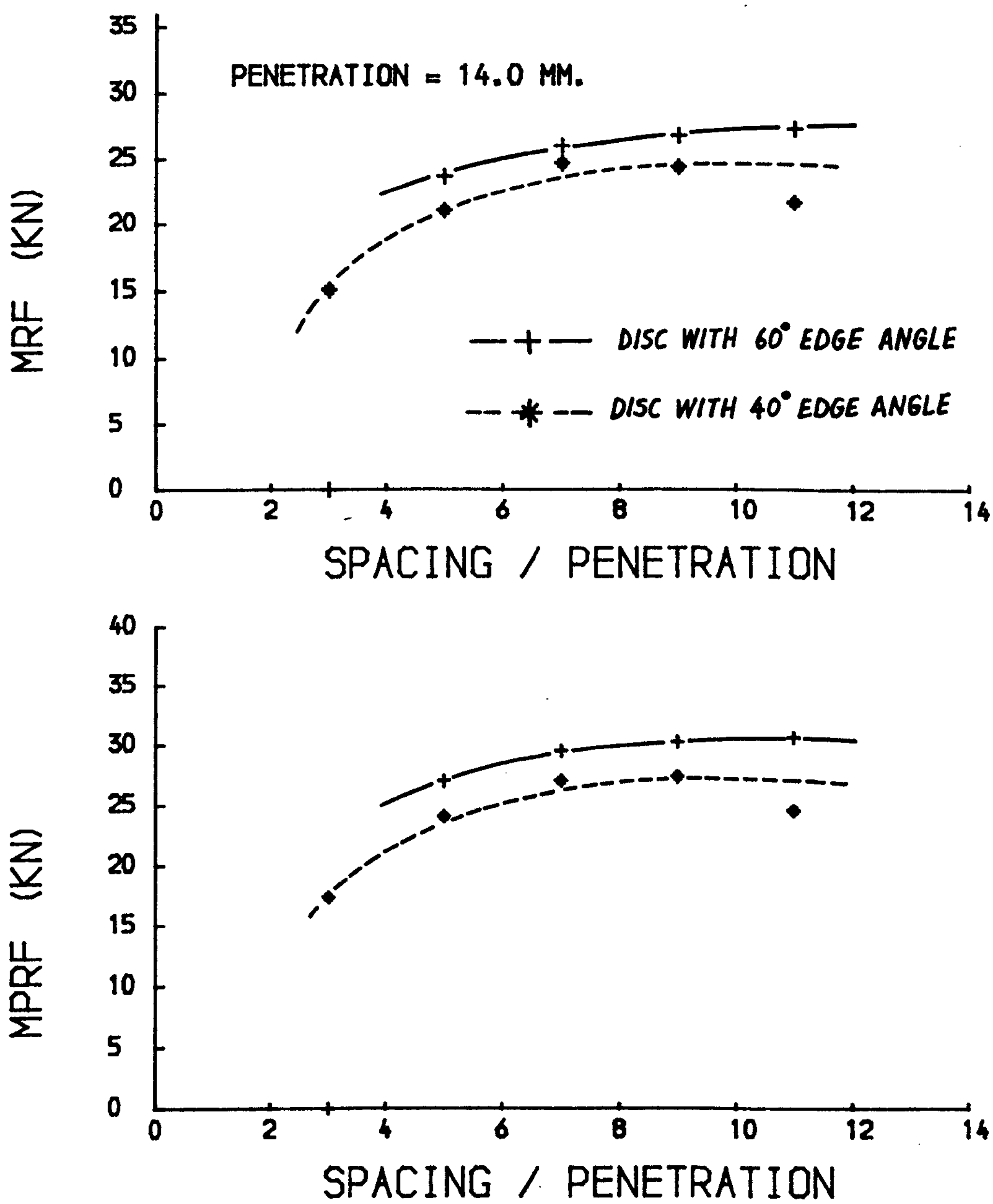


FIG.103 VARIATION OF ROLLING FORCES WITH S/P RATIO, GROOVE DEEPENING CUTTING MODE.

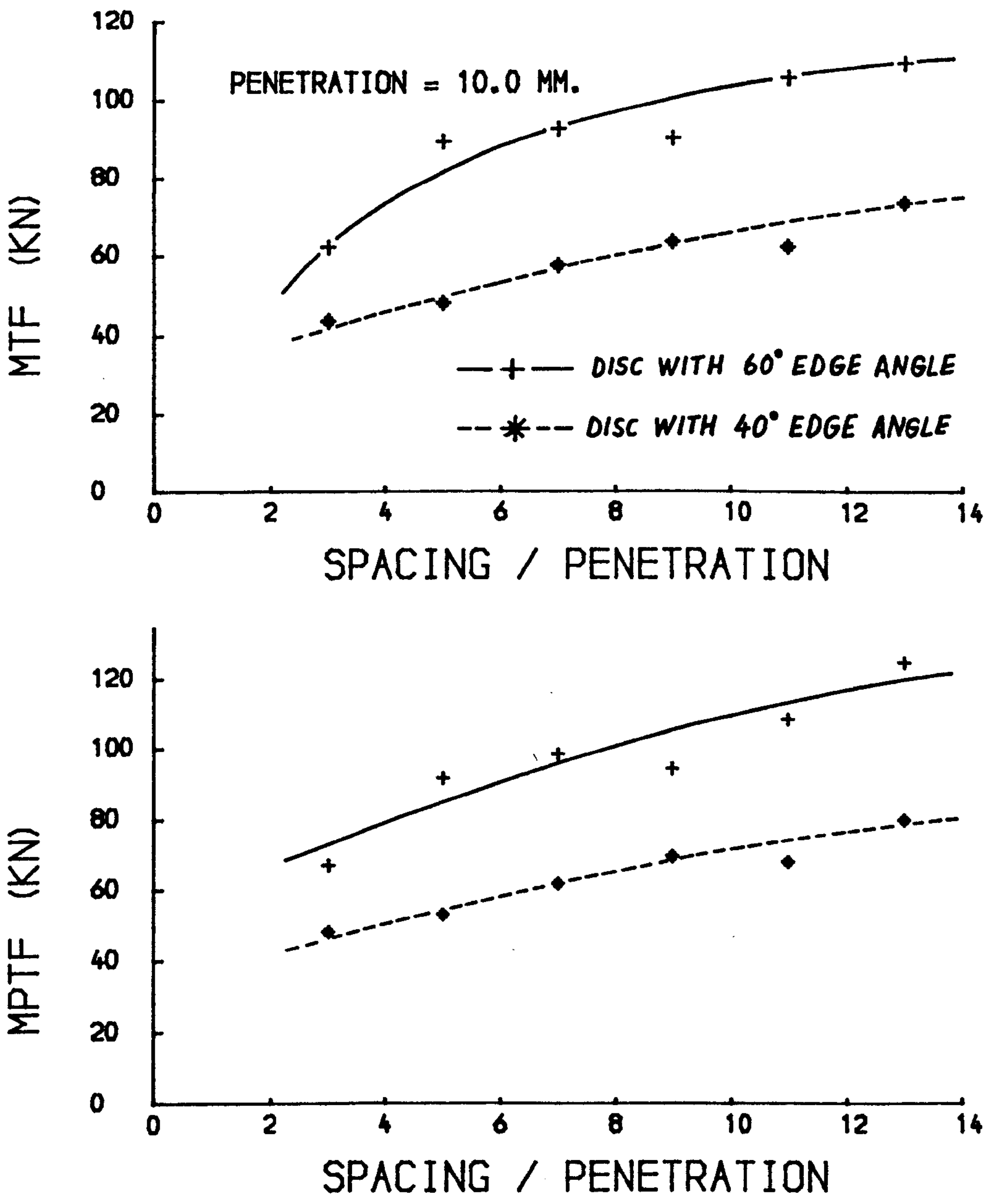


FIG.104 VARIATION OF THRUST FORCES WITH S/P RATIO, GROOVE DEEPENING CUTTING MODE.

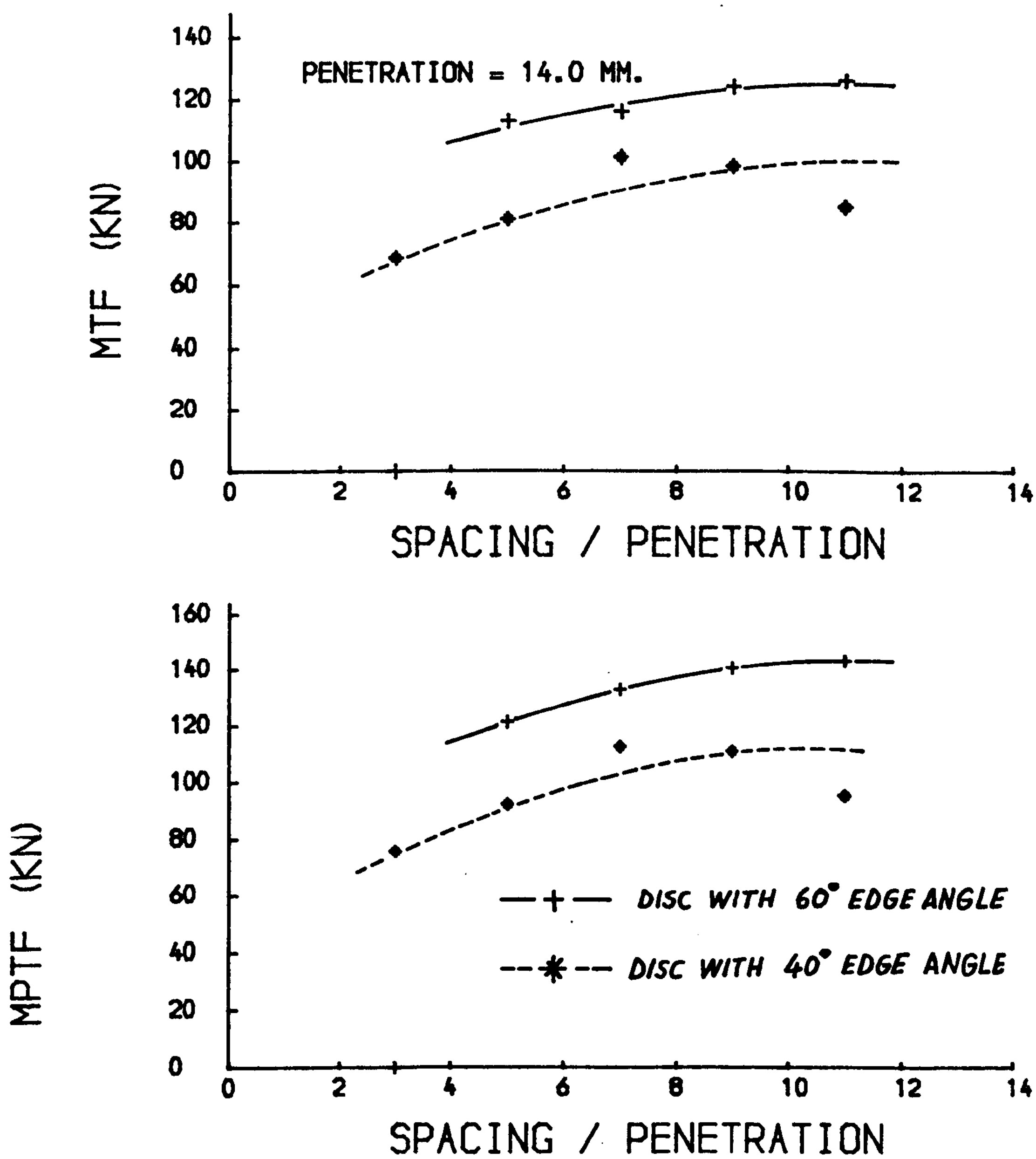


FIG.105 VARIATION OF THRUST FORCES WITH S/P RATIO, GROOVE DEEPENING CUTTING MODE.

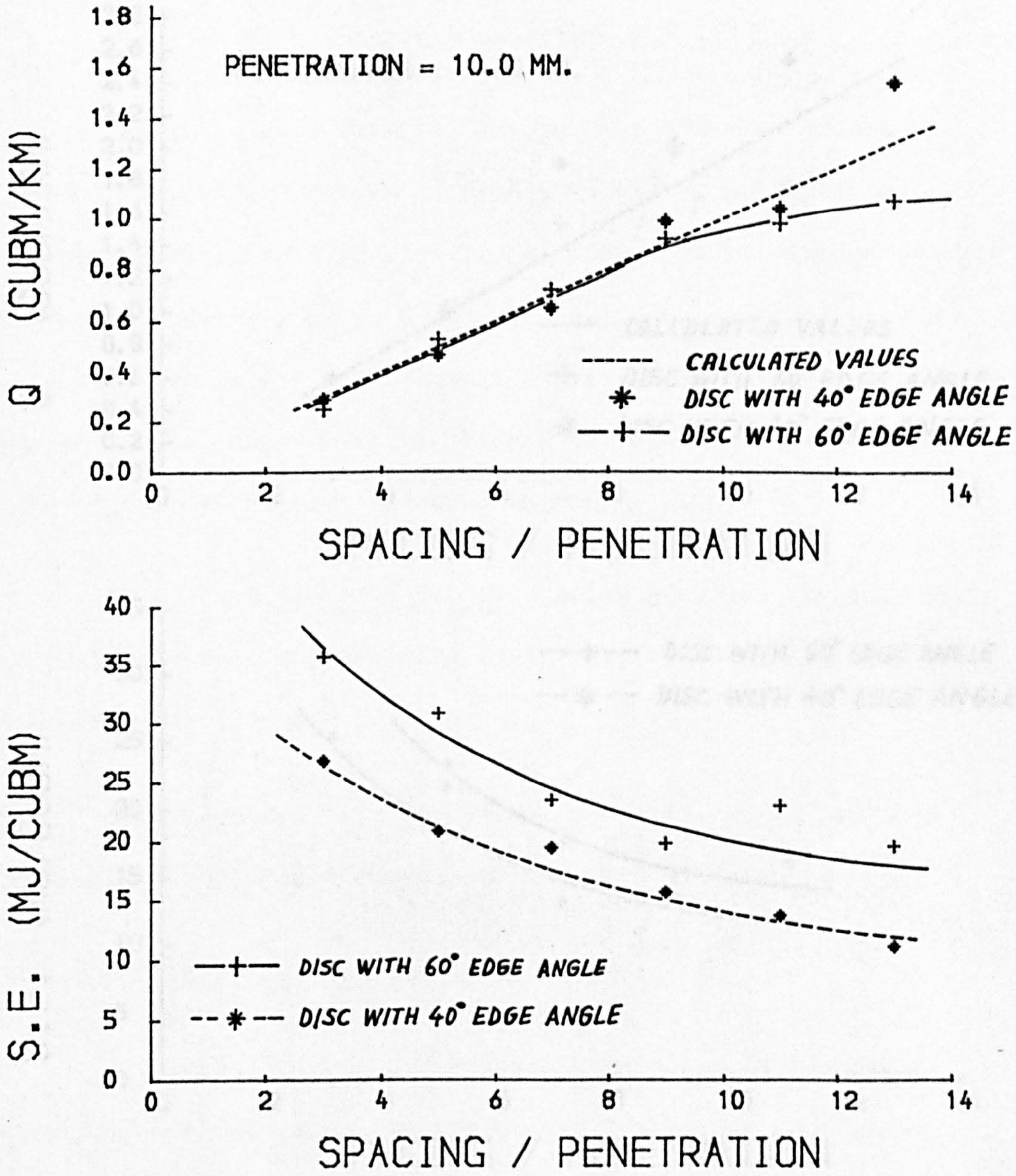


FIG.106 VARIATION OF YIELD AND S.E. WITH S/P RATIO, GROOVE DEEPENING CUTTING MODE.

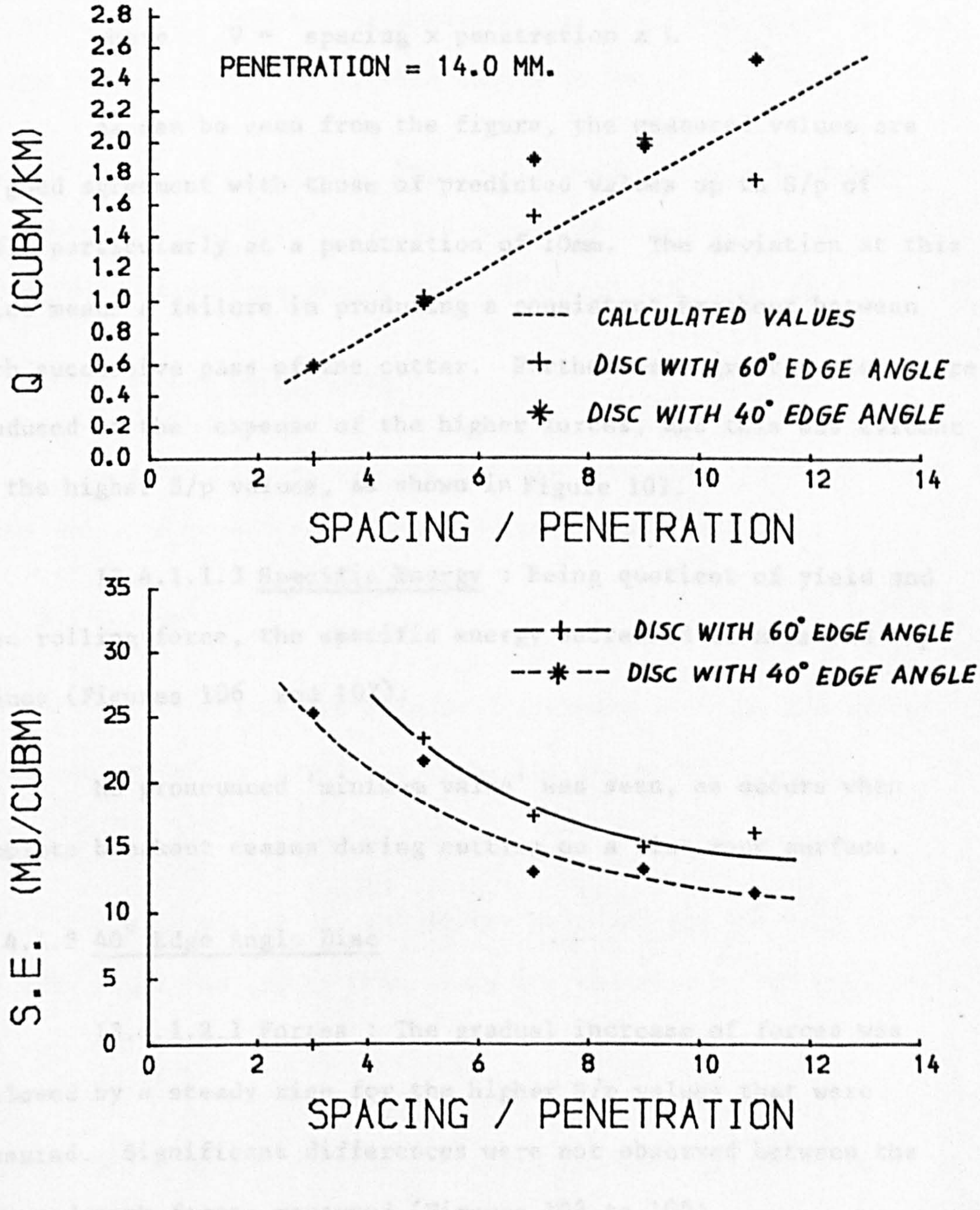


FIG.107 VARIATION OF YIELD AND S.E. WITH S/P RATIO, GROOVE DEEPENING CUTTING MODE.

$$Q_p\ (m^3/km) = \frac{\text{Volume broken out}}{\text{Length of cutter travel}} = \frac{V\ (m^3)}{L(km)} \quad \ldots\ldots (13.1)$$

where $V =$ spacing x penetration x L

As can be seen from the figure, the measured values are in good agreement with those of predicted values up to S/p of 9-11, particularly at a penetration of 10mm. The deviation at this point means a failure in producing a consistent breakout between each successive pass of the cutter. Furthermore, greater yields are produced at the expense of the higher forces, and this was evident at the higher S/p values, as shown in Figure 107.

13.4.1.1.3 Specific Energy : Being quotient of yield and mean rolling force, the specific energy decreased at measured S/p values (Figures 106 and 107).

No pronounced 'minimum value' was seen, as occurs when complete breakout ceases during cutting on a flat rock surface.

13.4.1.2 40° Edge Angle Disc

13.4.1.2.1 Forces : The gradual increase of forces was followed by a steady rise for the higher S/p values that were measured. Significant differences were not observed between the mean and peak forces measured (Figures 102 to 105).

13.4.1.2.2 Yield : At lower S/p values, the measured values presented a reasonable agreement with those calculated from equation (13.1) as illustrated in Figures 106 and 107. At higher S/p values, the yield measured showed a much greater variation due to the variable breakout between cutter paths.

13.4.1.2.3 Specific Energy : Specific energy gradually increased at lower S/p ratios and tended to level out at higher values of spacing-penetration ratio (Figures 106 and 107).

13.4.2 Skew Cut Experiments

The results are plotted for both types of disc cutter and these are also presented in tabular form in Appendix 8B .

13.4.2.1 Forces

The forces showed a gradual increase at lower S/p ratios and thend tended to level out at higher values of S/p. T. (Figures 108, 109).

The magnitude of the forces measured for the disc with 60° edge angle was higher than those for the disc of 40° edge angle.

13.4.2.2 Yield

Yield values for the two discs increase gradually up to an S/p of 7 and fall rapidly at a constant value, as shown in Figure 110.

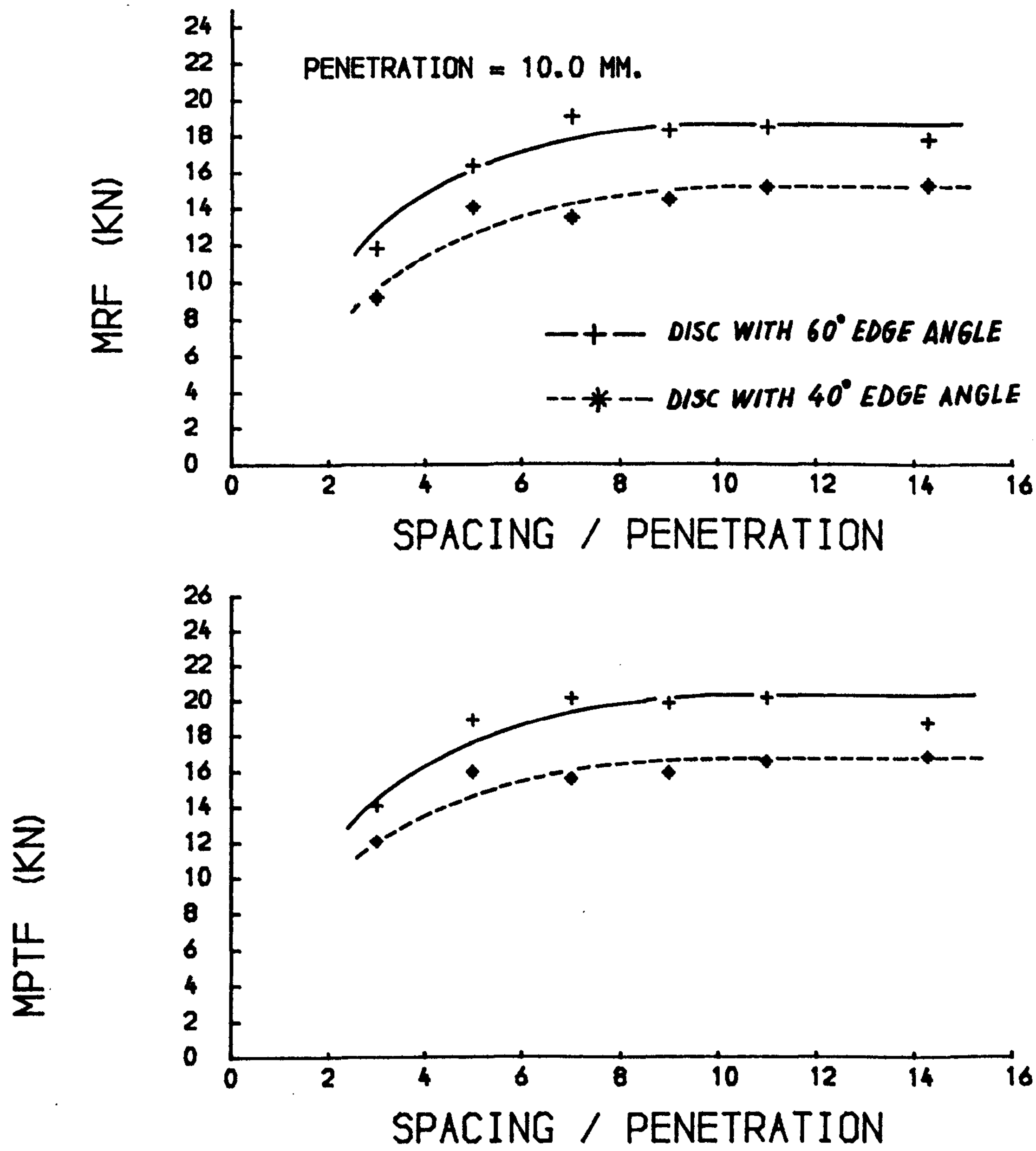


FIG.108 VARIATION OF ROLLING FORCES WITH S/P RATIO, SKEW CUT TRIALS, SKEW ANGLE= 2.5 DEGREE.

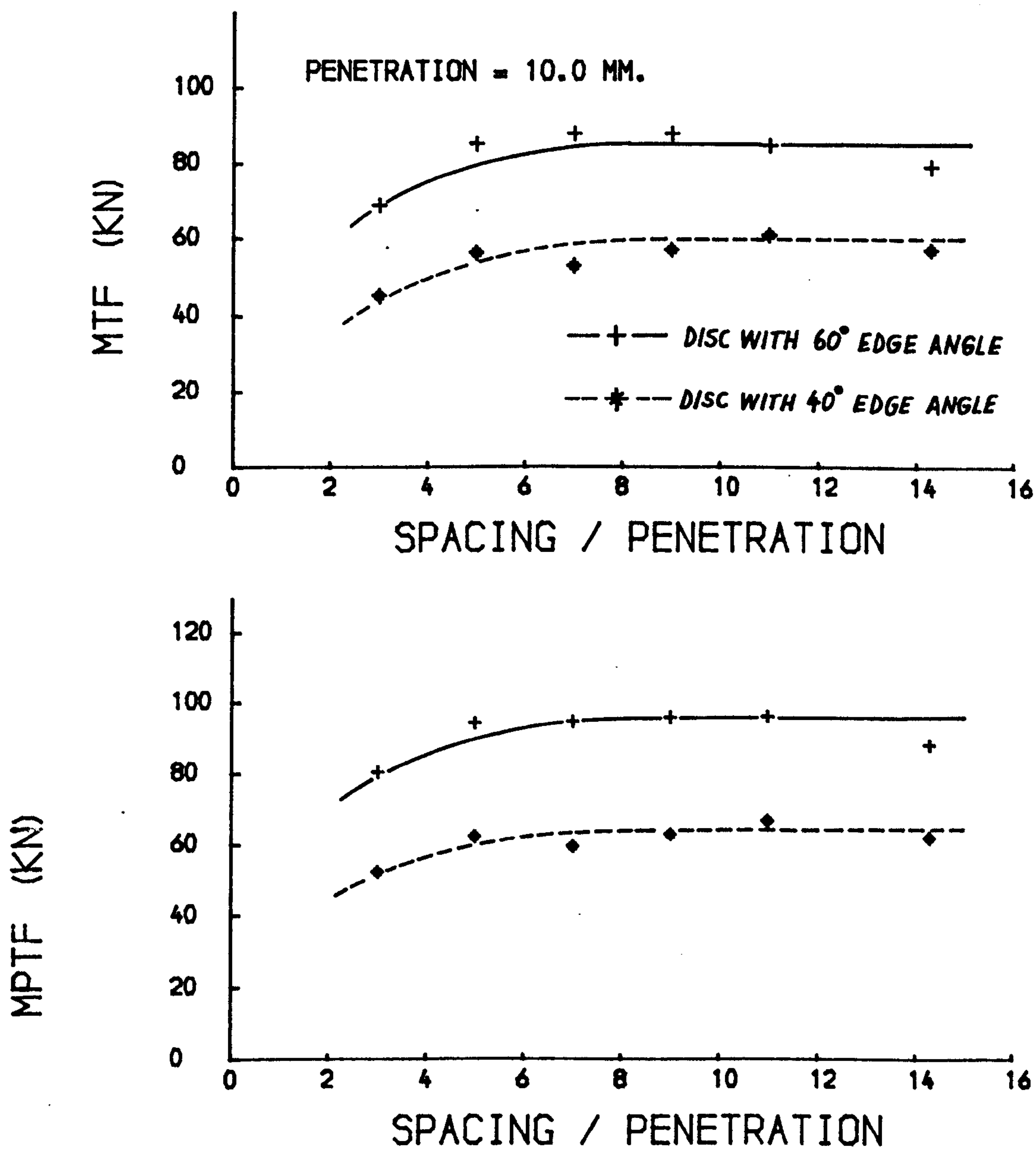


FIG.109 VARIATION OF THRUST FORCES WITH S/P RATIO, SKEW CUT TRIALS, SKEW ANGLE= 2.5 DEGREE.

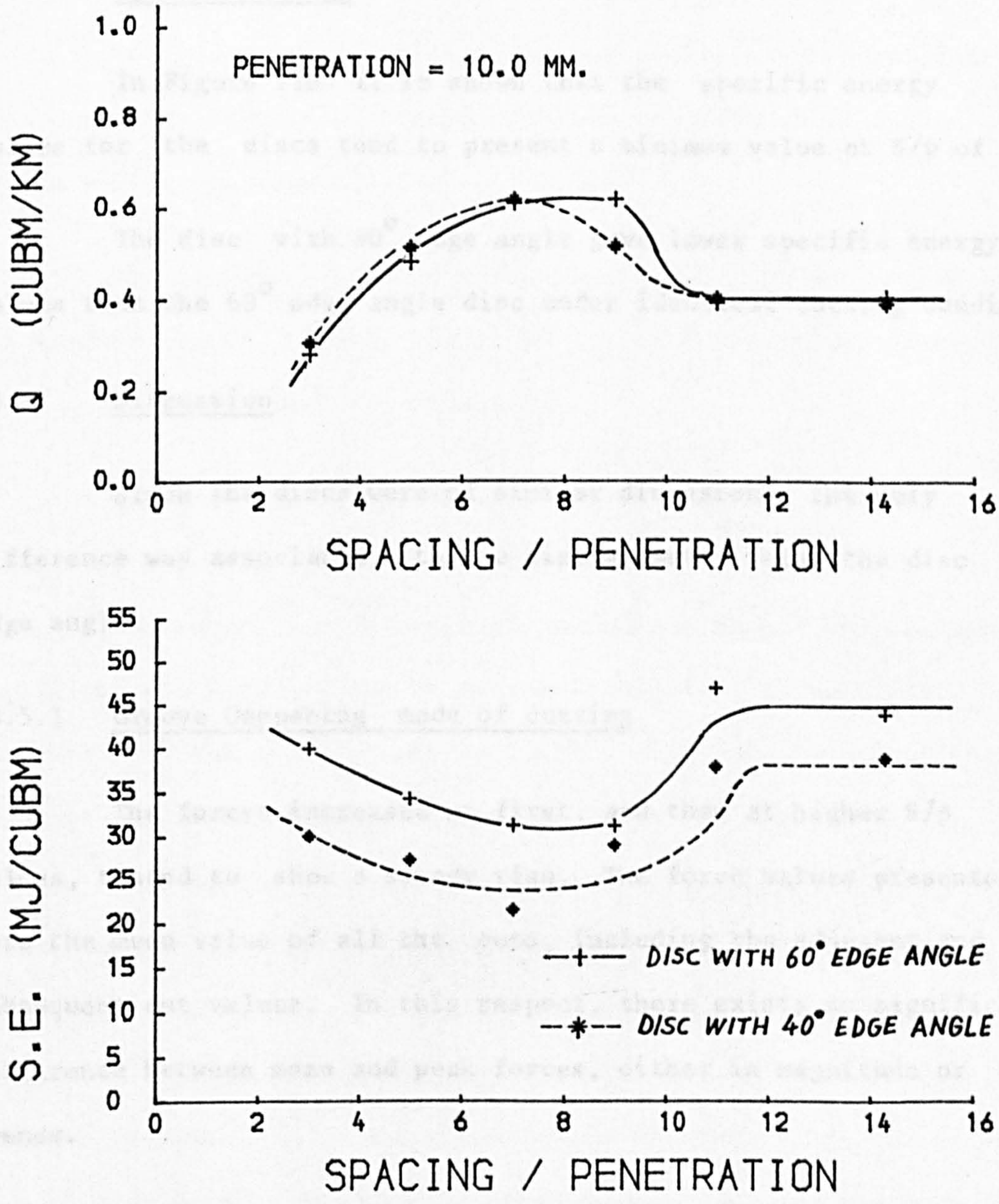


FIG.110 VARIATION OF YIELD AND S.E. WITH S/P RATIO, SKEW CUT TRIALS, SKEW ANGLE=2.5 DEGREE.

There was no significant differences in yield values for the two discs.

13.4.2.3 Specific Energy

In Figure 110 it is shown that the specific energy values for the discs tend to present a minimum value at S/p of 7.

The disc with 40° edge angle gave lower specific energy values than the 60° edge angle disc under identical cutting conditions.

13.5 Discussion

Since the discs were of similar dimensions, the only difference was associated with the disc geometry being the disc edge angle.

13.5.1 Groove Deepening mode of cutting

The forces increased at first, and then at higher S/p values, tended to show a steady rise. The force values presented were the mean value of all the cuts, including the adjacent and subsequent cut values. In this respect, there exists no significant difference between mean and peak forces, either in magnitude or trends.

Measured thrust force values for the disc with 60° edge angle were approximately 30% higher than those of the 40° edge angle disc, whilst the rolling force values were found to be about 20% higher.

For the two discs, the force values obtained from each successive pass of the cutters were not consistent at higher S/p ratios.

The yield values which were averaged over the total cuts at a particular S/p value tended to show a random character at higher values of spacing.

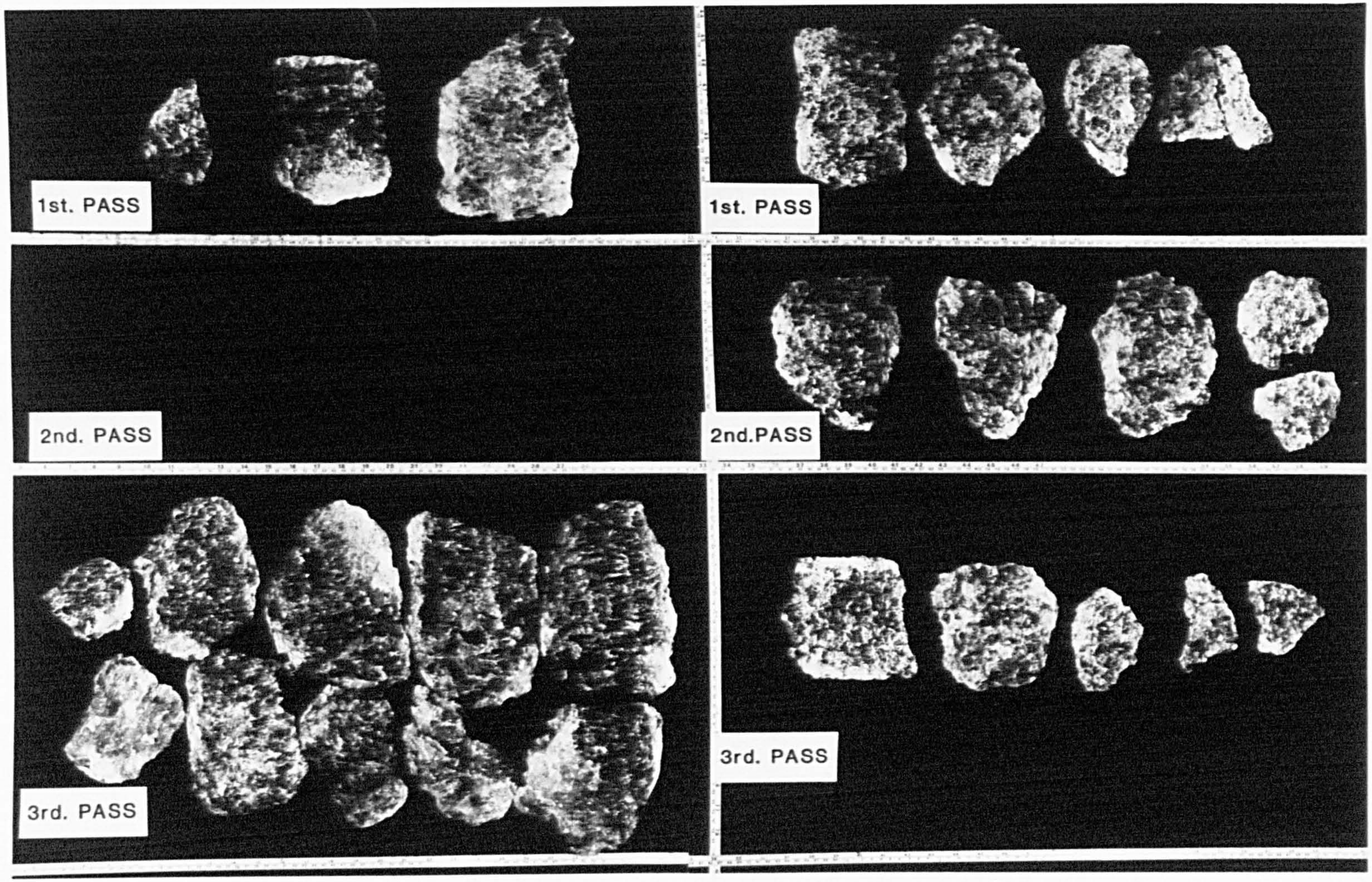
The state of breakout and coarseness of the product which are shown in Table 12 and Plate 28 for each disc respectively may provide an insight into this trend.

In Table 12 it may be significant that the standard deviations also rise with increasing yield values as the S/p ratios increase; however, a wide range of randomised values for standard deviations was expected due to non-uniform nature of rock salt. From the table and the plate it can be clearly seen that non-consistent breakouts exist between subsequent passes of the discs. It was further observed that a groove exhibiting a poor breakout and low yield, can produce complete breakout after the successive passes, due to the removal of ridges formed by the previous pass. This was found to be the situation when cutting with the disc of 40^{o} edge angle as shown in Plate 28. Among the debris obtained after the second pass of this cutter, no fragment coarser than 50mm was obtained, whereas after the third pass the total debris gave about 70% of product being coarser than 50mm and this clearly accounts for the non-consistent breakout between the successive passes.

TABLE 12

s/p	EDGE ANGLE = 60^{o} ($Q \pm s.d.$)	EDGE ANGLE = 40^{o} ($Q \pm s.d.$)
5	1.023 ± 0.054	0.989 ± 0.112
7	1.528 ± 0.270	1.895 ± 0.189
9	2.020 ± 0.776	1.979 ± 0.572
11	1.763 ± 0.495	2.527 ± 1.746

Variation of Yield with S/p ratios for the two discs.



WITH 40° EDGE ANGLE   WITH 60° EDGE ANGLE

PENETRATION : 14mm.   SPACING / PENETRATION : 11

Plate 28

Accordingly, the initial passes of the disc cutter caused the creation of high ridges between adjacent grooves at higher S/p values and these ridges were remvoed after further passes of the cutter. Hence a cyclic deepening of grooves was indicated. Experimental results have shown that this process of cyclic deepening requires more subsequent passes for the disc having a 40° edge angle in order to produce a complete breakout. This phenomenon is illustrated in Figure 111.

It is reported that in such a cyclic groove deepening mode of cutting, the cutters will wear more quickly than a corresponding tool cutting in an optimally relieved situation (53). This is because of increased rubbing area between tool and rock and the increased forces on the cutter. However, in some practical conditions the disc cutters may not operate at the nominal spacing; for instance, when cutting a very abrasive or an extremely strong rock, and a reduced advance per revolution of the cutter head may be taken (54). Under these circumstances, the effective S/p ratios would increase and, as a consequence, the process of a cyclic deepening of the groove may come into action.

The experimental results in this work have also indicated that in such a groove deepening situation, a larger contact area exists between the rock and the disc with 40° edge angle. This implies that the disc cutters with acute edge angle may become more susceptible to wear under the above mentioned conditions.

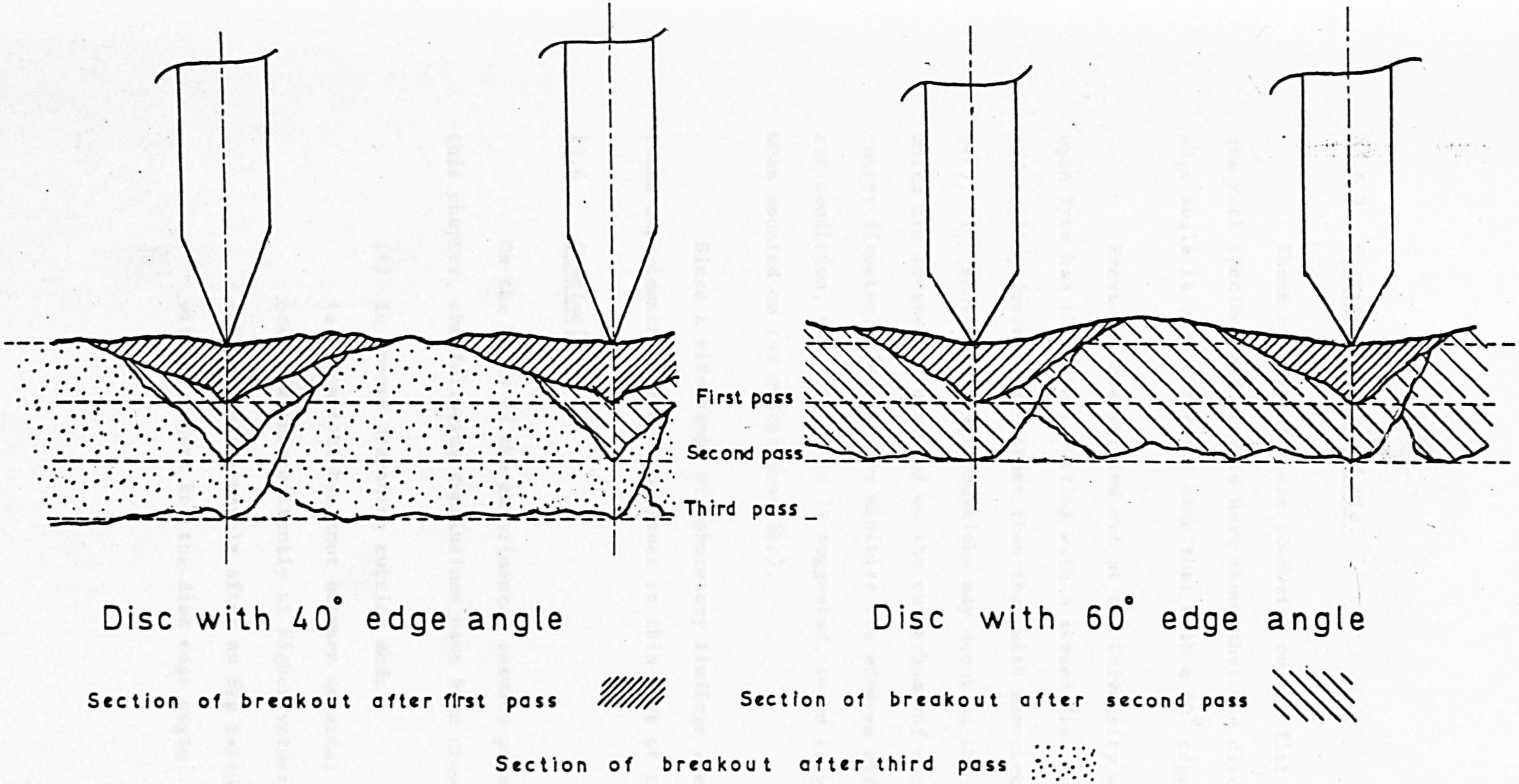


Fig.111 Illustration of complete breakouts between adjacent grooves for two different discs.

13.5.2 Cutting with Skewed Disc

These experiments were conducted on the flat surface of the rock specimen and results have shown that the disc with a 40° edge angle is more efficient than that with a 60° edge angle.

Previous work carried out at the University of Newcastle upon Tyne has shown that cutting with a skewed disc is inefficient and rolling forces were higher than that with non-skewed cutter (47). The skewed cutting conditions may occur at the face cutters which are located at a radius on the cutterhead of about one disc cutter diameter. In order to minimise the adverse effect of skew cut condition, the cutter, it is suggested, to be slightly skewed when mounted on the cutter head (47).

Since a wide range of laboratory findings are available, these experiments were not continued in this part of the work.

13.6 Conclusions

On the basis of the experimental results presented in this chapter, the following conclusions have been drawn:

(1) In groove deepening cutting mode:

(a) Complete breakout between adjacent grooves occurred intermittently at higher values of S/p ratios (approximately after an S/p ratio of 7) without regard to the disc edge angle.

(b) For complete breakout the 40° disc required more successive passes of the disc cutter than the 60° disc.

(c) Intermittency in complete breakouts indicated the formation of high ridges between adjacent grooves with the disc of 40° edge angle.

(2) In skew cut, optimum cutting conditions tended to occur at a spacing-penetration of 7 and the disc with 40° edge angle exhibited lower forces and specific energy values.

* * *

14. CONCLUSIONS AND RECOMMENDATIONS

In this chapter a summary of the main findings from this work is given together with a presentation of their practical significance for cutting head design of rock excavation systems.

14.1 Use of saltcrete as a medium for rock cutting experiments

Both cutting experiments and material property tests have shown that saltcrete did not perfectly present the same material properties and cutting characteristics as those of the natural rock salt, due mainly to the presence of cement which bonds the rock salt aggregates together. However, the discrepancies between saltcrete and rock salt are not highly significant since results obtained from both materials are reasonably similar.

Saltcrete may, therefore, be used for large scale cutting trials of evaporite rocks where the rock supply is costly, providing that the saltcrete is adequately cured.

14.2 Effect of lateral tool spacing and tool type

The experiments were carried out in such a way that the practical cutting action of a tool was simulated. The variables considered were tool spacing, number of tools per line and tool type.

The findings for this section are as follows:

(1) Simulation of a cutting pattern at various tool spacings on a simple shearer drum has revealed that,

with increasing line spacings, specific energy decreases and tool forces show a continual increase. After a certain spacing where the adjacent grooves no longer interact with each other a constant level is likely to be reached. This was evident when cutting with the two tools per line mode of cutting when the constant level was reached with no breakout interaction between grooves. Specific energy values tend to decrease steadily approximately after a spacing equal to d tan ($\theta/2$) (where θ is unrelieved breakout angle when cutting on a flat rock surface). Machine stability may be improved if the line spacing does not exceed this value.

(2) To employ a cutting pattern with two tools per line in which the tools successively deepen a groove was found to be an inefficient tool arrangement. The cutting pattern with one tool per line at which a tool cuts midway between the adjacent tools of previous sequences (relief cut) was shown to be the best method for a tool lacing pattern.

It should be noted also that a 'relief cutting' mode may not be seen on a three-start cutting head with one tool per line, although this phenomenon was not substantiated with any cutting experimental data.

(3) Higher tool forces were generated when cutting with point attack tools, compared with radial tools. The decreasing specific energy trend with spacing was similar for both tool types, within the measured spacing values investigated in the relief cutting mode. The relationship for force component against spacing was of an exponential form for the point attack tools and of linear form for the radial tools.

It should be borne in mind that these relationships were found only within the measured spacing levels and they were not investigated up to a spacing value where the interaction between the adjacent grooves had ceased in the relief cutting mode. This was evident in the groove deepening cutting mode, where the force-spacing relationship is no longer in a linear form when cutting with radial tools.

14.3 Effect of tilt angle when operating a traversing mode

The findings for this section are as follows:

(1) If the line spacing is kept constant on a given cutting head:

(a) tool forces and tool duties become different with tilt angle; and

(b) effective tool spacing, depth of cut and tool cutting positions continuously vary with tilt angle.

(2) Increasing the tilt angle of the corner cutting tool significantly decreases the tool forces and the corner cutting tool behaves as a gauge tool after the value where the tilt angle is approximately equal to the breakout angle of the rock when cutting on a flat rock surface (θ). Furthermore, the possibility of dust make increases with increased tilt angles of gauge tools.

(3) Tool forces were found to be linearly related to the cross-sectional area cut by a pick. This may suggest that tool duties are compatible with the cross-sectional areas rather than evenly equal line spacing at a given operational parameter.

(4) By analogy from the corner cutting experiments, the tool axis should be perpencicular to the cutting head surface rather than parallel to the direction of advance.

14.4 Effect of cutting head geometry when operating in traversing mode

In this section, the only variables were the tilt angle of gauge and corner cutting tools. Thus operational parameters and tool lacing pattern were constant for all the cutting heads investigated.

The findings for this section are as follows:

(1) On a spherical head each tool cut a different cross-sectional area, while on a conical head the same

cross-section is cut by all tools, provided the tilt angle of the corner cutting tool is greater than or equal to θ.

(2) On a conical cutting head, by increasing the cone angle tool forces decrease and specific energy increases. Furthermore, travelling distance taken by the tools located at the machine side becomes higher and the cross-sectional areas for all tools diminish with increasing cone angle and thus problems of dust make and tool wear are likely to arise.

(3) As a compromise, using a combined cutting head with a moderate cone angle and a corner cutting tool with a tilt angle slightly greater than θ, may provide an efficient excavation.

14.5 Effects of the total number of tools when cutting in traversing mode

The only variable was the total number of cutting tools and all other parameters were kept constant.

The findings for this section are as follows:

(1) Variation in the total number of picks on a head results in changes to effective depths, effective spacing and the tools' cutting positions.

(2) Increasing the number of tools slightly reduced the forces on the corner cutting tools while it had no pronounced influence on the gauge tools within the measured levels.

14.6 Influence of cutting sequence starting point

The cutting heads were investigated in traversing mode of operation and all the operational and design parameters were kept constant. It was found that cutting towards the nose side of the head is more beneficial than cutting away from it. However, it seems that to cut in either mode does not change the duty of gauge tools with zero tilt angle.

14.7 Effect of arcing mode of operation

The findings for this section are based on the theoretical investigations though they are valid, their practical significance will be very small:

(1) Length of cutting boom affects the level of tool forces in such a way that for a given cutting head the forces tend to decrease with increasing boom length. However, with a longer, unsupported boom, stability of a cutting machine is likely to be reduced.

(2) Corner cutting tools and the gauge tools on a cutting head operating in an arcing mode have more difficult cutting duties than when operating in the traversing mode when all other parameters are kept constant.

14.8 Influence of disc edge angle on the performance of disc cutters

In this section the performance of two disc cutters was studied in accordance with their actual cutting conditions and the only important variable was the disc edge angle.

The findings for this section are:

(1) A cyclic deepening of the adjacent grooves was found to exist when the successive passes of the disc cutter takes place.

(2) In order to provide complete breakout between the adjacent grooves, the disc with a 40^{o} edge angle required more successive passes than the one with a 60^{o} edge angle.

14.9 Recommendations

The results detailed in this work were obtained only from laboratory trials; however, the findings may be related to the design and operational aspects of rock excavation machines.

The trend in the development of current roadheaders is to produce more robust and heavier machines in order to excavate the higher strength rock materials. Along with increased power and weight, the design of cutting heads should also be taken into account so that the available power on the cutting head is efficiently utilised. A proper cutting head design is mainly compatible with an equal distribution of cutting duties on each pick, e.g. compromise between the level of individual pick forces, fluctuations in torque and axle forces, and tool wear. Equal force distributions on each cutting tool can reduce the force fluctuations but it is unlikely to completely eliminate them as the major factor influencing the torque fluctuations is the lacing pattern.The relative influence of these fluctuations on the performance of roadheader cutting heads should be investigated through the use of an instrumented machine. The equations which were developed in this work for the definition of cross-sectional areas may prove to be useful in the prediction of relative tool forces on a roadheader cutting head.

The total number of tools on a roadheader cutting head is considered to be an important parameter which has been shown to have an influence on the performance of corner cutting tools. Although no significant effect was observed on the gauge tools, it may be of interest to invesigate this aspect in more detail since the number of variables considered in this work was small. Simplified laboratory trials which involve a large number of variables and less costly and laborious experiments may be undertaken for this investigation.

Further research on the instrumented roadheader cutting rig in the University of Newcastle upon Tyne should also be undertaken with a view to validating the conclusions from the simulated linear cutting experiments and to investigate other relevant practical aspects of cutting head design.

Recent developments in rock cutting technology indicate that in the near future roadheaders may incorporate high pressure water jets, which has been proved to be an effective excavation method. Along with some field trials, there has been a number of laboratory research programmes on several aspects of the hybrid-cutting method. It is recommended that these experiments be carried out on a pre-cut rock surface as was used during this programme of work.

Furthermore, during the disc cutting experiments, the number of variables was limited and simulation experiments were carried out only in groove deepending mode of cutting. Simulation trials with disc cutters in relief cutting mode may also provide an insight into cutting head design of tunnel boring machines.

It is hoped that this work has contributed to the science of rock cutting technology.

* * *

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APPENDICES

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Appendix 6A1

Details of spherical heads.

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Results for disc cutting experiments : groove deepening cuts : penetration 10.0mm.

Appendix 7A2

Results for disc cutting experiments : groove deepening cuts : penetration 14.0mm.

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Results for disc cutting experiments : skew cuts : penetration = 10.0mm.

Appendix 8A

The computer program for the calculation of cutting head parameters.

*   *   *

The material used is F.M. Parkin (Sheffield) Ltd. type FMP 338 tool steel. The discs were fabricated and then heat treated prior to finish grinding of the bore dimension.

The heat treatment was as follows:

a) Preheat to 350°C

b) Heat for 15 minutes in salt bath at 960°C

c) Quench in oil

d) Temper 1 hr at 200°C

The hardness measurements indicated a hardness of Rockwell C59 - 62.

APPENDIX 1

Disc Cutter Specification (47)

Location : Springwell, Gateshead, Tyne & Wear.

Mineralogy :

Sphericity : Poor to moderate

Rounding : Poor

Mineralogical content (500 number of points counted)

	%
Quartz	63
Rock fragments	17
Ferromagnesian	3
Feldspar	1
Iron Oxide	2
Matrix	14

Uniaxial Compressive Strength : 43.21 ± 1.51 MPa

Indirect Tensile Strength : 2.99 ± 0.22 MPa

Triaxial Strength :

Confining Pressure MPa	Failure Stress (MPa)
0.00	43.21
3.45	63.62
6.20	81.05
10.34	95.44
13.79	113.23
17.24	127.25
20.69	132.55
24.14	144.67
27.58	157.17

APPENDIX 2 : PHYSICAL AND MECHANICAL PROPERTIES OF SPRINGWELL SANDSTONE (90)

Dynamic Elastic Moduli	:	1.79×10^4 MN/m^2
Bulk Density	:	2.21 gm/cc
Shore Hardness	:	36.70 ± 6.29
Schmidt Hammer Rebound Number	:	52.03 ± 1.07
Cone Indenter Hardness	:	1.98 ± 0.41

Appendix 2(contd)

3.1

Spacing to Depth Ratio (s/d)	Material Type	Parameters Measured					
		MCF (kN) ±s.d.	MPCF (kN) ±s.d.	MNF (kN) ±s.d.	MPNF (kN) ±s.d.	$Qx10^{-1}$ m^3/km ±s.d.	S.E. (MJ/m^3) ±s.d.
3	R*	0.86±0.36	1.47±0.25	0.78±0.35	1.10±0.37	0.548±0.050	15.69
	S*	0.79±0.06	1.25±0.05	1.17±0.06	1.54±0.02	0.474±0.042	16.67
4	R	1.07±0.07	1.60±0.14	1.24±0.11	1.54±0.1	0.977±0.052	10.95±2.51
	S	1.15±0.14	1.80±0.15	1.51±0.23	1.87±0.22	0.826±0.042	14.30±1.18
5	R	1.58±0.32	2.49±0.29	1.68±0.51	2.12±0.40	0.995±0.027	15.87±2.04
	S	1.44±0.34	2.31±0.39	1.63±0.52	2.10±0.49	0.995±0.127	14.47±1.12
6	R	1.78±0.28	2.69±0.31	1.74±0.40	2.38±0.39	1.79±0.12	21.78±3.11
	S	1.55±0.10	2.35±0.09	1.57±0.20	2.00±0.14	1.97±0.14	16.76±2.45
7	R	2.05±0.16	3.01±0.27	2.48±0.19	2.95±0.17	0.804±0.082	25.50±2.15
	S	1.84±0.18	2.51±0.21	1.94±0.41	2.48±0.21	0.845±0.066	21.77±2.07

R* = Rock salt, S* = Saltcrete

APPENDIX 3 Relieved cutting results for rock salt and saltcrete, Experiments with point attack tools on flat rock surface

Spacing to Depth Ratio (s/d)	Material Type	Parameters Measured					
		MCF (kN) ±s.d.	MPCF (kN) ±s.d.	MNF (kN) ±s.d.	MPNF (kN) ±s.d.	$Qx10^{-1}$ m^3/km ±s.d.	S.E. (MJ/m^3) ±s.d.
8	R S	1.84±0.14 1.68±0.23	2.80±0.19 2.52±0.22	1.69±0.19 1.99±0.23	2.22±0.19 2.45±0.32	0.817±0.119 0.667±0.108	22.52±3.10 25.19±1.03
9	R S	2.01±0.18 1.71±0.20	3.04±0.29 2.61±0.31	2.01±0.32 1.53±0.30	2.54±0.31 2.01±0.41	0.598±0.087 0.742±0.084	34.12±3.12 23.04±4.01
Unrelieved	R S	1.91±0.39 1.75±0.03	3.01±0.24 2.76±0.08	1.83±0.55 1.61±0.15	2.30±0.52 1.98±0.16	0.680±0.041 0.667±0.023	27.94±5.61 26.24±0.93

(Appendix 3 continued)

Parameters Measured ± s.d.	SPACING/PENETRATION (s/d) RATIO				
	2	4	6	8	10
MCF (kN)	0.57 ± 0.04	0.77 ± 0.04	0.82 ± 0.01	0.87 ± 0.03	0.83 ± 0.02
MPCF (kN)	2.11 ± 0.16	2.79 ± 0.05	2.78 ± 0.05	3.00 ± 0.08	2.80 ± 0.05
MNF (kN)	0.46 ± 0.04	0.64 ± 0.02	0.65 ± 0.01	0.74 ± 0.02	0.67 ± 0.01
MPNF (kN)	1.21 ± 0.06	1.46 ± 0.02	1.50 ± 0.02	1.68 ± 0.07	1.60 ± 0.02
$Q(m^3/km)x10^{-1}$	0.62 ± 0.06	0.80 ± 0.01	0.80 ± 0.05	0.77 ± 0.05	0.83 ± 0.04
$S.E.(MJ/m^3)$	9.27 ± 0.66	9.54 ± 0.58	10.21 ± 0.76	11.20 ± 1.28	11.06 ± 0.45

APPENDIX : 4A1 Cutting Results

Cutting on the flat rock surface with radial tools

Parameters Measured	SPACING/DEPTH (s/d) RATIO				
	2	4	6	8	10
MCF (kN)	0.61 ± 0.04	0.94 ± 0.04	1.26 ± 0.06	1.50 ± 0.10	2.17 ± 0.01
MPCF (kN)	2.30 ± 0.05	2.53 ± 1.89	4.57 ± 0.18	5.46 ± 0.31	7.04 ± 0.33
MNF (kN)	0.52 ± 0.03	0.76 ± 0.04	0.90 ± 0.04	1.11 ± 0.07	1.37 ± 0.15
MPNF (kN)	1.32 ± 0.03	1.87 ± 0.05	2.16 ± 0.05	2.60 ± 0.13	3.21 ± 1.97
Qm*(m^3/km)x10^{-1}	0.69 ± 0.05	1.48 ± 0.04	2.16 ± 0.14	2.46 ± 0.23	3.74 ± 0.32
Qc*(m^3/km(x10^{-1}	0.72	1.44	2.16	2.88	3.6
S.E.(MJ/m^3)	8.81 ± 1.04	6.37 ± 0.15	5.87 ± 0.52	5.69 ± 0.22	5.60 ± 0.55

*Qm : Measured Yield, Qc = Calculated Yield

APPENDIX : 4A2 Cutting Results

Relief cuts (S_L = S/2 condition) with Radial Tools

Parameters Measured ± s.d.	SPACING/PENETRATION (s/d) RATIO			
	2	4	6	8
MCF (kN)	0.67 ± 0.04	1.27 ± 0.07	2.06 ± 0.10	7.4 ± 1.82
MPCF (kN)	2.54 ± 0.12	4.26 ± 0.09	5.92 ± 0.13	11.8 ± 1.22
MNF (kN)	0.57 ± 0.03	0.94 ± 0.03	1.31 ± 0.03	3.25 ± 1.08
MPNF (kN)	1.45 ± 0.03	2.10 ± 0.10	2.66 ± 0.05	4.62 ± 1.31
Qm(m^3/km)x 10^{-1}	0.73 ± 0.04	1.39 ± 0.07	1.99 ± 0.09	0.22 ± 0.01
S.E. (MJ/m^3)	9.15 ± 0.97	9.14 ± 0.45	10.36 ± 0.80	74.2 ± 2.62

APPENDIX : 4A3 Cutting Results

Groove Deepening Cuts (S_L = S condition) with Radial Tools

Parameters Measured	SPACING/DEPTH (s/d) RATIO				
	2	4	6	8	10
MCF (kN)	0.95 $\pm$ 0.13	1.18 $\pm$ 0.12	1.30 $\pm$ 0.24	1.24 $\pm$ 0.15	1.28 $\pm$ 0.18
MPCF (kN)	3.05 $\pm$ 0.20	4.16 $\pm$ 0.19	4.32 $\pm$ 0.18	4.47 $\pm$ 0.23	4.42 $\pm$ 0.21
MNF (kN)	1.26 $\pm$ 0.21	1.42 $\pm$ 0.13	1.58 $\pm$ 0.32	1.51 $\pm$ 0.21	1.84 $\pm$ 0.28
MPNF (kN)	2.66 $\pm$ 0.18	3.92 $\pm$ 0.23	4.25 $\pm$ 0.35	4.28 $\pm$ 0.40	4.32 $\pm$ 0.31
Qm(m^3/km) x 10^{-1}	0.62 $\pm$ 0.05	0.90 $\pm$ 0.04	1.01 $\pm$ 0.06	0.88 $\pm$ 0.03	0.88 $\pm$ 0.05
S.E.(MJ/m^3)	17.17$\pm$ 2.79	13.11 $\pm$ 1.07	12.94 $\pm$ 3.16	14.17 $\pm$ 1.91	14.51 $\pm$ 2.41

APPENDIX : 4A4 Cutting Results

Cutting on the flat rock surface with Point Attack Tools

Parameters Measured	SPACING/DEPTH (s/d) RATIO				
	2	4	6	8	10
MCF (kN)	1.09 ± 0.12	1.20 ± 0.22	1.65 ± 0.09	2.01 ± 0.19	2.35 ± 0.27
MPCF (kN)	3.52 ± 0.24	4.35 ± 0.32	5.61 ± 0.45	7.12 ± 0.68	7.75 ± 0.11
MNF (kN)	1.35 ± 0.19	1.49 ± 0.29	1.76 ± 0.14	2.38 ± 0.34	2.81 ± 0.31
MPNF (kN)	3.12 ± 0.42	4.16 ± 0.45	5.04 ± 0.38	6.32 ± 0.32	7.06 ± 0.27
Qm*(m^3/km) x 10^{-1}	0.74 ± 0.01	1.45 ± 0.09	2.30 ± 0.09	2.75 ± 0.03	3.62 ± 0.10
Qc*(m^3/km)x 10^{-1}	0.72	1.44	2.16	2.88	3.60
S.E. (MJ/m^3)	14.62 ± 1.68	8.25 ± 2.26	7.10 ± 0.96	7.31 ± 0.77	6.50 ± 0.07

*Qm = Measured Values, *Qc = Calculated values

APPENDIX : 4A5 Cutting Results

Relief cuts (S_L = S/2 condition) with Point Attack Tools

Variable	Parameter	Curve Type	Value of A	Value of B	Index of Determination
SPACING TO DEPTH	MCF	Y = A+B*X	0.1920	0.1840	0.9645
	MPCF	Y = A+B*X	0.6570	0.6205	0.9609
	MNF	Y = A+B*X	0.3170	0.1025	0.9914
	MPNF	Y = A*B*X	0.8790	0.2255	0.9874
	Qm	Y = A+B*X	-0.180 0.0180	0.3540	0.9649
	S.E.	Y = X/(A+B*X)	-0.1648	0.1967	0.9976

APPENDIX : 4B1

Least Squares Curve Fitting Analysis

Initial Experiments with Radial Tools

Simulated, $S_L = S/2$

Variable	Parameter	Curve Type	Value of 'A'	Value of 'B'	Index of Determination
SPACING/ DEPTH RATIO	MCF	Y = A x exp(BxX)	0.27737	0.38467	0.95239
	MPCF	Y = A x exp(BxX)	1.52228	0.2476	0.98140
	MNF	Y = A x exp(BxX)	0.31592	0.26867	0.96411
	MPNF	Y = A x exp(BxX)	0.98834	0.18236	0.97718

APPENDIX : 4B2

Least Square Curve Fitting Analysis
Groove Deepening Cuts with Radial Tools

Variable	Parameter	Curve Type	Value of A	Value of B	Index of Determination
SPACING TO DEPTH	MCF	Y = A*exp(B*X)	0.8596	0.1026	0.9779
	MPCF	Y = A*exp(B*X)	2.9194	0.1035	0.9791
	MNF	Y = A*exp(B*X)	1.0539	0.0967	0.9715
	MPNF	Y = A*exp(B*X)	2.6654	0.1026	0.9803
	Qm	Y = A+B*X	0.0540	0.3530	0.9931
	S.E.	Y = X/(A+B*X)	-0.2030	0.1706	0.9769

APPENDIX : 4B3

Least Squares Curve Fitting Analysis

Initial Experiments with Point Attack Tools

Simulated, $S_L = S/2$

Tilt Angle (Degree)	Parameters Measured							
	Total Number of Picks	MCF (kN) ±s.d	MPCF (kN) ±s.d.	MNF (kN) ±s.d	MPNF (kN) ±s.d.	Qm (m^3/km) ±s.d.	Qc (m^3/km)	S.E. (MJ/m^3) ±s.d.
4.63	16	2.29 ±0.49	6.23 ±0.57	2.14 ±0.37	5.48 ±0.24	2.159 ±0.09	2.153	10.61 ±3.09
	8	-	-	-	-	-	-	-
9.25	16	2.05 ±0.20	6.66 ±0.32	2.06 ±0.25	5.50 ±0.18	2.218 ±0.03	2.132	9.70 ±1.92
	8	-	6.95 -	2.51 -	6.27 -	- -	- -	- -
13.88	16	2.11 ±0.18	6.19 ±0.12	2.01 ±0.15	5.14 ±0.18	2.182 ±0.04	2.096	9.67 ±2.01
	8	- -	6.92 -	2.45 -	6.21 -	- -	- -	- -
18.51	16	2.17 ±0.15	6.60 ±0.18	1.98 ±0.11	5.60 +0.27	1.761 ±0.06	2.048	12.40 ±2.18
	8	2.22 ±0.30	6.99 ±0.57	2.48 ±0.34	6.23 ±0.56	- -	- -	- -
23.14	16	2.12 ±0.17	6.14 ±0.22	1.84 ±0.25	4.95 ±0.31	2.054 ±0.10	1.986	10.32 ±2.10
	8	2.12 ±0.26	6.67 ±0.30	2.53 ±0.18	5.25 ±0.28	- -	- -	- -
27.77	16	2.15 ±0.35	6.22 ±0.29	1.93 ±0.22	5.26 ±0.42	1.736 ±0.04	1.911	12.38 ±3.12
	8	1.97 ±0.25	6.94 ±0.17	2.40 ±0.11	6.03 ±0.15	- -	- -	- -

APPENDIX : 5A1 CUTTING RESULTS FOR GAUGE TOOLS

Simulation of Roadheader Cutting Heads with 16 and 8 tools : Cutting from machine side.

Tilt Angle (Degree)	Parameters Measured							
	Total Number of Picks	MCF (kN) ±s.d.	MPCF (kN) ±s.d.	MNF (kN) ±s.d.	MPNF (kN) ±s.d.	Qm (m^3/km) ±s.d.	Qc (m^3/km)	S.E. (MJ/m^3) ± s.d.
32.39	16	1.99 ±0.11	6.11 ±0.19	1.95 ±0.27	5.18 ±0.32	1.686 ±0.080	1.824	11.80 ±2.01
	8	1.86 ±0.10	6.03 ±0.18	2.14 ±0.21	5.38 ±0.25	1.704 ±0.050	1.824	10.92 ±3.11
37.02	16	1.95 ±0.17	5.68 ±0.18	1.92 ±0.15	4.95 ±0.17	1.609 ±0.077	1.724	12.61 ±1.92
	8	1.89 ±0.21	5.69 ±0.19	1.78 ±0.12	5.03 ±0.29	- - -	1.724	- -
41.65	16	1.83 ±0.13	5.14 ±0.18	1.72 ±0.11	4.47 ±0.19	1.607 ±0.068	1.614 -	11.39 ±2.02
	8	1.69 ±0.12	5.66 ±0.29	1.97 ±0.14	4.93 ±0.21	- -	1.614 -	- -
46.28	16	1.56 ±0.21	4.78 ±0.26	1.59 ±0.15	3.80 ±0.22	1.482 ±0.017	1.493 -	10.53 ±1.87
	8	1.51 ±0.17	5.15 ±0.21	1.75 ±0.18	4.32 ±0.16	- -	- -	- -
50.90	16	1.57 ±0.12	5.70 ±0.28	1.65 ±0.18	4.30 ±0.21	1.323 ±0.021	1.362	11.87 ±2.18
	8	-	-	-	-	-	-	-
55.53	16	1.47 ±0.12	4.98 ±0.21	1.56 ±0.11	4.37 ±0.30	1.150 ±0.028	1.222	12.78 ±2.18
	8	1.54 ±0.20	5.48 ±0.40	1.71 ±0.23	5.08 ±0.36	1.223 ±0.172		12.65 ±0.71

APPENDIX 5A1 (contd)

Tilt Angle (Degree)	Parameters Measured							
	Total Number of Picks	MCF (kN) ±s.d.	MPCF (kN) ±s.d.	MNF (kN) ±s.d.	MPNF (kN) ±s.d.	Qm (m^3/km) ±s.d.	Qc (m^3/km)	S.E. (MJ/m^3) ±s.d.
55.53	16	1.47 ±0.12	4.98 ±0.21	1.56 +0.11	4.37 ±0.30	1.150 ±0.028	1.222	12.78 ±2.18
	8	1.54 ±0.20	5.48 ±0.40	1.71 ±0.23	5.08 0.36	1.223 0.172		12.56 ±0.71
60.16	16	1.36 ±0.14	4.86 ±0.19	1.54 ±0.14	4.06 ±0.17	1.032 0.038	1.075	12.59 ±1.98
	8	1.12 ±0.12	4.21 ±0.15	1.27 ±0.14	3.69 ±0.20	1.091 ±0.91		9.85 ±0.84
64.79	16	1.15 ±0.22	4.26 ±0.45	1.41 ±0.18	3.78 ±0.31	0.952 ±0.077	0.920	12.08 ±1.90
	8	1.16 ±0.03	4.24 ±0.47	1.29 ±0.13	3.76 ±0.28	0.882 ±0.064		13.19 ±1.50
69.42	16	0.96 ±0.08	3.79 ±0.14	1.13 ±0.09	3.35 ±0.05	0.773 ±0.071	0.760	12.42 ±2.05
	8	0.87 ±0.17	3.62 ±0.18	1.20 ±0.15	3.18 ±0.22	0.714 ±0.059		12.18 ±0.52
74.05	16	0.87 ±0.17	3.62 ±0.18	1.20 ±0.15	3.18 ±0.22	0.714 ±0.059	0.593	12.18 ±0.52
	8	0.71 ±0.09	2.81 ±0.32	0.97 ±0.17	2.92 ±0.42	0.554 ±0.027		12.81 1.29
78.68	16	0.77 ±0.11	2.87 ±0.14	0.98 ±0.09	2.62 ±0.16	0.462 ±0.041	0.424	16.67 ±1.18
	8	0.65 ±0.12	2.52 ±0.09	0.89 ±0.14	2.35 ±0.11	0.454 ±0.36		14.32 ±0.87

APPENDIX 5A1 contd

Tilt Angle (Degree)	Parameters Measured							
	Total Number of Picks	MCF (kN) ±s.d.	MPCF (kN) ±s.d.	MNF (kN) ±s.d.	MPNF (kN) ±s.d.	Qm (m^3/km) ±s.d.	Qc (m^3/km)	S.E. (MJ/m^3) ±s.d.
83.31	16	0.53 ±0.09	2.25 ±0.12	0.68 ±0.14	2.05 ±0.16	0.286 ±0.206	0.252	18.53 ±3.17
	8	0.48 ±0.12	1.99 ±0.21	0.61 ±0.08	1.86 ±0.13	0.275 ±0.198		17.45 ±2.34
* 87.94	16	0.39 ±0.09	1.42 ±0.10	0.54 ±0.10	1.45 ±0.13	0.100 ±0.082	0.078	39.00 ±1.26
	8	0.41 ±0.06	1.47 ±0.08	0.59 ±0.08	1.86 ±0.09	0.109 ±0.027		37.61 ±0.82

*These values were obtained from corner cutting trials which at this tilt angle exhibited the same results.

APPENDIX 5A1 contd.

Tilt Angle (Degree)	Parameters Measured						
	Total Number of Picks	MCF (kN) ±s.d.	MPCF (kN) ±s.d.	MNF (kN) ±s.d.	MPNF (kN) ±s.d.	$Qm \times 10^{-1}$ (m^3/km) ±s.d.	S.E. (MJ/m^3) ±s.d.
23.14	16	4.25 ±0.98	8.70 ±1.10	4.22 ±1.01	8.17 ±0.82	1.614 ±0.049	26.33 ±3.89
	8	-	-	-	-	-	-
27.02	16	3.32 ±0.41	7.86 ±0.23	3.28 ±0.52	7.12 ±0.64	1.245 ±0.009	26.67 ±3.13
	8	-	-	-	-	-	-
50.90	16	2.21 ±0.37	5.80 ±0.24	2.19 ±0.21	5.07 ±0.30	1.086 ±0.018	20.35 ±2.18
	8	2.18 ±0.02	6.44 ±0.44	2.58 ±0.21	5.68 ±0.08	0.782 ±0.009	26.98 ±1.02
55.53	16	1.82 ±0.28	5.41 ±0.32	2.42 ±0.27	4.96 ±0.19	1.086 ±0.012	16.76 ±1.21
	8	-	-	-	-	-	-
60.16	16	1.59 ±0.10	5.96 ±0.18	2.04 ±0.20	4.48 ±0.23	0.986 ±0.050	16.16 ±1.81
	8	1.31 ±0.02	4.73 ±0.25	1.58 ±0.06	4.26 ±0.15	1.000 ±0.168	18.27 ±2.67
67.79	16	1.21 ±0.01	4.28 ±0.52	1.62 ±0.18	3.90 ±0.32	0.864 ±0.018	14.00 ±0.25
	8	-	-	-	-	-	-

APPENDIX : 5A2

Cutting Results for Corner Cutting Tools;
Simultation of Roadheader Cutting Heads with 8 and 16 tools;
Cutting from Machine Side.

Tilt Angle (Degree)	Parameters Measured						
	Total Number of Picks	MCF (kN) ±s.d.	MPCF (kN) ±s.d.	MNF (kN) ±s.d.	MPNF (kN) ±s.d.	Qmx10^{-1} (m^3/km) ±s.d.	S.E. (MJ/m^3) ±s.d.
69.42	16	0.97 ±0.12	3.76 ±0.23	1.19 ±0.16	3.22 ±0.26	0.761 ±0.091	13.3 ±1.51
	8	0.92 ±0.10	3.42 ±0.15	1.04 ±0.20	2.93 ±0.23	0.814 ±0.032	11.29 ±0.84
78.68	16	0.67 ±0.07	2.51 ±0.01	0.82 ±0.09	2.24 ±0.13	0.454 ±0.009	14.76 ±0.42
	8	0.75 ±0.02	2.85 ±0.02	0.83 ±0.10	2.59 ±0.03	0.473 ±0.023	15.86 ±1.15
87.94	16	0.39 ±0.09	1.42 ±0.10	0.54 ±0.20	1.45 ±0.13	0.100 ±0.082	39.00 ±1.26
	8	0.41 ±0.06	1.47 ±0.08	0.59 ±0.09	1.51 ±0.09	0.109 ±0.027	37.61 ±0.82

APPENDIX 5A2 Contd.

Tilt Angle (Degree)	Parameters Measured							
	Total Number of Picks	MCF (kN) ±s.d.	MPCF (kN) ±s.d.	MNF (kN) ±s.d.	MPNF (kN) ±s.d.	$Qm \times 10^{-1}$ (m^3/km) ±s.d.	$Qc \times 10^{-1}$ (m^3/km)	S.E. (MJ/m^3) ±s.d.
23.14	24	1.81 ±0.26	6.78 ±0.14	2.10 ±0.19	5.67 ±0.21	- -	-	- -
	32	1.57 ±0.11	6.17 ±0.14	1.79 ±0.17	5.41 ±0.16	- -		- -
27.77	24	1.46 ±0.11	5.83 ±0.28	1.59 ±0.13	5.14 ±0.48	- -	-	- -
	32	1.68 ±0.05	6.49 ±0.10	2.01 ±0.04	5.92 ±0.17	- -		- -
32.39	24	1.70 ±0.06	5.76 ±0.73	1.71 ±0.58	5.04 ±1.02	1.818 ±0.008	1.824	9.35 ±2.11
	32	1.42 ±0.09	6.27 ±0.17	1.56 ±0.13	5.47 ± 0.04	1.848 ±0.010		7.68 ±2.42
37.02	24	1.52 ±0.12	6.03 ±0.54	1.76 ±0.20	5.14 ±0.25	- -	-	- -
	32	1.65 ±0.05	6.06 ±0.10	1.82 ±0.17	5.37 ±0.22	- -		- -
41.65	24	1.37 ±0.21	5.48 ±0.28	1.46 ±0.28	4.75 ±0.29	- -	-	- -
	32	1.27 ±0.22	5.40 ±0.17	1.46 ±0.50	4.83 ±0.56	- -		- -
46.28	24	1.30 ±0.19	5.20 ±0.61	1.48 ±0.26	4.45 ±0.78	-	-	-
	32	1.14 ±0.19	4.78 ±0.76	1.23 ±0.20	3.95 ±0.59	- -		- -

APPENDIX : 5A3

Cutting Results for Gauge Tools; Simulation of Roadheader Cutting Heads with 24 and 32 tools; Cutting from Machine Side.

Tilt Angle (Degree)	Parameters Measured				
	Total Number of Picks	MCF (kN) ±s.d.	MPCF (kN) ±s.d.	MNF (kN) ±s.d.	MPNF (kN) ±s.d.
50.93	8	2.18 ±0.02	6.44 ±0.44	2.58 ±0.21	5.68 ±0.08
	16	2.21 ±0.37	5.80 ±0.24	2.19 ±0.21	5.07 ±0.30
	24	1.67 ±0.01	5.58 ±0.03	2.00 ±0.03	4.88 ±0.17
	32	1.62 ±0.13	5.51 ±0.14	1.94 ±0.26	4.78 ±0.39

APPENDIX : 5A4

Cutting Results for corner cutting tools; simulation of roadheader cutting heads with 8, 16, 24 and 32 tools; cutting from machine side.

Tilt Angle (Degree)	Mode of Cutting	Parameters Measured						
		MCF (kN) ±s.d.	MPCF (kN) ±s.d.	MNF (kN) ±s.d.	MPNF (kN) ±s.d.	Qmx10^{-1} (m^3/km) ±s.d.	Qcx10^{-1} (m^3/km)	S.E. (MJ/m^3) ±s.d.
32.39	TN	1.99 ±0.11	6.11 ±0.19	1.95 ±0.27	5.18 ±0.32	1.686 ±0.080	1.824	11.80 ±2.01
	FN	2.73 ±0.09	6.51 ±0.52	2.34 ±0.21	5.64 ±0.57	1.771 ±0.005	1.824	15.91 ±0.26
37.02	TN	1.95 ±0.21	5.68 ±0.18	1.92 ±0.15	4.95 ±0.17	1.609 ±0.077	1.724	12.61 ±1.92
	FN	2.49 ±0.09	6.16 ±0.19	2.14 ±0.11	5.09 ±0.06	1.782 ±0.027	1.724	13.99 ±0.56
41.65	TN	1.83 ±0.13	5.14 ±0.18	1.72 ±0.11	4.47 ±0.19	1.607 ±0.068	1.614	11.39 ±0.02
	FN	2.55 ±0.13	6.07 ±0.26	2.24 ±0.10	5.20 ±0.20	1.418 ±0.050	1.614	18.48 ±1.01
46.28	TN	1.56 ±0.21	4.78 ±0.26	1.59 ±0.15	3.80 ±0.22	1.482 ±0.017	1.493	10.53 ±1.87
	FN	2.29 ±0.25	6.04 ±0.38	2.05 ±0.32	5.04 ±0.39	1.186 ±0.49	1.493	19.2 ±4.67
50.90	TN	1.57 ±0.12	5.70 ±0.28	1.65 ±0.18	4.30 ±0.21	1.323 ±0.021	1.362	11.87 ±1.18
	FN	1.85 ±0.17	5.26 ±0.61	2.12 ±0.44	5.02 ±0.81	1.273 ±0.032	1.362	14.53 ±0.94
55.53	TN	1.47 ±0.12	4.98 ±0.21	1.56 ±0.11	4.37 ±0.30	1.150 ±0.028	1.222	12.78 ±2.18
	FN	1.81 ±0.36	5.17 ±0.34	1.86 +0.34	4.65 ±0.30	1.227 ±0.009	1.222	14.75 ±0.89

APPENDIX : 5A5

Cutting Results for gauge tools, simulation of Roadheader cutting heads with 16 tools; comparison of cutting from nose and machine side

Tilt Angle (Degree)	Mode of Cutting	Parameters Measured						
		MCF (kN) ±s.d.	MPCF (kNO ±s.d.	MNF (kN) ±s.d.	MPNF (kN) ±s.d.	Qmx10^{-1} (m^3/km) ±s.d.	Qcx10^{-1} (m^3/km)	S.E. (MJ/m^3) ±s.d.
60.16	TN	1.36 ±0.14	4.86 ±0.19	1.54 ±0.14	4.06 ±0.17	1.032 0.038	1.075	12.59 ±1.98
	FN	1.44 ±0.44	4.49 ±0.34	1.86 ±0.27	4.18 ±0.67	0.919 ±0.023	1.075	15.67 3.18
64.79	TN	1.15 ±0.22	4.26 ±0.45	1.41 ±0.18	3.78 0.31	0.952 ±0.077	0.920	12.08 ±1.90
	FN	1.39 ±0.05	3.91 ±0.10	1.28 ±0.12	3.61 ±0.21	0.930 ±0.068	0.920	14.94 ±1.64
69.42	TN	0.96 ±0.08	3.79 ±0.14	1.13 ±0.09	3.35 ±0.05	0.773 ±0.071	0.760	12.42 ±2.05
	FN	1.04 ±0.02	3.77 ±0.30	1.09 ±0.15	3.21 ±0.14	0.810 ±0.109	0.760	12.84 ±2.01
74.07	TN	0.89 ±0.11	3.32 ±0.15	1.09 ±0.14	3.03 ±0.19	0.568 ±0.098	0.593	15.67 ±2.35
	FN	0.79 ±0.06	3.20 ±0.10	1.05 ±0.26	2.78 ±0.19	0.668 ±0.045	0.593	11.83 ±3.19
78.68	TN	0.77 ±0.11	2.87 ±0.14	0.98 ±0.03	2.62 ±0.16	0.462 ±0.041	0.424	16.67 ±1.18
		0.76 ±0.15	2.43 ±0.16	0.85 ±0.20	2.19 ±0.35	0.463 ±0.068	0.424	16.41 ±2.02

*TN : Cutting towards the nose from the machine side.

*FN : Cutting away from the nose towards the machine side.

APPENDIX 5A5 contd.

Tilt Angle (Degree)	Mode of Cutting	Parameters Measured						
		MCF (kN) ±s.d.	MPCF (kN) ±s.d.	MNF (kN) ±s.d.	MPNF (kN) ±s.d.	Qmx10^{-1} (m^3/km) ±s.d.	Qcx10^{-1} (m^3/km)	S.E. (MJ/m^3) ±s.d.
83.31	TN	0.53 ±0.09	2.25 ±0.12	0.68 ±0.14	2.05 ±0.16	0.286 ±0.206	0.252	
	FN	0.59 ±0.09	2.12 ±0.20	0.70 ±0.08	1.89 ±0.11	0.282 ±0.45	0.252	21.22 ±0.04
87.94*	TN	0.39 ±0.09	1.42 ±0.10	0.54 ±0.10	1.45 ±0.13	0.100 ±0.082	0.078	39.00 ±1.26
	FN	0.52 ±0.02	1.58 ±0.04	0.68 ±0.03	1.53 ±0.10	0.109 ±0.009	0.078	47.71 ±4.72

*These values were obtained from the corner cutting trials, which, at this tilt angle exhibited the similar results.

APPENDIX 5A5 contd.

Tilt Angle (Degree)	Mode of cutting	Parameters Measured					
		MCF (kN) ±s.d.	MPCF (kN) ±s.d.	MNF (kN) ±s.d.	MPNF (kN) ±s.d.	Qm x 10^{-1} (m^3/km) ±s.d.	S.E. (MJ/m^3) ±s.d.
50.90	TN	2.21 ±0.37	5.80 ±0.24	2.19 ±0.21	5.07 ±0.30	1.086 ±0.018	20.35 ±2.18
	FN	2.78 ±0.28	6.28 ±0.37	2.45 ±0.95	5.25 ±0.27	1.036 ±0.04	26.78 ±2.28
69.42	TN	0.97 ±0.12	3.76 ±0.23	1.19 ±0.16	3.22 ±0.26	0.761 ±0.091	13.3 ±1.51
	FN	1.01 ±0.09	3.56 ±0.37	1.10 ±0.24	3.17 ±0.20	0.714 ±0.018	14.14 ±0.88
78.68	TN	0.67 ±0.07	2.51 ±0.01	0.82 ±0.09	2.24 ±0.13	0.454 ±0.009	14.76 ±0.42
	FN	0.74 ±0.08	2.69 ±0.14	0.79 ±0.09	2.41 ±0.10	0.532 ±0.15	17.16 ±2.18
87.94	TN	0.39 ±0.09	1.42 ±0.10	0.54 ±0.10	1.45 ±0.13	0.100 ±0.092	39.00 ±1.26
	FN	0.52 ±0.02	1.58 ±0.04	0.68 ±0.03	1.53 +0.10	0.109 ±0.009	47.71 ±4.72

APPENDIX : 5A6

Cutting results for corner cutting tools, simulation of Roadheader cutting heads with 16 tools; comparison of cutting from nose and machine side.

Variable	Parameter	Curve Type	Value of A	Value of B	Index of Determination
AREA CUT PER (GAUGE) TOOL	MCF	Y = A + B*X	0.3512	0.8819	0.9860
	MPCF	Y = A + B*X	1.9323	2.2006	0.9437
	MNF	Y = A + B*X	0.6395	0.6844	0.9604
	MPNF	Y = A + B*X	1.8374	1.7308	0.9409

APPENDIX : 5B1

Least Squares Curve Fitting Analysis;
Simulation of Cutting Heads with Spherical Geometry

Total number of Picks : 16

Variable	Parameter	Curve Type	Value of A	Value of B	Index of Determination
TOTAL NUMBER OF CUTTING TOOLS	MCF	Y = A + B x X	2.47500	-0.02775	0.810059
	MPCF	Y = A + B x X	6.58500	-0.03762	0.84221
	MNF	Y = A + B x X	2.70500	-0.02637	0.89015
	MPNF	Y = A + B x X	5.82500	-0.03612	0.85562

APPENDIX : 5B2

Least Square Fitting Analysis:

Corner Cutting Tools; Cutting from machine side:

Simultation of Roadheader Cutting Heads with 8, 16, 24 and 32 tools.

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : SPHERICAL
TILT ANGLE OF THE FIRST TOOL : 0.0 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 64.82 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	64.82	0.0948	1.16	1.27
2	60.19	0.1108	1.30	1.37
3	55.56	0.1261	1.43	1.48
4	50.93	0.1405	1.55	1.57
5	46.30	0.1540	1.67	1.66
6	41.67	0.1665	1.77	1.74
7	37.04	0.1779	1.87	1.82
8	32.41	0.1882	1.96	1.89
9	27.78	0.1972	2.04	1.95
10	23.15	0.2050	2.10	2.00
11	18.52	0.2114	2.16	2.04
12	13.89	0.2164	2.20	2.07
13	9.26	0.2200	2.23	2.10
14	4.63	0.2222	2.25	2.11
15	0.0	0.2229	2.26	2.12
16	0.0	0.2229	2.26	2.12

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.80390 + 0.11167	0.90603 + 0.16251
SLEWING FORCE + S.D. (KN)	12.13471 + 0.34096	6.08803 + 0.64741
VOLUME SWEPT (CUBM)	0.0009994	0.0004997
SPECIFIC ENERGY (MJ/CUBM)	11.3405	11.3918

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : SPHERICAL

TILT ANGLE OF THE FIRST TOOL : 0.0 DEGREE

TILT ANGLE OF THE CORNER CUTTING TOOL : 69.45 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	69.45	0.0782	1.02	1.16
2	64.82	0.0948	1.16	1.27
3	60.19	0.1108	1.30	1.37
4	55.56	0.1261	1.43	1.48
5	50.93	0.1405	1.55	1.57
6	46.30	0.1540	1.67	1.66
7	41.67	0.1665	1.77	1.74
8	37.04	0.1779	1.87	1.82
9	32.41	0.1882	1.96	1.89
10	27.78	0.1972	2.04	1.95
11	23.15	0.2050	2.10	2.00
12	18.52	0.2114	2.16	2.04
13	13.89	0.2164	2.20	2.07
14	9.26	0.2200	2.23	2.10
15	4.63	0.2222	2.25	2.11
16	0.0	0.2229	2.26	2.12

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.66922 + 0.12000	0.83841 + 0.16561
SLEWING FORCE + S.D. (KN)	11.69809 + 0.37847	5.86909 + 0.66149
VOLUME SWEPT (CUBM)	0.0009177	0.0004588
SPECIFIC ENERGY (MJ/CUBM)	11.4290	11.4809

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : SPHERICAL
TILT ANGLE OF THE FIRST TOOL : 4.63 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 74.08 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	74.08	0.0611	0.87	1.05
2	69.45	0.0782	1.02	1.16
3	64.82	0.0948	1.16	1.27
4	60.19	0.1108	1.30	1.37
5	55.56	0.1261	1.43	1.48
6	50.93	0.1405	1.55	1.57
7	46.30	0.1540	1.67	1.66
8	41.67	0.1665	1.77	1.74
9	37.04	0.1779	1.87	1.82
10	32.41	0.1882	1.96	1.89
11	27.78	0.1972	2.04	1.95
12	23.15	0.2050	2.10	2.00
13	18.52	0.2114	2.16	2.04
14	13.89	0.2164	2.20	2.07
15	9.26	0.2200	2.23	2.10
16	4.63	0.2222	2.25	2.11

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.52615 + 0.12638	0.76657 + 0.16711
SLEWING FORCE + S.D. (KN)	11.20985 + 0.41615	5.62426 + 0.67650
VOLUME SWEPT (CUBM)	0.0008310	0.0004155
SPECIFIC ENERGY (MJ/CUBM)	11.5392	11.5919

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : SPHERICAL
TILT ANGLE OF THE FIRST TOOL : 9.26 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 78.71 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	78.71	0.0436	0.72	0.93
2	74.08	0.0611	0.87	1.05
3	69.45	0.0782	1.02	1.16
4	64.82	0.0948	1.16	1.27
5	60.19	0.1108	1.30	1.37
6	55.56	0.1261	1.43	1.48
7	50.93	0.1405	1.55	1.57
8	46.30	0.1540	1.67	1.66
9	41.67	0.1665	1.77	1.74
10	37.04	0.1779	1.87	1.82
11	32.41	0.1882	1.96	1.89
12	27.78	0.1972	2.04	1.95
13	23.15	0.2050	2.10	2.00
14	18.52	0.2114	2.16	2.04
15	13.89	0.2164	2.20	2.07
16	9.26	0.2200	2.23	2.10

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.37710 + 0.12987	0.69172 + 0.16632
SLEWING FORCE + S.D. (KN)	10.67098 + 0.45176	5.35404 + 0.69129
VOLUME SWEPT (CUBM)	0.0007415	0.0003708
SPECIFIC ENERGY (MJ/CUBM)	11.6689	11.7227

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : SPHERICAL

TILT ANGLE OF THE FIRST TOOL : 13.89 DEGREE

TILT ANGLE OF THE CORNER CUTTING TOOL : 83.34 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	83.34	0.0259	0.57	0.81
2	78.71	0.0436	0.72	0.93
3	74.08	0.0611	0.87	1.05
4	69.45	0.0782	1.02	1.16
5	64.82	0.0948	1.16	1.27
6	60.19	0.1108	1.30	1.37
7	55.56	0.1261	1.43	1.48
8	50.93	0.1405	1.55	1.57
9	46.30	0.1540	1.67	1.66
10	41.67	0.1665	1.77	1.74
11	37.04	0.1779	1.87	1.82
12	32.41	0.1882	1.96	1.89
13	27.78	0.1972	2.04	1.95
14	23.15	0.2050	2.10	2.00
15	18.52	0.2114	2.16	2.04
16	13.89	0.2164	2.20	2.07

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.22556 + 0.13041	0.61562 + 0.16304
SLEWING FORCE + S.D. (KN)	10.08499 + 0.48492	5.06019 + 0.70540
VOLUME SWEPT (CUBM)	0.0006515	0.0003258
SPECIFIC ENERGY (MJ/CUBM)	11.8195	11.8743

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : SPHERICAL
TILT ANGLE OF THE FIRST TOOL : 18.52 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 87.97 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	87.97	0.0079	0.42	0.69
2	83.34	0.0259	0.57	0.81
3	78.71	0.0436	0.72	0.93
4	74.08	0.0611	0.87	1.05
5	69.45	0.0782	1.02	1.16
6	64.82	0.0948	1.16	1.27
7	60.19	0.1108	1.30	1.37
8	55.56	0.1261	1.43	1.48
9	50.93	0.1405	1.55	1.57
10	46.30	0.1540	1.67	1.66
11	41.67	0.1665	1.77	1.74
12	37.04	0.1779	1.87	1.82
13	32.41	0.1882	1.96	1.89
14	27.78	0.1972	2.04	1.95
15	23.15	0.2050	2.10	2.00
16	18.52	0.2114	2.16	2.04

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.07506 + 0.12799	0.54004 + 0.15717
SLEWING FORCE + S.D. (KN)	9.45571 + 0.51533	4.74462 + 0.71840
VOLUME SWEPT (CUBM)	0.0005633	0.0002817
SPECIFIC ENERGY (MJ/CUBM)	11.9906	12.0466

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : CONICAL
HEAD CONE ANGLE : 64.82 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 64.82 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	64.82	0.0948	1.16	1.27
2	64.82	0.1111	1.16	1.27
3	64.82	0.1274	1.16	1.27
4	64.82	0.1437	1.16	1.27
5	64.82	0.1600	1.16	1.27
6	64.82	0.1763	1.16	1.27
7	64.82	0.1926	1.16	1.27
8	64.82	0.2089	1.16	1.27
9	64.82	0.2252	1.16	1.27
10	64.82	0.2414	1.16	1.27
11	64.82	0.2577	1.16	1.27
12	64.82	0.2740	1.16	1.27
13	64.82	0.2903	1.16	1.27
14	64.82	0.3066	1.16	1.27
15	64.82	0.3229	1.16	1.27
16	64.82	0.3392	1.16	1.27

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.28381 + 0.08139	0.64481 + 0.11485
SLEWING FORCE + S.D. (KN)	8.03196 + 0.06928	4.03007 + 0.36912
VOLUME SWEPT (CUBM)	0.0005983	0.0002991
SPECIFIC ENERGY (MJ/CUBM)	13.4825	13.5435

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : CONICAL
HEAD CONE ANGLE : 69.45 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 69.45 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	69.45	0.0782	1.02	1.16
2	69.45	0.0951	1.02	1.16
3	69.45	0.1120	1.02	1.16
4	69.45	0.1288	1.02	1.16
5	69.45	0.1457	1.02	1.16
6	69.45	0.1625	1.02	1.16
7	69.45	0.1794	1.02	1.16
8	69.45	0.1962	1.02	1.16
9	69.45	0.2131	1.02	1.16
10	69.45	0.2299	1.02	1.16
11	69.45	0.2468	1.02	1.16
12	69.45	0.2636	1.02	1.16
13	69.45	0.2805	1.02	1.16
14	69.45	0.2974	1.02	1.16
15	69.45	0.3142	1.02	1.16
16	69.45	0.3311	1.02	1.16

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.06292 + 0.07388	0.53387 + 0.10072
SLEWING FORCE + S.D. (KN)	7.23066 + 0.06082	3.62820 + 0.33709
VOLUME SWEPT (CUBM)	0.0004655	0.0002328
SPECIFIC ENERGY (MJ/CUBM)	14.3466	14.4118

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : CONICAL
HEAD CONE ANGLE : 74.08 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 74.08 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	74.08	0.0611	0.87	1.05
2	74.08	0.0784	0.87	1.05
3	74.08	0.0958	0.87	1.05
4	74.08	0.1131	0.87	1.05
5	74.08	0.1304	0.87	1.05
6	74.08	0.1477	0.87	1.05
7	74.08	0.1650	0.87	1.05
8	74.08	0.1823	0.87	1.05
9	74.08	0.1996	0.87	1.05
10	74.08	0.2169	0.87	1.05
11	74.08	0.2342	0.87	1.05
12	74.08	0.2515	0.87	1.05
13	74.08	0.2689	0.87	1.05
14	74.08	0.2862	0.87	1.05
15	74.08	0.3035	0.87	1.05
16	74.08	0.3208	0.87	1.05

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	0.84966 + 0.06496	0.42677 + 0.08580
SLEWING FORCE + S.D. (KN)	6.40470 + 0.05210	3.21396 + 0.30407
VOLUME SWEPT (CUBM)	0.0003394	0.0001697
SPECIFIC ENERGY (MJ/CUBM)	15.7283	15.8001

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : CONICAL
HEAD CONE ANGLE : 78.71 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 78.71 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	78.71	0.0436	0.72	0.93
2	78.71	0.0613	0.72	0.93
3	78.71	0.0789	0.72	0.93
4	78.71	0.0966	0.72	0.93
5	78.71	0.1142	0.72	0.93
6	78.71	0.1319	0.72	0.93
7	78.71	0.1495	0.72	0.93
8	78.71	0.1672	0.72	0.93
9	78.71	0.1849	0.72	0.93
10	78.71	0.2025	0.72	0.93
11	78.71	0.2202	0.72	0.93
12	78.71	0.2378	0.72	0.93
13	78.71	0.2555	0.72	0.93
14	78.71	0.2731	0.72	0.93
15	78.71	0.2908	0.72	0.93
16	78.71	0.3084	0.72	0.93

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	0.64910 + 0.05487	0.32604 + 0.07039
SLEWING FORCE + S.D. (KN)	5.55947 + 0.04318	2.79006 + 0.27030
VOLUME SWEPT (CUBM)	0.0002233	0.0001117
SPECIFIC ENERGY (MJ/CUBM)	18.2635	18.3472

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : CONICAL
HEAD CONE ANGLE : 83.34 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 83.34 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	83.34	0.0259	0.57	0.81
2	83.34	0.0437	0.57	0.81
3	83.34	0.0616	0.57	0.81
4	83.34	0.0795	0.57	0.81
5	83.34	0.0974	0.57	0.81
6	83.34	0.1152	0.57	0.81
7	83.34	0.1331	0.57	0.81
8	83.34	0.1510	0.57	0.81
9	83.34	0.1689	0.57	0.81
10	83.34	0.1868	0.57	0.81
11	83.34	0.2046	0.57	0.81
12	83.34	0.2225	0.57	0.81
13	83.34	0.2404	0.57	0.81
14	83.34	0.2583	0.57	0.81
15	83.34	0.2762	0.57	0.81
16	83.34	0.2940	0.57	0.81

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	0.46596 + 0.04389	0.23405 + 0.05481
SLEWING FORCE + S.D. (KN)	4.70049 + 0.03412	2.35925 + 0.23599
VOLUME SWEPT (CUBM)	0.0001202	0.0000601
SPECIFIC ENERGY (MJ/CUBM)	24.3569	24.4692

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : CONICAL
HEAD CONE ANGLE : 87.97 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 87.97 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	87.97	0.0079	0.42	0.69
2	87.97	0.0259	0.42	0.69
3	87.97	0.0439	0.42	0.69
4	87.97	0.0619	0.42	0.69
5	87.97	0.0799	0.42	0.69
6	87.97	0.0978	0.42	0.69
7	87.97	0.1158	0.42	0.69
8	87.97	0.1338	0.42	0.69
9	87.97	0.1518	0.42	0.69
10	87.97	0.1698	0.42	0.69
11	87.97	0.1878	0.42	0.69
12	87.97	0.2058	0.42	0.69
13	87.97	0.2238	0.42	0.69
14	87.97	0.2417	0.42	0.69
15	87.97	0.2597	0.42	0.69
16	87.97	0.2777	0.42	0.69

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	0.30444 + 0.03230	0.15293 + 0.03934
SLEWING FORCE + S.D. (KN)	3.83336 + 0.02496	1.92437 + 0.20137
VOLUME SWEPT (CUBM)	0.0000328	0.0000164
SPECIFIC ENERGY (MJ/CUBM)	58.3536	58.6243

APPENDIX 6A3

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 4.63 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 64.82 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	64.82	0.0948	1.16	1.27
2	60.19	0.1108	1.30	1.37
3	55.56	0.1261	1.43	1.48
4	50.93	0.1405	1.55	1.57
5	46.30	0.1540	1.67	1.66
6	41.67	0.1665	1.77	1.74
7	37.04	0.1779	1.87	1.82
8	32.41	0.1882	1.96	1.89
9	27.78	0.1972	2.04	1.95
10	23.15	0.2050	2.10	2.00
11	18.52	0.2114	2.16	2.04
12	13.89	0.2164	2.20	2.07
13	9.26	0.2200	2.23	2.10
14	4.63	0.2222	2.25	2.11
15	4.63	0.2236	2.25	2.11
16	4.63	0.2251	2.25	2.11

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.80509 + 0.11257	0.90663 + 0.16296
SLEWING FORCE + S.D. (KN)	12.13032 + 0.33996	6.08582 + 0.64643
VOLUME SWEPT (CUBM)	0.0009996	0.0004998
SPECIFIC ENERGY (MJ/CUBM)	11.3458	11.3971

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 9.26 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 64.82 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	64.82	0.0948	1.16	1.27
2	60.19	0.1108	1.30	1.37
3	55.56	0.1261	1.43	1.48
4	50.93	0.1405	1.55	1.57
5	46.30	0.1540	1.67	1.66
6	41.67	0.1665	1.77	1.74
7	37.04	0.1779	1.87	1.82
8	32.41	0.1882	1.96	1.89
9	27.78	0.1972	2.04	1.95
10	23.15	0.2050	2.10	2.00
11	18.52	0.2114	2.16	2.04
12	13.89	0.2164	2.20	2.07
13	9.26	0.2200	2.23	2.10
14	9.26	0.2229	2.23	2.10
15	9.26	0.2258	2.23	2.10
16	9.26	0.2287	2.23	2.10

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.80573 + 0.11294	0.90695 + 0.16317
SLEWING FORCE + S.D. (KN)	12.11061 + 0.33306	6.07593 + 0.64161
VOLUME SWEPT (CUBM)	0.0009992	0.0004996
SPECIFIC ENERGY (MJ/CUBM)	11.3550	11.4064

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 13.89 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 64.82 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	64.82	0.0948	1.16	1.27
2	60.19	0.1108	1.30	1.37
3	55.56	0.1261	1.43	1.48
4	50.93	0.1405	1.55	1.57
5	46.30	0.1540	1.67	1.66
6	41.67	0.1665	1.77	1.74
7	37.04	0.1779	1.87	1.82
8	32.41	0.1882	1.96	1.89
9	27.78	0.1972	2.04	1.95
10	23.15	0.2050	2.10	2.00
11	18.52	0.2114	2.16	2.04
12	13.89	0.2164	2.20	2.07
13	13.89	0.2207	2.20	2.07
14	13.89	0.2250	2.20	2.07
15	13.89	0.2293	2.20	2.07
16	13.89	0.2337	2.20	2.07

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.80488 + 0.11337	0.90653 + 0.16313
SLEWING FORCE + S.D. (KN)	12.06698 + 0.32197	6.05405 + 0.63203
VOLUME SWEPT (CUBM)	0.0009973	0.0004987
SPECIFIC ENERGY (MJ/CUBM)	11.3708	11.4222

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 18.52 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 64.82 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	64.82	0.0948	1.16	1.27
2	60.19	0.1108	1.30	1.37
3	55.56	0.1261	1.43	1.48
4	50.93	0.1405	1.55	1.57
5	46.30	0.1540	1.67	1.66
6	41.67	0.1665	1.77	1.74
7	37.04	0.1779	1.87	1.82
8	32.41	0.1882	1.96	1.89
9	27.78	0.1972	2.04	1.95
10	23.15	0.2050	2.10	2.00
11	18.52	0.2114	2.16	2.04
12	18.52	0.2171	2.16	2.04
13	18.52	0.2228	2.16	2.04
14	18.52	0.2285	2.16	2.04
15	18.52	0.2342	2.16	2.04
16	18.52	0.2399	2.16	2.04

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.80146 + 0.11438	0.90481 + 0.16309
SLEWING FORCE + S.D. (KN)	11.99114 + 0.30922	6.01599 + 0.61895
VOLUME SWEPT (CUBM)	0.0009933	0.0004966
SPECIFIC ENERGY (MJ/CUBM)	11.3955	11.4471

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 23.15 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 64.82 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	64.82	0.0948	1.16	1.27
2	60.19	0.1108	1.30	1.37
3	55.56	0.1261	1.43	1.48
4	50.93	0.1405	1.55	1.57
5	46.30	0.1540	1.67	1.66
6	41.67	0.1665	1.77	1.74
7	37.04	0.1779	1.87	1.82
8	32.41	0.1882	1.96	1.89
9	27.78	0.1972	2.04	1.95
10	23.15	0.2050	2.10	2.00
11	23.15	0.2120	2.10	2.00
12	23.15	0.2191	2.10	2.00
13	23.15	0.2262	2.10	2.00
14	23.15	0.2333	2.10	2.00
15	23.15	0.2403	2.10	2.00
16	23.15	0.2474	2.10	2.00

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.79421 + 0.11478	0.90117 + 0.16332
SLEWING FORCE + S.D. (KN)	11.87515 + 0.28843	5.95782 + 0.60458
VOLUME SWEPT (CUBM)	0.0009861	0.0004931
SPECIFIC ENERGY (MJ/CUBM)	11.4322	11.4840

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 27.78 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 64.82 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	64.82	0.0948	1.16	1.27
2	60.19	0.1108	1.30	1.37
3	55.56	0.1261	1.43	1.48
4	50.93	0.1405	1.55	1.57
5	46.30	0.1540	1.67	1.66
6	41.67	0.1665	1.77	1.74
7	37.04	0.1779	1.87	1.82
8	32.41	0.1882	1.96	1.89
9	27.78	0.1972	2.04	1.95
10	27.78	0.2056	2.04	1.95
11	27.78	0.2140	2.04	1.95
12	27.78	0.2224	2.04	1.95
13	27.78	0.2308	2.04	1.95
14	27.78	0.2392	2.04	1.95
15	27.78	0.2475	2.04	1.95
16	27.78	0.2559	2.04	1.95

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.78168 + 0.11843	0.89487 + 0.16457
SLEWING FORCE + S.D. (KN)	11.71157 + 0.28333	5.87574 + 0.59381
VOLUME SWEPT (CUBM)	0.0009748	0.0004874
SPECIFIC ENERGY (MJ/CUBM)	11.4841	11.5361

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 32.41 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 64.82 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	64.82	0.0948	1.16	1.27
2	60.19	0.1108	1.30	1.37
3	55.56	0.1261	1.43	1.48
4	50.93	0.1405	1.55	1.57
5	46.30	0.1540	1.67	1.66
6	41.67	0.1665	1.77	1.74
7	37.04	0.1779	1.87	1.82
8	32.41	0.1882	1.96	1.89
9	32.41	0.1978	1.96	1.89
10	32.41	0.2075	1.96	1.89
11	32.41	0.2171	1.96	1.89
12	32.41	0.2268	1.96	1.89
13	32.41	0.2364	1.96	1.89
14	32.41	0.2461	1.96	1.89
15	32.41	0.2557	1.96	1.89
16	32.41	0.2654	1.96	1.89

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.76221 + 0.11873	0.88510 + 0.16457
SLEWING FORCE + S.D. (KN)	11.49354 + 0.26187	5.76639 + 0.57910
VOLUME SWEPT (CUBM)	0.0009582	0.0004791
SPECIFIC ENERGY (MJ/CUBM)	11.5551	11.6075

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 37.04 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 64.82 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	64.82	0.0948	1.16	1.27
2	60.19	0.1108	1.30	1.37
3	55.56	0.1261	1.43	1.48
4	50.93	0.1405	1.55	1.57
5	46.30	0.1540	1.67	1.66
6	41.67	0.1665	1.77	1.74
7	37.04	0.1779	1.87	1.82
8	37.04	0.1888	1.87	1.82
9	37.04	0.1996	1.87	1.82
10	37.04	0.2105	1.87	1.82
11	37.04	0.2213	1.87	1.82
12	37.04	0.2321	1.87	1.82
13	37.04	0.2430	1.87	1.82
14	37.04	0.2538	1.87	1.82
15	37.04	0.2647	1.87	1.82
16	37.04	0.2755	1.87	1.82

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.73402 + 0.12103	0.87094 + 0.16405
SLEWING FORCE + S.D. (KN)	11.21489 + 0.25628	5.62659 + 0.56414
VOLUME SWEPT (CUBM)	0.0009352	0.0004676
SPECIFIC ENERGY (MJ/CUBM)	11.6504	11.7032

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 41.67 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 64.82 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	64.82	0.0948	1.16	1.27
2	60.19	0.1108	1.30	1.37
3	55.56	0.1261	1.43	1.48
4	50.93	0.1405	1.55	1.57
5	46.30	0.1540	1.67	1.66
6	41.67	0.1665	1.77	1.74
7	41.67	0.1785	1.77	1.74
8	41.67	0.1904	1.77	1.74
9	41.67	0.2024	1.77	1.74
10	41.67	0.2144	1.77	1.74
11	41.67	0.2263	1.77	1.74
12	41.67	0.2383	1.77	1.74
13	41.67	0.2503	1.77	1.74
14	41.67	0.2622	1.77	1.74
15	41.67	0.2742	1.77	1.74
16	41.67	0.2862	1.77	1.74

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.69527 + 0.11750	0.85148 + 0.16016
SLEWING FORCE + S.D. (KN)	10.87023 + 0.22485	5.45374 + 0.53866
VOLUME SWEPT (CUBM)	0.0009044	0.0004522
SPECIFIC ENERGY (MJ/CUBM)	11.7771	11.8306

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 46.30 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 64.82 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	64.82	0.0948	1.16	1.27
2	60.19	0.1108	1.30	1.37
3	55.56	0.1261	1.43	1.48
4	50.93	0.1405	1.55	1.57
5	46.30	0.1540	1.67	1.66
6	46.30	0.1670	1.67	1.66
7	46.30	0.1800	1.67	1.66
8	46.30	0.1930	1.67	1.66
9	46.30	0.2061	1.67	1.66
10	46.30	0.2191	1.67	1.66
11	46.30	0.2321	1.67	1.66
12	46.30	0.2451	1.67	1.66
13	46.30	0.2581	1.67	1.66
14	46.30	0.2711	1.67	1.66
15	46.30	0.2841	1.67	1.66
16	46.30	0.2971	1.67	1.66

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.64407 + 0.11331	0.82576 + 0.15376
SLEWING FORCE + S.D. (KN)	10.45503 + 0.19719	5.24545 + 0.50628
VOLUME SWEPT (CUBM)	0.0008648	0.0004324
SPECIFIC ENERGY (MJ/CUBM)	11.9449	11.9990

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 50.93 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 64.82 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	64.82	0.0948	1.16	1.27
2	60.19	0.1108	1.30	1.37
3	55.56	0.1261	1.43	1.48
4	50.93	0.1405	1.55	1.57
5	50.93	0.1545	1.55	1.57
6	50.93	0.1684	1.55	1.57
7	50.93	0.1824	1.55	1.57
8	50.93	0.1964	1.55	1.57
9	50.93	0.2104	1.55	1.57
10	50.93	0.2243	1.55	1.57
11	50.93	0.2383	1.55	1.57
12	50.93	0.2523	1.55	1.57
13	50.93	0.2663	1.55	1.57
14	50.93	0.2802	1.55	1.57
15	50.93	0.2942	1.55	1.57
16	50.93	0.3082	1.55	1.57

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.57867 + 0.10627	0.79292 + 0.14521
SLEWING FORCE + S.D. (KN)	9.96568 + 0.16056	5.00002 + 0.46961
VOLUME SWEPT (CUBM)	0.0008152	0.0004076
SPECIFIC ENERGY (MJ/CUBM)	12.1683	12.2235

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 55.56 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 64.82 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	64.82	0.0948	1.16	1.27
2	60.19	0.1108	1.30	1.37
3	55.56	0.1261	1.43	1.48
4	55.56	0.1409	1.43	1.48
5	55.56	0.1557	1.43	1.48
6	55.56	0.1706	1.43	1.48
7	55.56	0.1854	1.43	1.48
8	55.56	0.2003	1.43	1.48
9	55.56	0.2151	1.43	1.48
10	55.56	0.2300	1.43	1.48
11	55.56	0.2448	1.43	1.48
12	55.56	0.2597	1.43	1.48
13	55.56	0.2745	1.43	1.48
14	55.56	0.2894	1.43	1.48
15	55.56	0.3042	1.43	1.48
16	55.56	0.3190	1.43	1.48

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.49754 + 0.09757	0.75216 + 0.13555
SLEWING FORCE + S.D. (KN)	9.39957 + 0.11771	4.71604 + 0.43334
VOLUME SWEPT (CUBM)	0.0007546	0.0003773
SPECIFIC ENERGY (MJ/CUBM)	12.4697	12.5262

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 60.19 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 64.82 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	64.82	0.0948	1.16	1.27
2	60.19	0.1108	1.30	1.37
3	60.19	0.1264	1.30	1.37
4	60.19	0.1420	1.30	1.37
5	60.19	0.1577	1.30	1.37
6	60.19	0.1733	1.30	1.37
7	60.19	0.1889	1.30	1.37
8	60.19	0.2045	1.30	1.37
9	60.19	0.2201	1.30	1.37
10	60.19	0.2358	1.30	1.37
11	60.19	0.2514	1.30	1.37
12	60.19	0.2670	1.30	1.37
13	60.19	0.2826	1.30	1.37
14	60.19	0.2982	1.30	1.37
15	60.19	0.3138	1.30	1.37
16	60.19	0.3295	1.30	1.37

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.39948 + 0.09101	0.70292 + 0.12572
SLEWING FORCE + S.D. (KN)	8.75515 + 0.09578	4.39285 + 0.40071
VOLUME SWEPT (CUBM)	0.0006824	0.0003412
SPECIFIC ENERGY (MJ/CUBM)	12.8860	12.9444

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 4.63 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 69.45 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	69.45	0.0782	1.02	1.16
2	64.82	0.0948	1.16	1.27
3	60.19	0.1108	1.30	1.37
4	55.56	0.1261	1.43	1.48
5	50.93	0.1405	1.55	1.57
6	46.30	0.1540	1.67	1.66
7	41.67	0.1665	1.77	1.74
8	37.04	0.1779	1.87	1.82
9	32.41	0.1882	1.96	1.89
10	27.78	0.1972	2.04	1.95
11	23.15	0.2050	2.10	2.00
12	18.52	0.2114	2.16	2.04
13	13.89	0.2164	2.20	2.07
14	9.26	0.2200	2.23	2.10
15	4.63	0.2222	2.25	2.11
16	4.63	0.2236	2.25	2.11

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.66930 + 0.12006	0.83845 + 0.16564
SLEWING FORCE + S.D. (KN)	11.69590 + 0.37667	5.86798 + 0.66080
VOLUME SWEPT (CUBM)	0.0009176	0.0004588
SPECIFIC ENERGY (MJ/CUBM)	11.4308	11.4828

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 9.26 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 69.45 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	69.45	0.0782	1.02	1.16
2	64.82	0.0948	1.16	1.27
3	60.19	0.1108	1.30	1.37
4	55.56	0.1261	1.43	1.48
5	50.93	0.1405	1.55	1.57
6	46.30	0.1540	1.67	1.66
7	41.67	0.1665	1.77	1.74
8	37.04	0.1779	1.87	1.82
9	32.41	0.1882	1.96	1.89
10	27.78	0.1972	2.04	1.95
11	23.15	0.2050	2.10	2.00
12	18.52	0.2114	2.16	2.04
13	13.89	0.2164	2.20	2.07
14	9.26	0.2200	2.23	2.10
15	9.26	0.2229	2.23	2.10
16	9.26	0.2258	2.23	2.10

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.66871 + 0.12048	0.83815 + 0.16555
SLEWING FORCE + S.D. (KN)	11.68275 + 0.37361	5.86139 + 0.65760
VOLUME SWEPT (CUBM)	0.0009168	0.0004584
SPECIFIC ENERGY (MJ/CUBM)	11.4360	11.4880

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 13.89 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 69.45 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	69.45	0.0782	1.02	1.16
2	64.82	0.0948	1.16	1.27
3	60.19	0.1108	1.30	1.37
4	55.56	0.1261	1.43	1.48
5	50.93	0.1405	1.55	1.57
6	46.30	0.1540	1.67	1.66
7	41.67	0.1665	1.77	1.74
8	37.04	0.1779	1.87	1.82
9	32.41	0.1882	1.96	1.89
10	27.78	0.1972	2.04	1.95
11	23.15	0.2050	2.10	2.00
12	18.52	0.2114	2.16	2.04
13	13.89	0.2164	2.20	2.07
14	13.89	0.2207	2.20	2.07
15	13.89	0.2250	2.20	2.07
16	13.89	0.2293	2.20	2.07

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.66662 + 0.11969	0.83710 + 0.16481
SLEWING FORCE + S.D. (KN)	11.65004 + 0.36197	5.84497 + 0.64894
VOLUME SWEPT (CUBM)	0.0009148	0.0004574
SPECIFIC ENERGY (MJ/CUBM)	11.4472	11.4993

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 18.52 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 69.45 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	69.45	0.0782	1.02	1.16
2	64.82	0.0948	1.16	1.27
3	60.19	0.1108	1.30	1.37
4	55.56	0.1261	1.43	1.48
5	50.93	0.1405	1.55	1.57
6	46.30	0.1540	1.67	1.66
7	41.67	0.1665	1.77	1.74
8	37.04	0.1779	1.87	1.82
9	32.41	0.1882	1.96	1.89
10	27.78	0.1972	2.04	1.95
11	23.15	0.2050	2.10	2.00
12	18.52	0.2114	2.16	2.04
13	18.52	0.2171	2.16	2.04
14	18.52	0.2228	2.16	2.04
15	18.52	0.2285	2.16	2.04
16	18.52	0.2342	2.16	2.04

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.66208 + 0.11890	0.83482 + 0.16361
SLEWING FORCE + S.D. (KN)	11.58936 + 0.34635	5.81454 + 0.63463
VOLUME SWEPT (CUBM)	0.0009107	0.0004553
SPECIFIC ENERGY (MJ/CUBM)	11.4673	11.5195

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 23.15 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 69.45 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	69.45	0.0782	1.02	1.16
2	64.82	0.0948	1.16	1.27
3	60.19	0.1108	1.30	1.37
4	55.56	0.1261	1.43	1.48
5	50.93	0.1405	1.55	1.57
6	46.30	0.1540	1.67	1.66
7	41.67	0.1665	1.77	1.74
8	37.04	0.1779	1.87	1.82
9	32.41	0.1882	1.96	1.89
10	27.78	0.1972	2.04	1.95
11	23.15	0.2050	2.10	2.00
12	23.15	0.2120	2.10	2.00
13	23.15	0.2191	2.10	2.00
14	23.15	0.2262	2.10	2.00
15	23.15	0.2333	2.10	2.00
16	23.15	0.2403	2.10	2.00

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.65402 + 0.11882	0.83077 + 0.16237
SLEWING FORCE + S.D. (KN)	11.49271 + 0.32991	5.76603 + 0.61689
VOLUME SWEPT (CUBM)	0.0009038	0.0004519
SPECIFIC ENERGY (MJ/CUBM)	11.4990	11.5513

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 27.78 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 69.45 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	69.45	0.0782	1.02	1.16
2	64.82	0.0948	1.16	1.27
3	60.19	0.1108	1.30	1.37
4	55.56	0.1261	1.43	1.48
5	50.93	0.1405	1.55	1.57
6	46.30	0.1540	1.67	1.66
7	41.67	0.1665	1.77	1.74
8	37.04	0.1779	1.87	1.82
9	32.41	0.1882	1.96	1.89
10	27.78	0.1972	2.04	1.95
11	27.78	0.2056	2.04	1.95
12	27.78	0.2140	2.04	1.95
13	27.78	0.2224	2.04	1.95
14	27.78	0.2308	2.04	1.95
15	27.78	0.2392	2.04	1.95
16	27.78	0.2475	2.04	1.95

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.64116 + 0.11796	0.82432 + 0.16144
SLEWING FORCE + S.D. (KN)	11.35249 + 0.30446	5.69571 + 0.59859
VOLUME SWEPT (CUBM)	0.0008931	0.0004466
SPECIFIC ENERGY (MJ/CUBM)	11.5458	11.5984

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 32.41 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 69.45 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	69.45	0.0782	1.02	1.16
2	64.82	0.0948	1.16	1.27
3	60.19	0.1108	1.30	1.37
4	55.56	0.1261	1.43	1.48
5	50.93	0.1405	1.55	1.57
6	46.30	0.1540	1.67	1.66
7	41.67	0.1665	1.77	1.74
8	37.04	0.1779	1.87	1.82
9	32.41	0.1882	1.96	1.89
10	32.41	0.1978	1.96	1.89
11	32.41	0.2075	1.96	1.89
12	32.41	0.2171	1.96	1.89
13	32.41	0.2268	1.96	1.89
14	32.41	0.2364	1.96	1.89
15	32.41	0.2461	1.96	1.89
16	32.41	0.2557	1.96	1.89

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.62210 + 0.12079	0.81474 + 0.16170
SLEWING FORCE + S.D. (KN)	11.16171 + 0.29856	5.59999 + 0.58572
VOLUME SWEPT (CUBM)	0.0008777	0.0004389
SPECIFIC ENERGY (MJ/CUBM)	11.6117	11.6645

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 37.04 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 69.45 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	69.45	0.0782	1.02	1.16
2	64.82	0.0948	1.16	1.27
3	60.19	0.1108	1.30	1.37
4	55.56	0.1261	1.43	1.48
5	50.93	0.1405	1.55	1.57
6	46.30	0.1540	1.67	1.66
7	41.67	0.1665	1.77	1.74
8	37.04	0.1779	1.87	1.82
9	37.04	0.1888	1.87	1.82
10	37.04	0.1996	1.87	1.82
11	37.04	0.2105	1.87	1.82
12	37.04	0.2213	1.87	1.82
13	37.04	0.2321	1.87	1.82
14	37.04	0.2430	1.87	1.82
15	37.04	0.2538	1.87	1.82
16	37.04	0.2647	1.87	1.82

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.59528 + 0.11989	0.80128 + 0.16051
SLEWING FORCE + S.D. (KN)	10.91403 + 0.27386	5.47577 + 0.56851
VOLUME SWEPT (CUBM)	0.0008566	0.0004283
SPECIFIC ENERGY (MJ/CUBM)	11.7017	11.7551

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 41.67 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 69.45 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	69.45	0.0782	1.02	1.16
2	64.82	0.0948	1.16	1.27
3	60.19	0.1108	1.30	1.37
4	55.56	0.1261	1.43	1.48
5	50.93	0.1405	1.55	1.57
6	46.30	0.1540	1.67	1.66
7	41.67	0.1665	1.77	1.74
8	41.67	0.1785	1.77	1.74
9	41.67	0.1904	1.77	1.74
10	41.67	0.2024	1.77	1.74
11	41.67	0.2144	1.77	1.74
12	41.67	0.2263	1.77	1.74
13	41.67	0.2383	1.77	1.74
14	41.67	0.2503	1.77	1.74
15	41.67	0.2622	1.77	1.74
16	41.67	0.2742	1.77	1.74

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.55906 + 0.12107	0.78308 + 0.15873
SLEWING FORCE + S.D. (KN)	10.60383 + 0.26758	5.32015 + 0.55154
VOLUME SWEPT (CUBM)	0.0008286	0.0004143
SPECIFIC ENERGY (MJ/CUBM)	11.8227	11.8766

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 46.30 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 69.45 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	69.45	0.0782	1.02	1.16
2	64.82	0.0948	1.16	1.27
3	60.19	0.1108	1.30	1.37
4	55.56	0.1261	1.43	1.48
5	50.93	0.1405	1.55	1.57
6	46.30	0.1540	1.67	1.66
7	46.30	0.1670	1.67	1.66
8	46.30	0.1800	1.67	1.66
9	46.30	0.1930	1.67	1.66
10	46.30	0.2061	1.67	1.66
11	46.30	0.2191	1.67	1.66
12	46.30	0.2321	1.67	1.66
13	46.30	0.2451	1.67	1.66
14	46.30	0.2581	1.67	1.66
15	46.30	0.2711	1.67	1.66
16	46.30	0.2841	1.67	1.66

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.51178 + 0.11622	0.75933 + 0.15336
SLEWING FORCE + S.D. (KN)	10.22638 + 0.23256	5.13084 + 0.52255
VOLUME SWEPT (CUBM)	0.0007926	0.0003963
SPECIFIC ENERGY (MJ/CUBM)	11.9843	12.0390

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 50.93 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 69.45 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	69.45	0.0782	1.02	1.16
2	64.82	0.0948	1.16	1.27
3	60.19	0.1108	1.30	1.37
4	55.56	0.1261	1.43	1.48
5	50.93	0.1405	1.55	1.57
6	50.93	0.1545	1.55	1.57
7	50.93	0.1684	1.55	1.57
8	50.93	0.1824	1.55	1.57
9	50.93	0.1964	1.55	1.57
10	50.93	0.2104	1.55	1.57
11	50.93	0.2243	1.55	1.57
12	50.93	0.2383	1.55	1.57
13	50.93	0.2523	1.55	1.57
14	50.93	0.2663	1.55	1.57
15	50.93	0.2802	1.55	1.57
16	50.93	0.2942	1.55	1.57

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.45185 + 0.11070	0.72923 + 0.14542
SLEWING FORCE + S.D. (KN)	9.77781 + 0.20209	4.90581 + 0.48603
VOLUME SWEPT (CUBM)	0.0007477	0.0003738
SPECIFIC ENERGY (MJ/CUBM)	12.2005	12.2561

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 55.56 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 69.45 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	69.45	0.0782	1.02	1.16
2	64.82	0.0948	1.16	1.27
3	60.19	0.1108	1.30	1.37
4	55.56	0.1261	1.43	1.48
5	55.56	0.1409	1.43	1.48
6	55.56	0.1557	1.43	1.48
7	55.56	0.1706	1.43	1.48
8	55.56	0.1854	1.43	1.48
9	55.56	0.2003	1.43	1.48
10	55.56	0.2151	1.43	1.48
11	55.56	0.2300	1.43	1.48
12	55.56	0.2448	1.43	1.48
13	55.56	0.2597	1.43	1.48
14	55.56	0.2745	1.43	1.48
15	55.56	0.2894	1.43	1.48
16	55.56	0.3042	1.43	1.48

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.37787 + 0.10240	0.69208 + 0.13534
SLEWING FORCE + S.D. (KN)	9.25524 + 0.16197	4.64373 + 0.44512
VOLUME SWEPT (CUBM)	0.0006930	0.0003465
SPECIFIC ENERGY (MJ/CUBM)	12.4930	12.5500

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 60.19 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 69.45 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	69.45	0.0782	1.02	1.16
2	64.82	0.0948	1.16	1.27
3	60.19	0.1108	1.30	1.37
4	60.19	0.1264	1.30	1.37
5	60.19	0.1420	1.30	1.37
6	60.19	0.1577	1.30	1.37
7	60.19	0.1733	1.30	1.37
8	60.19	0.1889	1.30	1.37
9	60.19	0.2045	1.30	1.37
10	60.19	0.2201	1.30	1.37
11	60.19	0.2358	1.30	1.37
12	60.19	0.2514	1.30	1.37
13	60.19	0.2670	1.30	1.37
14	60.19	0.2826	1.30	1.37
15	60.19	0.2982	1.30	1.37
16	60.19	0.3138	1.30	1.37

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.28875 + 0.09251	0.64730 + 0.12420
SLEWING FORCE + S.D. (KN)	8.65685 + 0.11486	4.34355 + 0.40525
VOLUME SWEPT (CUBM)	0.0006278	0.0003139
SPECIFIC ENERGY (MJ/CUBM)	12.8971	12.9558

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 64.82 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 69.45 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	69.45	0.0782	1.02	1.16
2	64.82	0.0948	1.16	1.27
3	64.82	0.1111	1.16	1.27
4	64.82	0.1274	1.16	1.27
5	64.82	0.1437	1.16	1.27
6	64.82	0.1600	1.16	1.27
7	64.82	0.1763	1.16	1.27
8	64.82	0.1926	1.16	1.27
9	64.82	0.2089	1.16	1.27
10	64.82	0.2252	1.16	1.27
11	64.82	0.2414	1.16	1.27
12	64.82	0.2577	1.16	1.27
13	64.82	0.2740	1.16	1.27
14	64.82	0.2903	1.16	1.27
15	64.82	0.3066	1.16	1.27
16	64.82	0.3229	1.16	1.27

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.18380 + 0.08457	0.59460 + 0.11293
SLEWING FORCE + S.D. (KN)	7.98187 + 0.09078	4.00503 + 0.37026
VOLUME SWEPT (CUBM)	0.0005520	0.0002760
SPECIFIC ENERGY (MJ/CUBM)	13.4749	13.5363

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 9.26 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 74.08 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	74.08	0.0611	0.87	1.05
2	69.45	0.0782	1.02	1.16
3	64.82	0.0948	1.16	1.27
4	60.19	0.1108	1.30	1.37
5	55.56	0.1261	1.43	1.48
6	50.93	0.1405	1.55	1.57
7	46.30	0.1540	1.67	1.66
8	41.67	0.1665	1.77	1.74
9	37.04	0.1779	1.87	1.82
10	32.41	0.1882	1.96	1.89
11	27.78	0.1972	2.04	1.95
12	23.15	0.2050	2.10	2.00
13	18.52	0.2114	2.16	2.04
14	13.89	0.2164	2.20	2.07
15	9.26	0.2200	2.23	2.10
16	9.26	0.2229	2.23	2.10

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.52535 + 0.12570	0.76616 + 0.16675
SLEWING FORCE + S.D. (KN)	11.20328 + 0.41068	5.62096 + 0.67423
VOLUME SWEPT (CUBM)	0.0008306	0.0004153
SPECIFIC ENERGY (MJ/CUBM)	11.5388	11.5915

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 13.89 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 74.08 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	74.08	0.0611	0.87	1.05
2	69.45	0.0782	1.02	1.16
3	64.82	0.0948	1.16	1.27
4	60.19	0.1108	1.30	1.37
5	55.56	0.1261	1.43	1.48
6	50.93	0.1405	1.55	1.57
7	46.30	0.1540	1.67	1.66
8	41.67	0.1665	1.77	1.74
9	37.04	0.1779	1.87	1.82
10	32.41	0.1882	1.96	1.89
11	27.78	0.1972	2.04	1.95
12	23.15	0.2050	2.10	2.00
13	18.52	0.2114	2.16	2.04
14	13.89	0.2164	2.20	2.07
15	13.89	0.2207	2.20	2.07
16	13.89	0.2250	2.20	2.07

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.52298 + 0.12559	0.76498 + 0.16604
SLEWING FORCE + S.D. (KN)	11.18147 + 0.40550	5.61002 + 0.66851
VOLUME SWEPT (CUBM)	0.0008289	0.0004145
SPECIFIC ENERGY (MJ/CUBM)	11.5440	11.5968

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 18.52 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 74.08 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	74.08	0.0611	0.87	1.05
2	69.45	0.0782	1.02	1.16
3	64.82	0.0948	1.16	1.27
4	60.19	0.1108	1.30	1.37
5	55.56	0.1261	1.43	1.48
6	50.93	0.1405	1.55	1.57
7	46.30	0.1540	1.67	1.66
8	41.67	0.1665	1.77	1.74
9	37.04	0.1779	1.87	1.82
10	32.41	0.1882	1.96	1.89
11	27.78	0.1972	2.04	1.95
12	23.15	0.2050	2.10	2.00
13	18.52	0.2114	2.16	2.04
14	18.52	0.2171	2.16	2.04
15	18.52	0.2228	2.16	2.04
16	18.52	0.2285	2.16	2.04

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.51824 + 0.12366	0.76259 + 0.16430
SLEWING FORCE + S.D. (KN)	11.13596 + 0.38913	5.58717 + 0.65562
VOLUME SWEPT (CUBM)	0.0008254	0.0004127
SPECIFIC ENERGY (MJ/CUBM)	11.5579	11.6108

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 23.15 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 74.08 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	74.08	0.0611	0.87	1.05
2	69.45	0.0782	1.02	1.16
3	64.82	0.0948	1.16	1.27
4	60.19	0.1108	1.30	1.37
5	55.56	0.1261	1.43	1.48
6	50.93	0.1405	1.55	1.57
7	46.30	0.1540	1.67	1.66
8	41.67	0.1665	1.77	1.74
9	37.04	0.1779	1.87	1.82
10	32.41	0.1882	1.96	1.89
11	27.78	0.1972	2.04	1.95
12	23.15	0.2050	2.10	2.00
13	23.15	0.2120	2.10	2.00
14	23.15	0.2191	2.10	2.00
15	23.15	0.2262	2.10	2.00
16	23.15	0.2333	2.10	2.00

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.51016 + 0.12168	0.75854 + 0.16190
SLEWING FORCE + S.D. (KN)	11.05864 + 0.36902	5.54839 + 0.63625
VOLUME SWEPT (CUBM)	0.0008191	0.0004096
SPECIFIC ENERGY (MJ/CUBM)	11.5835	11.6365

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 27.78 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 74.08 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	74.08	0.0611	0.87	1.05
2	69.45	0.0782	1.02	1.16
3	64.82	0.0948	1.16	1.27
4	60.19	0.1108	1.30	1.37
5	55.56	0.1261	1.43	1.48
6	50.93	0.1405	1.55	1.57
7	46.30	0.1540	1.67	1.66
8	41.67	0.1665	1.77	1.74
9	37.04	0.1779	1.87	1.82
10	32.41	0.1882	1.96	1.89
11	27.78	0.1972	2.04	1.95
12	27.78	0.2056	2.04	1.95
13	27.78	0.2140	2.04	1.95
14	27.78	0.2224	2.04	1.95
15	27.78	0.2308	2.04	1.95
16	27.78	0.2392	2.04	1.95

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.49770 + 0.12052	0.75227 + 0.15943
SLEWING FORCE + S.D. (KN)	10.94179 + 0.34897	5.48975 + 0.61359
VOLUME SWEPT (CUBM)	0.0008095	0.0004048
SPECIFIC ENERGY (MJ/CUBM)	11.6243	11.6774

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 32.41 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 74.08 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	74.08	0.0611	0.87	1.05
2	69.45	0.0782	1.02	1.16
3	64.82	0.0948	1.16	1.27
4	60.19	0.1108	1.30	1.37
5	55.56	0.1261	1.43	1.48
6	50.93	0.1405	1.55	1.57
7	46.30	0.1540	1.67	1.66
8	41.67	0.1665	1.77	1.74
9	37.04	0.1779	1.87	1.82
10	32.41	0.1882	1.96	1.89
11	32.41	0.1978	1.96	1.89
12	32.41	0.2075	1.96	1.89
13	32.41	0.2171	1.96	1.89
14	32.41	0.2268	1.96	1.89
15	32.41	0.2364	1.96	1.89
16	32.41	0.2461	1.96	1.89

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.47962 + 0.11844	0.74320 + 0.15733
SLEWING FORCE + S.D. (KN)	10.77827 + 0.31901	5.40774 + 0.59125
VOLUME SWEPT (CUBM)	0.0007957	0.0003978
SPECIFIC ENERGY (MJ/CUBM)	11.6842	11.7377

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 37.04 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 74.08 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	74.08	0.0611	0.87	1.05
2	69.45	0.0782	1.02	1.16
3	64.82	0.0948	1.16	1.27
4	60.19	0.1108	1.30	1.37
5	55.56	0.1261	1.43	1.48
6	50.93	0.1405	1.55	1.57
7	46.30	0.1540	1.67	1.66
8	41.67	0.1665	1.77	1.74
9	37.04	0.1779	1.87	1.82
10	37.04	0.1888	1.87	1.82
11	37.04	0.1996	1.87	1.82
12	37.04	0.2105	1.87	1.82
13	37.04	0.2213	1.87	1.82
14	37.04	0.2321	1.87	1.82
15	37.04	0.2430	1.87	1.82
16	37.04	0.2538	1.87	1.82

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.45460 + 0.12039	0.73063 + 0.15655
SLEWING FORCE + S.D. (KN)	10.56154 + 0.31237	5.29900 + 0.57630
VOLUME SWEPT (CUBM)	0.0007766	0.0003883
SPECIFIC ENERGY (MJ/CUBM)	11.7683	11.8221

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 41.67 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 74.08 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	74.08	0.0611	0.87	1.05
2	69.45	0.0782	1.02	1.16
3	64.82	0.0948	1.16	1.27
4	60.19	0.1108	1.30	1.37
5	55.56	0.1261	1.43	1.48
6	50.93	0.1405	1.55	1.57
7	46.30	0.1540	1.67	1.66
8	41.67	0.1665	1.77	1.74
9	41.67	0.1785	1.77	1.74
10	41.67	0.1904	1.77	1.74
11	41.67	0.2024	1.77	1.74
12	41.67	0.2144	1.77	1.74
13	41.67	0.2263	1.77	1.74
14	41.67	0.2383	1.77	1.74
15	41.67	0.2503	1.77	1.74
16	41.67	0.2622	1.77	1.74

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.42121 + 0.11833	0.71386 + 0.15416
SLEWING FORCE + S.D. (KN)	10.28581 + 0.28460	5.16072 + 0.55664
VOLUME SWEPT (CUBM)	0.0007514	0.0003757
SPECIFIC ENERGY (MJ/CUBM)	11.8835	11.9379

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 46.30 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 74.08 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	74.08	0.0611	0.87	1.05
2	69.45	0.0782	1.02	1.16
3	64.82	0.0948	1.16	1.27
4	60.19	0.1108	1.30	1.37
5	55.56	0.1261	1.43	1.48
6	50.93	0.1405	1.55	1.57
7	46.30	0.1540	1.67	1.66
8	46.30	0.1670	1.67	1.66
9	46.30	0.1800	1.67	1.66
10	46.30	0.1930	1.67	1.66
11	46.30	0.2061	1.67	1.66
12	46.30	0.2191	1.67	1.66
13	46.30	0.2321	1.67	1.66
14	46.30	0.2451	1.67	1.66
15	46.30	0.2581	1.67	1.66
16	46.30	0.2711	1.67	1.66

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.37799 + 0.11839	0.69215 + 0.15113
SLEWING FORCE + S.D. (KN)	9.94610 + 0.27768	4.99029 + 0.53773
VOLUME SWEPT (CUBM)	0.0007192	0.0003596
SPECIFIC ENERGY (MJ/CUBM)	12.0391	12.0941

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 50.93 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 74.08 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	74.08	0.0611	0.87	1.05
2	69.45	0.0782	1.02	1.16
3	64.82	0.0948	1.16	1.27
4	60.19	0.1108	1.30	1.37
5	55.56	0.1261	1.43	1.48
6	50.93	0.1405	1.55	1.57
7	50.93	0.1545	1.55	1.57
8	50.93	0.1684	1.55	1.57
9	50.93	0.1824	1.55	1.57
10	50.93	0.1964	1.55	1.57
11	50.93	0.2104	1.55	1.57
12	50.93	0.2243	1.55	1.57
13	50.93	0.2383	1.55	1.57
14	50.93	0.2523	1.55	1.57
15	50.93	0.2663	1.55	1.57
16	50.93	0.2802	1.55	1.57

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.32353 + 0.11236	0.66480 + 0.14441
SLEWING FORCE + S.D. (KN)	9.53831 + 0.23931	4.78577 + 0.50527
VOLUME SWEPT (CUBM)	0.0006789	0.0003395
SPECIFIC ENERGY (MJ/CUBM)	12.2488	12.3049

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 55.56 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 74.08 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	74.08	0.0611	0.87	1.05
2	69.45	0.0782	1.02	1.16
3	64.82	0.0948	1.16	1.27
4	60.19	0.1108	1.30	1.37
5	55.56	0.1261	1.43	1.48
6	55.56	0.1409	1.43	1.48
7	55.56	0.1557	1.43	1.48
8	55.56	0.1706	1.43	1.48
9	55.56	0.1854	1.43	1.48
10	55.56	0.2003	1.43	1.48
11	55.56	0.2151	1.43	1.48
12	55.56	0.2300	1.43	1.48
13	55.56	0.2448	1.43	1.48
14	55.56	0.2597	1.43	1.48
15	55.56	0.2745	1.43	1.48
16	55.56	0.2894	1.43	1.48

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.25656 + 0.10567	0.63115 + 0.13513
SLEWING FORCE + S.D. (KN)	9.05930 + 0.20626	4.54546 + 0.46463
VOLUME SWEPT (CUBM)	0.0006299	0.0003150
SPECIFIC ENERGY (MJ/CUBM)	12.5338	12.5911

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 60.19 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 74.08 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	74.08	0.0611	0.87	1.05
2	69.45	0.0782	1.02	1.16
3	64.82	0.0948	1.16	1.27
4	60.19	0.1108	1.30	1.37
5	60.19	0.1264	1.30	1.37
6	60.19	0.1420	1.30	1.37
7	60.19	0.1577	1.30	1.37
8	60.19	0.1733	1.30	1.37
9	60.19	0.1889	1.30	1.37
10	60.19	0.2045	1.30	1.37
11	60.19	0.2201	1.30	1.37
12	60.19	0.2358	1.30	1.37
13	60.19	0.2514	1.30	1.37
14	60.19	0.2670	1.30	1.37
15	60.19	0.2826	1.30	1.37
16	60.19	0.2982	1.30	1.37

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.17607 + 0.09633	0.59072 + 0.12379
SLEWING FORCE + S.D. (KN)	8.50694 + 0.16297	4.26844 + 0.41946
VOLUME SWEPT (CUBM)	0.0005716	0.0002858
SPECIFIC ENERGY (MJ/CUBM)	12.9285	12.9876

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 64.82 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 74.08 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	74.08	0.0611	0.87	1.05
2	69.45	0.0782	1.02	1.16
3	64.82	0.0948	1.16	1.27
4	64.82	0.1111	1.16	1.27
5	64.82	0.1274	1.16	1.27
6	64.82	0.1437	1.16	1.27
7	64.82	0.1600	1.16	1.27
8	64.82	0.1763	1.16	1.27
9	64.82	0.1926	1.16	1.27
10	64.82	0.2089	1.16	1.27
11	64.82	0.2252	1.16	1.27
12	64.82	0.2414	1.16	1.27
13	64.82	0.2577	1.16	1.27
14	64.82	0.2740	1.16	1.27
15	64.82	0.2903	1.16	1.27
16	64.82	0.3066	1.16	1.27

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.08141 + 0.08552	0.54318 + 0.11148
SLEWING FORCE + S.D. (KN)	7.88017 + 0.11194	3.95403 + 0.37599
VOLUME SWEPT (CUBM)	0.0005036	0.0002518
SPECIFIC ENERGY (MJ/CUBM)	13.4928	13.5544

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 69.45 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 74.08 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	74.08	0.0611	0.87	1.05
2	69.45	0.0782	1.02	1.16
3	69.45	0.0951	1.02	1.16
4	69.45	0.1120	1.02	1.16
5	69.45	0.1288	1.02	1.16
6	69.45	0.1457	1.02	1.16
7	69.45	0.1625	1.02	1.16
8	69.45	0.1794	1.02	1.16
9	69.45	0.1962	1.02	1.16
10	69.45	0.2131	1.02	1.16
11	69.45	0.2299	1.02	1.16
12	69.45	0.2468	1.02	1.16
13	69.45	0.2636	1.02	1.16
14	69.45	0.2805	1.02	1.16
15	69.45	0.2974	1.02	1.16
16	69.45	0.3142	1.02	1.16

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	0.97246 + 0.07643	0.48845 + 0.09905
SLEWING FORCE + S.D. (KN)	7.17903 + 0.08583	3.60239 + 0.33869
VOLUME SWEPT (CUBM)	0.0004260	0.0002130
SPECIFIC ENERGY (MJ/CUBM)	14.3420	14.4075

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 13.89 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 78.71 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	78.71	0.0436	0.72	0.93
2	74.08	0.0611	0.87	1.05
3	69.45	0.0782	1.02	1.16
4	64.82	0.0948	1.16	1.27
5	60.19	0.1108	1.30	1.37
6	55.56	0.1261	1.43	1.48
7	50.93	0.1405	1.55	1.57
8	46.30	0.1540	1.67	1.66
9	41.67	0.1665	1.77	1.74
10	37.04	0.1779	1.87	1.82
11	32.41	0.1882	1.96	1.89
12	27.78	0.1972	2.04	1.95
13	23.15	0.2050	2.10	2.00
14	18.52	0.2114	2.16	2.04
15	13.89	0.2164	2.20	2.07
16	13.89	0.2207	2.20	2.07

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.37543 + 0.12846	0.69088 + 0.16554
SLEWING FORCE + S.D. (KN)	10.66007 + 0.44258	5.34855 + 0.68724
VOLUME SWEPT (CUBM)	0.0007408	0.0003704
SPECIFIC ENERGY (MJ/CUBM)	11.6659	11.7196

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 18.52 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 78.71 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	78.71	0.0436	0.72	0.93
2	74.08	0.0611	0.87	1.05
3	69.45	0.0782	1.02	1.16
4	64.82	0.0948	1.16	1.27
5	60.19	0.1108	1.30	1.37
6	55.56	0.1261	1.43	1.48
7	50.93	0.1405	1.55	1.57
8	46.30	0.1540	1.67	1.66
9	41.67	0.1665	1.77	1.74
10	37.04	0.1779	1.87	1.82
11	32.41	0.1882	1.96	1.89
12	27.78	0.1972	2.04	1.95
13	23.15	0.2050	2.10	2.00
14	18.52	0.2114	2.16	2.04
15	18.52	0.2171	2.16	2.04
16	18.52	0.2228	2.16	2.04

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.37137 + 0.12782	0.68884 + 0.16417
SLEWING FORCE + S.D. (KN)	10.62973 + 0.43528	5.33334 + 0.67878
VOLUME SWEPT (CUBM)	0.0007383	0.0003691
SPECIFIC ENERGY (MJ/CUBM)	11.6715	11.7252

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 23.15 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 78.71 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	78.71	0.0436	0.72	0.93
2	74.08	0.0611	0.87	1.05
3	69.45	0.0782	1.02	1.16
4	64.82	0.0948	1.16	1.27
5	60.19	0.1108	1.30	1.37
6	55.56	0.1261	1.43	1.48
7	50.93	0.1405	1.55	1.57
8	46.30	0.1540	1.67	1.66
9	41.67	0.1665	1.77	1.74
10	37.04	0.1779	1.87	1.82
11	32.41	0.1882	1.96	1.89
12	27.78	0.1972	2.04	1.95
13	23.15	0.2050	2.10	2.00
14	23.15	0.2120	2.10	2.00
15	23.15	0.2191	2.10	2.00
16	23.15	0.2262	2.10	2.00

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.36410 + 0.12478	0.68518 + 0.16142
SLEWING FORCE + S.D. (KN)	10.57174 + 0.41423	5.30422 + 0.66140
VOLUME SWEPT (CUBM)	0.0007332	0.0003666
SPECIFIC ENERGY (MJ/CUBM)	11.6891	11.7428

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 27.78 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 78.71 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	78.71	0.0436	0.72	0.93
2	74.08	0.0611	0.87	1.05
3	69.45	0.0782	1.02	1.16
4	64.82	0.0948	1.16	1.27
5	60.19	0.1108	1.30	1.37
6	55.56	0.1261	1.43	1.48
7	50.93	0.1405	1.55	1.57
8	46.30	0.1540	1.67	1.66
9	41.67	0.1665	1.77	1.74
10	37.04	0.1779	1.87	1.82
11	32.41	0.1882	1.96	1.89
12	27.78	0.1972	2.04	1.95
13	27.78	0.2056	2.04	1.95
14	27.78	0.2140	2.04	1.95
15	27.78	0.2224	2.04	1.95
16	27.78	0.2308	2.04	1.95

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.35272 + 0.12166	0.67947 + 0.15783
SLEWING FORCE + S.D. (KN)	10.47826 + 0.38974	5.25734 + 0.63672
VOLUME SWEPT (CUBM)	0.0007251	0.0003625
SPECIFIC ENERGY (MJ/CUBM)	11.7221	11.7761

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 32.41 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 78.71 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	78.71	0.0436	0.72	0.93
2	74.08	0.0611	0.87	1.05
3	69.45	0.0782	1.02	1.16
4	64.82	0.0948	1.16	1.27
5	60.19	0.1108	1.30	1.37
6	55.56	0.1261	1.43	1.48
7	50.93	0.1405	1.55	1.57
8	46.30	0.1540	1.67	1.66
9	41.67	0.1665	1.77	1.74
10	37.04	0.1779	1.87	1.82
11	32.41	0.1882	1.96	1.89
12	32.41	0.1978	1.96	1.89
13	32.41	0.2075	1.96	1.89
14	32.41	0.2171	1.96	1.89
15	32.41	0.2268	1.96	1.89
16	32.41	0.2364	1.96	1.89

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.33621 + 0.11946	0.67118 + 0.15417
SLEWING FORCE + S.D. (KN)	10.34199 + 0.36620	5.18896 + 0.60899
VOLUME SWEPT (CUBM)	0.0007130	0.0003565
SPECIFIC ENERGY (MJ/CUBM)	11.7747	11.8288

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 37.04 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 78.71 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	78.71	0.0436	0.72	0.93
2	74.08	0.0611	0.87	1.05
3	69.45	0.0782	1.02	1.16
4	64.82	0.0948	1.16	1.27
5	60.19	0.1108	1.30	1.37
6	55.56	0.1261	1.43	1.48
7	50.93	0.1405	1.55	1.57
8	46.30	0.1540	1.67	1.66
9	41.67	0.1665	1.77	1.74
10	37.04	0.1779	1.87	1.82
11	37.04	0.1888	1.87	1.82
12	37.04	0.1996	1.87	1.82
13	37.04	0.2105	1.87	1.82
14	37.04	0.2213	1.87	1.82
15	37.04	0.2321	1.87	1.82
16	37.04	0.2430	1.87	1.82

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.31344 + 0.11624	0.65974 + 0.15091
SLEWING FORCE + S.D. (KN)	10.15623 + 0.33193	5.09579 + 0.58254
VOLUME SWEPT (CUBM)	0.0006963	0.0003482
SPECIFIC ENERGY (MJ/CUBM)	11.8519	11.9065

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 41.65 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 78.71 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	78.71	0.0436	0.72	0.93
2	74.08	0.0611	0.87	1.05
3	69.45	0.0782	1.02	1.16
4	64.82	0.0948	1.16	1.27
5	60.19	0.1108	1.30	1.37
6	55.56	0.1261	1.43	1.48
7	50.93	0.1405	1.55	1.57
8	46.30	0.1540	1.67	1.66
9	41.67	0.1665	1.77	1.74
10	41.65	0.1666	1.77	1.74
11	41.65	0.1785	1.77	1.74
12	41.65	0.1905	1.77	1.74
13	41.65	0.2024	1.77	1.74
14	41.65	0.2144	1.77	1.74
15	41.65	0.2264	1.77	1.74
16	41.65	0.2383	1.77	1.74

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.23622 + 0.11632	0.62094 + 0.14462
SLEWING FORCE + S.D. (KN)	9.91606 + 0.32463	4.97529 + 0.56566
VOLUME SWEPT (CUBM)	0.0006742	0.0003371
SPECIFIC ENERGY (MJ/CUBM)	11.5210	11.5737

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 46.30 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 78.71 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	78.71	0.0436	0.72	0.93
2	74.08	0.0611	0.87	1.05
3	69.45	0.0782	1.02	1.16
4	64.82	0.0948	1.16	1.27
5	60.19	0.1108	1.30	1.37
6	55.56	0.1261	1.43	1.48
7	50.93	0.1405	1.55	1.57
8	46.30	0.1540	1.67	1.66
9	46.30	0.1670	1.67	1.66
10	46.30	0.1800	1.67	1.66
11	46.30	0.1930	1.67	1.66
12	46.30	0.2061	1.67	1.66
13	46.30	0.2191	1.67	1.66
14	46.30	0.2321	1.67	1.66
15	46.30	0.2451	1.67	1.66
16	46.30	0.2581	1.67	1.66

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.24417 + 0.11413	0.62495 + 0.14555
SLEWING FORCE + S.D. (KN)	9.61300 + 0.29395	4.82330 + 0.54354
VOLUME SWEPT (CUBM)	0.0006455	0.0003228
SPECIFIC ENERGY (MJ/CUBM)	12.1098	12.1655

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 50.93 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 78.71 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	78.71	0.0436	0.72	0.93
2	74.08	0.0611	0.87	1.05
3	69.45	0.0782	1.02	1.16
4	64.82	0.0948	1.16	1.27
5	60.19	0.1108	1.30	1.37
6	55.56	0.1261	1.43	1.48
7	50.93	0.1405	1.55	1.57
8	50.93	0.1545	1.55	1.57
9	50.93	0.1684	1.55	1.57
10	50.93	0.1824	1.55	1.57
11	50.93	0.1964	1.55	1.57
12	50.93	0.2104	1.55	1.57
13	50.93	0.2243	1.55	1.57
14	50.93	0.2383	1.55	1.57
15	50.93	0.2523	1.55	1.57
16	50.93	0.2663	1.55	1.57

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.19517 + 0.11308	0.60033 + 0.14134
SLEWING FORCE + S.D. (KN)	9.24599 + 0.28643	4.63917 + 0.52281
VOLUME SWEPT (CUBM)	0.0006099	0.0003049
SPECIFIC ENERGY (MJ/CUBM)	12.3133	12.3698

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 55.56 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 78.71 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	78.71	0.0436	0.72	0.93
2	74.08	0.0611	0.87	1.05
3	69.45	0.0782	1.02	1.16
4	64.82	0.0948	1.16	1.27
5	60.19	0.1108	1.30	1.37
6	55.56	0.1261	1.43	1.48
7	55.56	0.1409	1.43	1.48
8	55.56	0.1557	1.43	1.48
9	55.56	0.1706	1.43	1.48
10	55.56	0.1854	1.43	1.48
11	55.56	0.2003	1.43	1.48
12	55.56	0.2151	1.43	1.48
13	55.56	0.2300	1.43	1.48
14	55.56	0.2448	1.43	1.48
15	55.56	0.2597	1.43	1.48
16	55.56	0.2745	1.43	1.48

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.13505 + 0.10604	0.57014 + 0.13343
SLEWING FORCE + S.D. (KN)	8.81052 + 0.24501	4.42077 + 0.48696
VOLUME SWEPT (CUBM)	0.0005664	0.0002832
SPECIFIC ENERGY (MJ/CUBM)	12.5919	12.6498

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 60.19 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 78.71 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	78.71	0.0436	0.72	0.93
2	74.08	0.0611	0.87	1.05
3	69.45	0.0782	1.02	1.16
4	64.82	0.0948	1.16	1.27
5	60.19	0.1108	1.30	1.37
6	60.19	0.1264	1.30	1.37
7	60.19	0.1420	1.30	1.37
8	60.19	0.1577	1.30	1.37
9	60.19	0.1733	1.30	1.37
10	60.19	0.1889	1.30	1.37
11	60.19	0.2045	1.30	1.37
12	60.19	0.2201	1.30	1.37
13	60.19	0.2358	1.30	1.37
14	60.19	0.2514	1.30	1.37
15	60.19	0.2670	1.30	1.37
16	60.19	0.2826	1.30	1.37

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.06289 + 0.09836	0.53389 + 0.12306
SLEWING FORCE + S.D. (KN)	8.30419 + 0.20963	4.16676 + 0.44228
VOLUME SWEPT (CUBM)	0.0005145	0.0002573
SPECIFIC ENERGY (MJ/CUBM)	12.9793	13.0389

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 64.82 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 78.71 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	78.71	0.0436	0.72	0.93
2	74.08	0.0611	0.87	1.05
3	69.45	0.0782	1.02	1.16
4	64.82	0.0948	1.16	1.27
5	64.82	0.1111	1.16	1.27
6	64.82	0.1274	1.16	1.27
7	64.82	0.1437	1.16	1.27
8	64.82	0.1600	1.16	1.27
9	64.82	0.1763	1.16	1.27
10	64.82	0.1926	1.16	1.27
11	64.82	0.2089	1.16	1.27
12	64.82	0.2252	1.16	1.27
13	64.82	0.2414	1.16	1.27
14	64.82	0.2577	1.16	1.27
15	64.82	0.2740	1.16	1.27
16	64.82	0.2903	1.16	1.27

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR 180 DEGREE	CUT SECTOR 90 DEGREE
TORQUE + S.D. (KNM)	0.97811 + 0.08824	0.49130 + 0.11077
SLEWING FORCE + S.D. (KN)	7.72564 + 0.16353	3.87660 + 0.39287
VOLUME SWEPT (CUBM)	0.0004541	0.0002270
SPECIFIC ENERGY (MJ/CUBM)	13.5345	13.5967

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 69.45 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 78.71 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	78.71	0.0436	0.72	0.93
2	74.08	0.0611	0.87	1.05
3	69.45	0.0782	1.02	1.16
4	69.45	0.0951	1.02	1.16
5	69.45	0.1120	1.02	1.16
6	69.45	0.1288	1.02	1.16
7	69.45	0.1457	1.02	1.16
8	69.45	0.1625	1.02	1.16
9	69.45	0.1794	1.02	1.16
10	69.45	0.1962	1.02	1.16
11	69.45	0.2131	1.02	1.16
12	69.45	0.2299	1.02	1.16
13	69.45	0.2468	1.02	1.16
14	69.45	0.2636	1.02	1.16
15	69.45	0.2805	1.02	1.16
16	69.45	0.2974	1.02	1.16

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	0.88052 + 0.07681	0.44228 + 0.09761
SLEWING FORCE + S.D. (KN)	7.07458 + 0.10897	3.55001 + 0.34578
VOLUME SWEPT (CUBM)	0.0003850	0.0001925
SPECIFIC ENERGY (MJ/CUBM)	14.3696	14.4355

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 74.08 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 78.71 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	78.71	0.0436	0.72	0.93
2	74.08	0.0611	0.87	1.05
3	74.08	0.0784	0.87	1.05
4	74.08	0.0958	0.87	1.05
5	74.08	0.1131	0.87	1.05
6	74.08	0.1304	0.87	1.05
7	74.08	0.1477	0.87	1.05
8	74.08	0.1650	0.87	1.05
9	74.08	0.1823	0.87	1.05
10	74.08	0.1996	0.87	1.05
11	74.08	0.2169	0.87	1.05
12	74.08	0.2342	0.87	1.05
13	74.08	0.2515	0.87	1.05
14	74.08	0.2689	0.87	1.05
15	74.08	0.2862	0.87	1.05
16	74.08	0.3035	0.87	1.05

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	0.77051 + 0.06681	0.38702 + 0.08435
SLEWING FORCE + S.D. (KN)	6.35187 + 0.08104	3.18755 + 0.30623
VOLUME SWEPT (CUBM)	0.0003078	0.0001539
SPECIFIC ENERGY (MJ/CUBM)	15.7290	15.8013

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 18.52 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 83.34 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	83.34	0.0259	0.57	0.81
2	78.71	0.0436	0.72	0.93
3	74.08	0.0611	0.87	1.05
4	69.45	0.0782	1.02	1.16
5	64.82	0.0948	1.16	1.27
6	60.19	0.1108	1.30	1.37
7	55.56	0.1261	1.43	1.48
8	50.93	0.1405	1.55	1.57
9	46.30	0.1540	1.67	1.65
10	41.67	0.1665	1.77	1.74
11	37.04	0.1779	1.87	1.82
12	32.41	0.1882	1.96	1.89
13	27.78	0.1972	2.04	1.95
14	23.15	0.2050	2.10	2.00
15	18.52	0.2114	2.16	2.04
16	18.52	0.2171	2.16	2.04

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.22308 + 0.12828	0.61437 + 0.16182
SLEWING FORCE + S.D. (KN)	10.06982 + 0.47206	5.05256 + 0.69943
VOLUME SWEPT (CUBM)	0.0006505	0.0003253
SPECIFIC ENERGY (MJ/CUBM)	11.8134	11.8680

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 23.15 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 83.34 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	83.34	0.0259	0.57	0.81
2	78.71	0.0436	0.72	0.93
3	74.08	0.0611	0.87	1.05
4	69.45	0.0782	1.02	1.16
5	64.82	0.0948	1.16	1.27
6	60.19	0.1108	1.30	1.37
7	55.56	0.1261	1.43	1.48
8	50.93	0.1405	1.55	1.57
9	46.30	0.1540	1.67	1.66
10	41.67	0.1665	1.77	1.74
11	37.04	0.1779	1.87	1.82
12	32.41	0.1882	1.96	1.89
13	27.78	0.1972	2.04	1.95
14	23.15	0.2050	2.10	2.00
15	23.15	0.2120	2.10	2.00
16	23.15	0.2191	2.10	2.00

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.21742 + 0.12710	0.61153 + 0.15980
SLEWING FORCE + S.D. (KN)	10.03116 + 0.46263	5.03316 + 0.68806
VOLUME SWEPT (CUBM)	0.0006472	0.0003236
SPECIFIC ENERGY (MJ/CUBM)	11.8198	11.8745

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 27.78 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 83.34 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	83.34	0.0259	0.57	0.81
2	78.71	0.0436	0.72	0.93
3	74.08	0.0611	0.87	1.05
4	69.45	0.0782	1.02	1.16
5	64.82	0.0948	1.16	1.27
6	60.19	0.1108	1.30	1.37
7	55.56	0.1261	1.43	1.48
8	50.93	0.1405	1.55	1.57
9	46.30	0.1540	1.67	1.66
10	41.67	0.1665	1.77	1.74
11	37.04	0.1779	1.87	1.82
12	32.41	0.1882	1.96	1.89
13	27.78	0.1972	2.04	1.95
14	27.78	0.2056	2.04	1.95
15	27.78	0.2140	2.04	1.95
16	27.78	0.2224	2.04	1.95

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.20784 + 0.12304	0.60671 + 0.15606
SLEWING FORCE + S.D. (KN)	9.96105 + 0.43702	4.99797 + 0.66602
VOLUME SWEPT (CUBM)	0.0006408	0.0003204
SPECIFIC ENERGY (MJ/CUBM)	11.8424	11.8971

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 32.41 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 83.34 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	83.34	0.0259	0.57	0.81
2	78.71	0.0436	0.72	0.93
3	74.08	0.0611	0.87	1.05
4	69.45	0.0782	1.02	1.16
5	64.82	0.0948	1.16	1.27
6	60.19	0.1108	1.30	1.37
7	55.56	0.1261	1.43	1.48
8	50.93	0.1405	1.55	1.57
9	46.30	0.1540	1.67	1.66
10	41.67	0.1665	1.77	1.74
11	37.04	0.1779	1.87	1.82
12	32.41	0.1882	1.96	1.89
13	32.41	0.1978	1.96	1.89
14	32.41	0.2075	1.96	1.89
15	32.41	0.2171	1.96	1.89
16	32.41	0.2268	1.96	1.89

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.19347 + 0.11887	0.59950 + 0.15135
SLEWING FORCE + S.D. (KN)	9.85203 + 0.40829	4.94329 + 0.63592
VOLUME SWEPT (CUBM)	0.0006309	0.0003155
SPECIFIC ENERGY (MJ/CUBM)	11.8854	11.9404

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 37.04 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 83.34 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	83.34	0.0259	0.57	0.81
2	78.71	0.0436	0.72	0.93
3	74.08	0.0611	0.87	1.05
4	69.45	0.0782	1.02	1.16
5	64.82	0.0948	1.16	1.27
6	60.19	0.1108	1.30	1.37
7	55.56	0.1261	1.43	1.48
8	50.93	0.1405	1.55	1.57
9	46.30	0.1540	1.67	1.66
10	41.67	0.1665	1.77	1.74
11	37.04	0.1779	1.87	1.82
12	37.04	0.1888	1.87	1.82
13	37.04	0.1996	1.87	1.82
14	37.04	0.2105	1.87	1.82
15	37.04	0.2213	1.87	1.82
16	37.04	0.2321	1.87	1.82

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.17339 + 0.11570	0.58940 + 0.14657
SLEWING FORCE + S.D. (KN)	9.69723 + 0.38142	4.86561 + 0.60305
VOLUME SWEPT (CUBM)	0.0006168	0.0003084
SPECIFIC ENERGY (MJ/CUBM)	11.9539	12.0091

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 41.65 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 83.34 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	83.34	0.0259	0.57	0.81
2	78.71	0.0436	0.72	0.93
3	74.08	0.0611	0.87	1.05
4	69.45	0.0782	1.02	1.16
5	64.82	0.0948	1.16	1.27
6	60.19	0.1108	1.30	1.37
7	55.56	0.1261	1.43	1.48
8	50.93	0.1405	1.55	1.57
9	46.30	0.1540	1.67	1.66
10	41.67	0.1665	1.77	1.74
11	41.65	0.1666	1.77	1.74
12	41.65	0.1785	1.77	1.74
13	41.65	0.1905	1.77	1.74
14	41.65	0.2024	1.77	1.74
15	41.65	0.2144	1.77	1.74
16	41.65	0.2264	1.77	1.74

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.10631 + 0.10427	0.55572 + 0.13498
SLEWING FORCE + S.D. (KN)	9.49137 + 0.34323	4.76237 + 0.57262
VOLUME SWEPT (CUBM)	0.0005977	0.0002989
SPECIFIC ENERGY (MJ/CUBM)	11.6295	11.6834

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 46.30 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 83.34 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	83.34	0.0259	0.57	0.81
2	78.71	0.0436	0.72	0.93
3	74.08	0.0611	0.87	1.05
4	69.45	0.0782	1.02	1.16
5	64.82	0.0948	1.16	1.27
6	60.19	0.1108	1.30	1.37
7	55.56	0.1261	1.43	1.48
8	50.93	0.1405	1.55	1.57
9	46.30	0.1540	1.67	1.66
10	46.30	0.1670	1.67	1.66
11	46.30	0.1800	1.67	1.66
12	46.30	0.1930	1.67	1.66
13	46.30	0.2061	1.67	1.66
14	46.30	0.2191	1.67	1.66
15	46.30	0.2321	1.67	1.66
16	46.30	0.2451	1.67	1.66

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.11190 + 0.11155	0.55852 + 0.13940
SLEWING FORCE + S.D. (KN)	9.22622 + 0.33511	4.62933 + 0.55363
VOLUME SWEPT (CUBM)	0.0005728	0.0002864
SPECIFIC ENERGY (MJ/CUBM)	12.1965	12.2528

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 50.93 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 83.34 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	83.34	0.0259	0.57	0.81
2	78.71	0.0436	0.72	0.93
3	74.08	0.0611	0.87	1.05
4	69.45	0.0782	1.02	1.16
5	64.82	0.0948	1.16	1.27
6	60.19	0.1108	1.30	1.37
7	55.56	0.1261	1.43	1.48
8	50.93	0.1405	1.55	1.57
9	50.93	0.1545	1.55	1.57
10	50.93	0.1684	1.55	1.57
11	50.93	0.1824	1.55	1.57
12	50.93	0.1964	1.55	1.57
13	50.93	0.2104	1.55	1.57
14	50.93	0.2243	1.55	1.57
15	50.93	0.2383	1.55	1.57
16	50.93	0.2523	1.55	1.57

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.06836 + 0.10742	0.53665 + 0.13478
SLEWING FORCE + S.D. (KN)	8.89998 + 0.30180	4.46571 + 0.52930
VOLUME SWEPT (CUBM)	0.0005416	0.0002708
SPECIFIC ENERGY (MJ/CUBM)	12.3934	12.4507

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 55.56 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 83.34 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	83.34	0.0259	0.57	0.81
2	78.71	0.0436	0.72	0.93
3	74.08	0.0611	0.87	1.05
4	69.45	0.0782	1.02	1.16
5	64.82	0.0948	1.16	1.27
6	60.19	0.1108	1.30	1.37
7	55.56	0.1261	1.43	1.48
8	55.56	0.1409	1.43	1.48
9	55.56	0.1557	1.43	1.48
10	55.56	0.1706	1.43	1.48
11	55.56	0.1854	1.43	1.48
12	55.56	0.2003	1.43	1.48
13	55.56	0.2151	1.43	1.48
14	55.56	0.2300	1.43	1.48
15	55.56	0.2448	1.43	1.48
16	55.56	0.2597	1.43	1.48

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.01494 + 0.10529	0.50981 + 0.12948
SLEWING FORCE + S.D. (KN)	8.50806 + 0.29374	4.26909 + 0.50688
VOLUME SWEPT (CUBM)	0.0005035	0.0002517
SPECIFIC ENERGY (MJ/CUBM)	12.6658	12.7243

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 60.19 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 83.34 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	83.34	0.0259	0.57	0.81
2	78.71	0.0436	0.72	0.93
3	74.08	0.0611	0.87	1.05
4	69.45	0.0782	1.02	1.16
5	64.82	0.0948	1.16	1.27
6	60.19	0.1108	1.30	1.37
7	60.19	0.1264	1.30	1.37
8	60.19	0.1420	1.30	1.37
9	60.19	0.1577	1.30	1.37
10	60.19	0.1733	1.30	1.37
11	60.19	0.1889	1.30	1.37
12	60.19	0.2045	1.30	1.37
13	60.19	0.2201	1.30	1.37
14	60.19	0.2358	1.30	1.37
15	60.19	0.2514	1.30	1.37
16	60.19	0.2670	1.30	1.37

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	0.95083 + 0.09744	0.47761 + 0.12059
SLEWING FORCE + S.D. (KN)	8.04776 + 0.24957	4.03823 + 0.46780
VOLUME SWEPT (CUBM)	0.0004579	0.0002289
SPECIFIC ENERGY (MJ/CUBM)	13.0474	13.1077

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 64.82 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 83.34 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	83.34	0.0259	0.57	0.81
2	78.71	0.0436	0.72	0.93
3	74.08	0.0611	0.87	1.05
4	69.45	0.0782	1.02	1.16
5	64.82	0.0948	1.16	1.27
6	64.82	0.1111	1.16	1.27
7	64.82	0.1274	1.16	1.27
8	64.82	0.1437	1.16	1.27
9	64.82	0.1600	1.16	1.27
10	64.82	0.1763	1.16	1.27
11	64.82	0.1926	1.16	1.27
12	64.82	0.2089	1.16	1.27
13	64.82	0.2252	1.16	1.27
14	64.82	0.2414	1.16	1.27
15	64.82	0.2577	1.16	1.27
16	64.82	0.2740	1.16	1.27

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	0.87547 + 0.08899	0.43975 + 0.10941
SLEWING FORCE + S.D. (KN)	7.51742 + 0.21214	3.77218 + 0.41919
VOLUME SWEPT (CUBM)	0.0004046	0.0002023
SPECIFIC ENERGY (MJ/CUBM)	13.5963	13.6590

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 69.45 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 83.34 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	83.34	0.0259	0.57	0.81
2	78.71	0.0436	0.72	0.93
3	74.08	0.0611	0.87	1.05
4	69.45	0.0782	1.02	1.16
5	69.45	0.0951	1.02	1.16
6	69.45	0.1120	1.02	1.16
7	69.45	0.1288	1.02	1.16
8	69.45	0.1457	1.02	1.16
9	69.45	0.1625	1.02	1.16
10	69.45	0.1794	1.02	1.16
11	69.45	0.1962	1.02	1.16
12	69.45	0.2131	1.02	1.16
13	69.45	0.2299	1.02	1.16
14	69.45	0.2468	1.02	1.16
15	69.45	0.2636	1.02	1.16
16	69.45	0.2805	1.02	1.16

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	0.78870 + 0.07836	0.39617 + 0.09650
SLEWING FORCE + S.D. (KN)	6.91645 + 0.16360	3.47078 + 0.36561
VOLUME SWEPT (CUBM)	0.0003436	0.0001718
SPECIFIC ENERGY (MJ/CUBM)	14.4238	14.4905

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 74.08 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 83.34 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	83.34	0.0259	0.57	0.81
2	78.71	0.0436	0.72	0.93
3	74.08	0.0611	0.87	1.05
4	74.08	0.0784	0.87	1.05
5	74.08	0.0958	0.87	1.05
6	74.08	0.1131	0.87	1.05
7	74.08	0.1304	0.87	1.05
8	74.08	0.1477	0.87	1.05
9	74.08	0.1650	0.87	1.05
10	74.08	0.1823	0.87	1.05
11	74.08	0.1996	0.87	1.05
12	74.08	0.2169	0.87	1.05
13	74.08	0.2342	0.87	1.05
14	74.08	0.2515	0.87	1.05
15	74.08	0.2689	0.87	1.05
16	74.08	0.2862	0.87	1.05

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	0.69082 + 0.06661	0.34700 + 0.08285
SLEWING FORCE + S.D. (KN)	6.24536 + 0.10601	3.13413 + 0.31488
VOLUME SWEPT (CUBM)	0.0002752	0.0001376
SPECIFIC ENERGY (MJ/CUBM)	15.7708	15.8435

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 78.71 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 83.34 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	83.34	0.0259	0.57	0.81
2	78.71	0.0436	0.72	0.93
3	78.71	0.0613	0.72	0.93
4	78.71	0.0789	0.72	0.93
5	78.71	0.0966	0.72	0.93
6	78.71	0.1142	0.72	0.93
7	78.71	0.1319	0.72	0.93
8	78.71	0.1495	0.72	0.93
9	78.71	0.1672	0.72	0.93
10	78.71	0.1849	0.72	0.93
11	78.71	0.2025	0.72	0.93
12	78.71	0.2202	0.72	0.93
13	78.71	0.2378	0.72	0.93
14	78.71	0.2555	0.72	0.93
15	78.71	0.2731	0.72	0.93
16	78.71	0.2908	0.72	0.93

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	0.58273 + 0.05598	0.29271 + 0.06911
SLEWING FORCE + S.D. (KN)	5.50578 + 0.07651	2.76321 + 0.27312
VOLUME SWEPT (CUBM)	0.0002004	0.0001002
SPECIFIC ENERGY (MJ/CUBM)	18.2749	18.3593

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 23.15 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 87.97 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	87.97	0.0079	0.42	0.69
2	83.34	0.0259	0.57	0.81
3	78.71	0.0436	0.72	0.93
4	74.08	0.0611	0.87	1.05
5	69.45	0.0782	1.02	1.16
6	64.82	0.0948	1.16	1.27
7	60.19	0.1108	1.30	1.37
8	55.56	0.1261	1.43	1.48
9	50.93	0.1405	1.55	1.57
10	46.30	0.1540	1.67	1.66
11	41.67	0.1665	1.77	1.74
12	37.04	0.1779	1.87	1.82
13	32.41	0.1882	1.96	1.89
14	27.78	0.1972	2.04	1.95
15	23.15	0.2050	2.10	2.00
16	23.15	0.2120	2.10	2.00

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.07182 + 0.12519	0.53841 + 0.15552
SLEWING FORCE + S.D. (KN)	9.43638 + 0.49882	4.73489 + 0.71040
VOLUME SWEPT (CUBM)	0.0005621	0.0002811
SPECIFIC ENERGY (MJ/CUBM)	11.9808	12.0365

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 27.78 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 87.97 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	87.97	0.0079	0.42	0.69
2	83.34	0.0259	0.57	0.81
3	78.71	0.0436	0.72	0.93
4	74.08	0.0611	0.87	1.05
5	69.45	0.0782	1.02	1.16
6	64.82	0.0948	1.16	1.27
7	60.19	0.1108	1.30	1.37
8	55.56	0.1261	1.43	1.48
9	50.93	0.1405	1.55	1.57
10	46.30	0.1540	1.67	1.66
11	41.67	0.1665	1.77	1.74
12	37.04	0.1779	1.87	1.82
13	32.41	0.1882	1.96	1.89
14	27.78	0.1972	2.04	1.95
15	27.78	0.2056	2.04	1.95
16	27.78	0.2140	2.04	1.95

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.06473 + 0.12350	0.53485 + 0.15286
SLEWING FORCE + S.D. (KN)	9.38964 + 0.48731	4.71145 + 0.69604
VOLUME SWEPT (CUBM)	0.0005580	0.0002790
SPECIFIC ENERGY (MJ/CUBM)	11.9886	12.0445

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 32.41 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 87.97 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	87.97	0.0079	0.42	0.69
2	83.34	0.0259	0.57	0.81
3	78.71	0.0436	0.72	0.93
4	74.08	0.0611	0.87	1.05
5	69.45	0.0782	1.02	1.16
6	64.82	0.0948	1.16	1.27
7	60.19	0.1108	1.30	1.37
8	55.56	0.1261	1.43	1.48
9	50.93	0.1405	1.55	1.57
10	46.30	0.1540	1.67	1.66
11	41.67	0.1665	1.77	1.74
12	37.04	0.1779	1.87	1.82
13	32.41	0.1882	1.96	1.89
14	32.41	0.1978	1.96	1.89
15	32.41	0.2075	1.96	1.89
16	32.41	0.2171	1.96	1.89

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.05309 + 0.11851	0.52899 + 0.14821
SLEWING FORCE + S.D. (KN)	9.30788 + 0.45729	4.67041 + 0.66925
VOLUME SWEPT (CUBM)	0.0005506	0.0002753
SPECIFIC ENERGY (MJ/CUBM)	12.0183	12.0742

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 37.04 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 87.97 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	87.97	0.0079	0.42	0.69
2	83.34	0.0259	0.57	0.81
3	78.71	0.0436	0.72	0.93
4	74.08	0.0611	0.87	1.05
5	69.45	0.0782	1.02	1.16
6	64.82	0.0948	1.16	1.27
7	60.19	0.1108	1.30	1.37
8	55.56	0.1261	1.43	1.48
9	50.93	0.1405	1.55	1.57
10	46.30	0.1540	1.67	1.66
11	41.67	0.1665	1.77	1.74
12	37.04	0.1779	1.87	1.82
13	37.04	0.1888	1.87	1.82
14	37.04	0.1996	1.87	1.82
15	37.04	0.2105	1.87	1.82
16	37.04	0.2213	1.87	1.82

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	1.03614 + 0.11340	0.52048 + 0.14249
SLEWING FORCE + S.D. (KN)	9.18404 + 0.42450	4.60830 + 0.63370
VOLUME SWEPT (CUBM)	0.0005392	0.0002696
SPECIFIC ENERGY (MJ/CUBM)	12.0749	12.1311

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 41.65 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 87.97 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	87.97	0.0079	0.42	0.69
2	83.34	0.0259	0.57	0.81
3	78.71	0.0436	0.72	0.93
4	74.08	0.0611	0.87	1.05
5	69.45	0.0782	1.02	1.16
6	64.82	0.0948	1.16	1.27
7	60.19	0.1108	1.30	1.37
8	55.56	0.1261	1.43	1.48
9	50.93	0.1405	1.55	1.57
10	46.30	0.1540	1.67	1.66
11	41.67	0.1665	1.77	1.74
12	41.65	0.1666	1.77	1.74
13	41.65	0.1785	1.77	1.74
14	41.65	0.1905	1.77	1.74
15	41.65	0.2024	1.77	1.74
16	41.65	0.2144	1.77	1.74

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	0.97950 + 0.10287	0.49201 + 0.12806
SLEWING FORCE + S.D. (KN)	9.01249 + 0.39461	4.52221 + 0.59588
VOLUME SWEPT (CUBM)	0.0005233	0.0002617
SPECIFIC ENERGY (MJ/CUBM)	11.7605	11.8148

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 46.30 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 87.97 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	87.97	0.0079	0.42	0.69
2	83.34	0.0259	0.57	0.81
3	78.71	0.0436	0.72	0.93
4	74.08	0.0611	0.87	1.05
5	69.45	0.0782	1.02	1.16
6	64.82	0.0948	1.16	1.27
7	60.19	0.1108	1.30	1.37
8	55.56	0.1261	1.43	1.48
9	50.93	0.1405	1.55	1.57
10	46.30	0.1540	1.67	1.66
11	46.30	0.1670	1.67	1.66
12	46.30	0.1800	1.67	1.66
13	46.30	0.1930	1.67	1.66
14	46.30	0.2061	1.67	1.66
15	46.30	0.2191	1.67	1.66
16	46.30	0.2321	1.67	1.66

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	0.98288 + 0.10418	0.49373 + 0.13140
SLEWING FORCE + S.D. (KN)	8.78523 + 0.35228	4.40823 + 0.56112
VOLUME SWEPT (CUBM)	0.0005022	0.0002511
SPECIFIC ENERGY (MJ/CUBM)	12.2977	12.3549

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 50.93 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 87.97 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	87.97	0.0079	0.42	0.69
2	83.34	0.0259	0.57	0.81
3	78.71	0.0436	0.72	0.93
4	74.08	0.0611	0.87	1.05
5	69.45	0.0782	1.02	1.16
6	64.82	0.0948	1.16	1.27
7	60.19	0.1108	1.30	1.37
8	55.56	0.1261	1.43	1.48
9	50.93	0.1405	1.55	1.57
10	50.93	0.1545	1.55	1.57
11	50.93	0.1684	1.55	1.57
12	50.93	0.1824	1.55	1.57
13	50.93	0.1964	1.55	1.57
14	50.93	0.2104	1.55	1.57
15	50.93	0.2243	1.55	1.57
16	50.93	0.2383	1.55	1.57

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	0.94480 + 0.10339	0.47459 + 0.12761
SLEWING FORCE + S.D. (KN)	8.49978 + 0.34379	4.26501 + 0.54046
VOLUME SWEPT (CUBM)	0.0004754	0.0002377
SPECIFIC ENERGY (MJ/CUBM)	12.4864	12.5443

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 55.56 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 87.97 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	87.97	0.0079	0.42	0.69
2	83.34	0.0259	0.57	0.81
3	78.71	0.0436	0.72	0.93
4	74.08	0.0611	0.87	1.05
5	69.45	0.0782	1.02	1.16
6	64.82	0.0948	1.16	1.27
7	60.19	0.1108	1.30	1.37
8	55.56	0.1261	1.43	1.48
9	55.56	0.1409	1.43	1.48
10	55.56	0.1557	1.43	1.48
11	55.56	0.1706	1.43	1.48
12	55.56	0.1854	1.43	1.48
13	55.56	0.2003	1.43	1.48
14	55.56	0.2151	1.43	1.48
15	55.56	0.2300	1.43	1.48
16	55.56	0.2448	1.43	1.48

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	0.89792 + 0.09839	0.45105 + 0.12204
SLEWING FORCE + S.D. (KN)	8.15140 + 0.30805	4.09029 + 0.51401
VOLUME SWEPT (CUBM)	0.0004424	0.0002212
SPECIFIC ENERGY (MJ/CUBM)	12.7517	12.8110

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 60.19 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 87.97 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	87.97	0.0079	0.42	0.69
2	83.34	0.0259	0.57	0.81
3	78.71	0.0436	0.72	0.93
4	74.08	0.0611	0.87	1.05
5	69.45	0.0782	1.02	1.16
6	64.82	0.0948	1.16	1.27
7	60.19	0.1108	1.30	1.37
8	60.19	0.1264	1.30	1.37
9	60.19	0.1420	1.30	1.37
10	60.19	0.1577	1.30	1.37
11	60.19	0.1733	1.30	1.37
12	60.19	0.1889	1.30	1.37
13	60.19	0.2045	1.30	1.37
14	60.19	0.2201	1.30	1.37
15	60.19	0.2358	1.30	1.37
16	60.19	0.2514	1.30	1.37

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	0.84156 + 0.09527	0.42273 + 0.11577
SLEWING FORCE + S.D. (KN)	7.73714 + 0.29951	3.88245 + 0.49007
VOLUME SWEPT (CUBM)	0.0004028	0.0002014
SPECIFIC ENERGY (MJ/CUBM)	13.1271	13.1879

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 64.82 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 87.97 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	87.97	0.0079	0.42	0.69
2	83.34	0.0259	0.57	0.81
3	78.71	0.0436	0.72	0.93
4	74.08	0.0611	0.87	1.05
5	69.45	0.0782	1.02	1.16
6	64.82	0.0948	1.16	1.27
7	64.82	0.1111	1.16	1.27
8	64.82	0.1274	1.16	1.27
9	64.82	0.1437	1.16	1.27
10	64.82	0.1600	1.16	1.27
11	64.82	0.1763	1.16	1.27
12	64.82	0.1926	1.16	1.27
13	64.82	0.2089	1.16	1.27
14	64.82	0.2252	1.16	1.27
15	64.82	0.2414	1.16	1.27
16	64.82	0.2577	1.16	1.27

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	0.77520 + 0.08681	0.38940 + 0.10614
SLEWING FORCE + S.D. (KN)	7.25501 + 0.25292	3.64065 + 0.44795
VOLUME SWEPT (CUBM)	0.0003563	0.0001781
SPECIFIC ENERGY (MJ/CUBM)	13.6708	13.7343

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 69.45 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 87.97 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	87.97	0.0079	0.42	0.69
2	83.34	0.0259	0.57	0.81
3	78.71	0.0436	0.72	0.93
4	74.08	0.0611	0.87	1.05
5	69.45	0.0782	1.02	1.16
6	69.45	0.0951	1.02	1.16
7	69.45	0.1120	1.02	1.16
8	69.45	0.1288	1.02	1.16
9	69.45	0.1457	1.02	1.16
10	69.45	0.1625	1.02	1.16
11	69.45	0.1794	1.02	1.16
12	69.45	0.1962	1.02	1.16
13	69.45	0.2131	1.02	1.16
14	69.45	0.2299	1.02	1.16
15	69.45	0.2468	1.02	1.16
16	69.45	0.2636	1.02	1.16

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	0.69870 + 0.07782	0.35097 + 0.09445
SLEWING FORCE + S.D. (KN)	6.70412 + 0.21373	3.36429 + 0.39561
VOLUME SWEPT (CUBM)	0.0003029	0.0001514
SPECIFIC ENERGY (MJ/CUBM)	14.4938	14.5610

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 74.08 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 87.97 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	87.97	0.0079	0.42	0.69
2	83.34	0.0259	0.57	0.81
3	78.71	0.0436	0.72	0.93
4	74.08	0.0611	0.87	1.05
5	74.08	0.0784	0.87	1.05
6	74.08	0.0958	0.87	1.05
7	74.08	0.1131	0.87	1.05
8	74.08	0.1304	0.87	1.05
9	74.08	0.1477	0.87	1.05
10	74.08	0.1650	0.87	1.05
11	74.08	0.1823	0.87	1.05
12	74.08	0.1996	0.87	1.05
13	74.08	0.2169	0.87	1.05
14	74.08	0.2342	0.87	1.05
15	74.08	0.2515	0.87	1.05
16	74.08	0.2689	0.87	1.05

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR 180 DEGREE	CUT SECTOR 90 DEGREE
TORQUE + S.D. (KNM)	0.61230 + 0.06697	0.30757 + 0.08128
SLEWING FORCE + S.D. (KN)	6.08465 + 0.16317	3.05361 + 0.33796
VOLUME SWEPT (CUBM)	0.0002429	0.0001215
SPECIFIC ENERGY (MJ/CUBM)	15.8365	15.9101

DETAILS OF THE CUTTING HEADS INVESTIGATED

HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 78.71 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 87.97 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	87.97	0.0079	0.42	0.69
2	83.34	0.0259	0.57	0.81
3	78.71	0.0436	0.72	0.93
4	78.71	0.0613	0.72	0.93
5	78.71	0.0789	0.72	0.93
6	78.71	0.0966	0.72	0.93
7	78.71	0.1142	0.72	0.93
8	78.71	0.1319	0.72	0.93
9	78.71	0.1495	0.72	0.93
10	78.71	0.1672	0.72	0.93
11	78.71	0.1849	0.72	0.93
12	78.71	0.2025	0.72	0.93
13	78.71	0.2202	0.72	0.93
14	78.71	0.2378	0.72	0.93
15	78.71	0.2555	0.72	0.93
16	78.71	0.2731	0.72	0.93

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	0.51677 + 0.05521	0.25958 + 0.06751
SLEWING FORCE + S.D. (KN)	5.39790 + 0.10309	2.70911 + 0.28359
VOLUME SWEPT (CUBM)	0.0001771	0.0000885
SPECIFIC ENERGY (MJ/CUBM)	18.3344	18.4193

DETAILS OF THE CUTTING HEADS INVESTIGATED

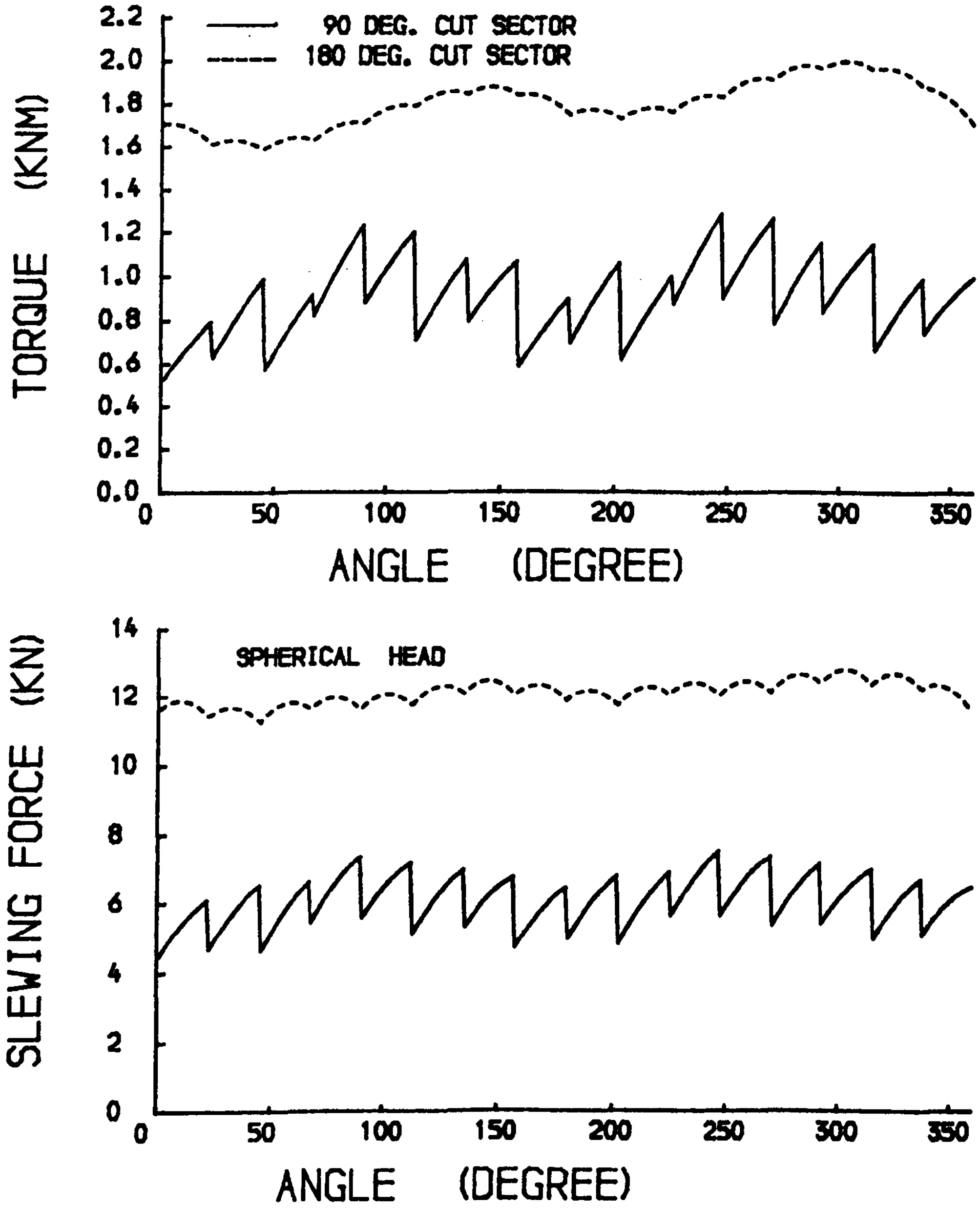
HEAD GEOMETRY : COMBINED
HEAD CONE ANGLE : 83.34 DEGREE
TILT ANGLE OF THE CORNER CUTTING TOOL : 87.97 DEGREE

CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING TOOL

TOOL NO.	TILT ANGLE (DEGREE)	CUTTING RADIUS (M)	MCF (KN)	MNF (KN)
1	87.97	0.0079	0.42	0.69
2	83.34	0.0259	0.57	0.81
3	83.34	0.0437	0.57	0.81
4	83.34	0.0616	0.57	0.81
5	83.34	0.0795	0.57	0.81
6	83.34	0.0974	0.57	0.81
7	83.34	0.1152	0.57	0.81
8	83.34	0.1331	0.57	0.81
9	83.34	0.1510	0.57	0.81
10	83.34	0.1689	0.57	0.81
11	83.34	0.1868	0.57	0.81
12	83.34	0.2046	0.57	0.81
13	83.34	0.2225	0.57	0.81
14	83.34	0.2404	0.57	0.81
15	83.34	0.2583	0.57	0.81
16	83.34	0.2762	0.57	0.81

CALCULATED PARAMETERS (ADV. / REV.)	CUT SECTOR	
	180 DEGREE	90 DEGREE
TORQUE + S.D. (KNM)	0.41347 + 0.04422	0.20770 + 0.05363
SLEWING FORCE + S.D. (KN)	4.64629 + 0.07239	2.33216 + 0.23963
VOLUME SWEPT (CUBM)	0.0001065	0.0000533
SPECIFIC ENERGY (MJ/CUBM)	24.3909	24.5042

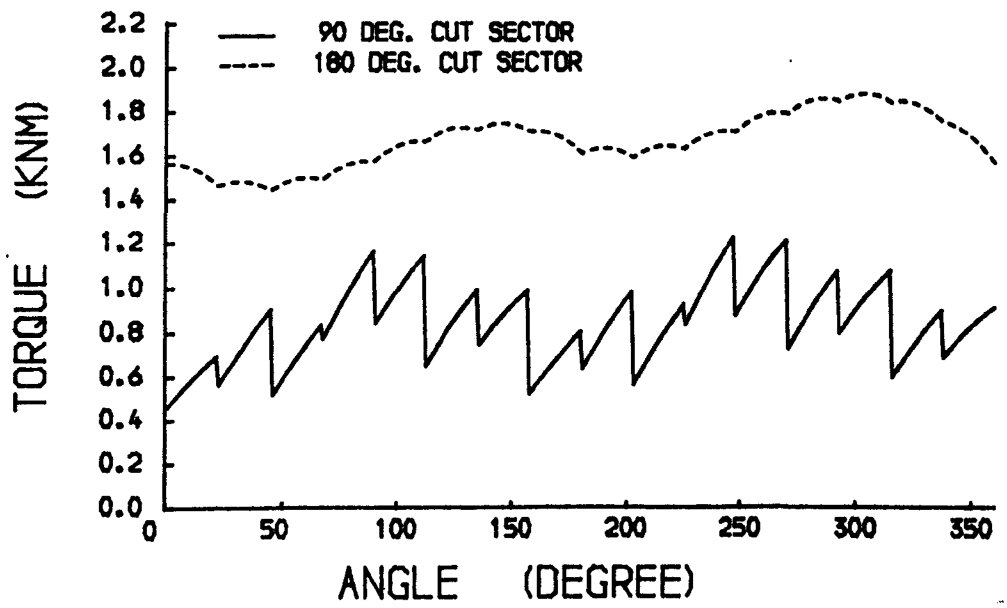
APPENDIX 6B1

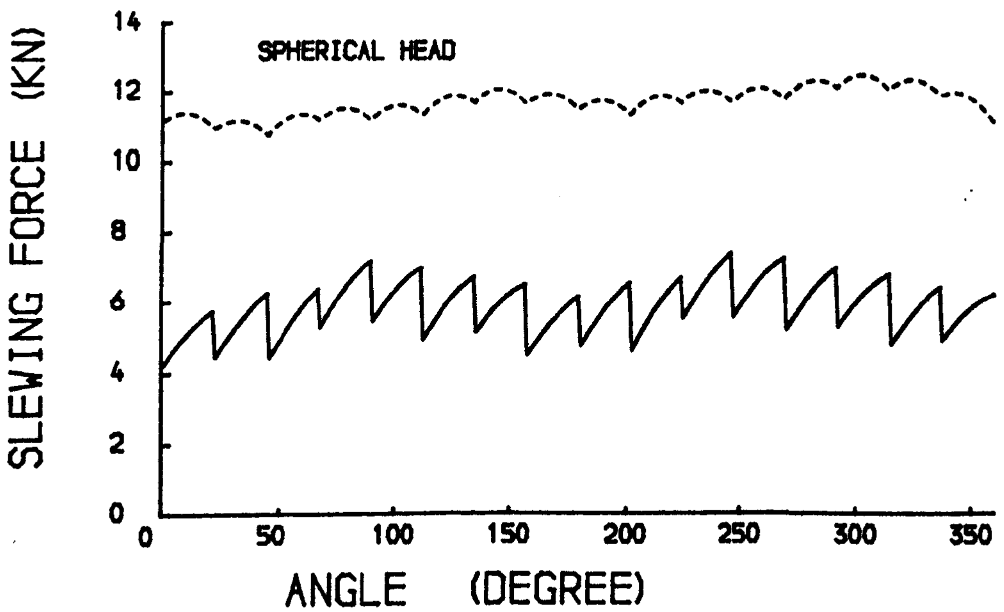


FLUCTUATIONS IN TORQUE AND SLEWING FORCE,

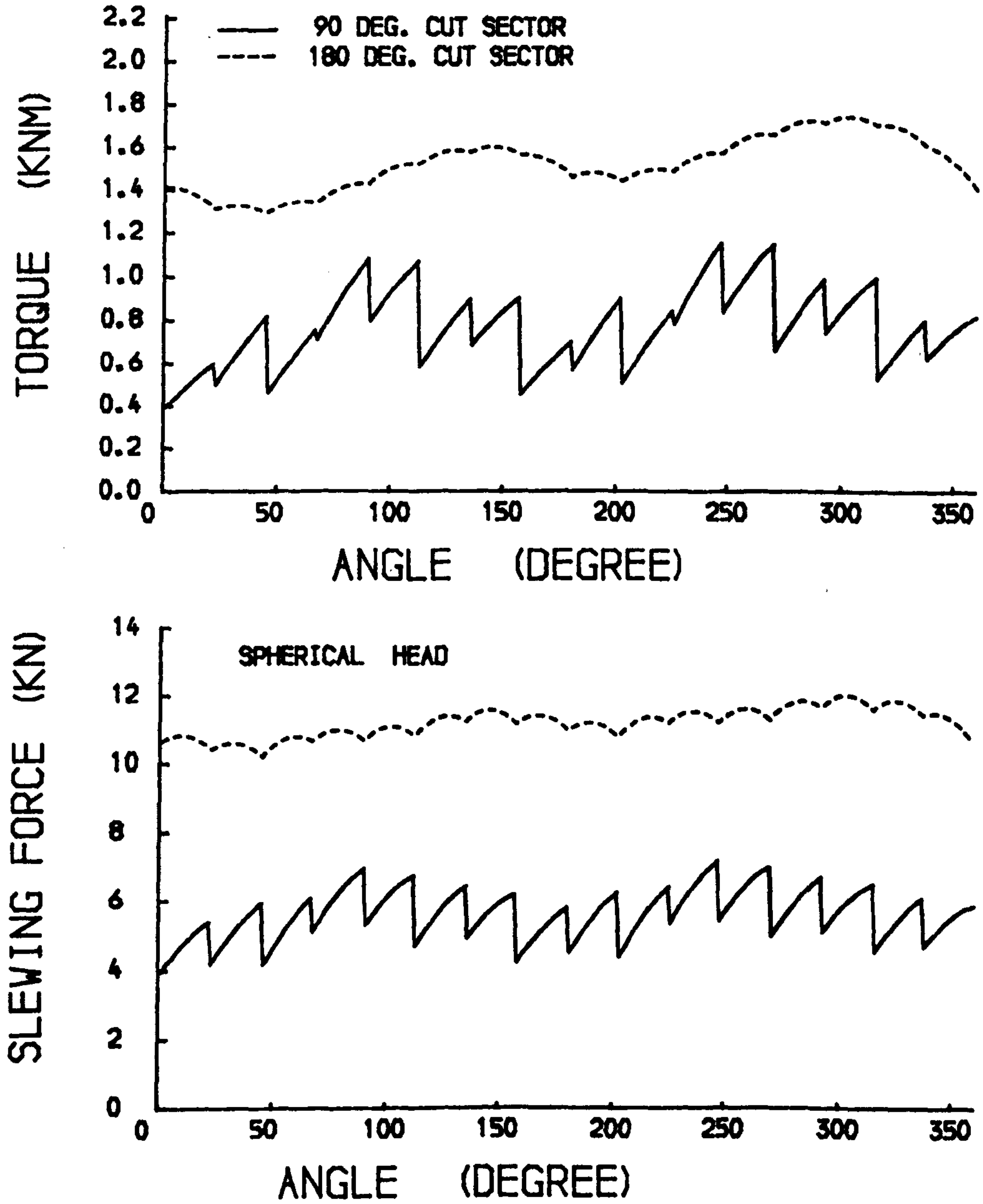
TILT ANGLE OF THE CORNER CUT. TOOL: 64.82 DEG.

TILT ANGLE OF THE FIRST AND SECOND TOOL: 0.0 DEG.

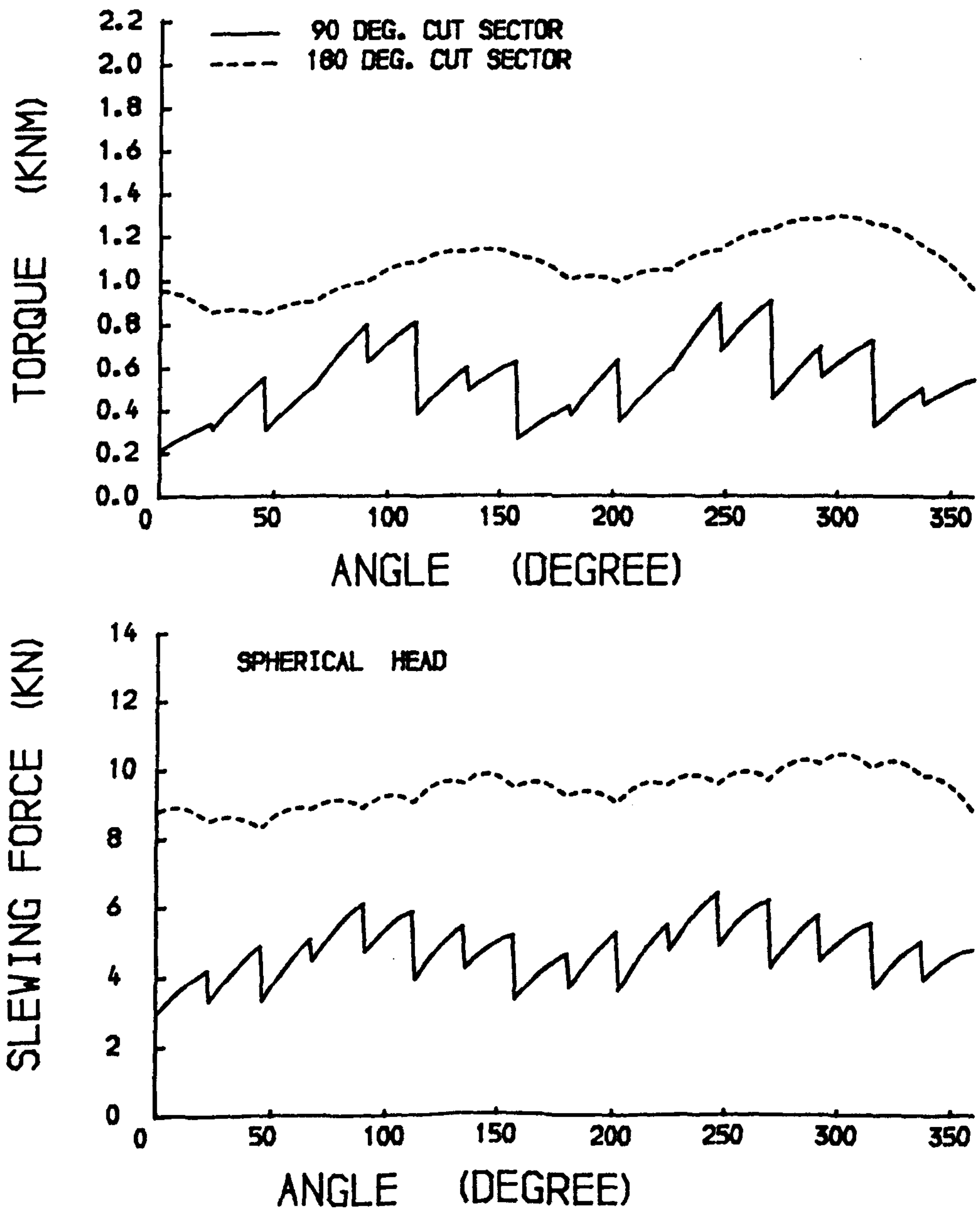




FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 69.45 DEG.
TILT ANGLE OF THE FIRST TOOL : 00.00 DEG.

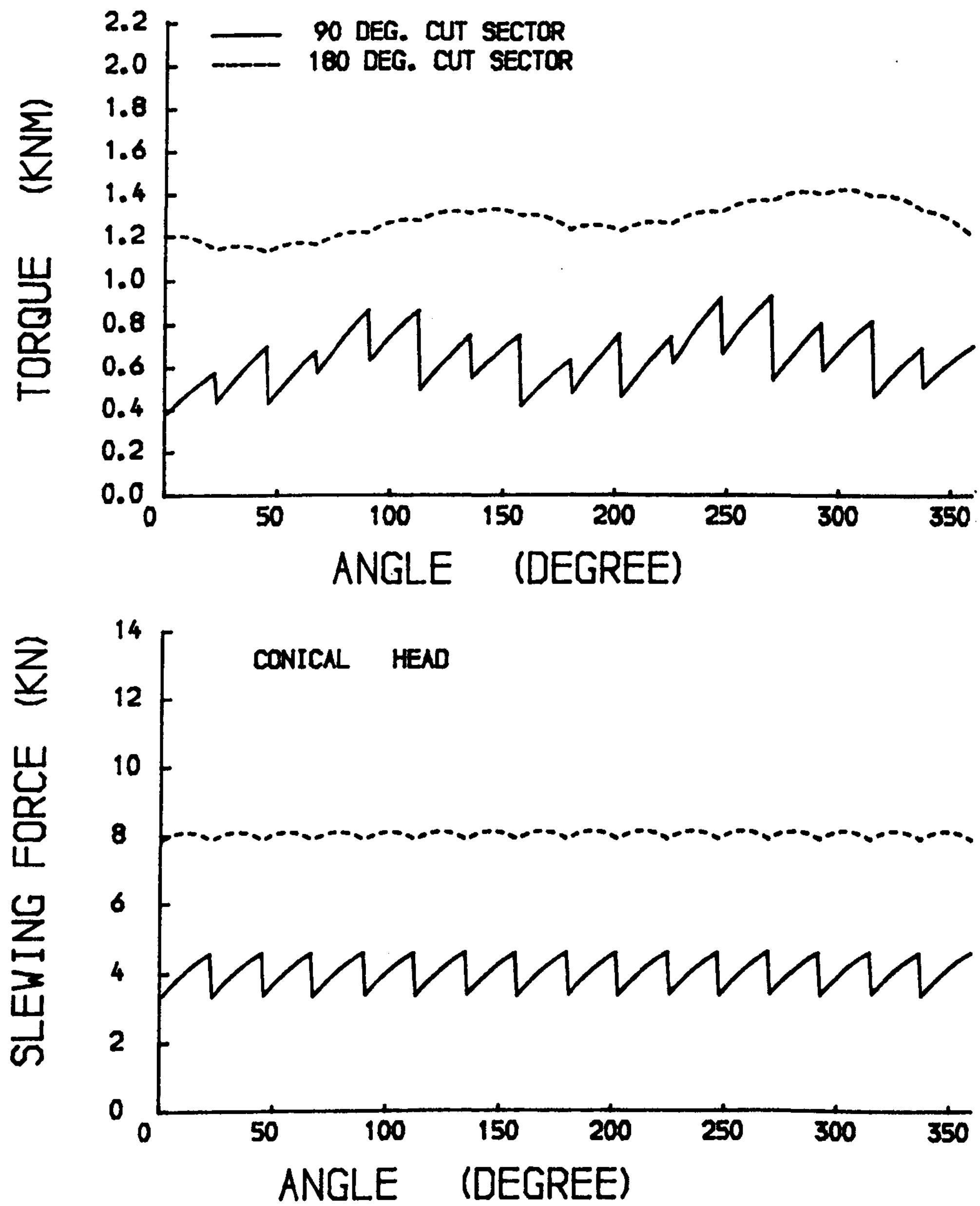


FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 74.08 DEG.
TILT ANGLE OF THE FIRST TOOL : 04.63 DEG.

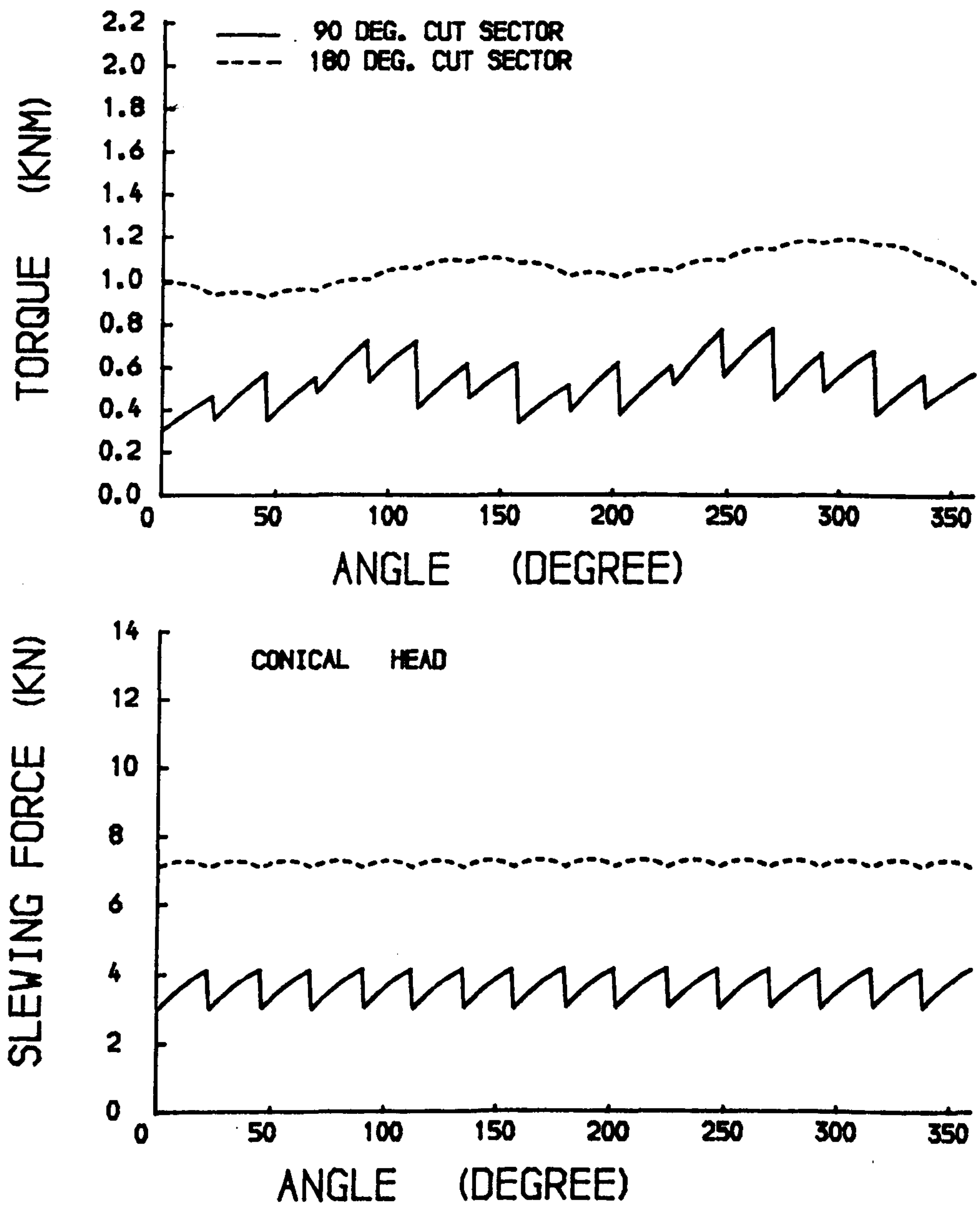


FLUCTUATIONS IN TORQUE AND SLEVING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 87.97 DEG.
TILT ANGLE OF THE FIRST TOOL : 18.52 DEG.

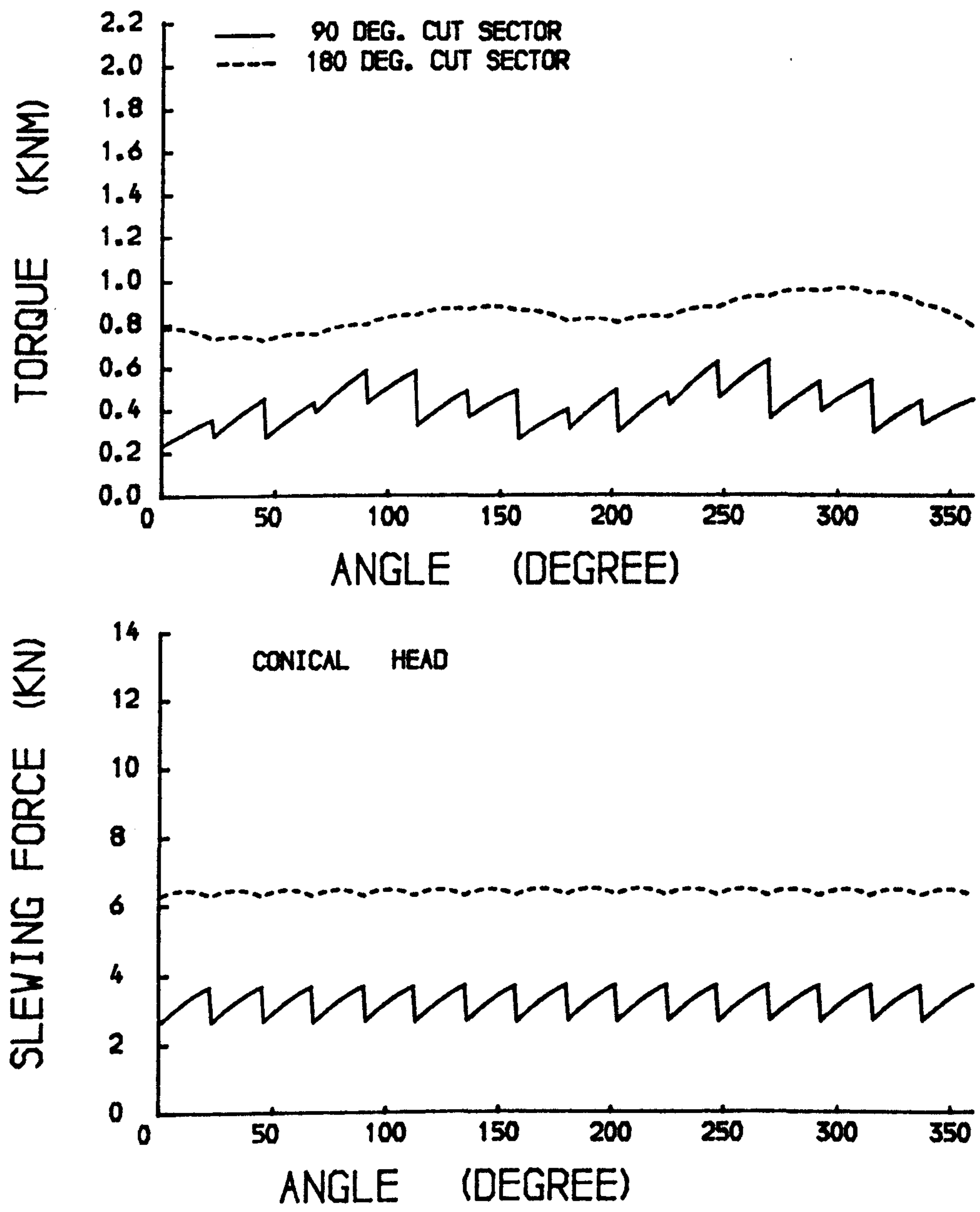
APPENDIX 6B2



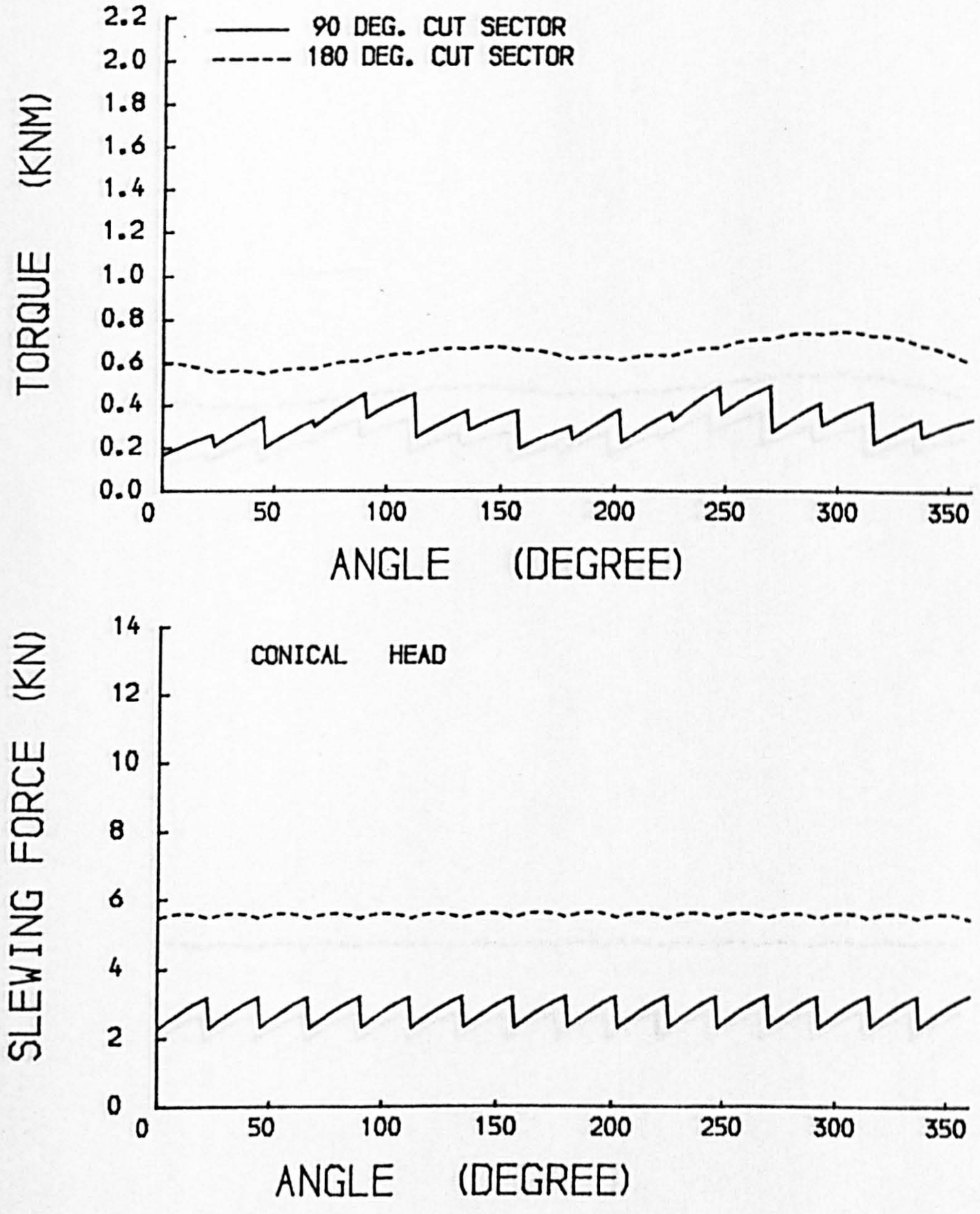
FLUCTUATIONS IN TORQUE AND SLEVING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 64.82 DEG.
CONE ANGLE OF THE CUT. HEAD : 64.82 DEG.



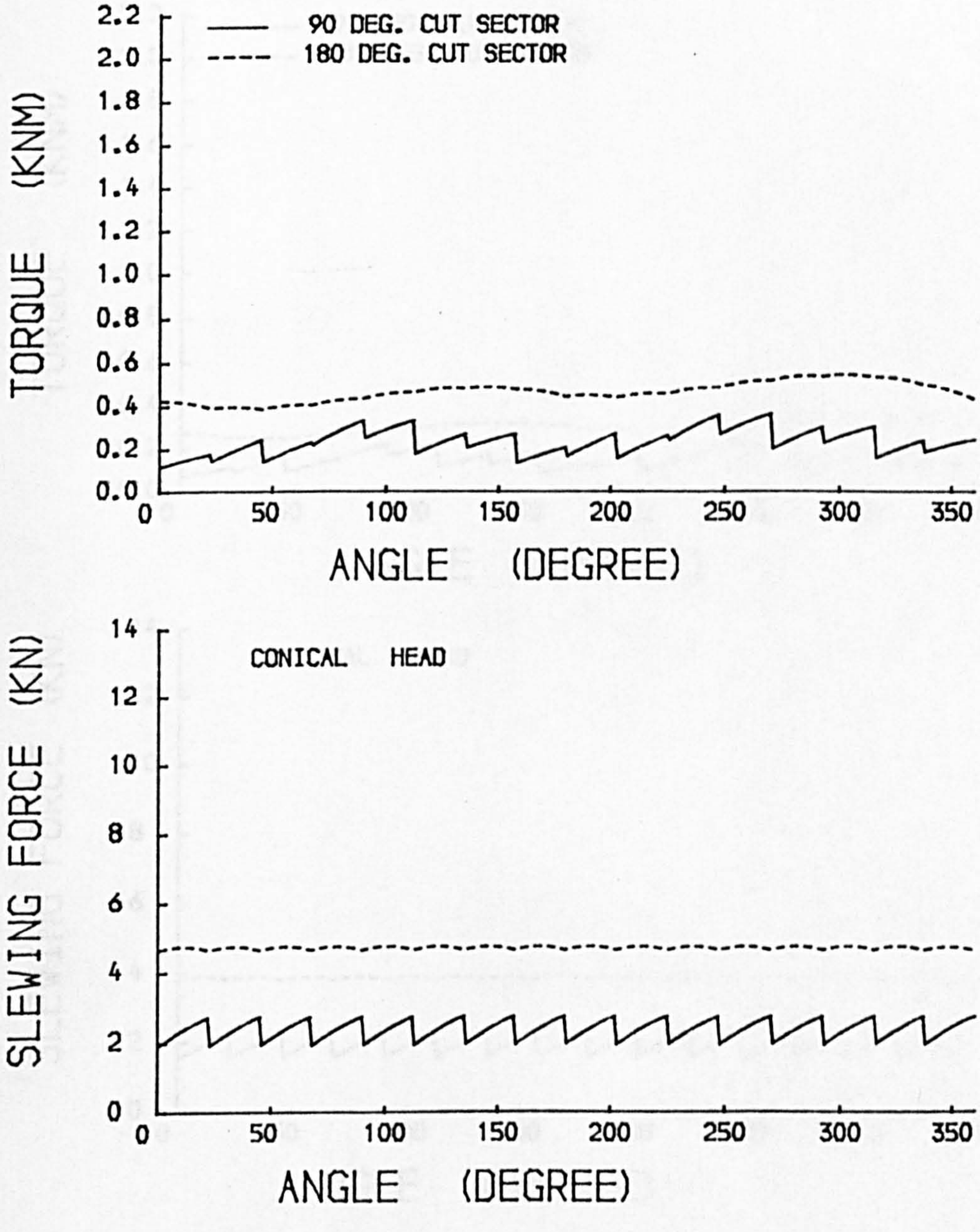
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 69.45 DEG.
CONE ANGLE OF THE CUT. HEAD : 69.45 DEG.



FLUCTUATIONS IN TORQUE AND SLEVING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 74.08 DEG.
CONE ANGLE OF THE CUT. HEAD : 74.08 DEG.



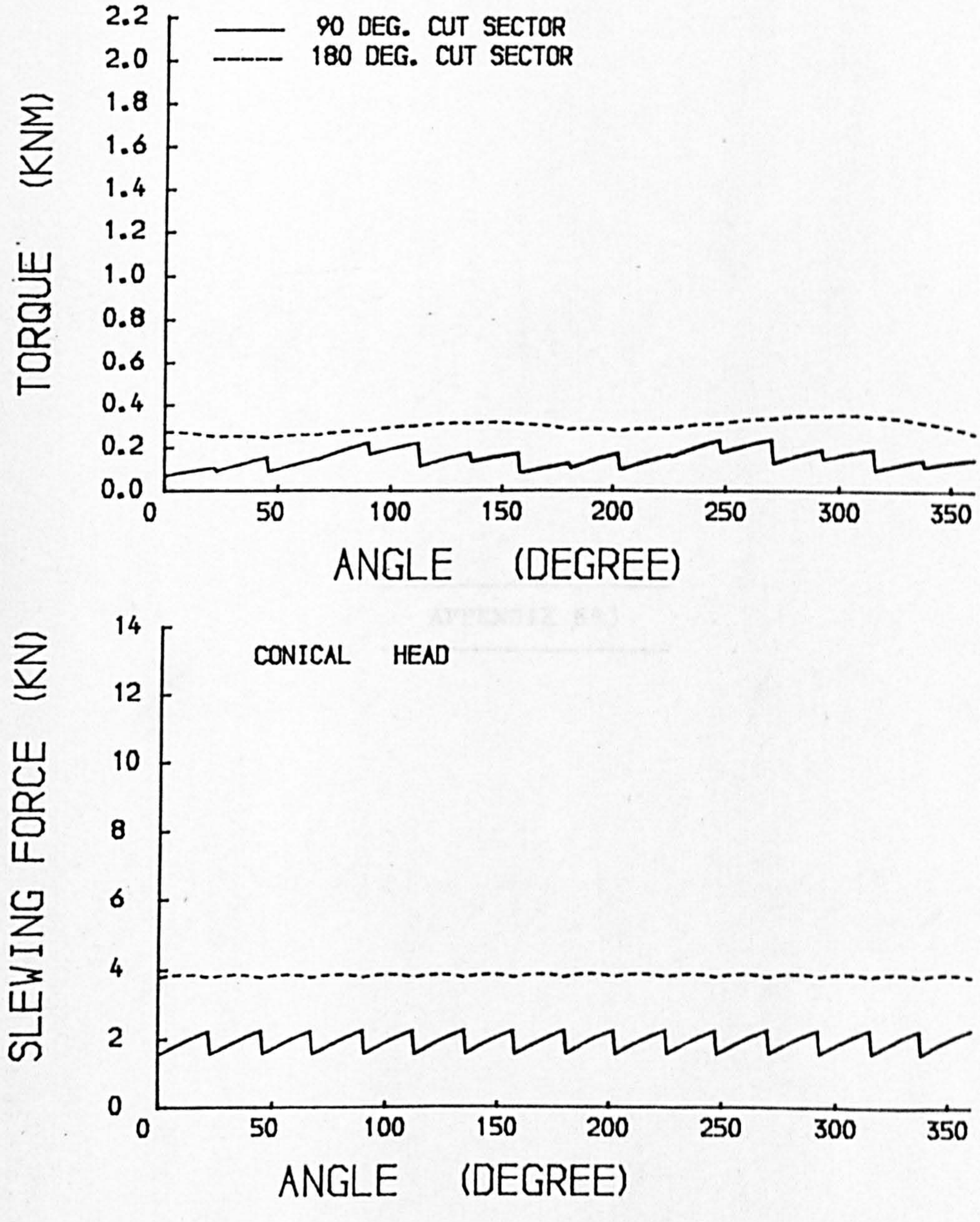
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL. 78.71 DEG.
CONE ANGLE OF THE CUT. HEAD . 78.71 DEG.



FLUCTUATIONS IN TORQUE AND SLEWING FORCE,

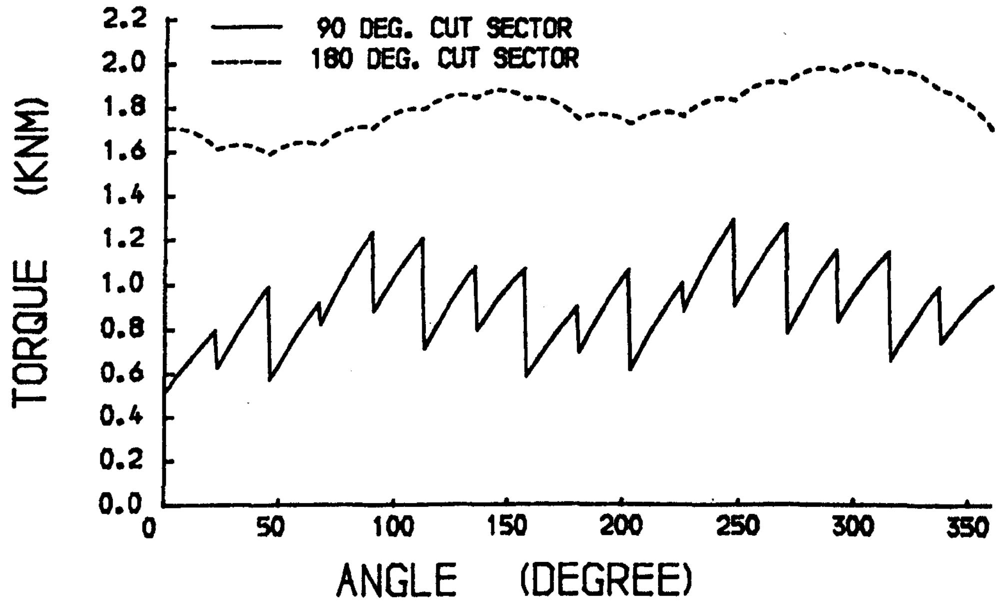
TILT ANGLE OF THE CORNER CUT. TOOL: 83.31 DEG.

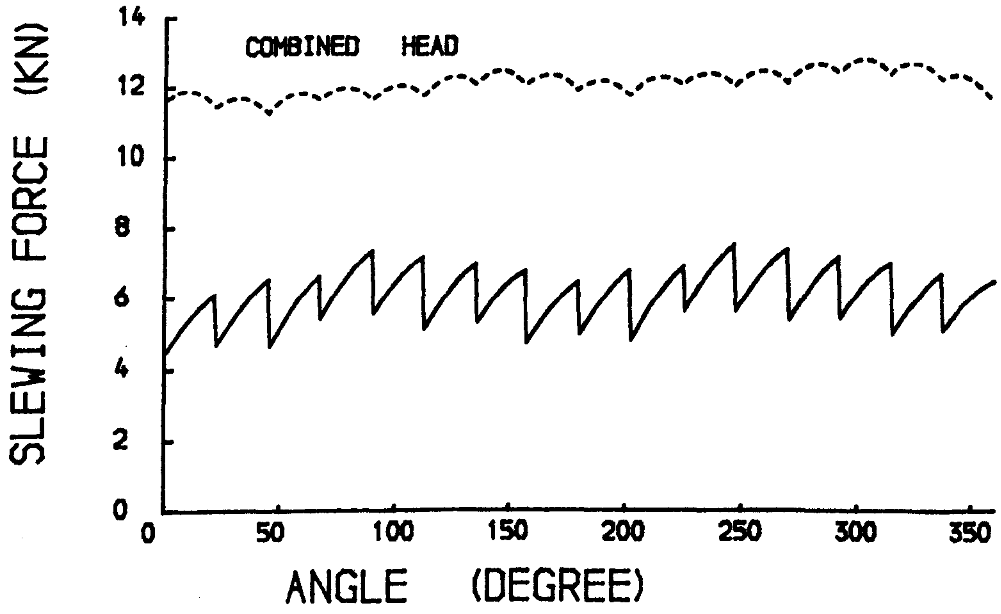
CONE ANGLE OF THE CUT. HEAD : 83.31 DEG.



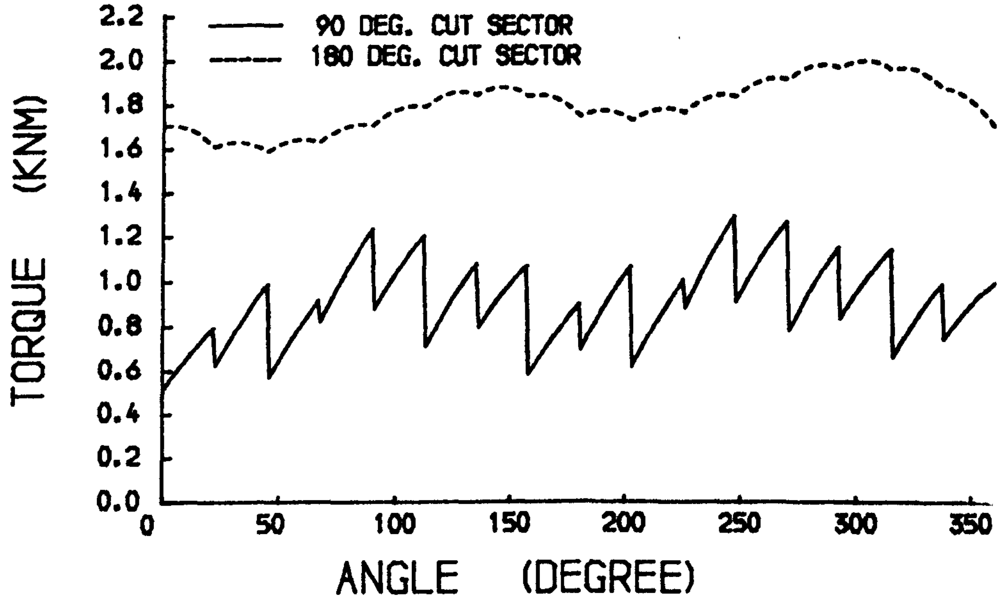
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 87.97 DEG.
CONE ANGLE OF THE CUT. HEAD : 87.97 DEG.

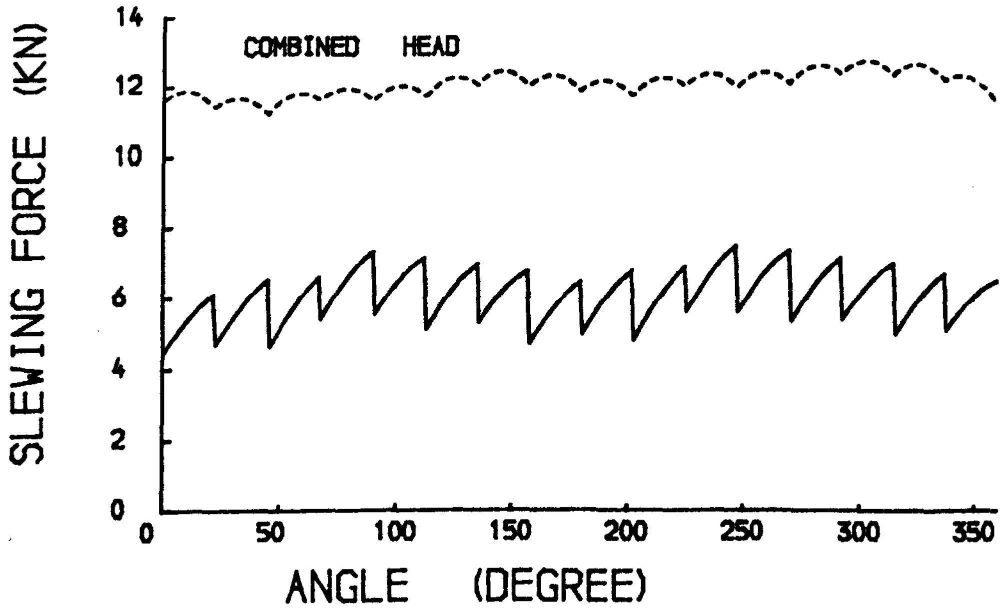
APPENDIX 6B3



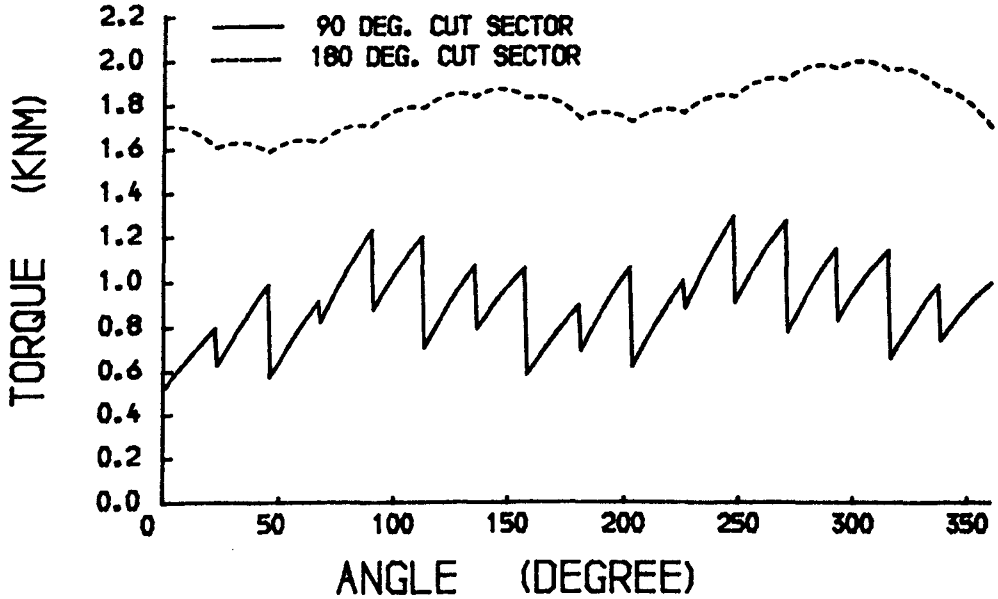


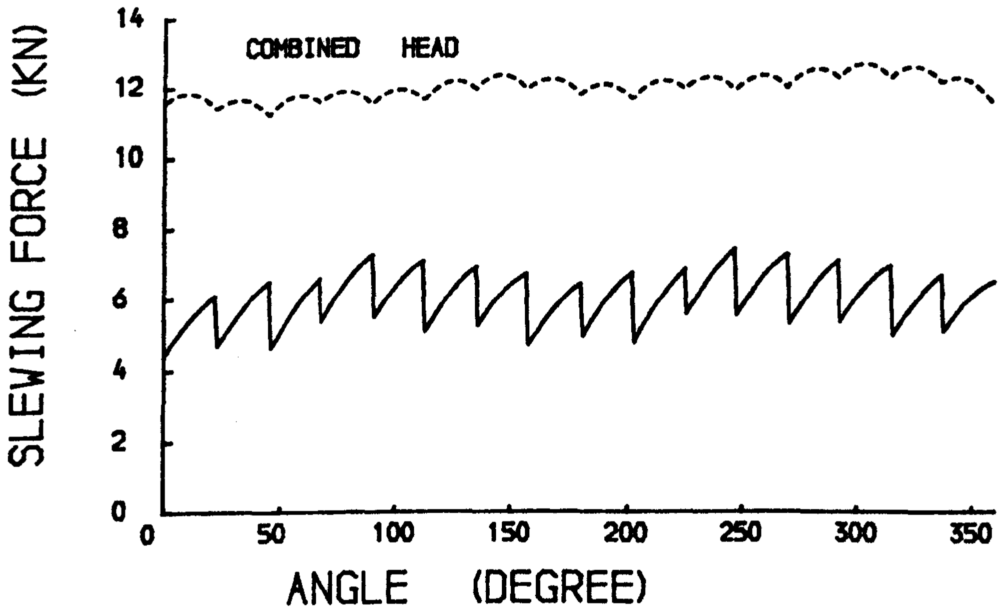
FLUCTUATIONS IN TORQUE AND SLEVING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 64.82 DEG.
CONE ANGLE OF THE CUT. HEAD : 04.63 DEG.



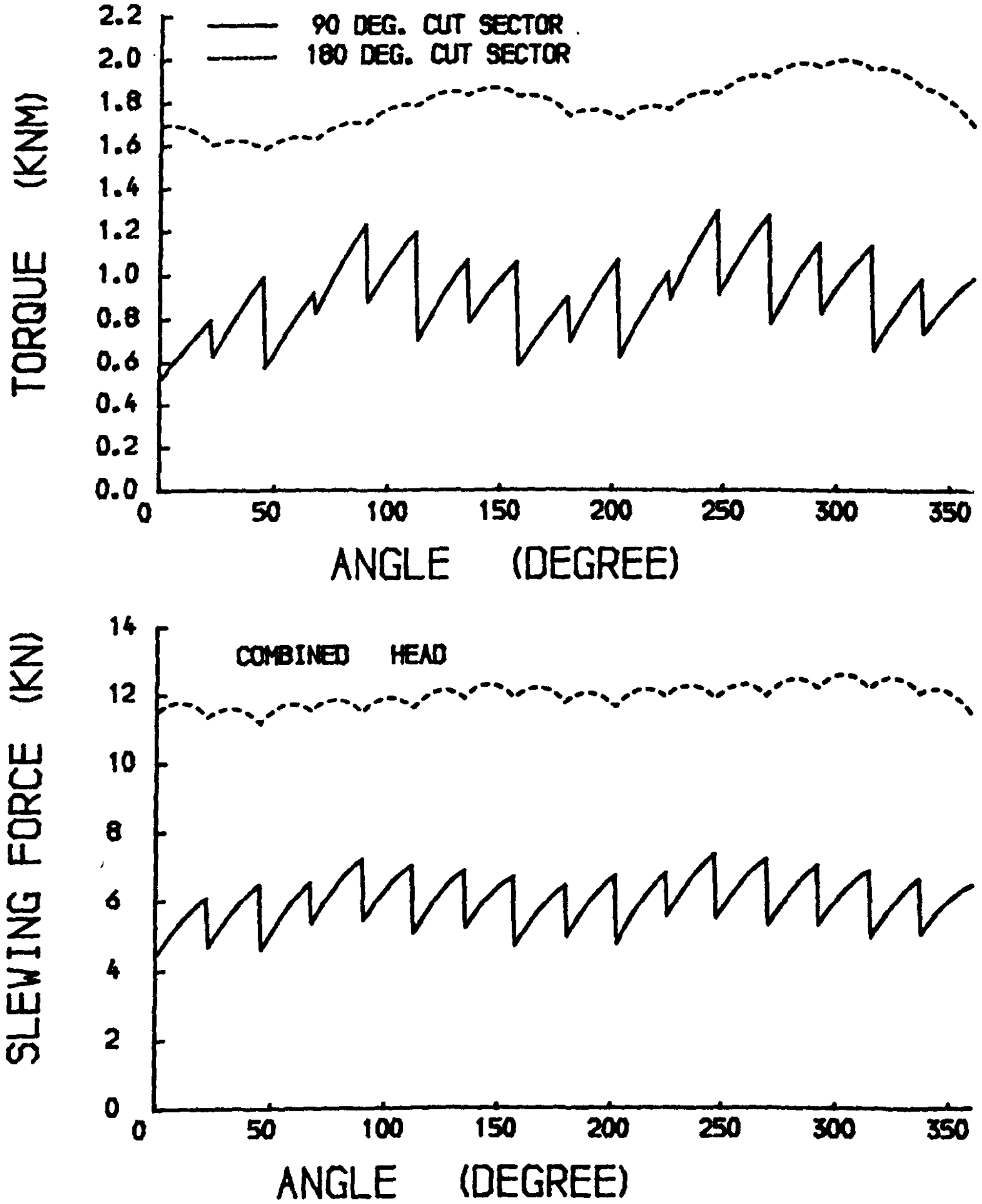


FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 64.82 DEG.
CONE ANGLE OF THE CUT. HEAD : 09.26 DEG.

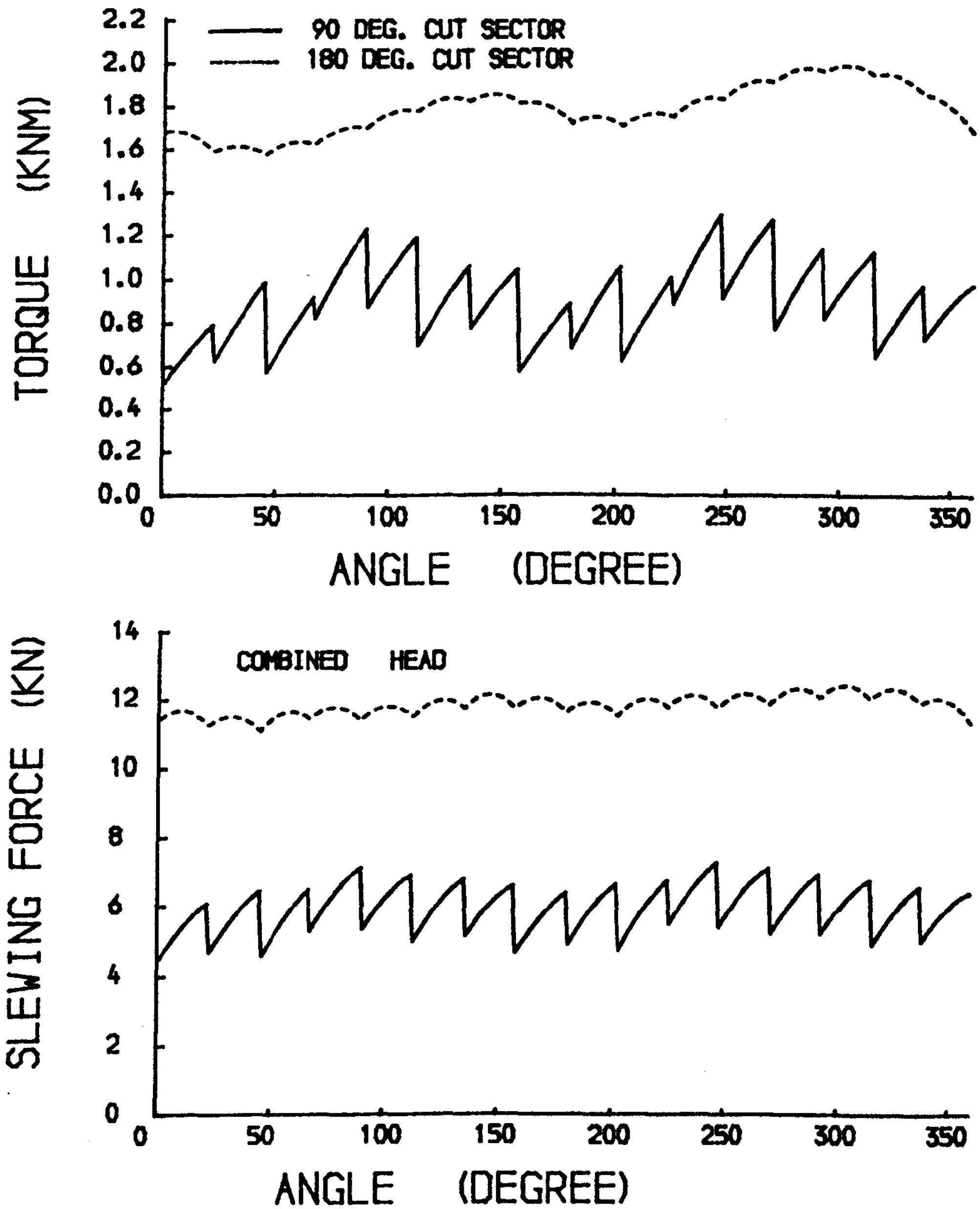




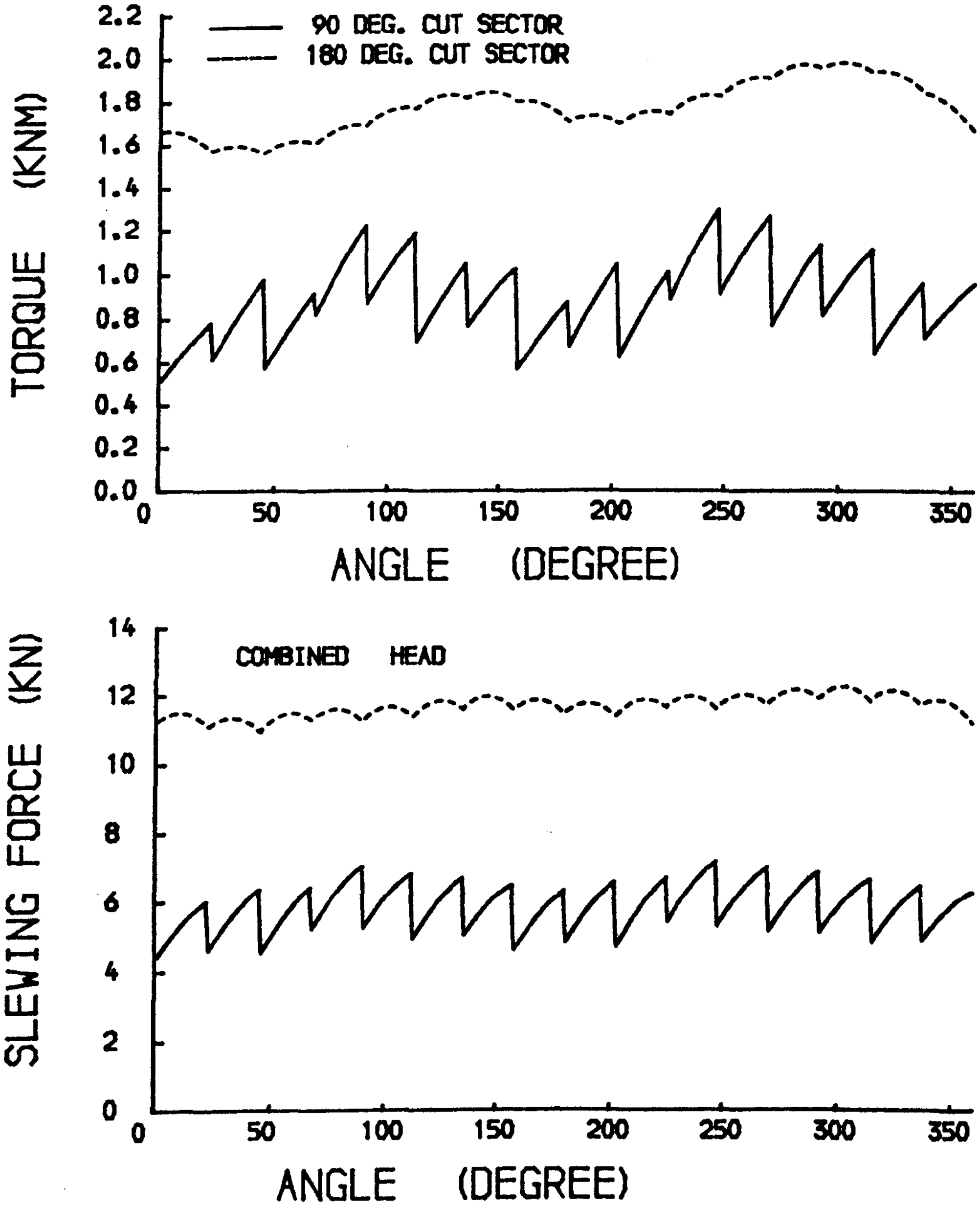
FLUCTUATIONS IN TORQUE AND SLEVING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 64.82 DEG.
CONE ANGLE OF THE CUT. HEAD : 13.89 DEG.



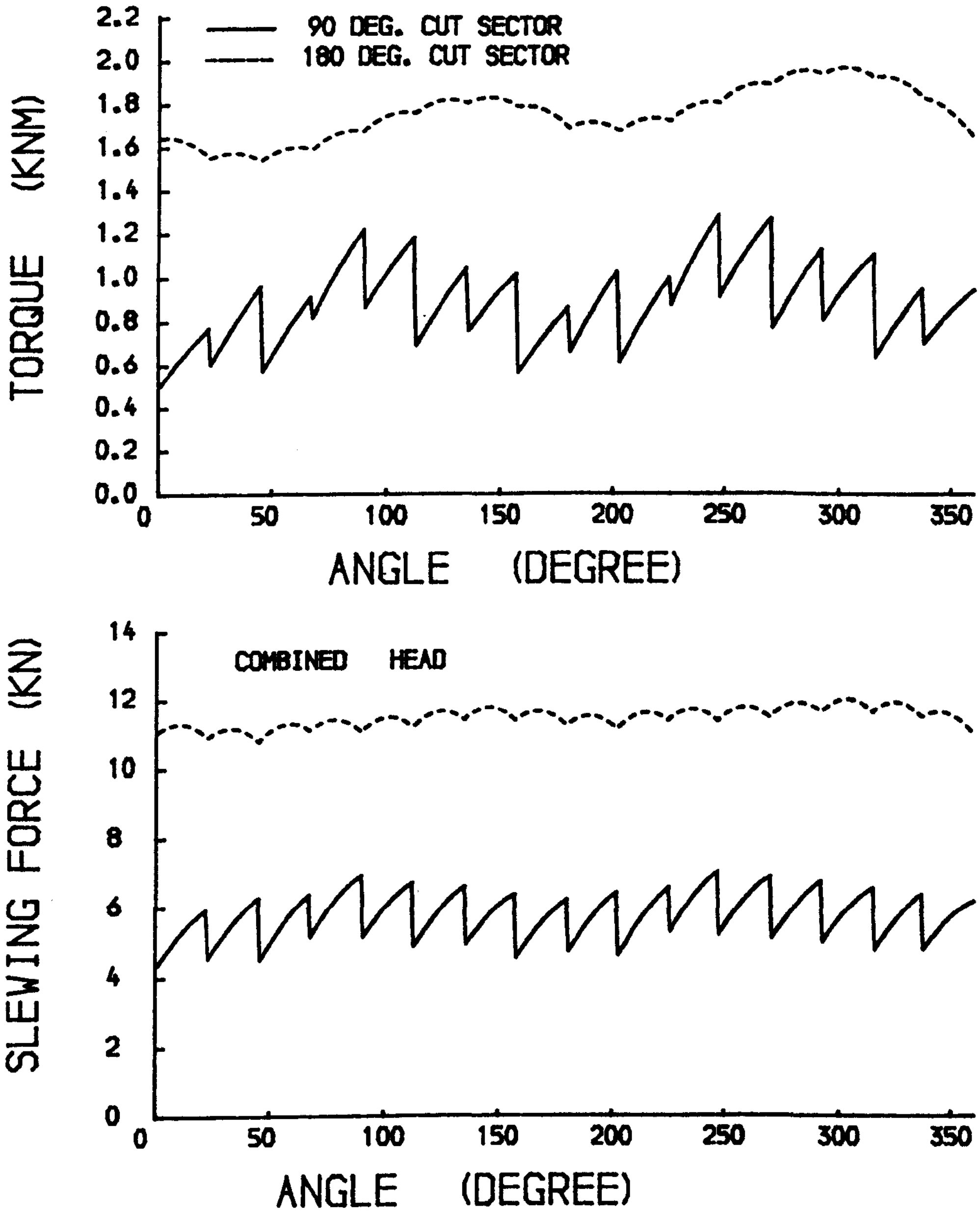
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 64.82 DEG.
CONE ANGLE OF THE CUT. HEAD : 18.52 DEG.



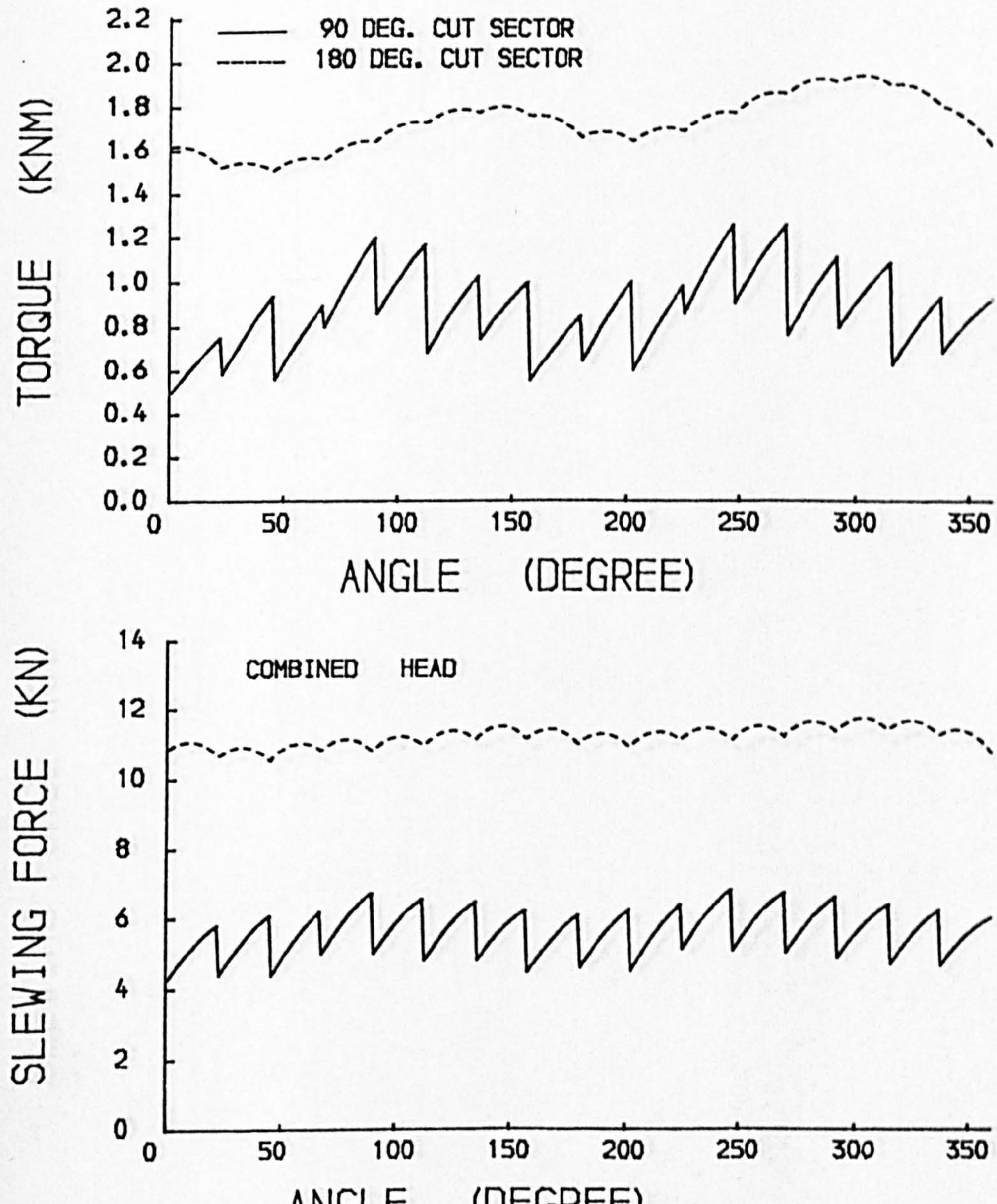
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 64.82 DEG.
CONE ANGLE OF THE CUT. HEAD : 23.15 DEG.



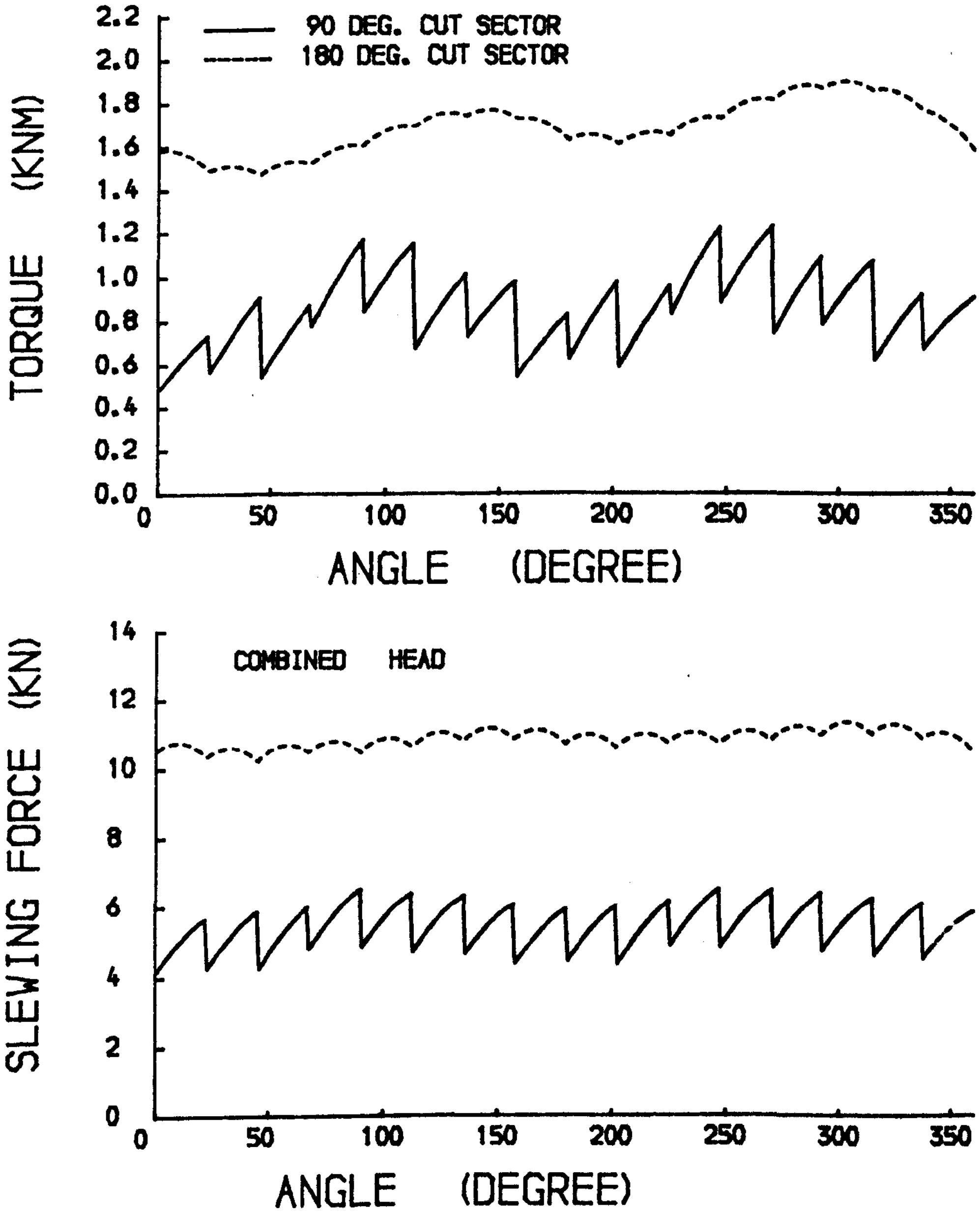
FLUCTUATIONS IN TORQUE AND SLEVING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 64.82 DEG.
CONE ANGLE OF THE CUT. HEAD : 27.78 DEG.



FLUCTUATIONS IN TORQUE AND SLEVING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 64.82 DEG.
CONE ANGLE OF THE CUT. HEAD : 32.41 DEG.



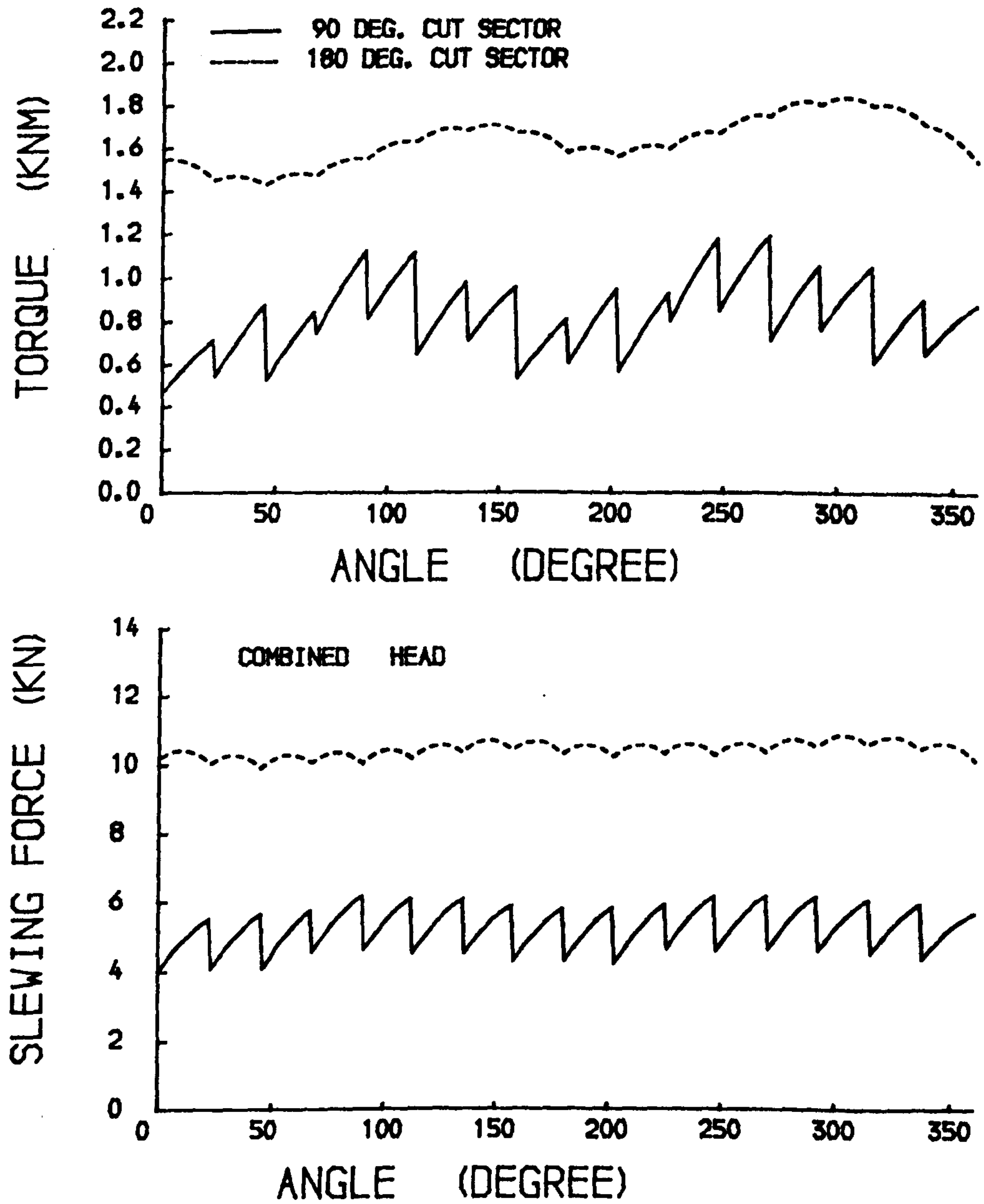
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL. 64.82 DEG.
CONE ANGLE OF THE CUT. HEAD . 37.04 DEG.



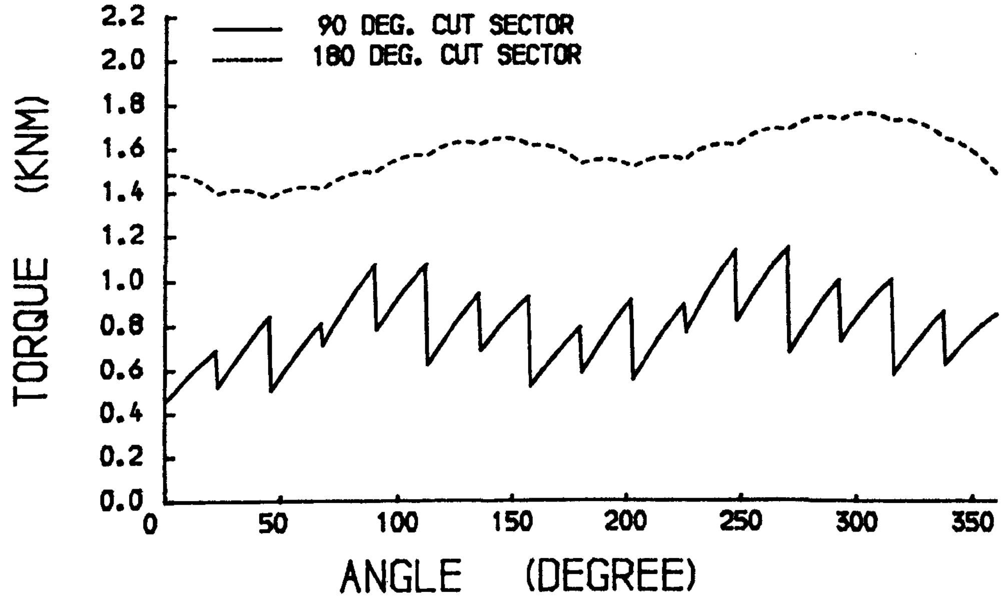
FLUCTUATIONS IN TORQUE AND SLEVING FORCE,

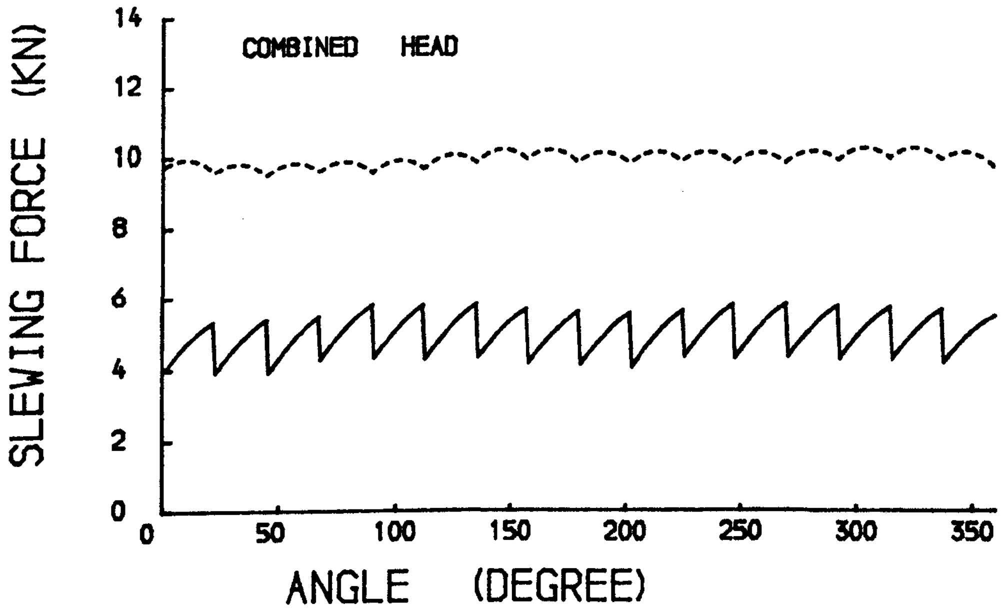
TILT ANGLE OF THE CORNER CUT. TOOL: 64.82 DEG.

CONE ANGLE OF THE CUT. HEAD : 41.67 DEG.



FLUCTUATIONS IN TORQUE AND SLEVING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 64.82 DEG.
CONE ANGLE OF THE CUT. HEAD : 46.30 DEG.

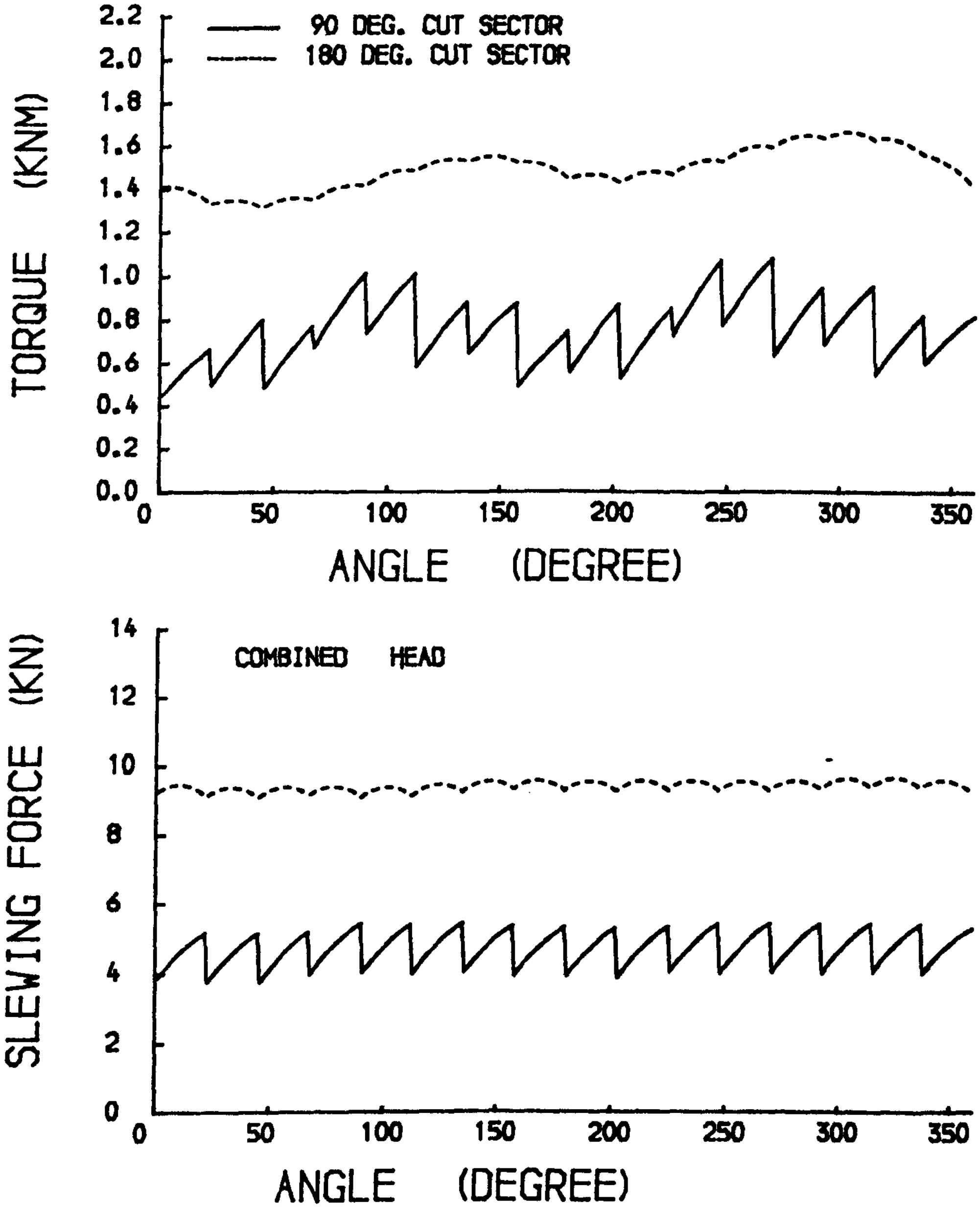




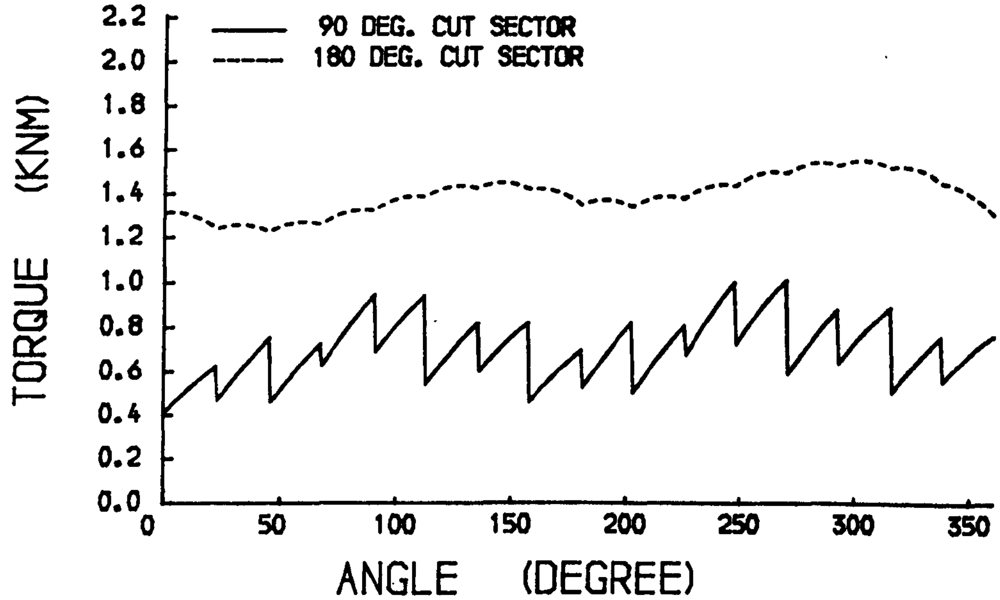
FLUCTUATIONS IN TORQUE AND SLEVING FORCE,

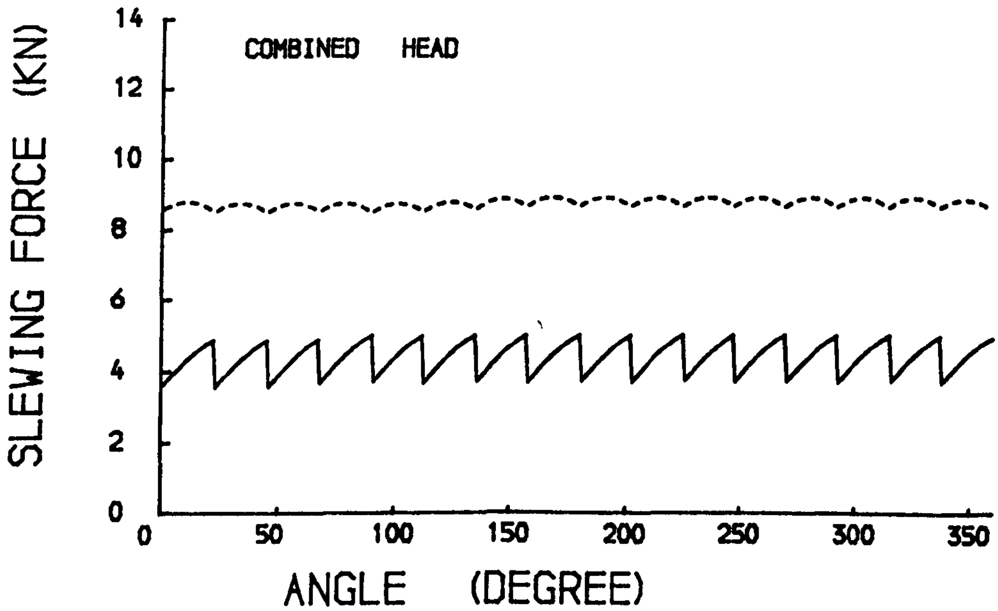
TILT ANGLE OF THE CORNER CUT. TOOL: 64.82 DEG.

CONE ANGLE OF THE CUT. HEAD : 50.93 DEG.

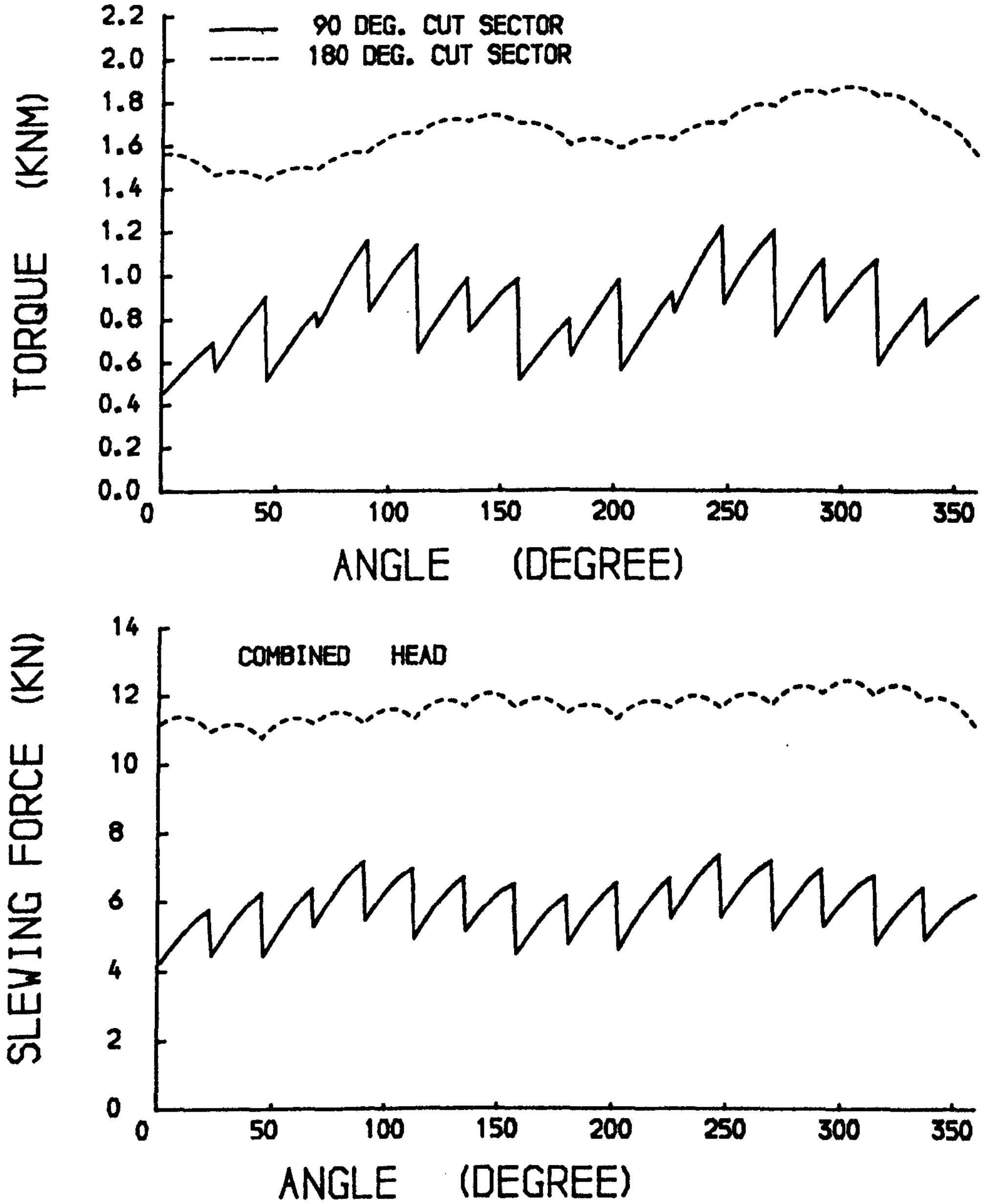


FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL. 64.82 DEG.
CONE ANGLE OF THE CUT. HEAD . 55.56 DEG.

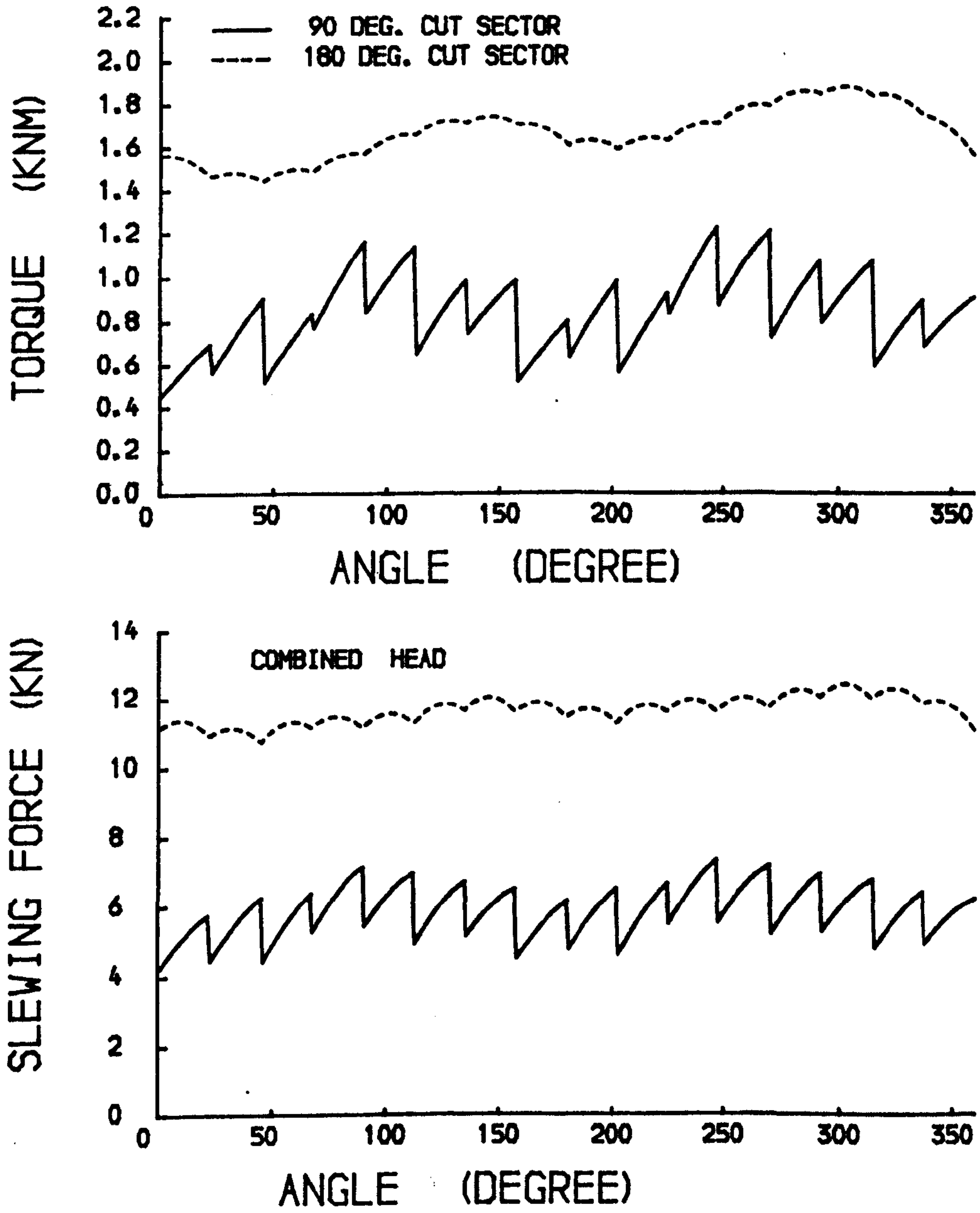




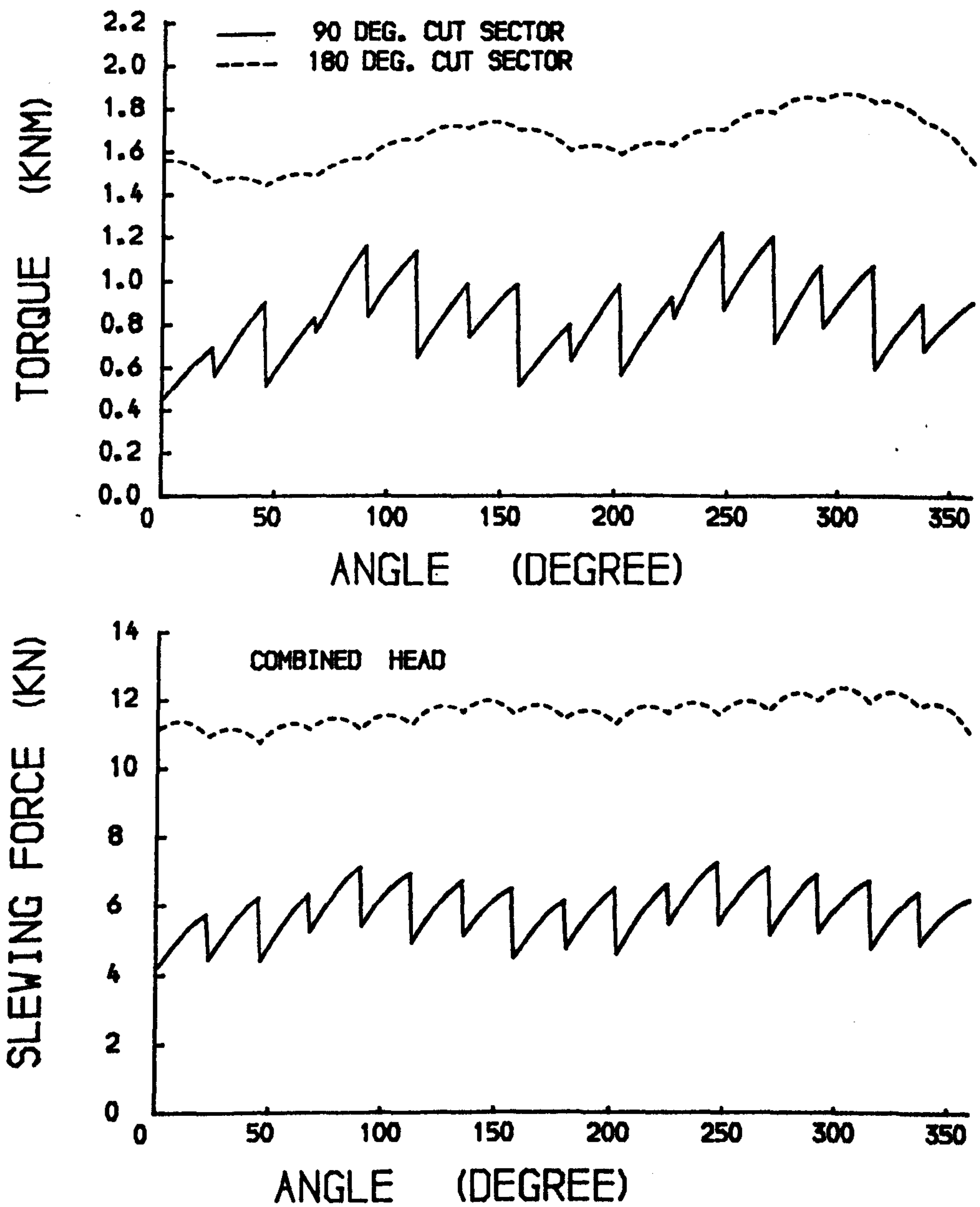
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 64.82 DEG.
CONE ANGLE OF THE CUT. HEAD : 60.19 DEG.



FLUCTUATIONS IN TORQUE AND SLEVING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 69.45 DEG.
CONE ANGLE OF THE CUT. HEAD : 4.63 DEG.



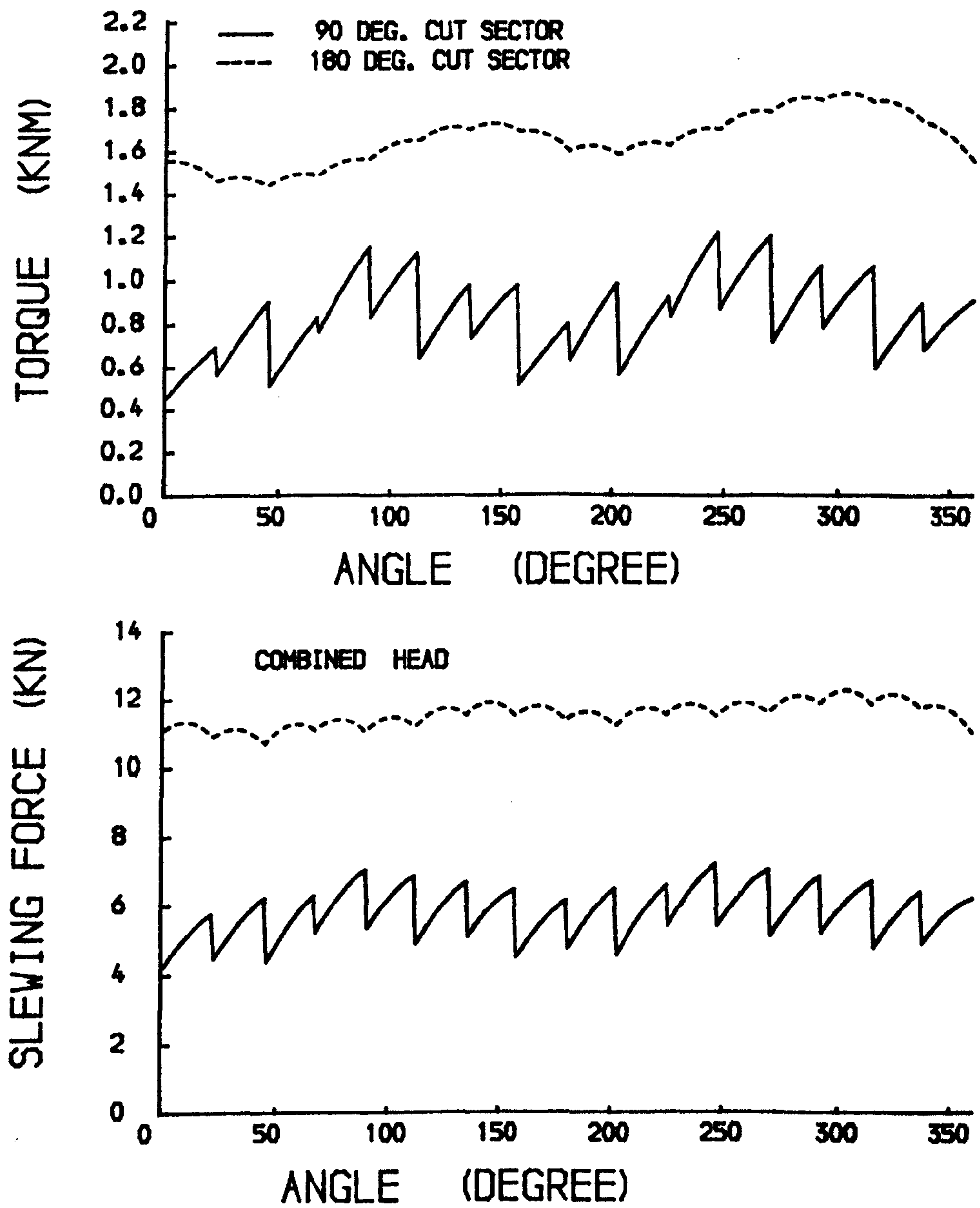
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 69.45 DEG.
CONE ANGLE OF THE CUT. HEAD : 09.26 DEG.



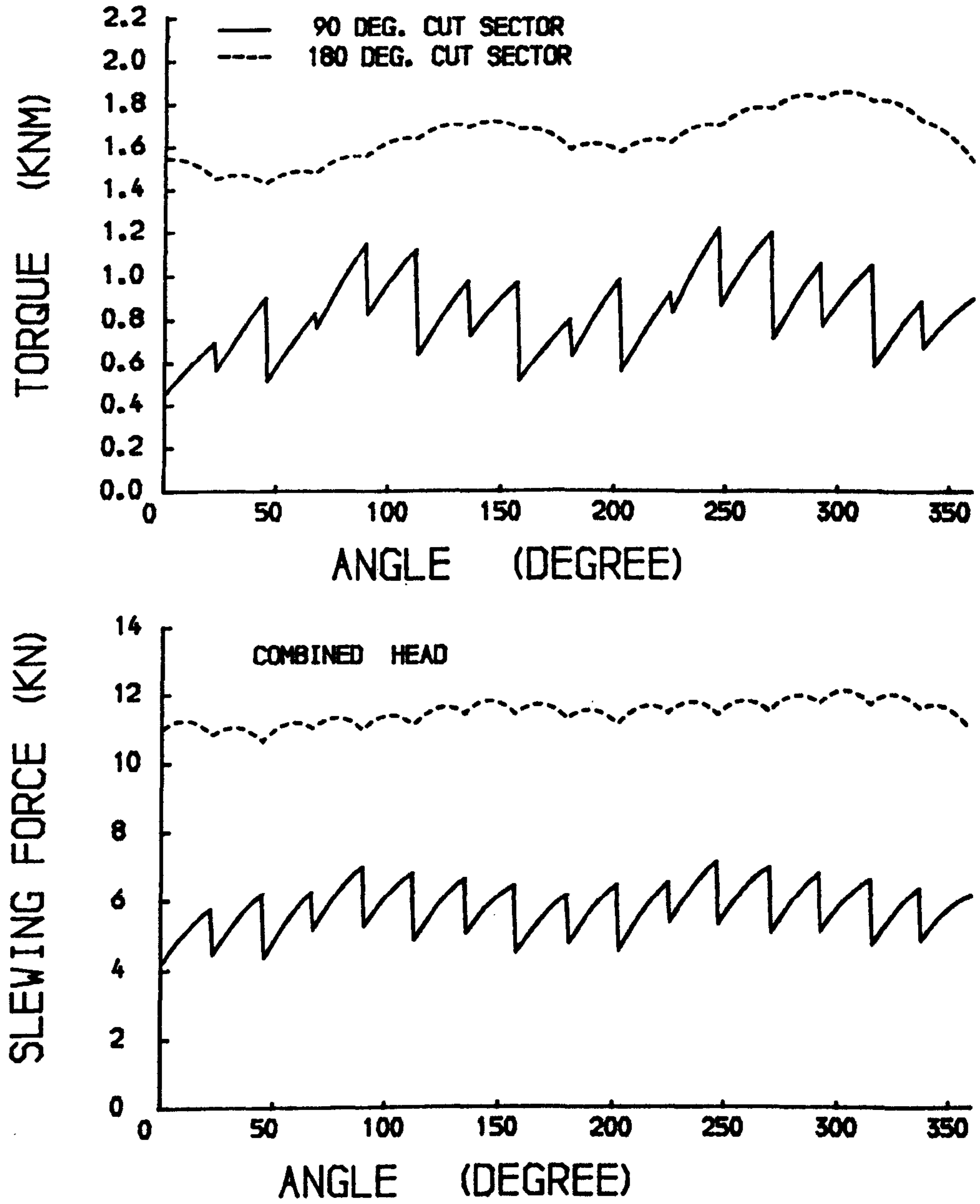
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,

TILT ANGLE OF THE CORNER CUT. TOOL: 69.45 DEG.

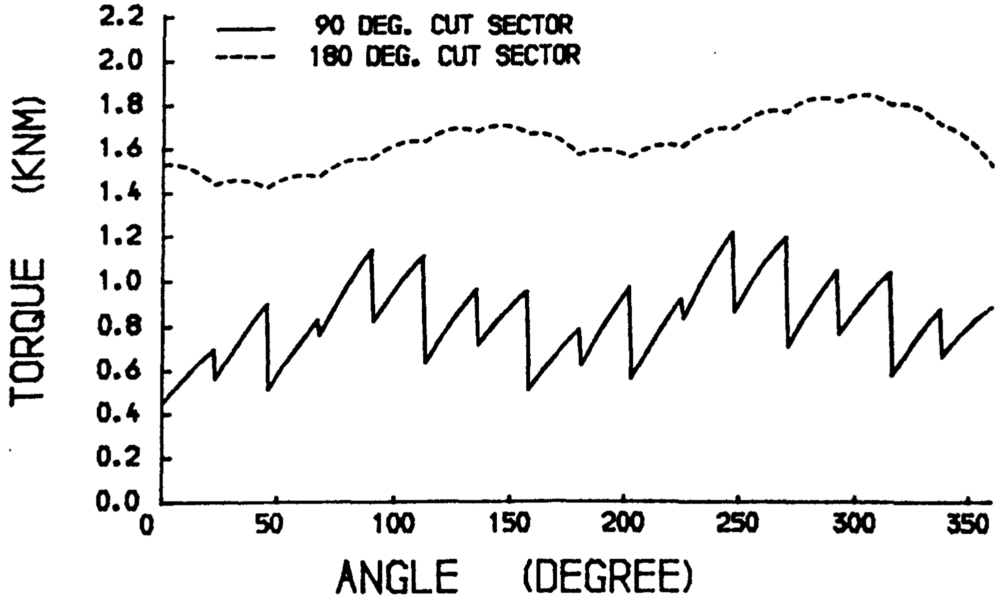
CONE ANGLE OF THE CUT. HEAD : 13.89 DEG.

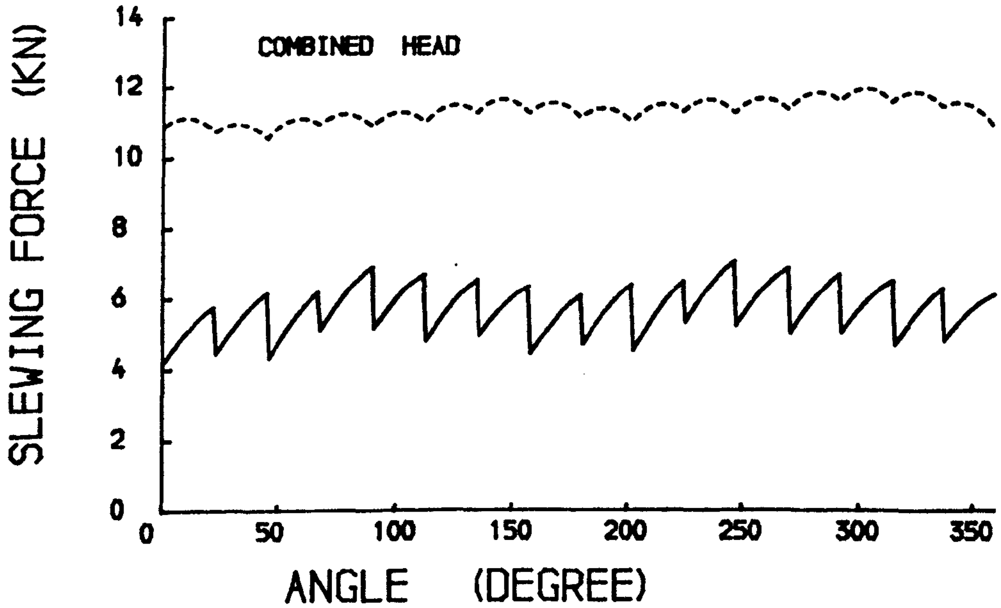


FLUCTUATIONS IN TORQUE AND SLEVING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 69.45 DEG.
CONE ANGLE OF THE CUT. HEAD : 18.52 DEG.

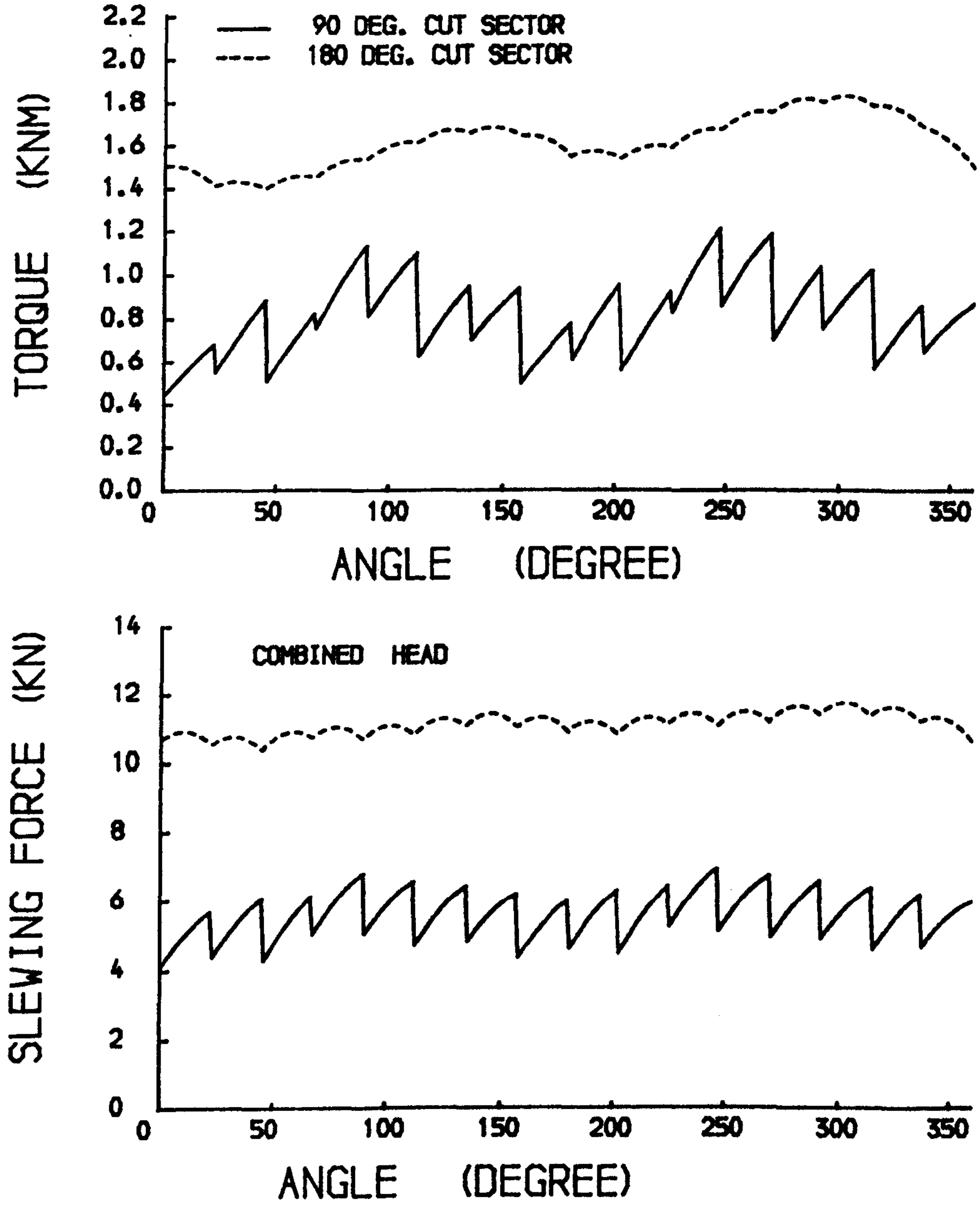


FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 69.45 DEG.
CONE ANGLE OF THE CUT. HEAD : 23.15 DEG.





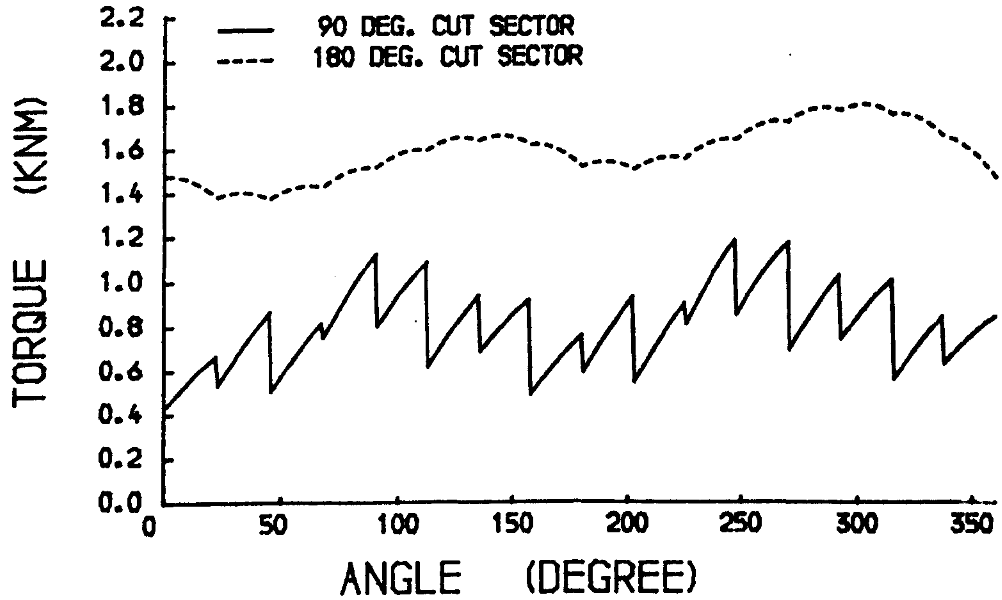
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 69.45 DEG.
CONE ANGLE OF THE CUT. HEAD : 27.78 DEG.

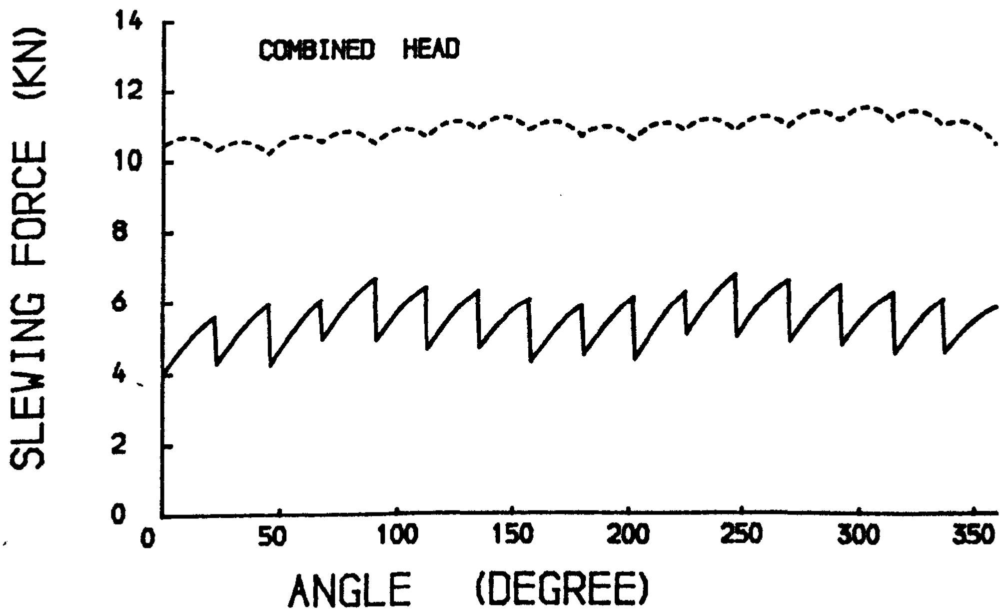


FLUCTUATIONS IN TORQUE AND SLEVING FORCE,

TILT ANGLE OF THE CORNER CUT. TOOL: 69.45 DEG.

CONE ANGLE OF THE CUT. HEAD : 32.41 DEG.

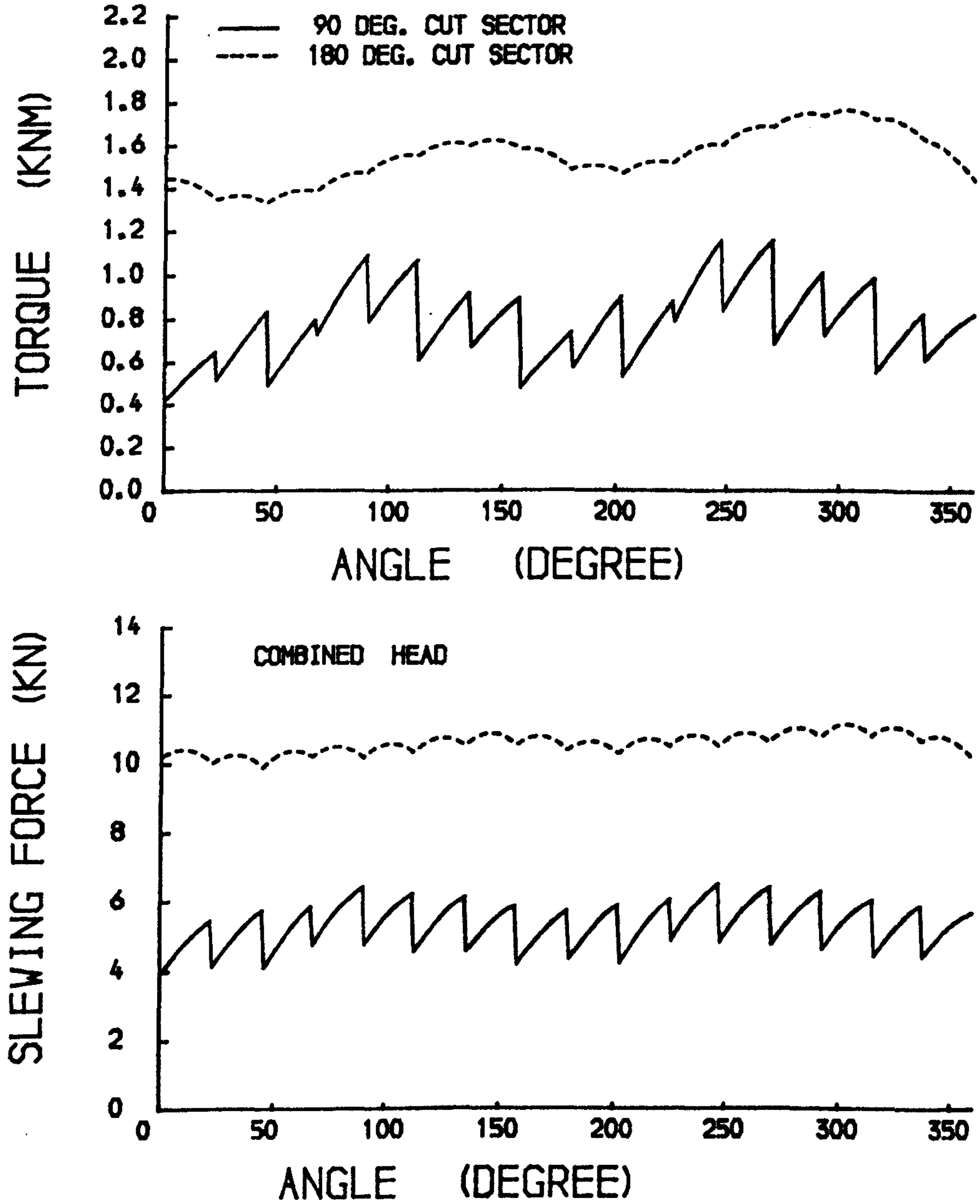




FLUCTUATIONS IN TORQUE AND SLEVING FORCE,

TILT ANGLE OF THE CORNER CUT. TOOL: 69.45 DEG.

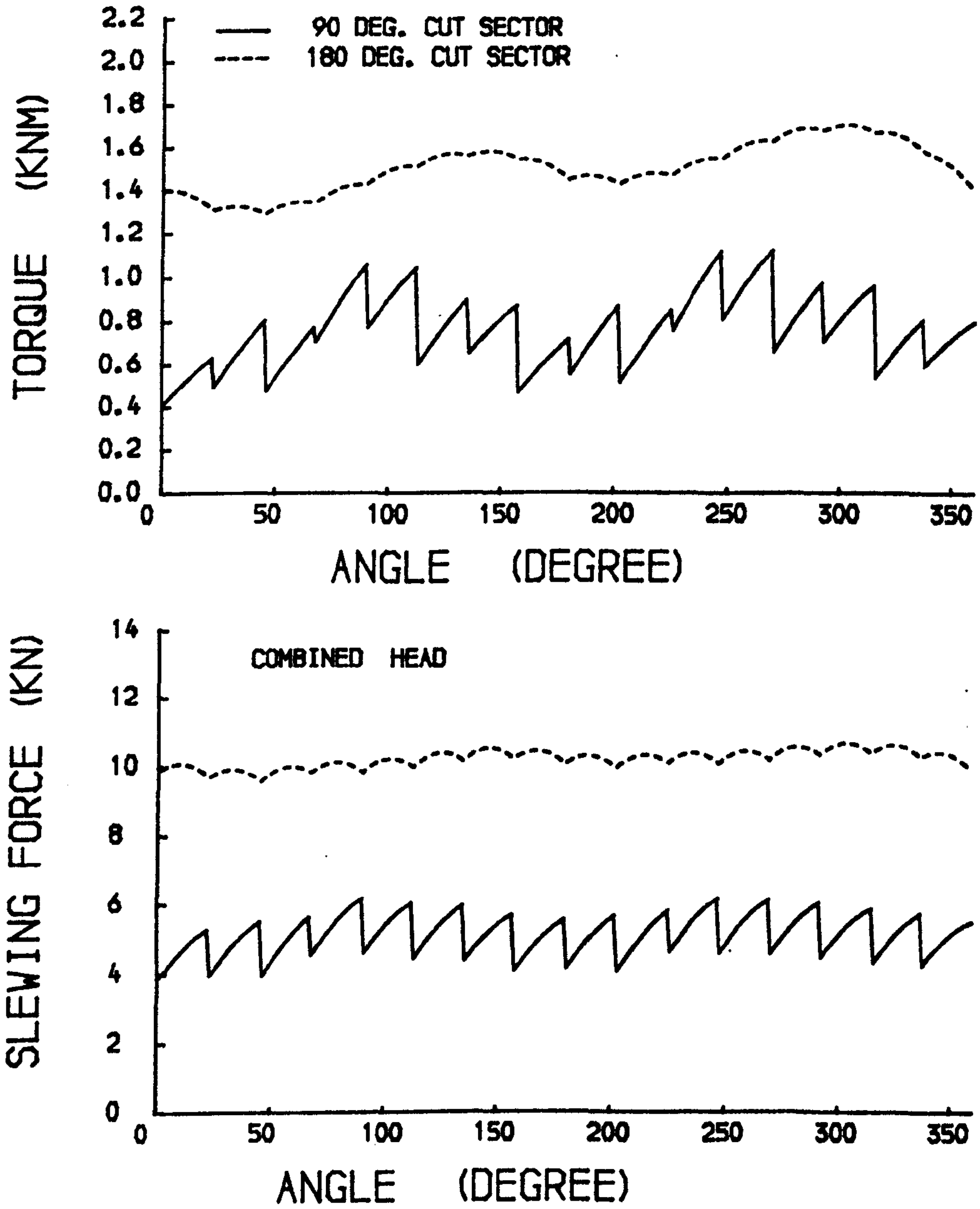
CONE ANGLE OF THE CUT. HEAD : 37.04 DEG.



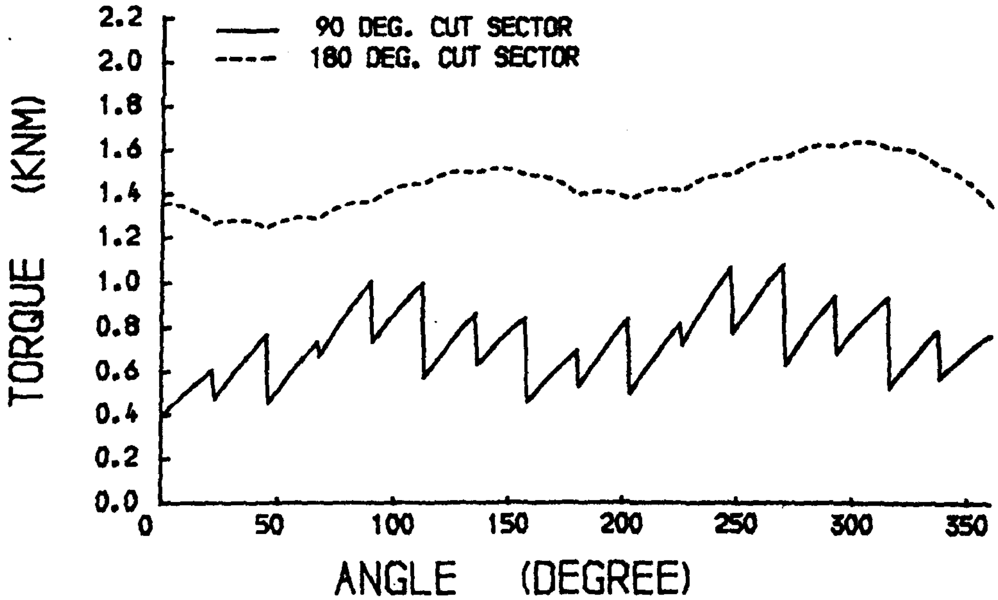
FLUCTUATIONS IN TORQUE AND SLEVING FORCE,

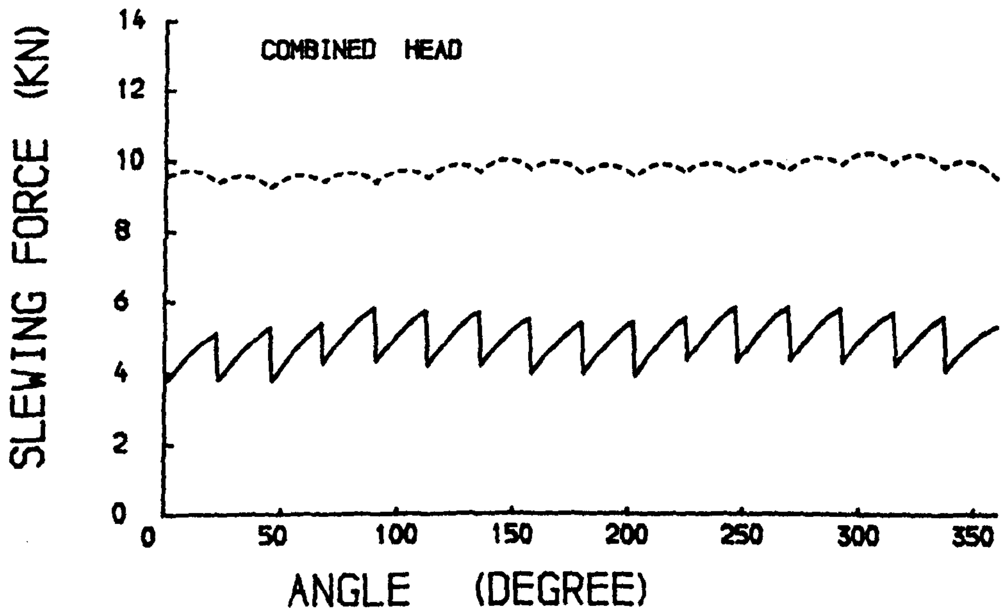
TILT ANGLE OF THE CORNER CUT. TOOL: 69.45 DEG.

CONE ANGLE OF THE CUT. HEAD : 41.67 DEG.

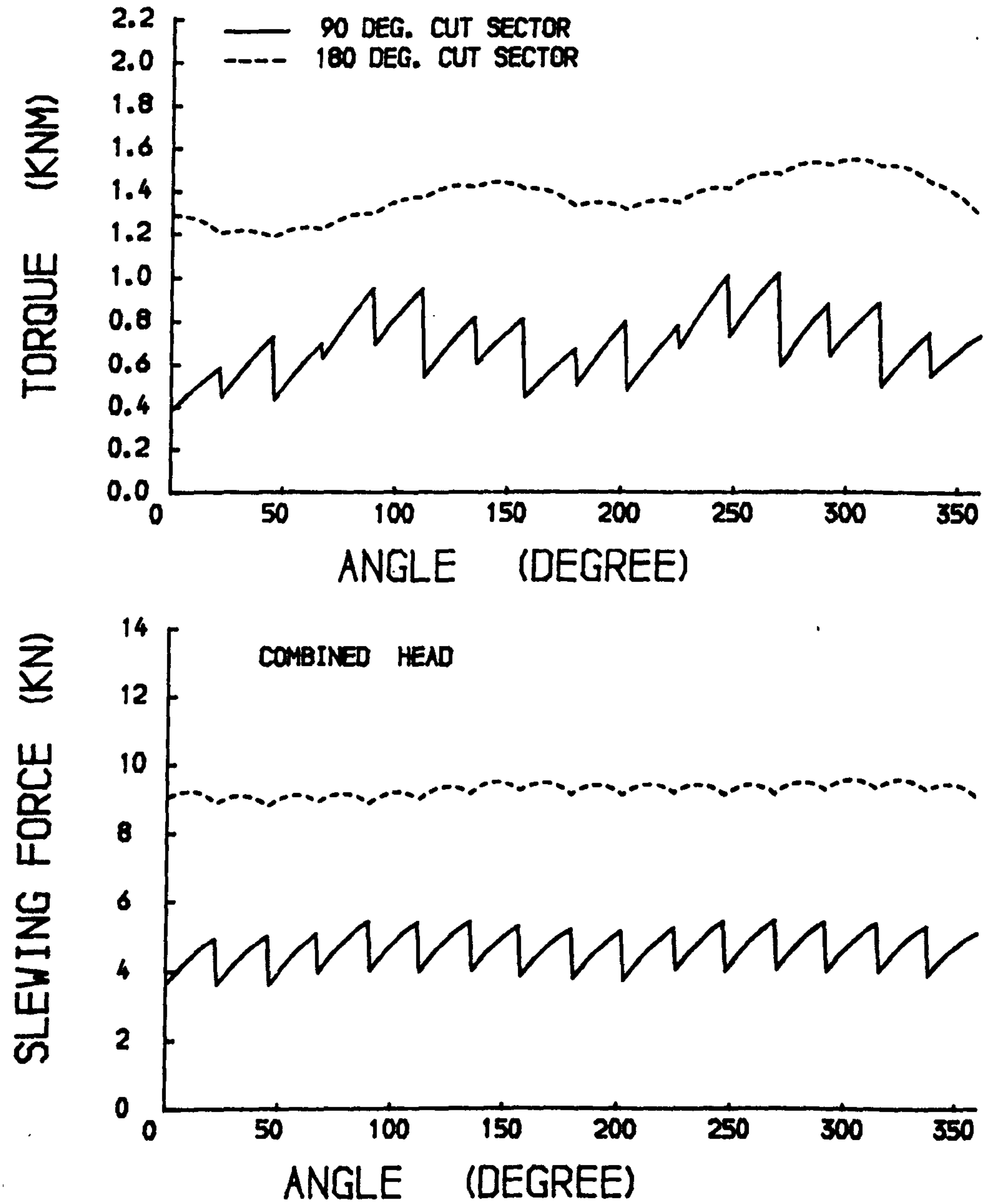


FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 69.45 DEG.
CONE ANGLE OF THE CUT. HEAD : 46.30 DEG.

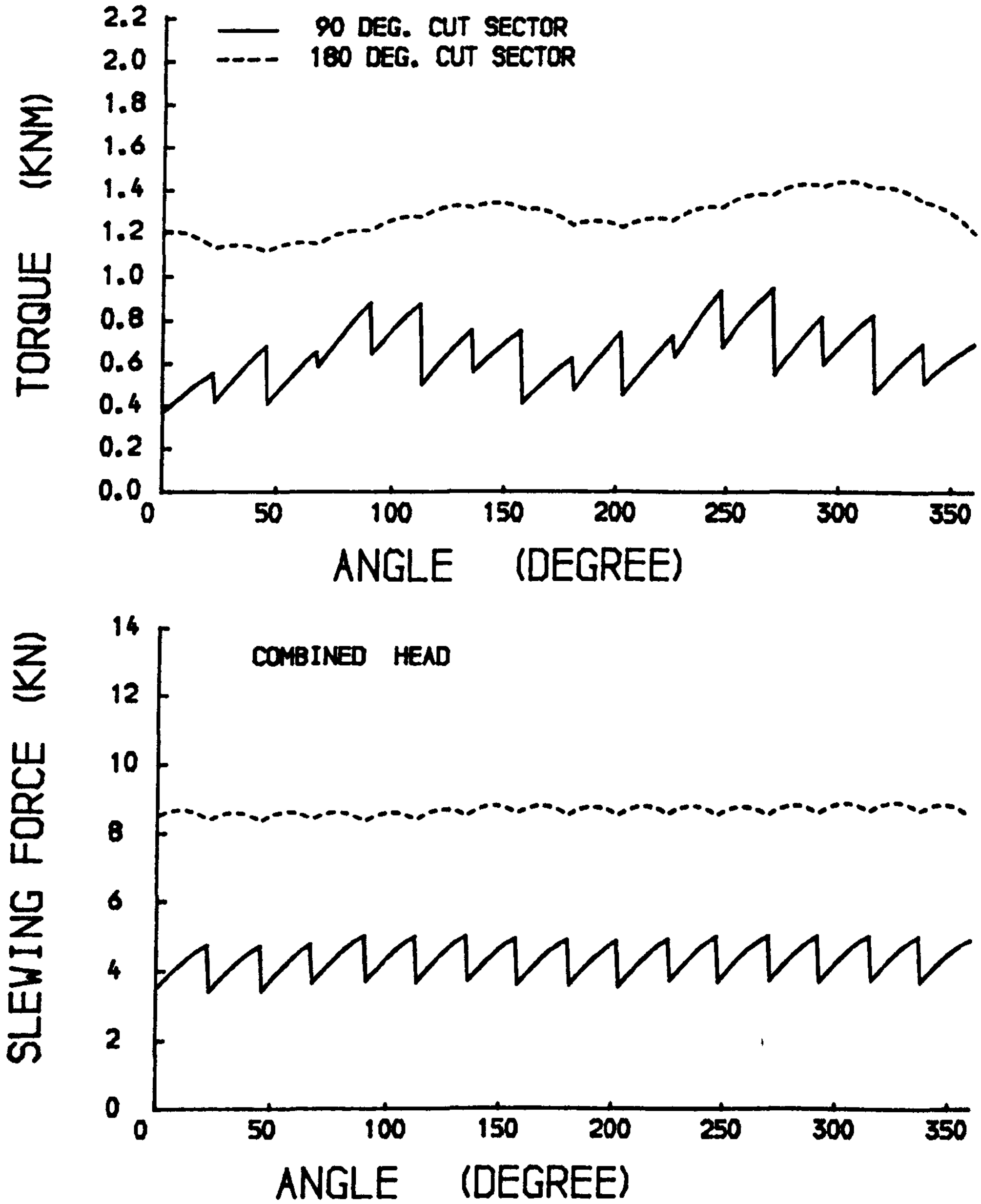




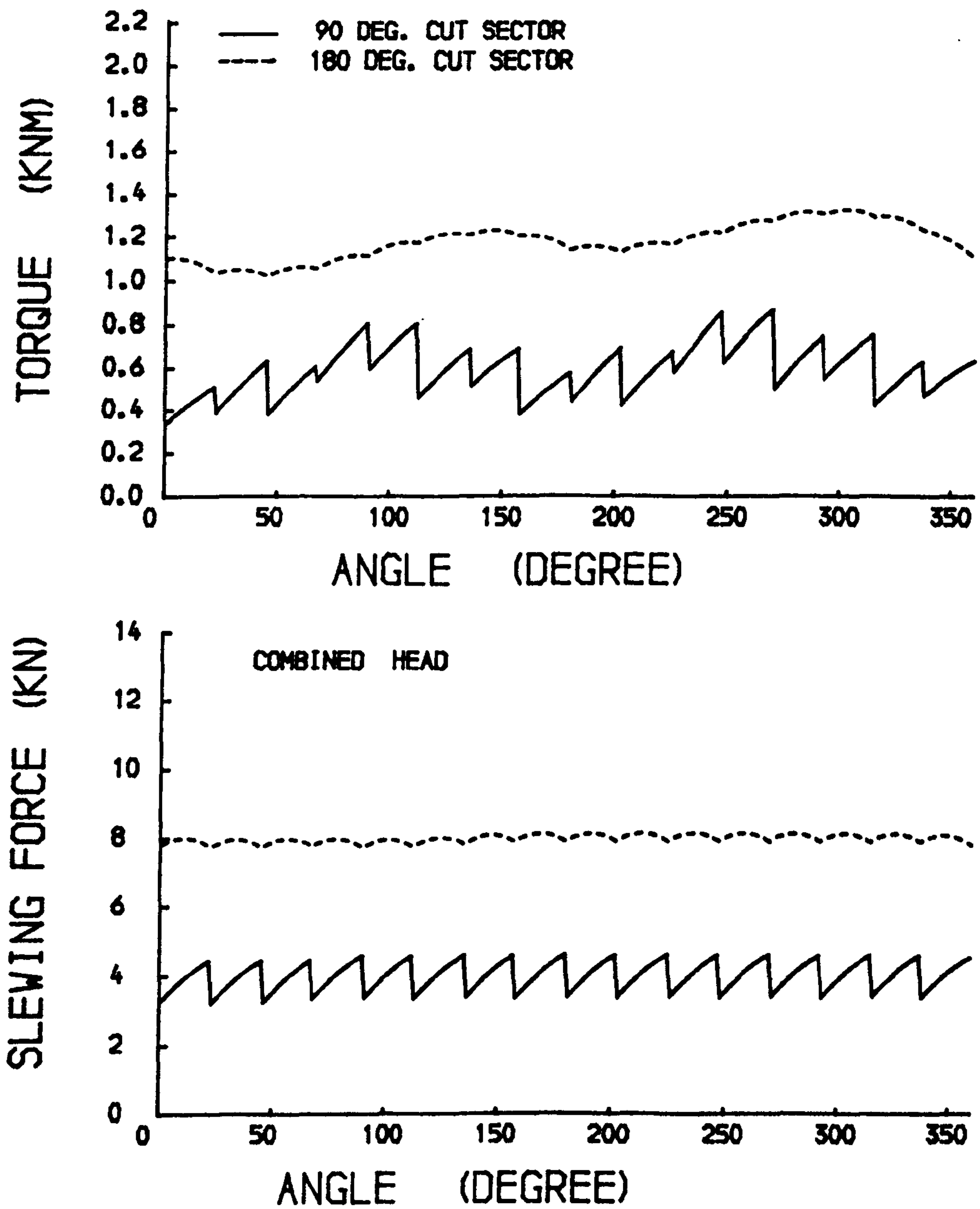
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 69.45 DEG.
CONE ANGLE OF THE CUT. HEAD : 50.93 DEG.



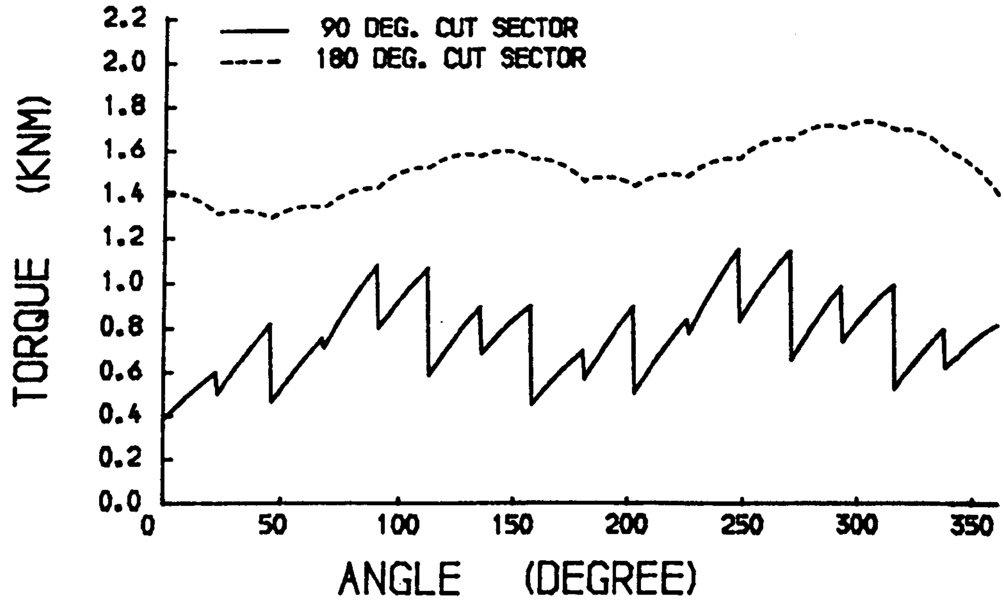
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 69.45 DEG.
CONE ANGLE OF THE CUT. HEAD : 55.56 DEG.

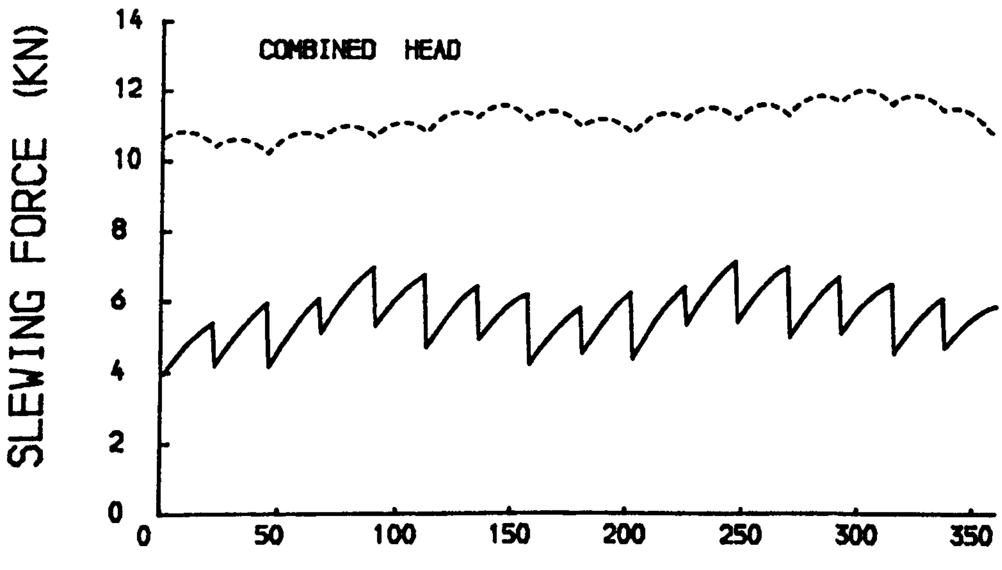


FLUCTUATIONS IN TORQUE AND SLEVING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL. 69.45 DEG.
CONE ANGLE OF THE CUT. HEAD . 60.19 DEG.

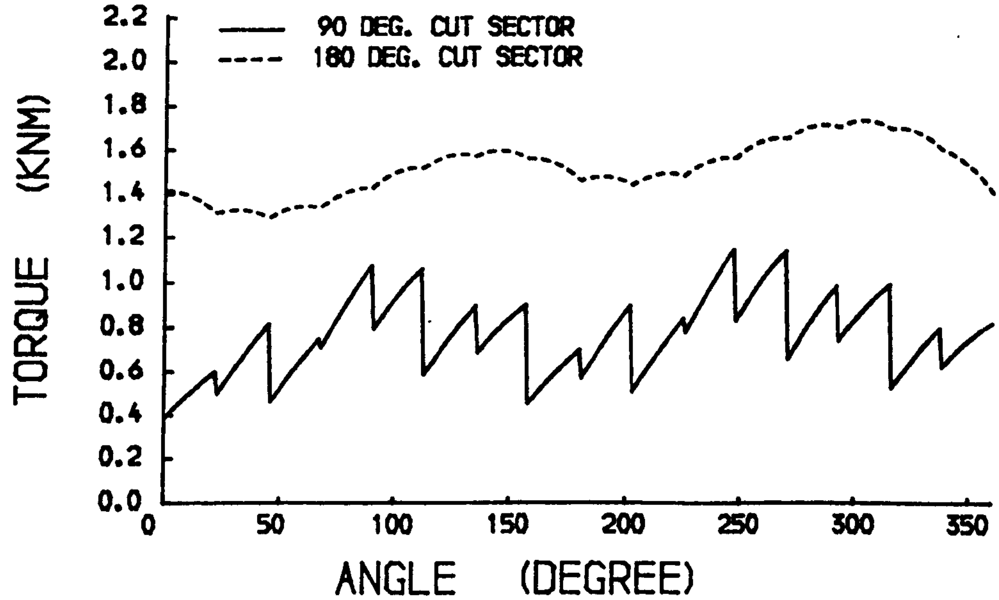


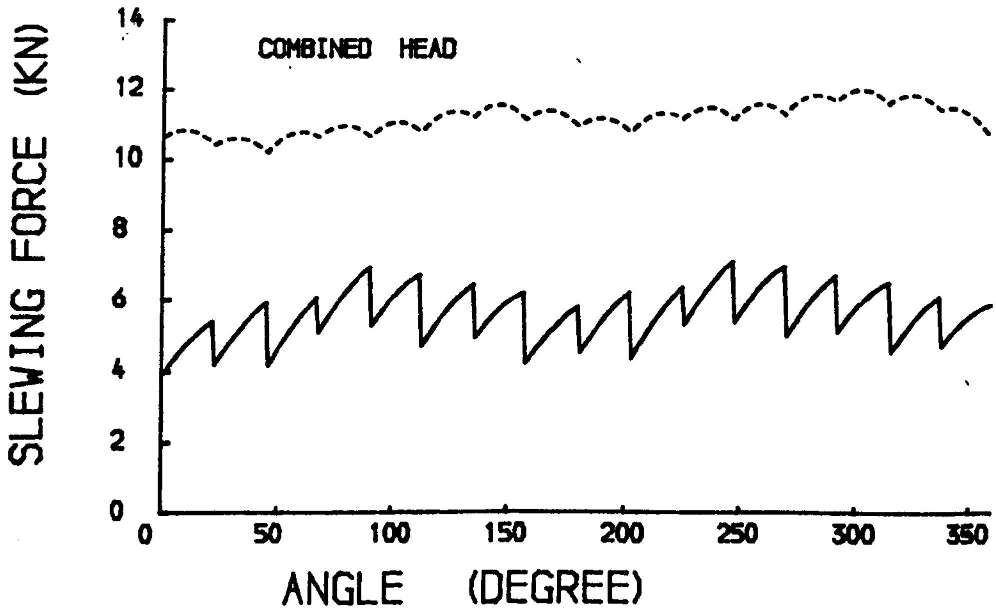
FLUCTUATIONS IN TORQUE AND SLEVING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 69.45 DEG.
CONE ANGLE OF THE CUT. HEAD : 64.82 DEG.





FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 74.08 DEG.
CONE ANGLE OF THE CUT. HEAD : 09.26 DEG.

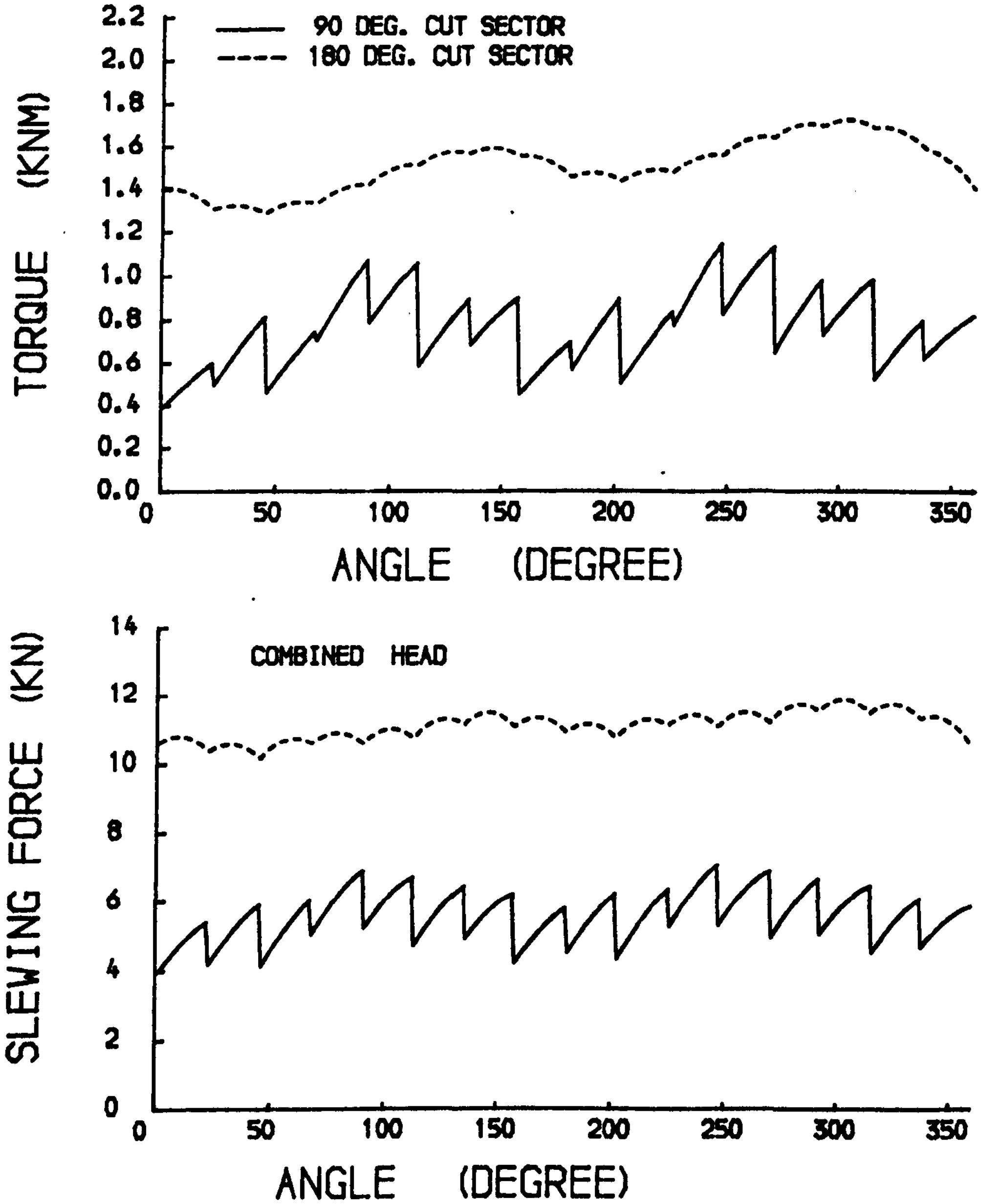




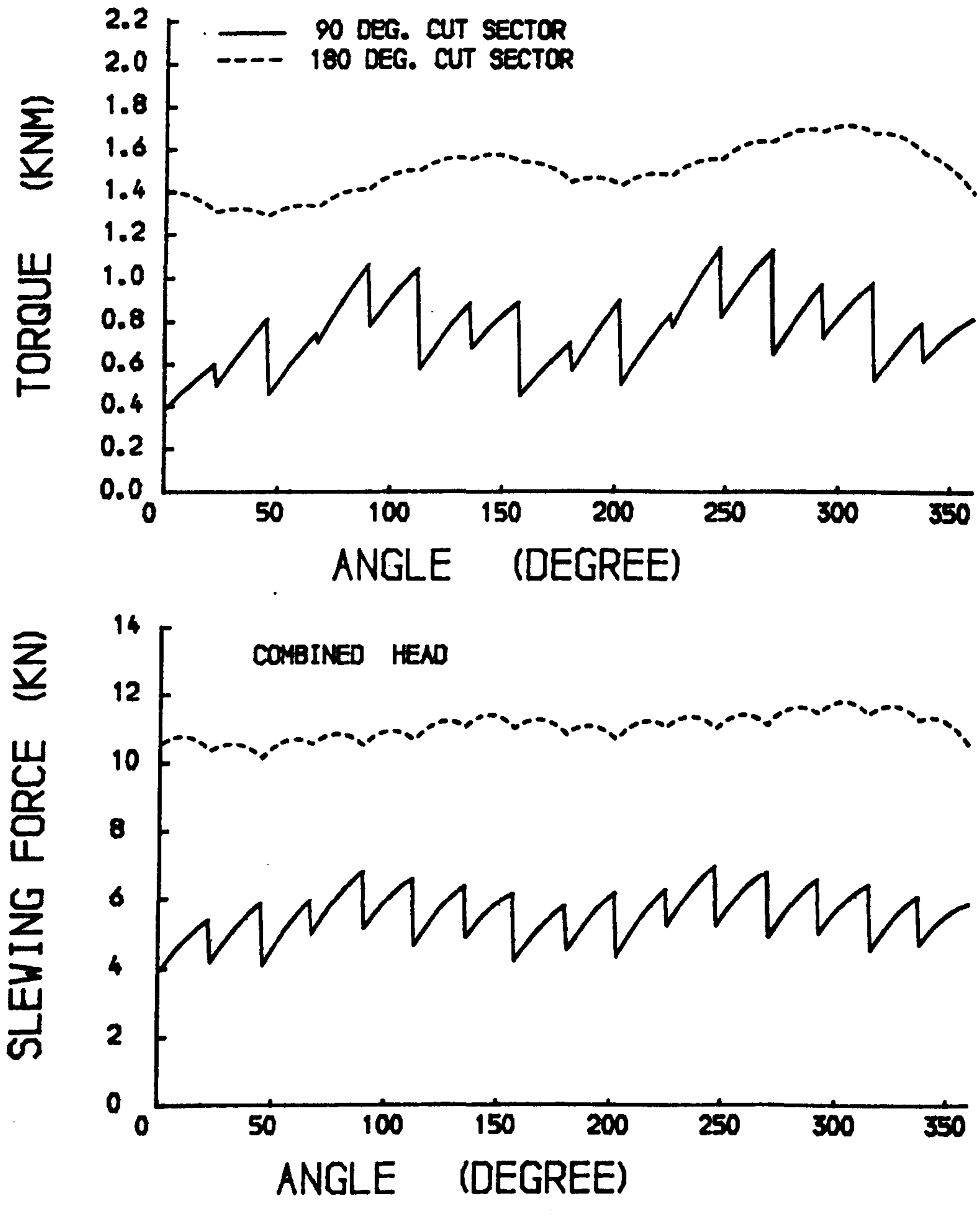
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,

TILT ANGLE OF THE CORNER CUT. TOOL: 74.08 DEG.

CONE ANGLE OF THE CUT. HEAD : 13.89 DEG.



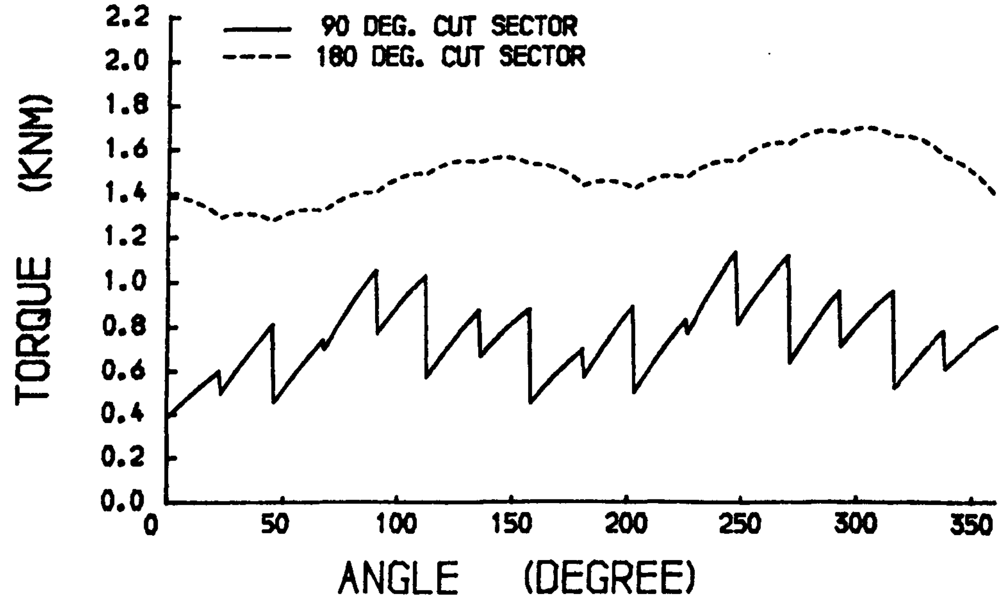
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 74.08 DEG.
CONE ANGLE OF THE CUT. HEAD : 18.52 DEG.

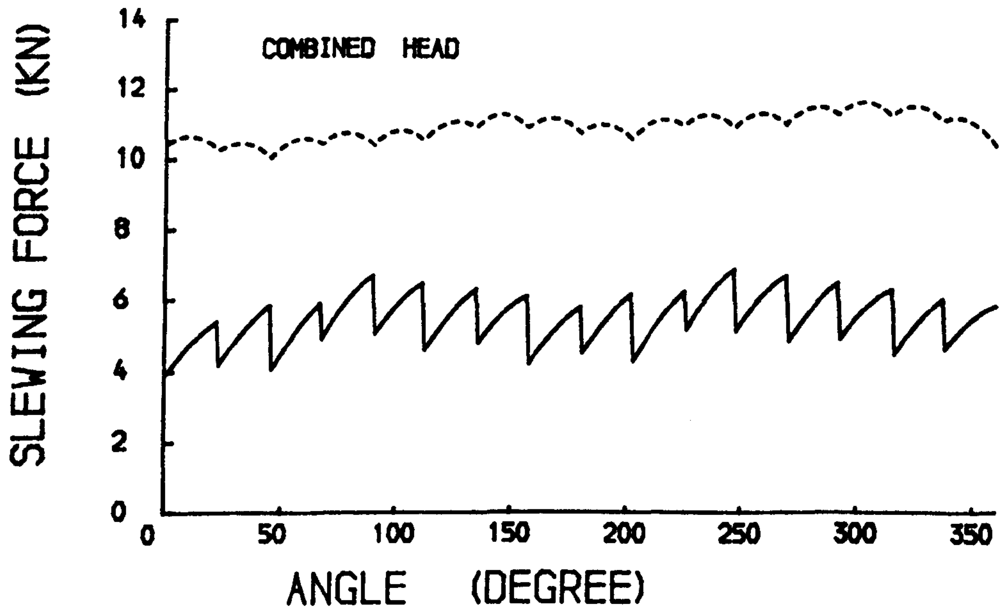


FLUCTUATIONS IN TORQUE AND SLEVING FORCE,

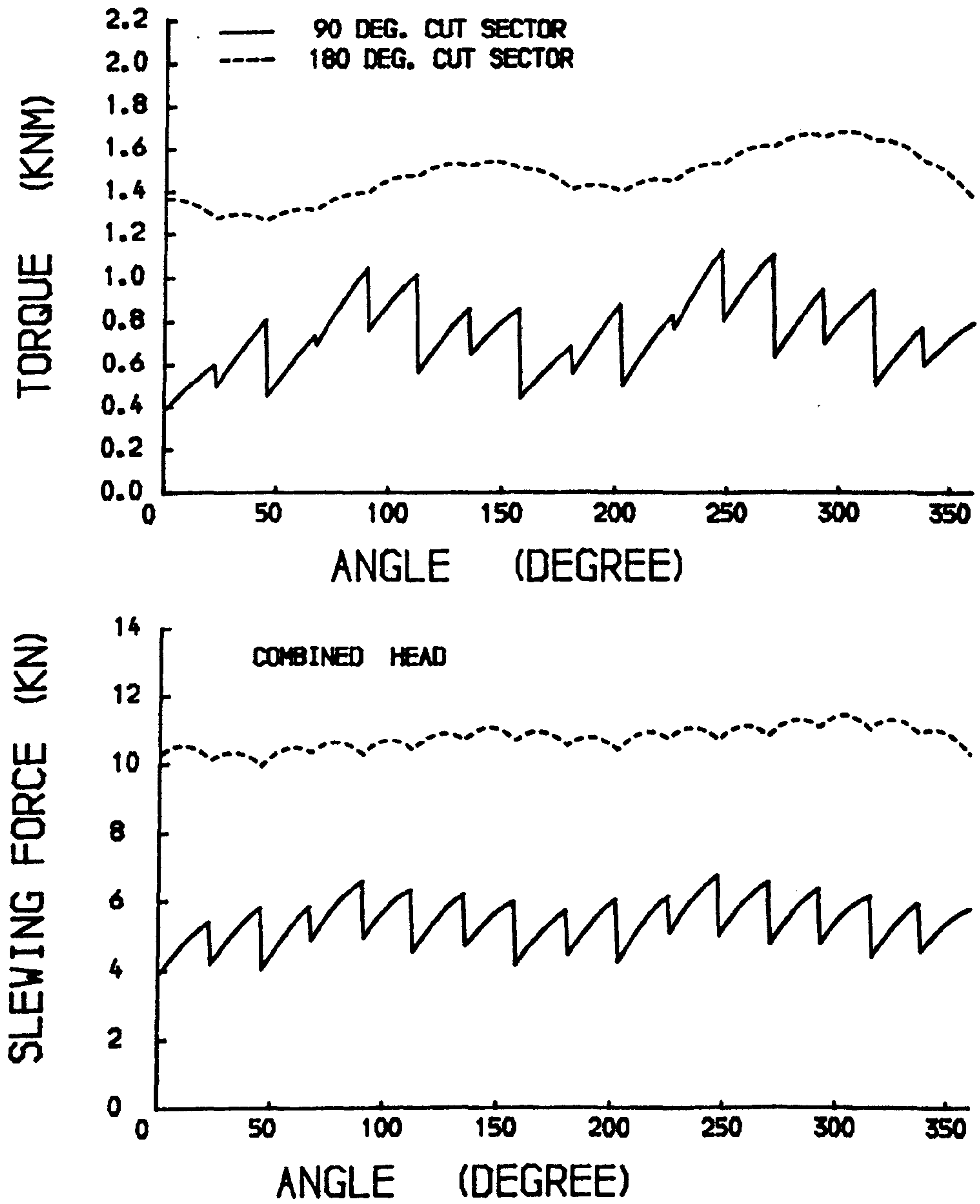
TILT ANGLE OF THE CORNER CUT. TOOL: 74.08 DEG.

CONE ANGLE OF THE CUT. HEAD : 23.15 DEG.

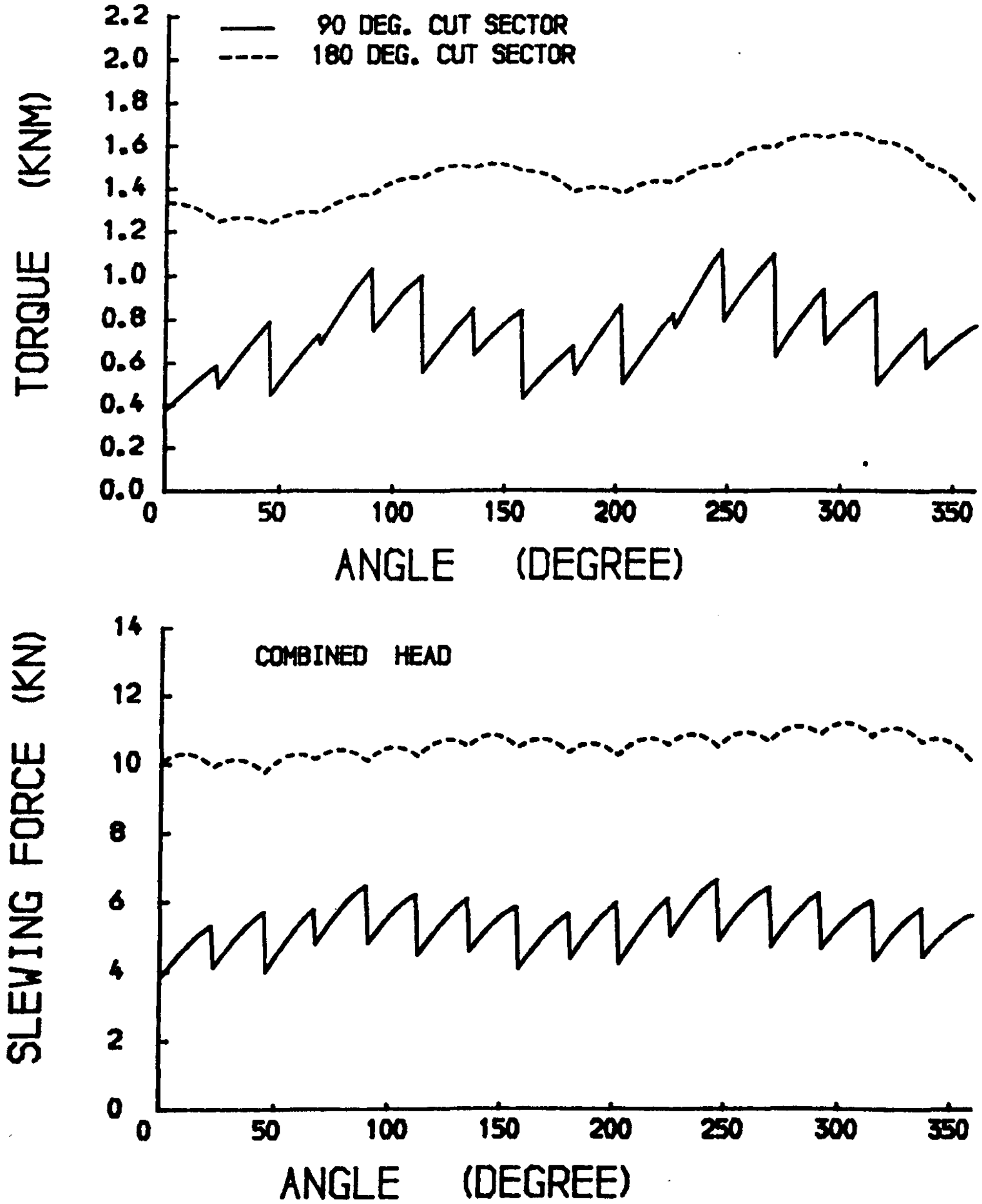




FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 74.08 DEG.
CONE ANGLE OF THE CUT. HEAD : 27.78 DEG.



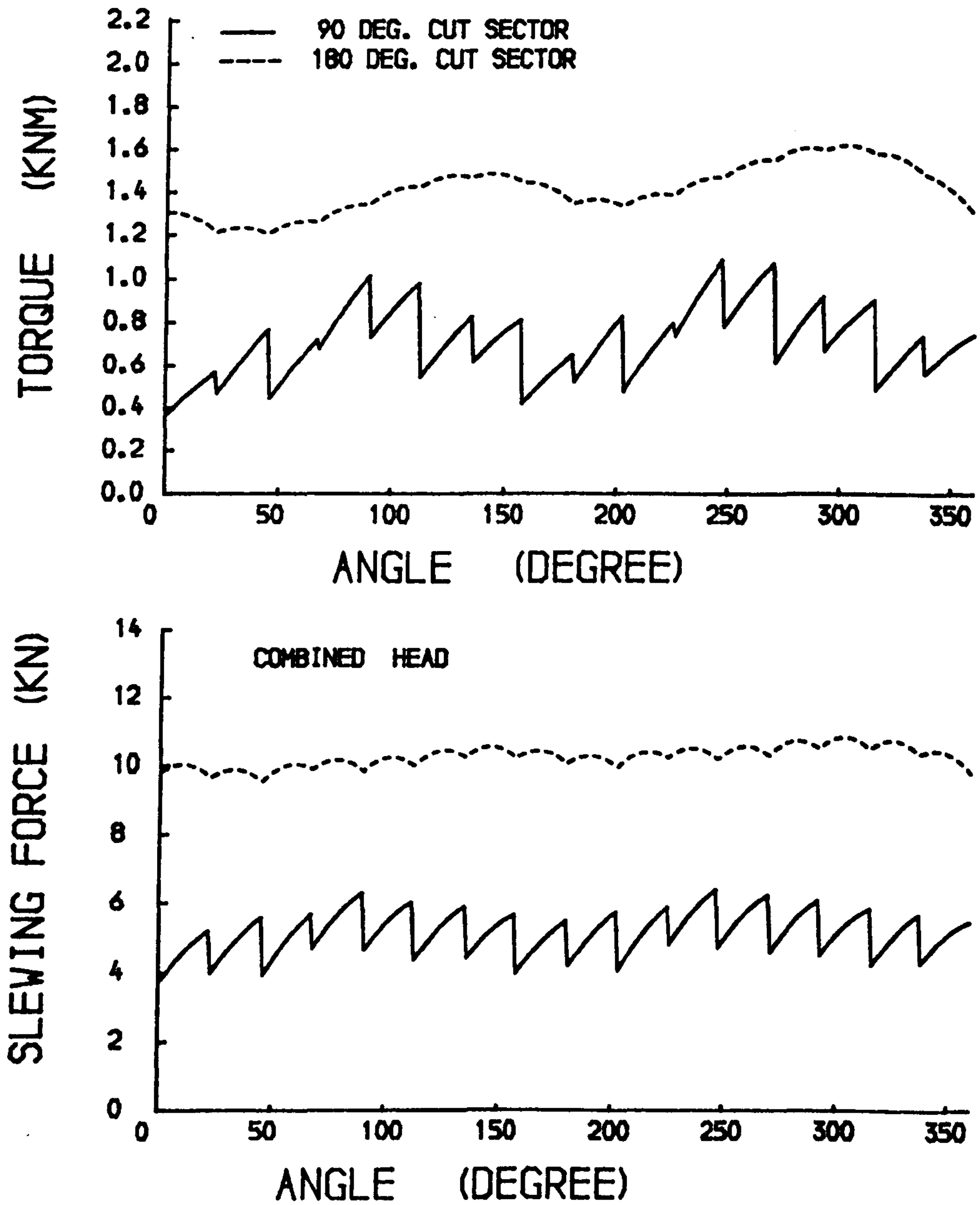
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 74.08 DEG.
CONE ANGLE OF THE CUT. HEAD : 32.41 DEG.



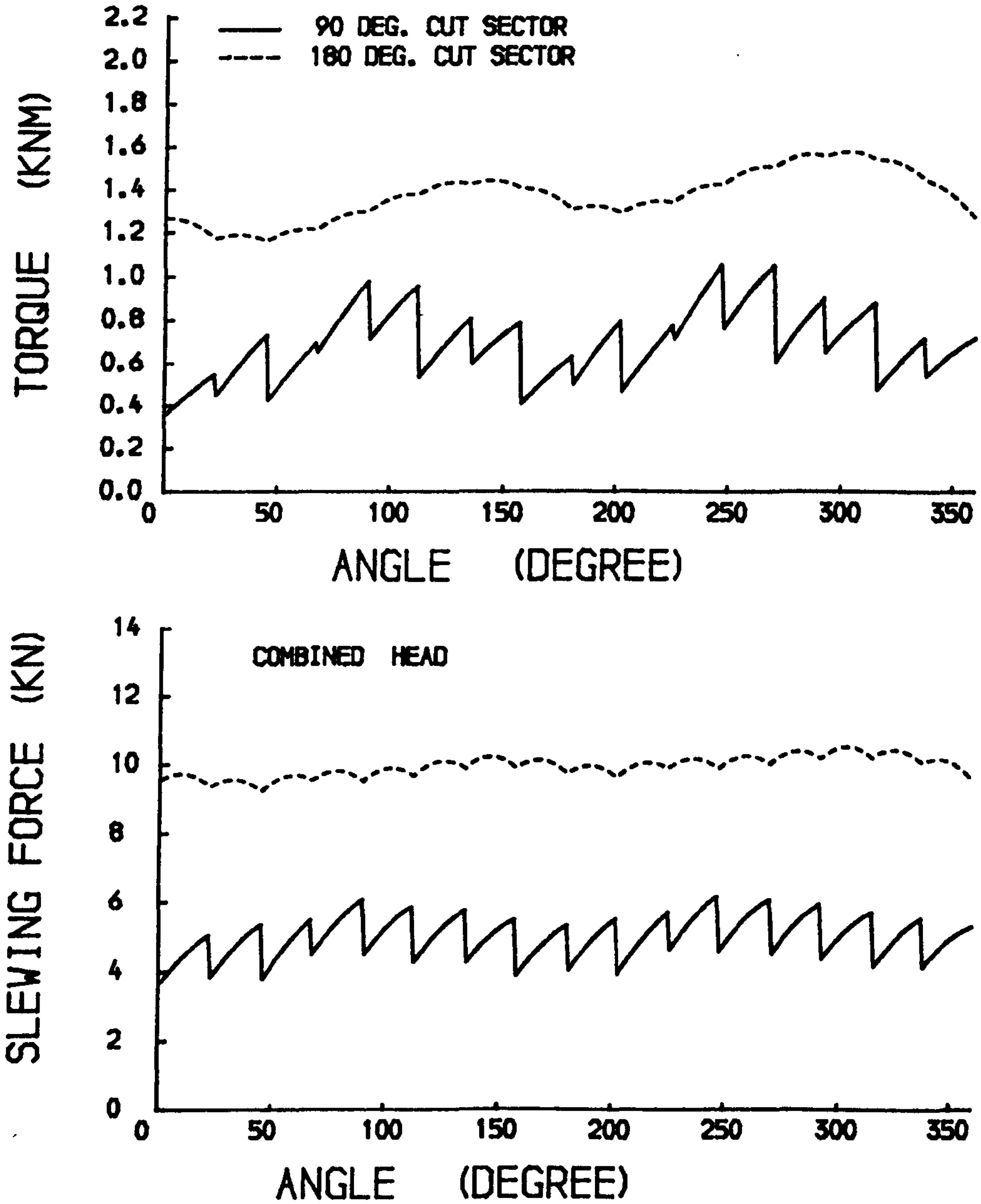
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,

TILT ANGLE OF THE CORNER CUT. TOOL: 74.08 DEG.

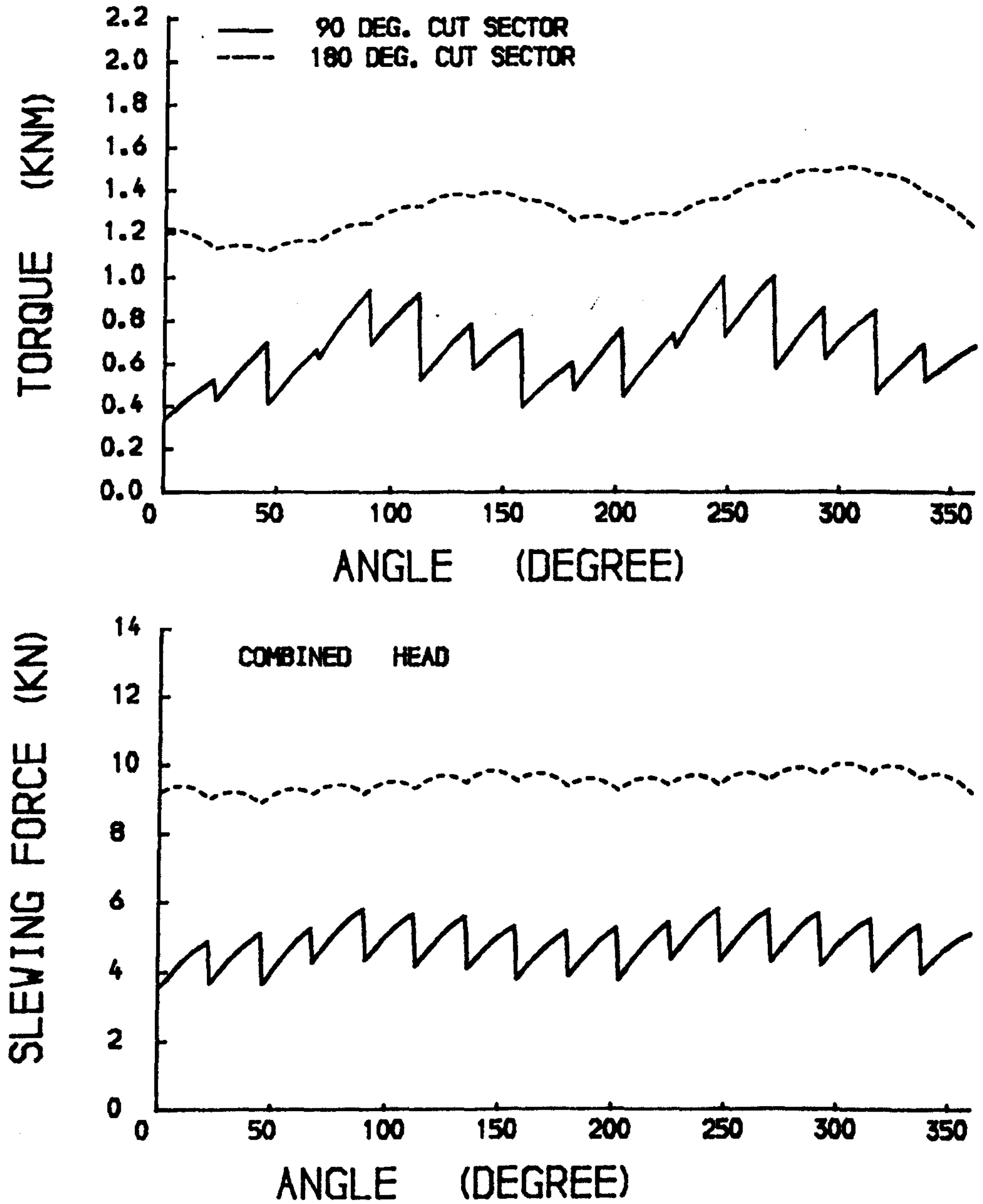
CONE ANGLE OF THE CUT. HEAD : 37.04 DEG.



FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 74.08 DEG.
CONE ANGLE OF THE CUT. HEAD : 41.67 DEG.



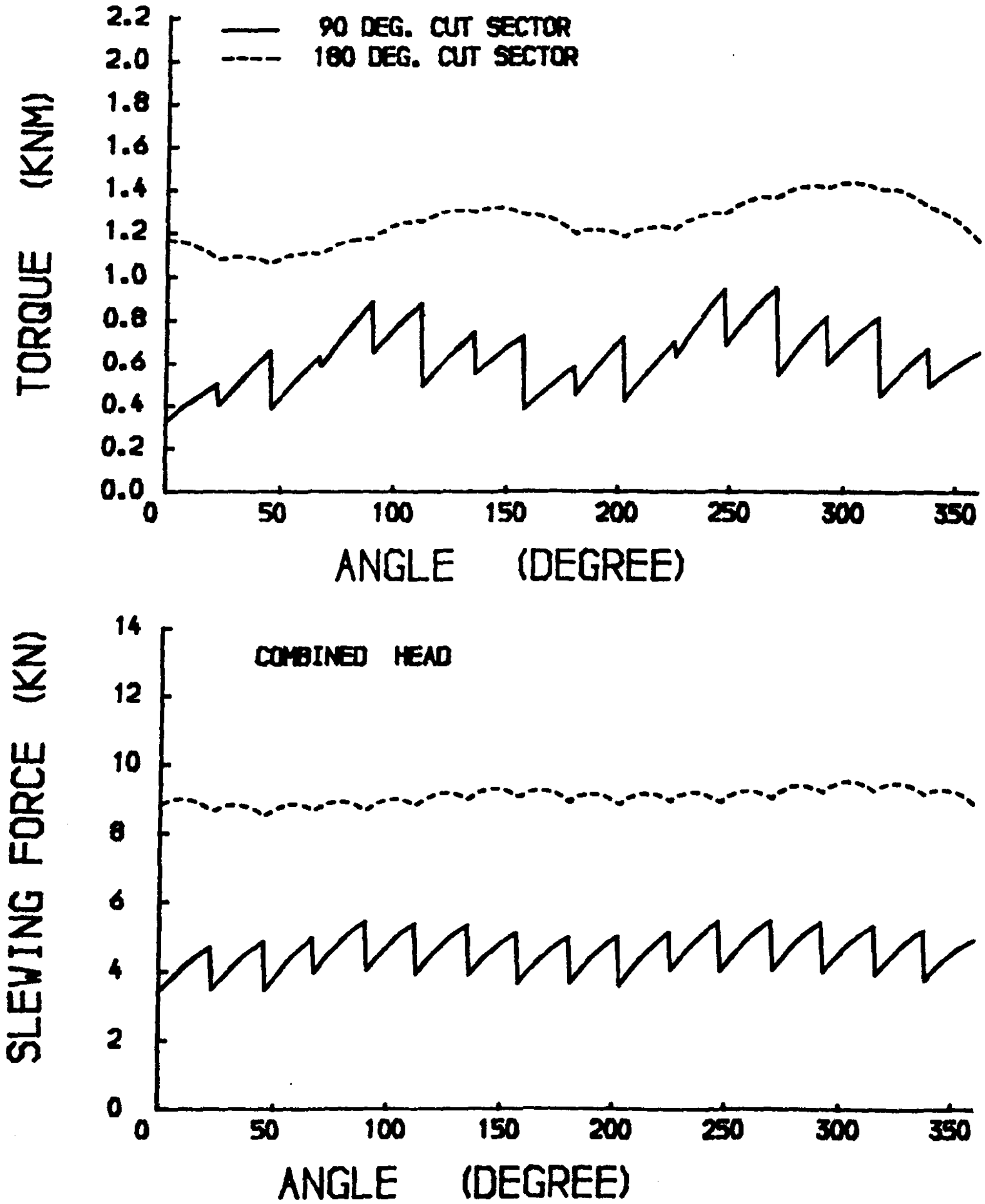
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 74.08 DEG.
CONE ANGLE OF THE CUT. HEAD : 46.30 DEG.



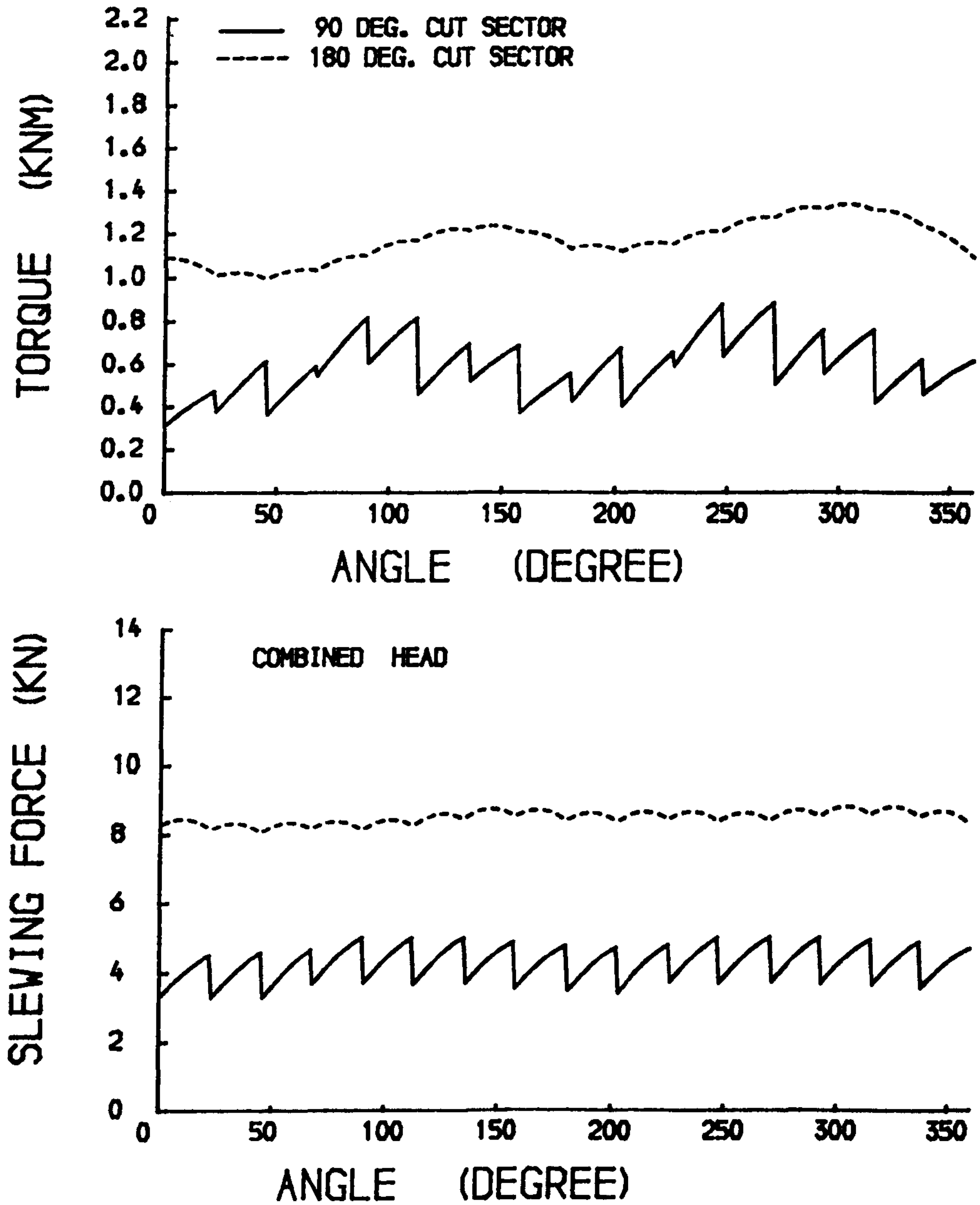
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,

TILT ANGLE OF THE CORNER CUT. TOOL: 74.08 DEG.

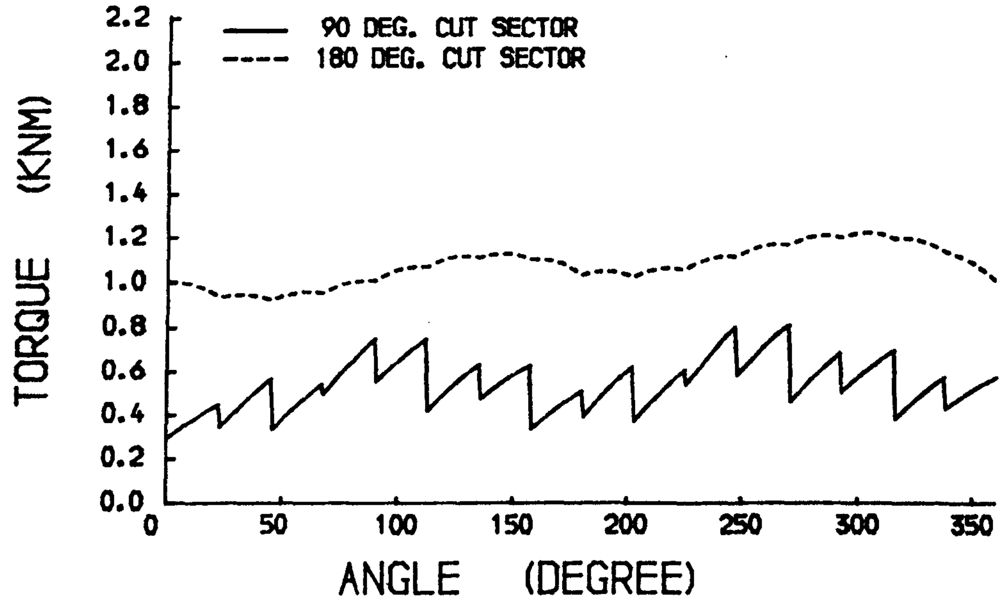
CONE ANGLE OF THE CUT. HEAD : 50.93 DEG.

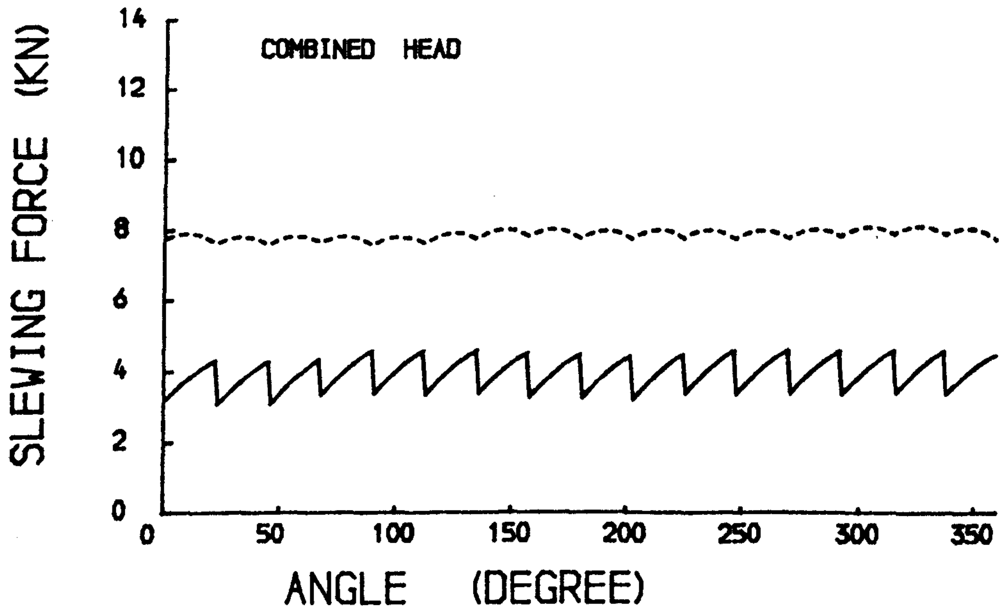


FLUCTUATIONS IN TORQUE AND SLEVING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 74.08 DEG.
CONE ANGLE OF THE CUT. HEAD : 55.56 DEG.

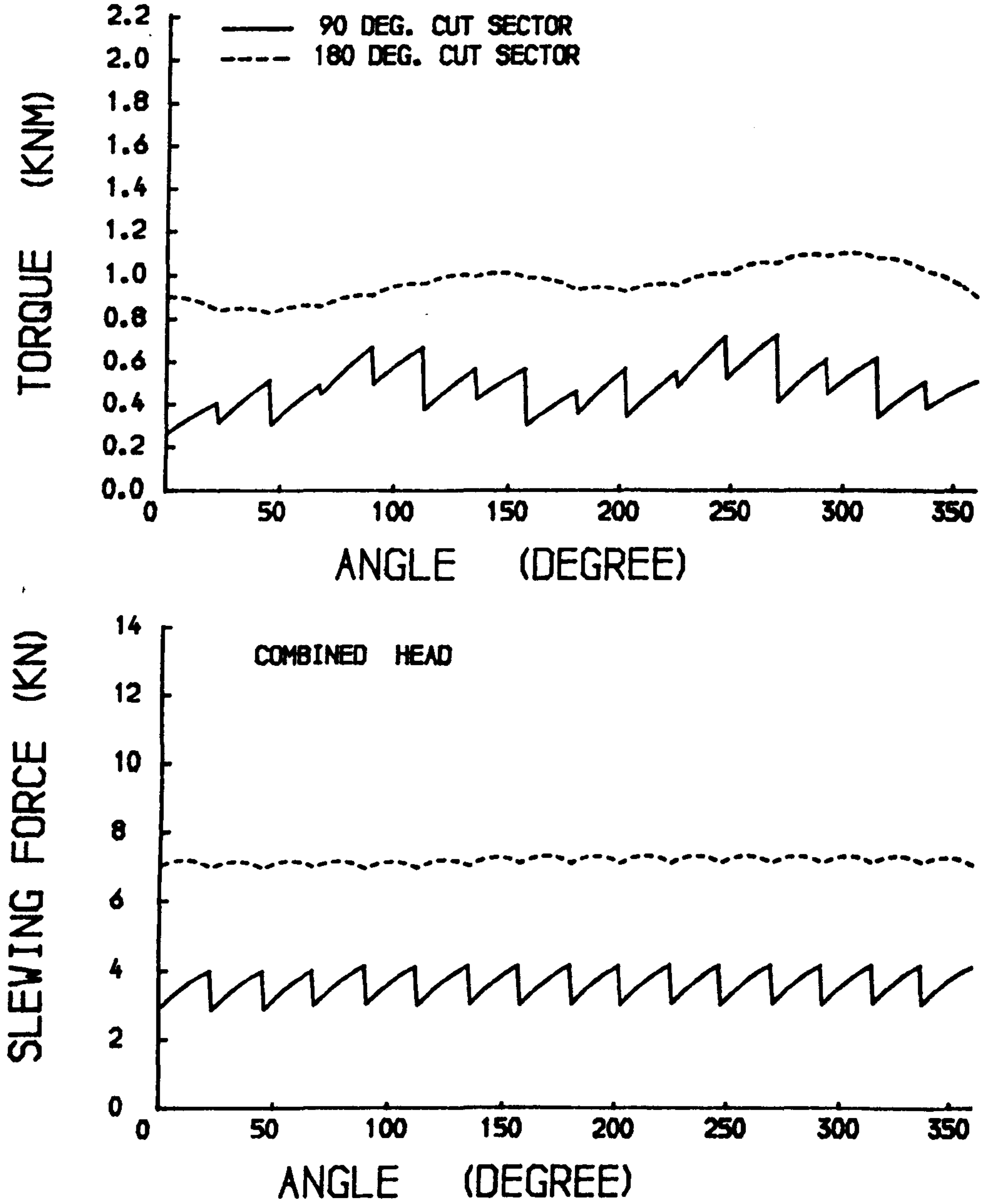


FLUCTUATIONS IN TORQUE AND SLEVING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 74.08 DEG.
CONE ANGLE OF THE CUT. HEAD : 60.19 DEG.

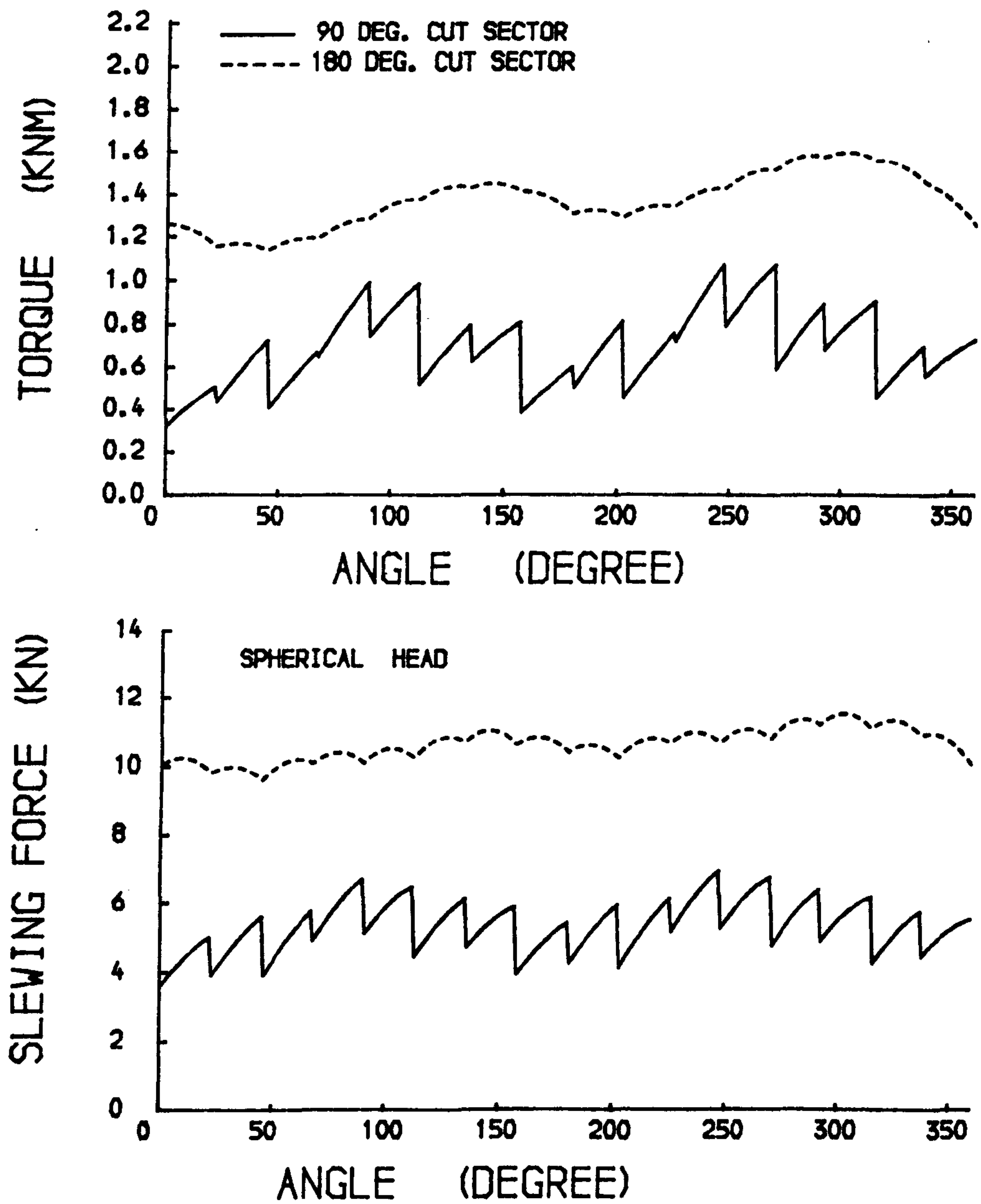




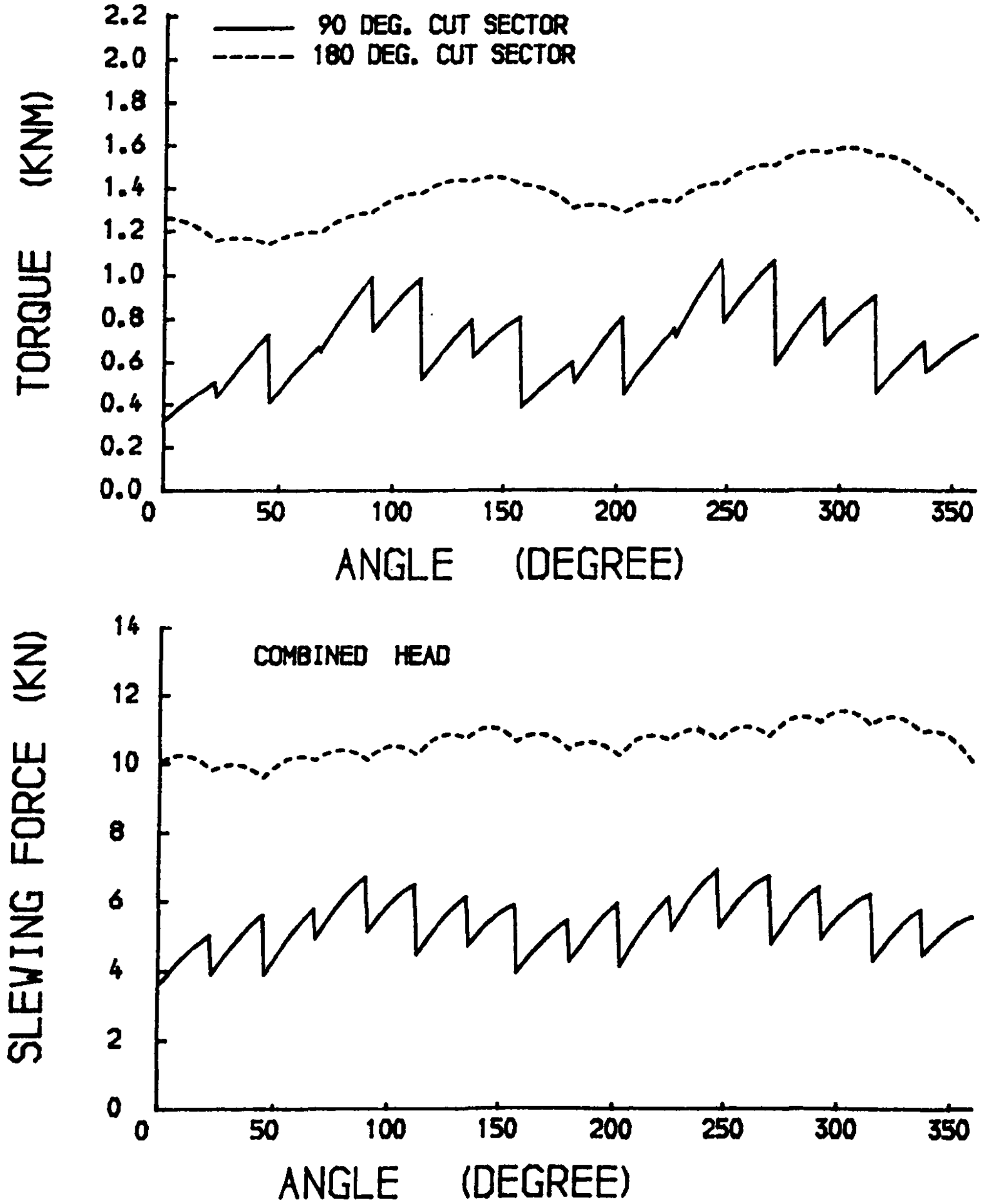
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 74.08 DEG.
CONE ANGLE OF THE CUT. HEAD : 64.82 DEG.



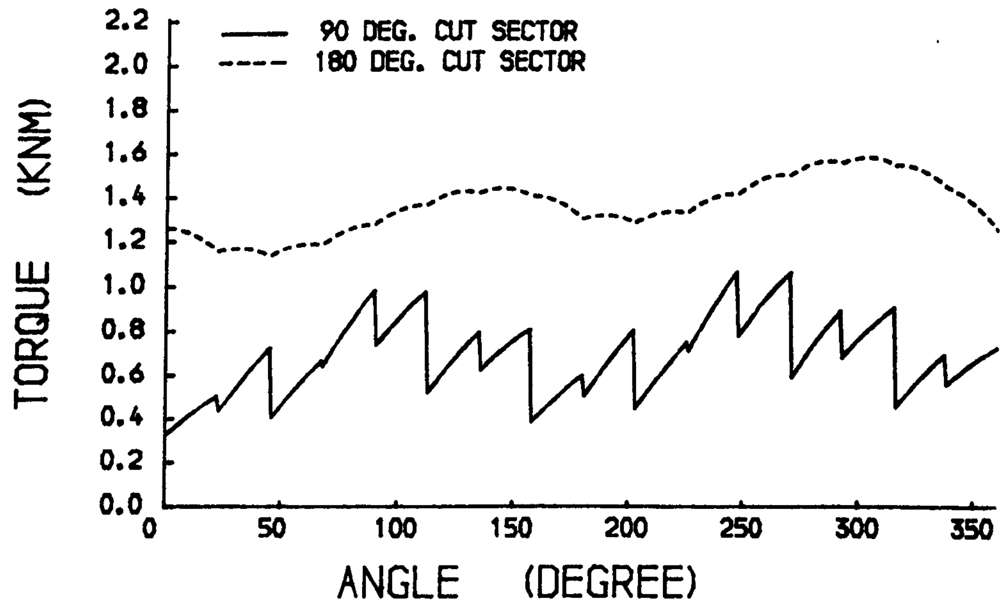
FLUCTUATIONS IN TORQUE AND SLEVING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 74.08 DEG.
CONE ANGLE OF THE CUT. HEAD : 69.45 DEG.

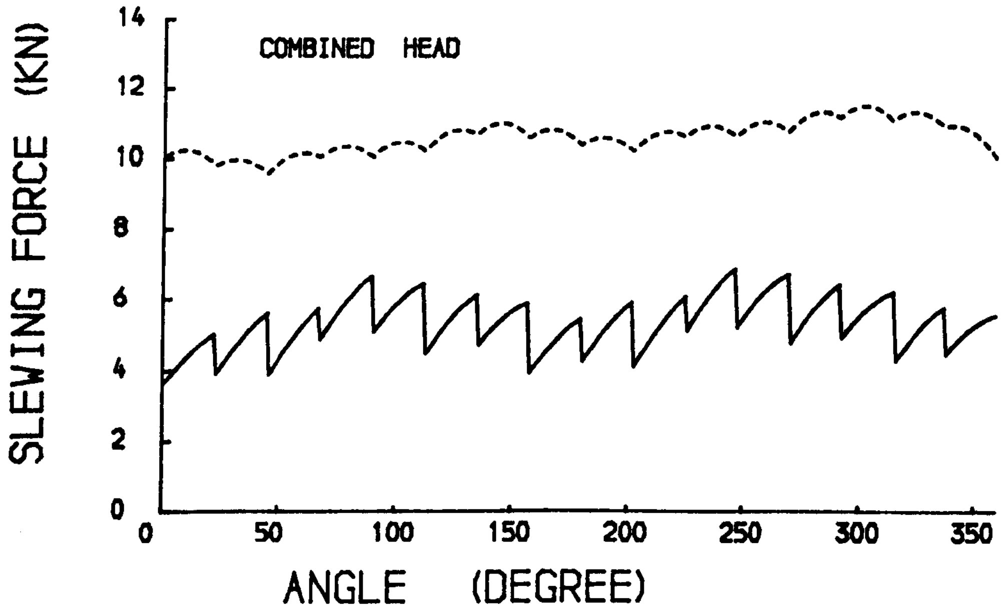


FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 78.71 DEG.
TILT ANGLE OF THE FIRST TOOL : 09.26 DEG.

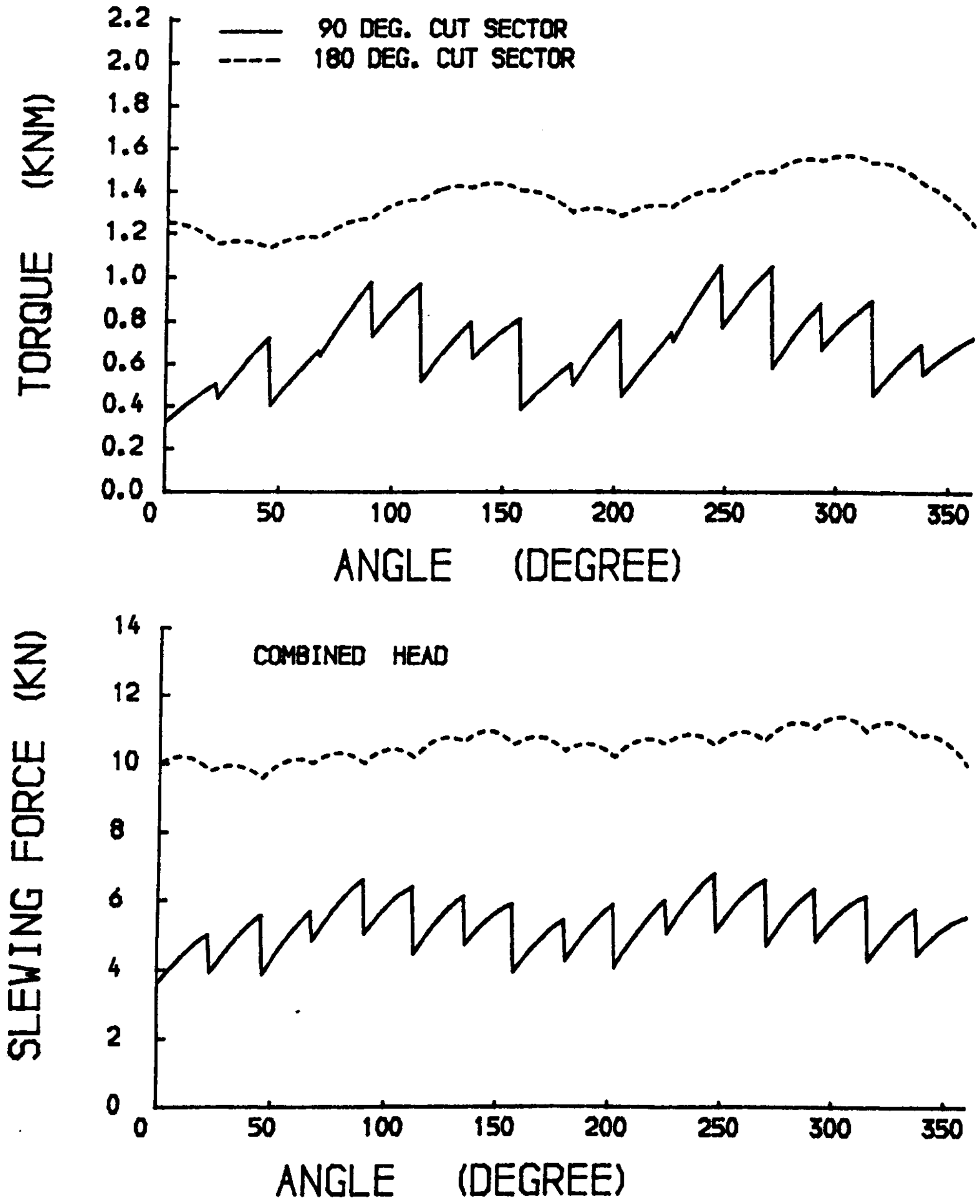


FLUCTUATIONS IN TORQUE AND SLEVING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 78.71 DEG.
CONE ANGLE OF THE CUT. HEAD : 13.89 DEG.

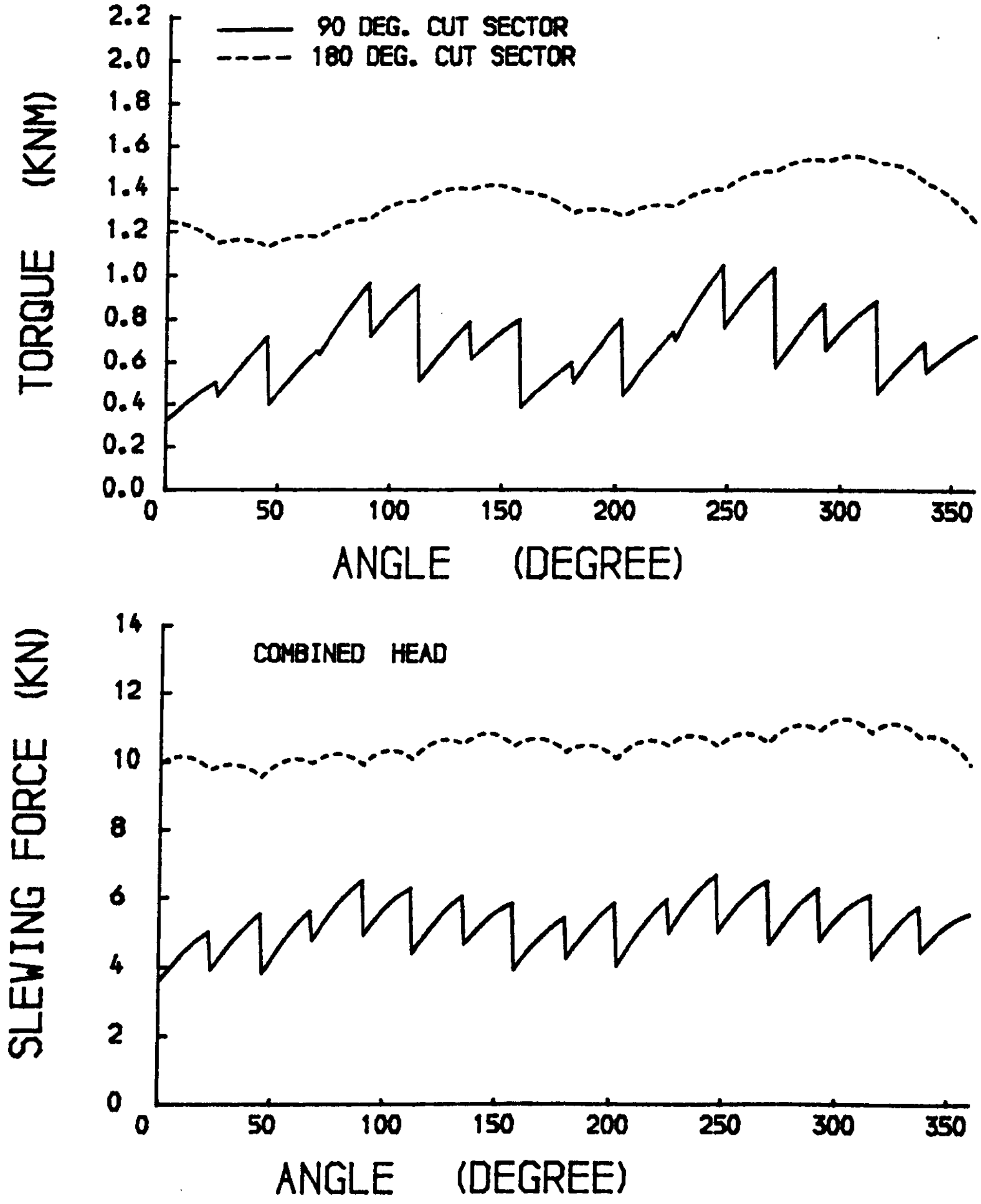




FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 78.71 DEG.
CONE ANGLE OF THE CUT. HEAD : 18.52 DEG.



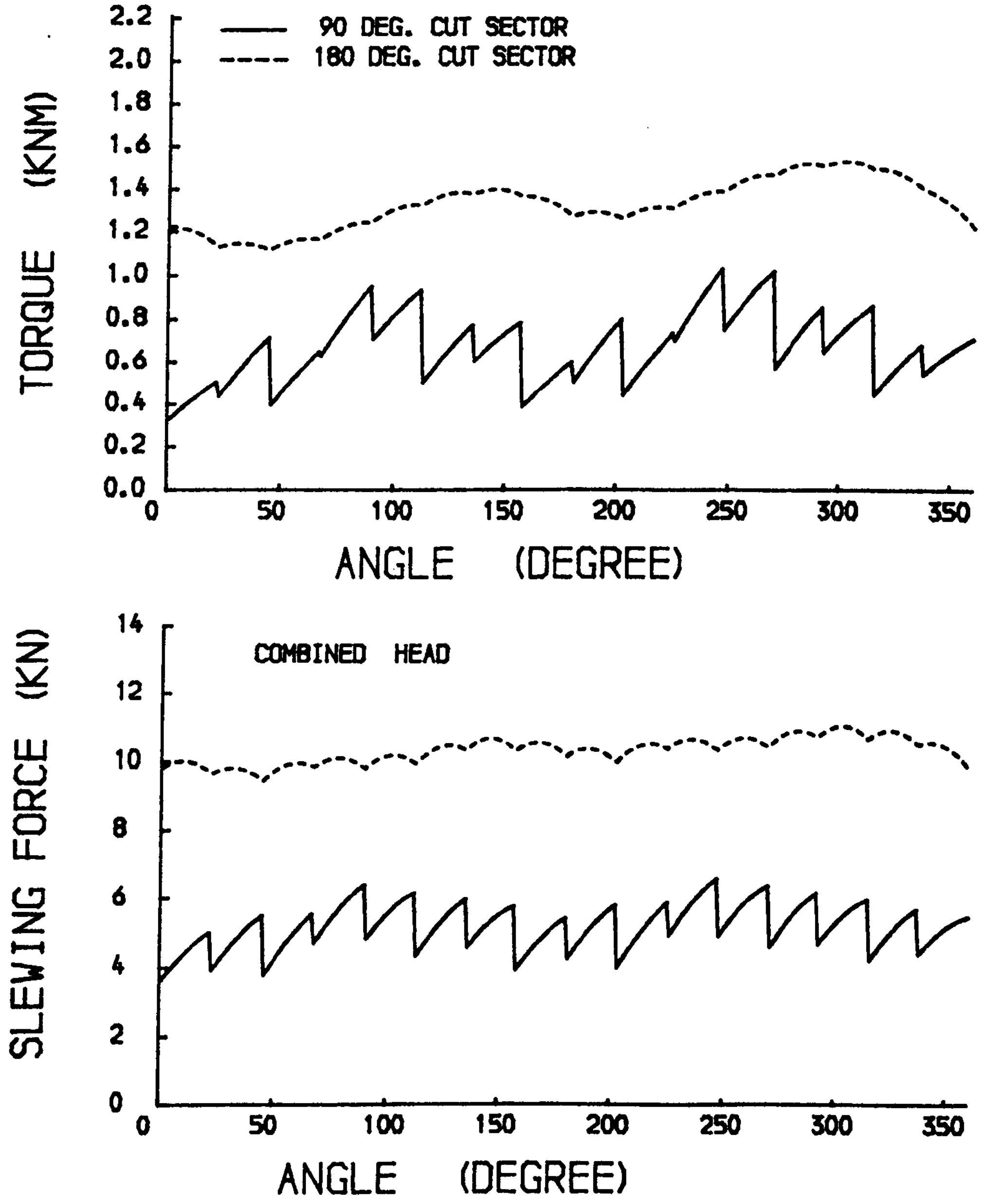
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 78.71 DEG.
CONE ANGLE OF THE CUT. HEAD : 23.15 DEG.



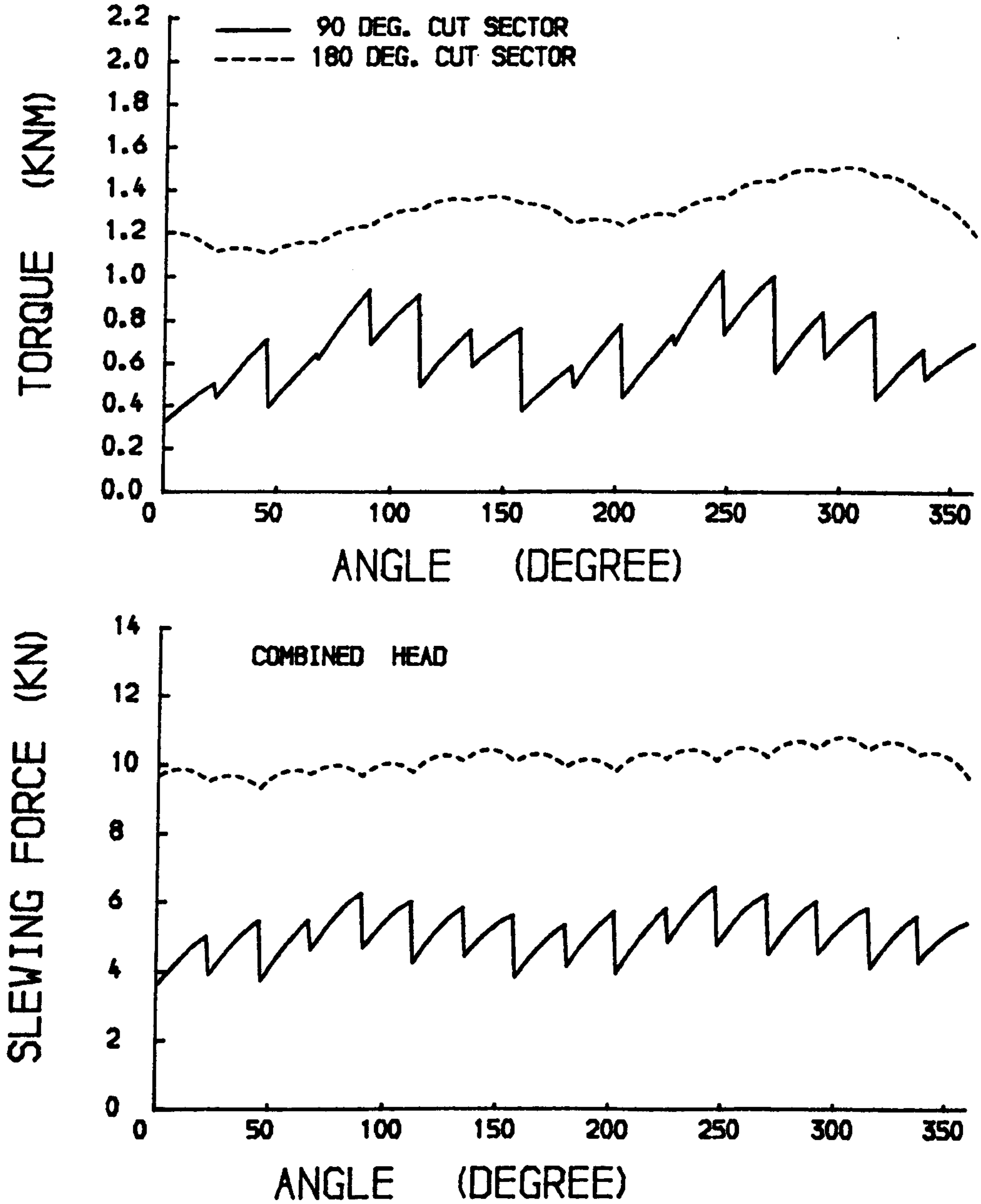
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,

TILT ANGLE OF THE CORNER CUT. TOOL: 78.71 DEG.

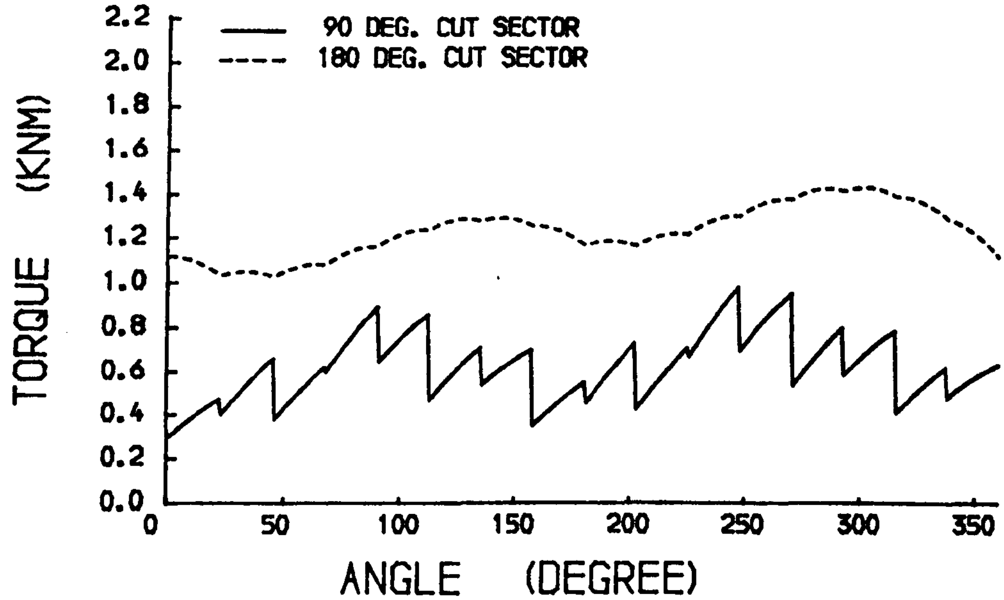
CONE ANGLE OF THE CUT. HEAD : 27.78 DEG.

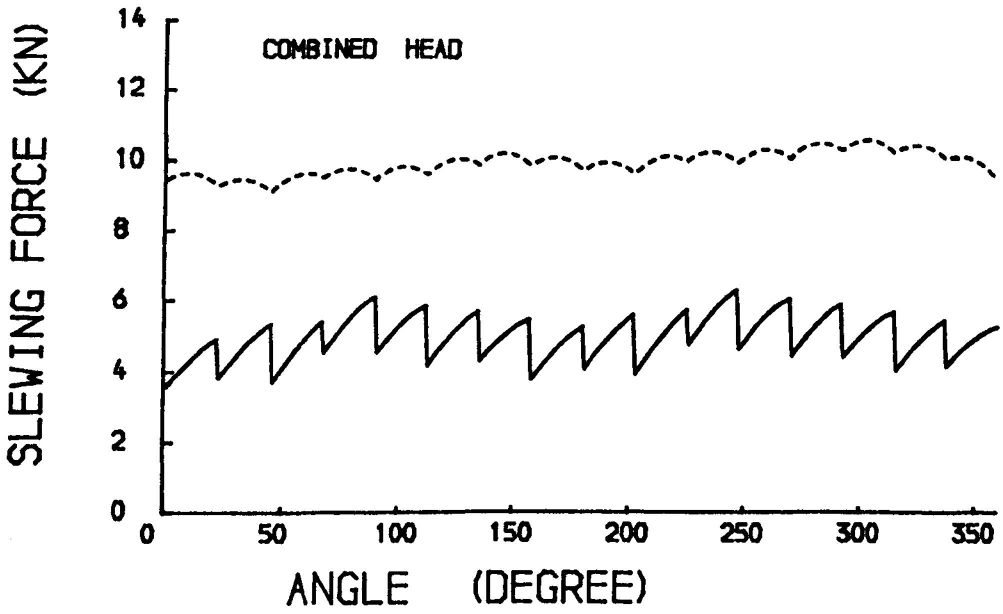


FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 78.71 DEG.
CONE ANGLE OF THE CUT. HEAD : 32.41 DEG.

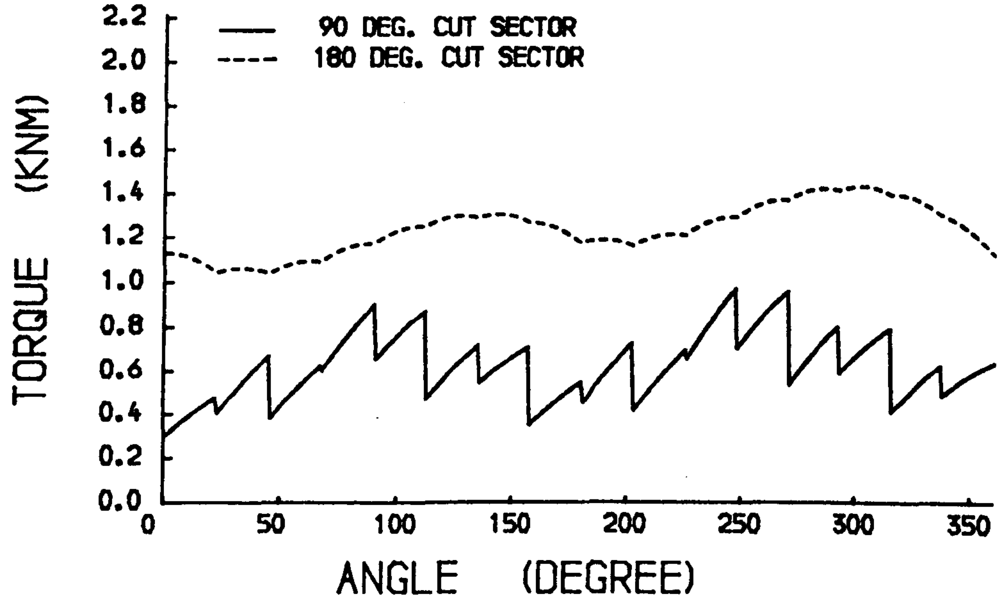


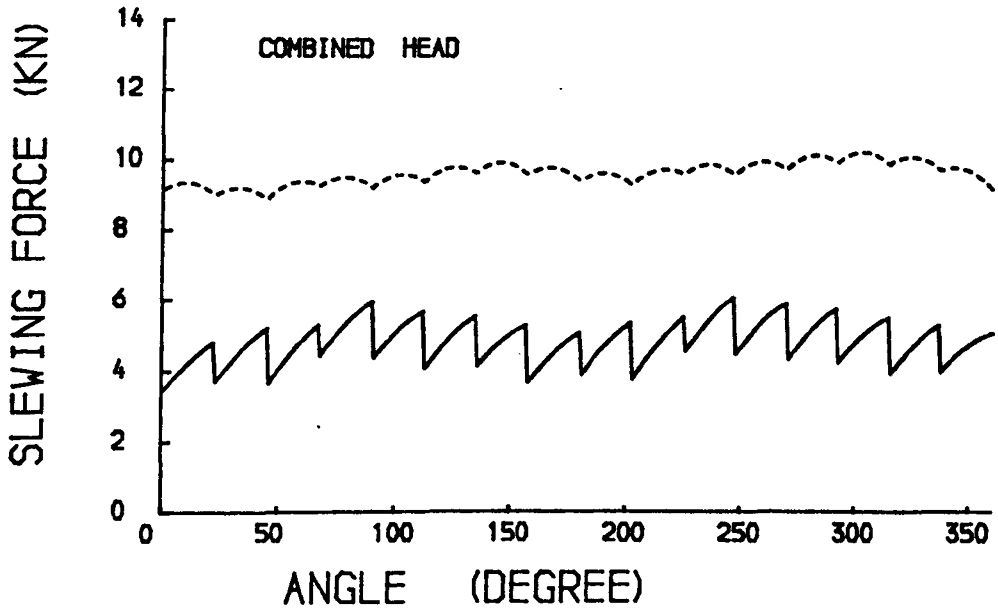
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 78.71 DEG.
CONE ANGLE OF THE CUT. HEAD : 37.04 DEG.



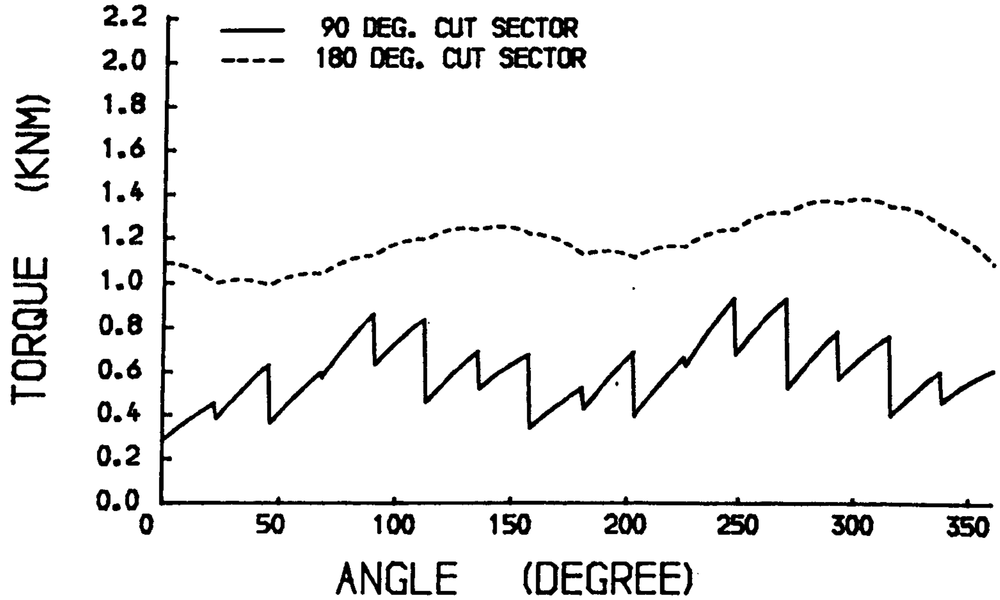


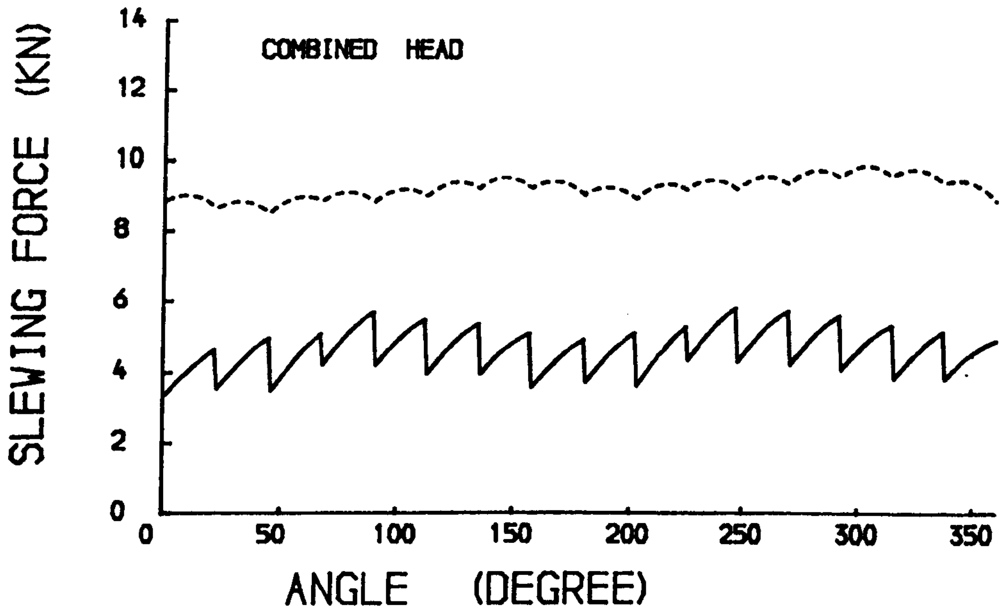
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 78.71 DEG.
CONE ANGLE OF THE CUT. HEAD : 41.65 DEG.



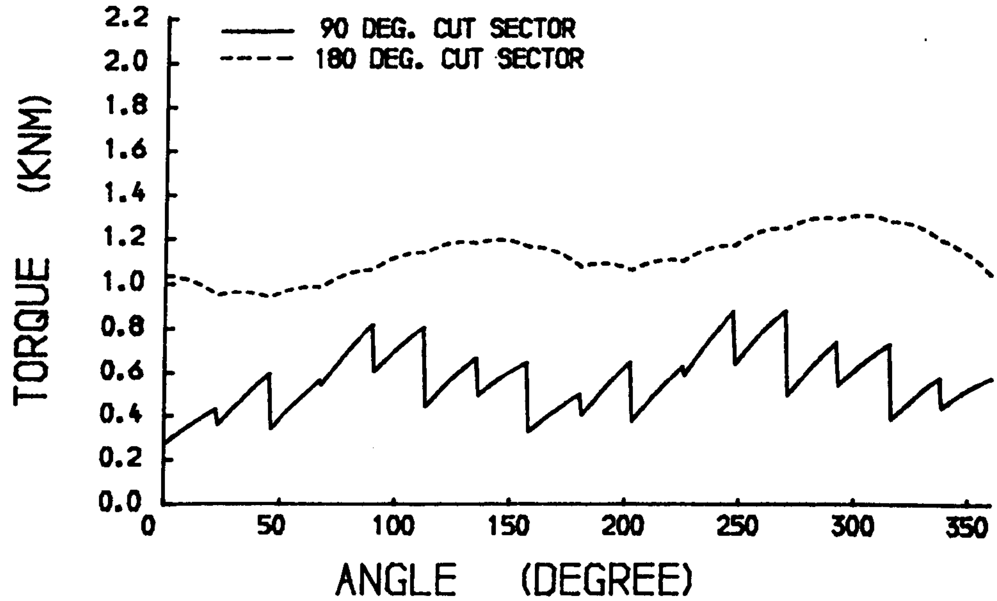


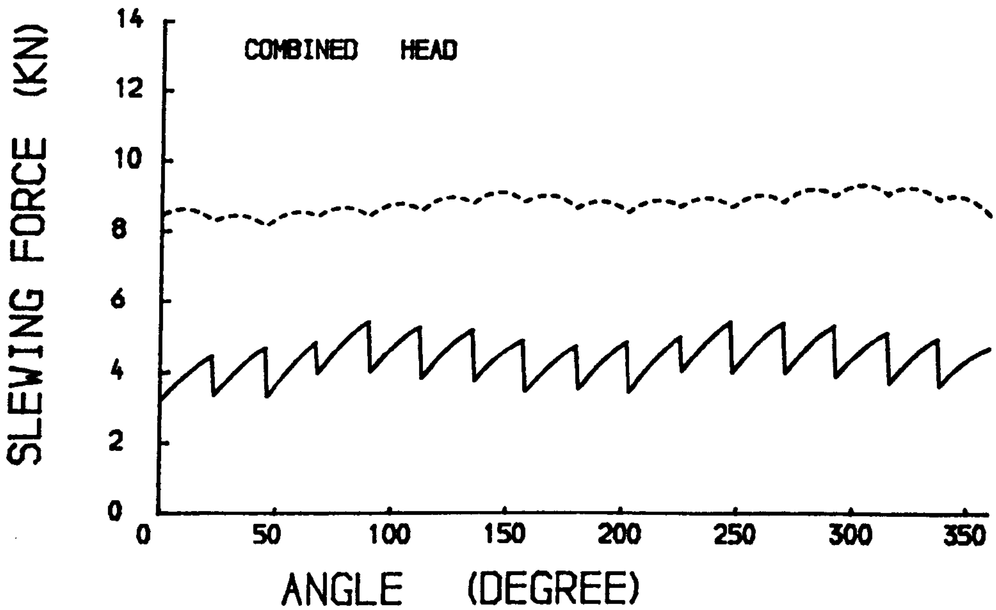
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL. 78.71 DEG.
CONE ANGLE OF THE CUT. HEAD . 46.30 DEG.



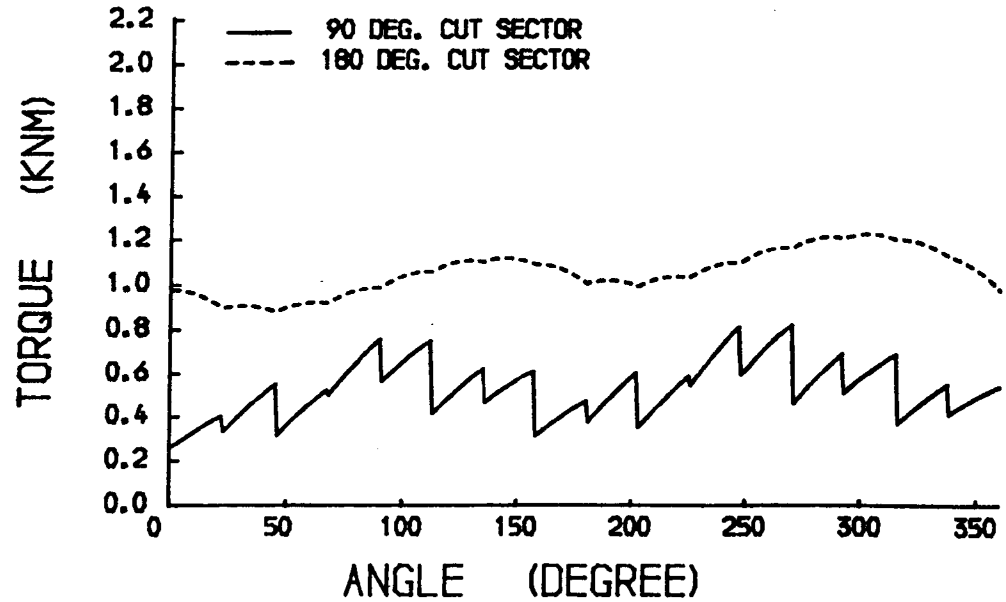


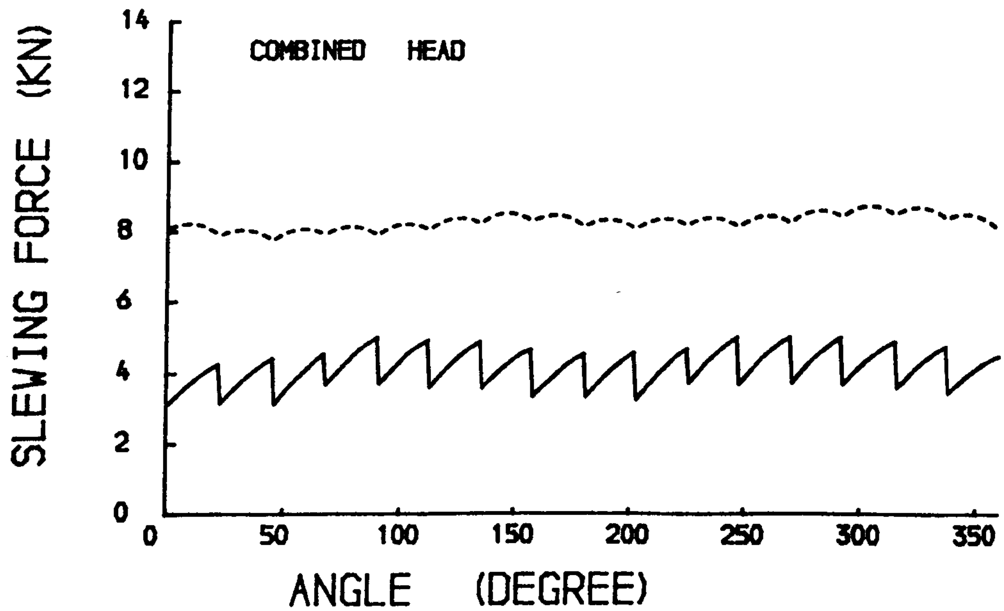
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 78.71 DEG.
CONE ANGLE OF THE CUT. HEAD : 50.93 DEG.



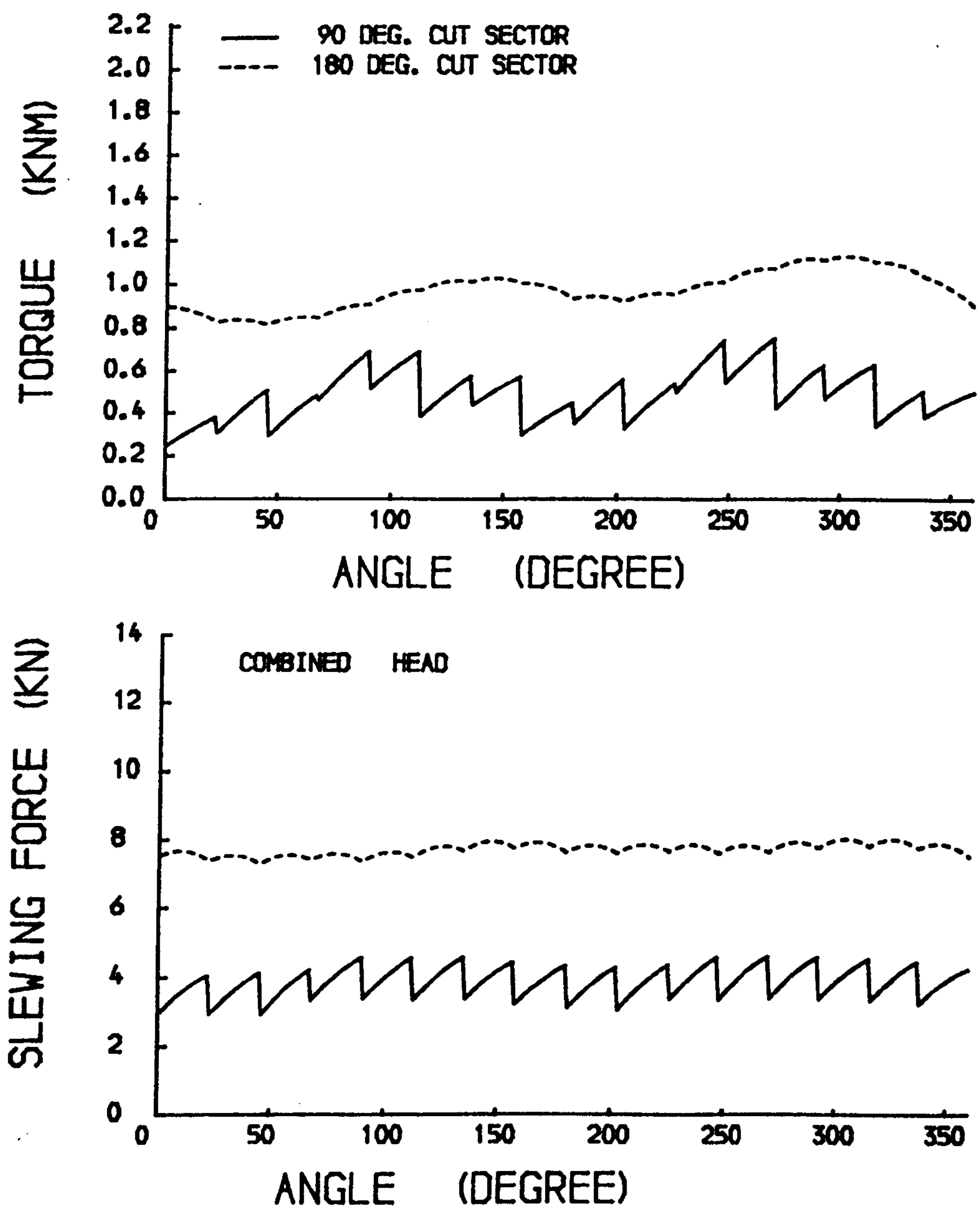


FLUCTUATIONS IN TORQUE AND SLEVING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 78.71 DEG.
CONE ANGLE OF THE CUT. HEAD : 55.56 DEG.

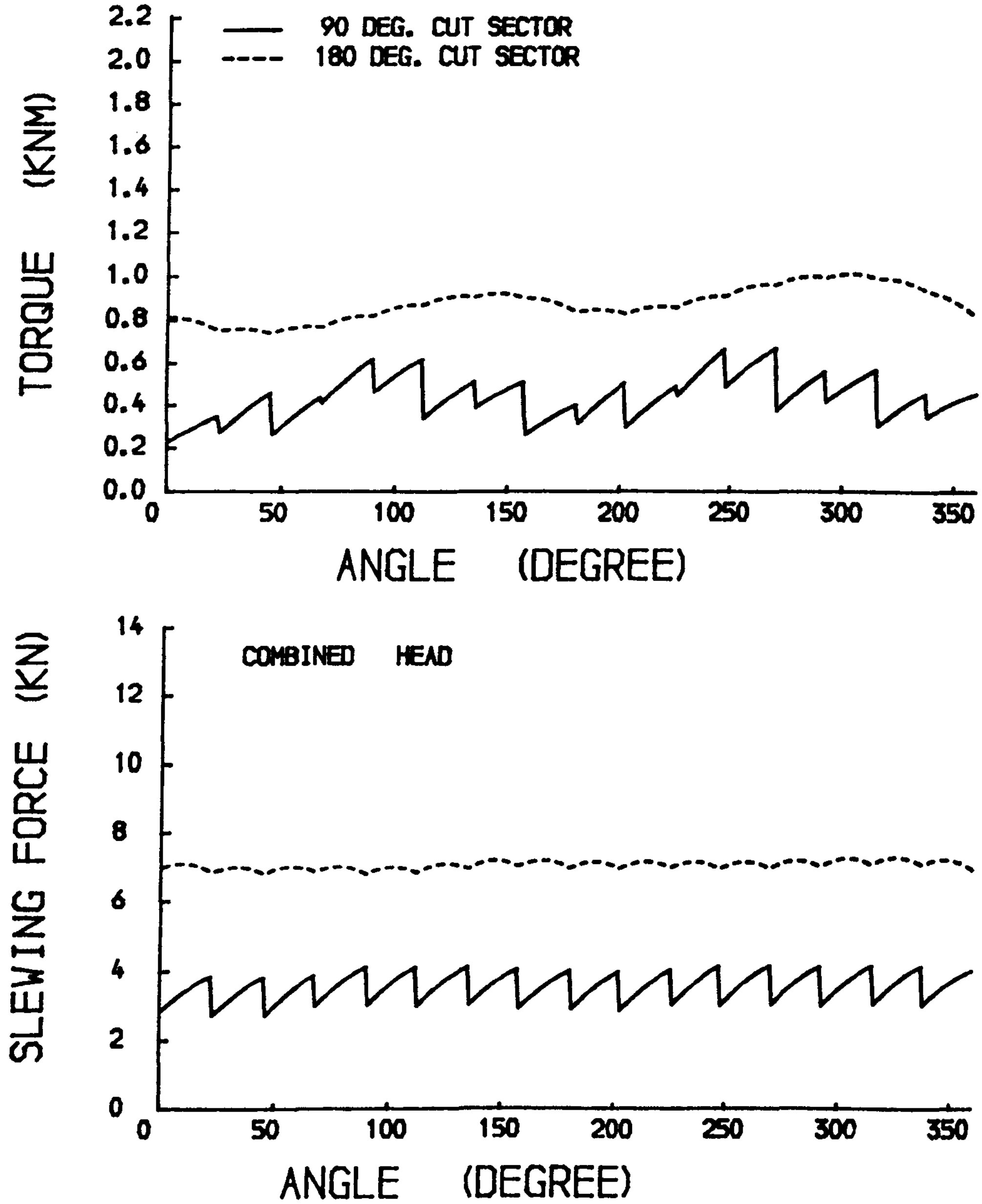




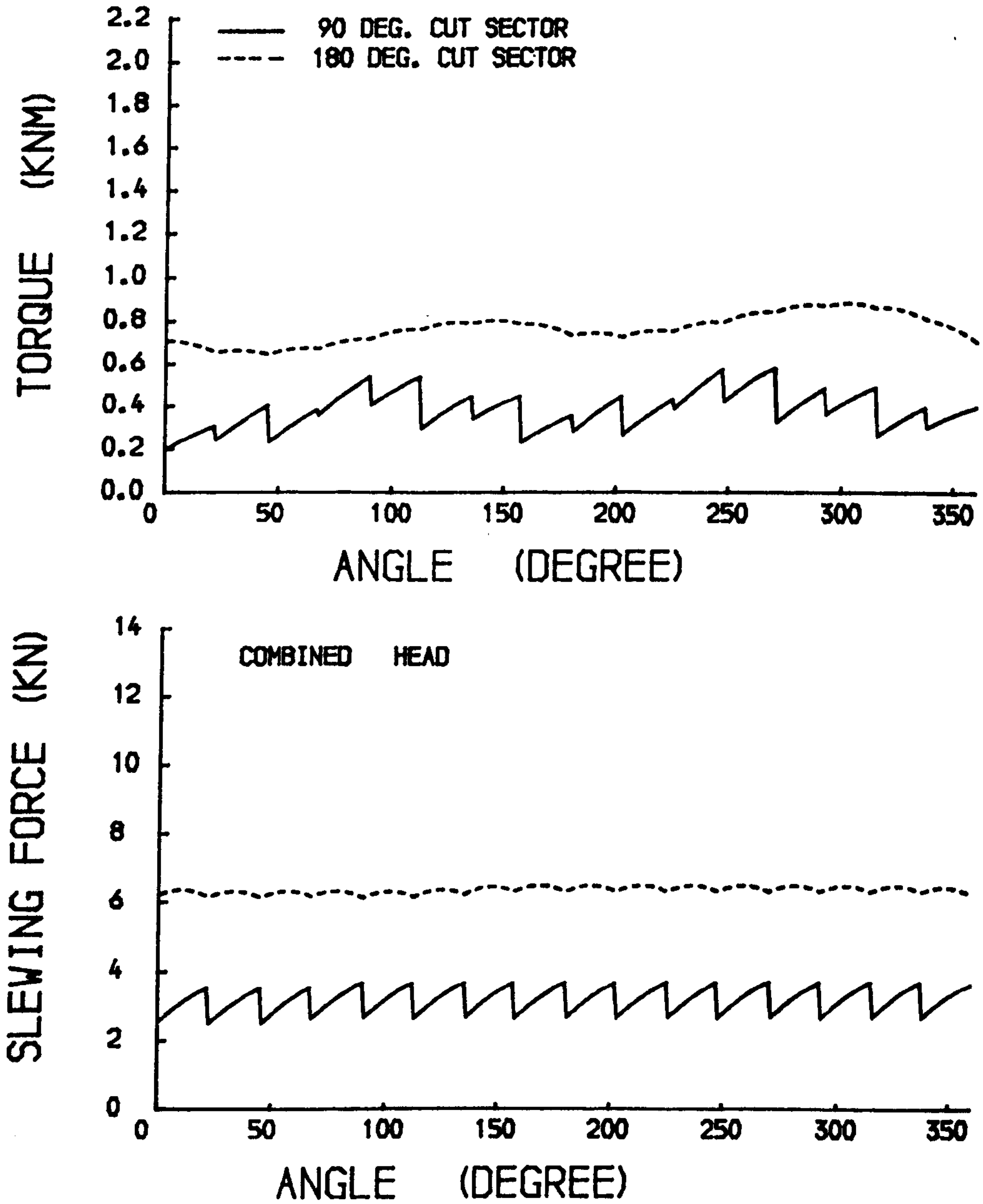
FLUCTUATIONS IN TORQUE AND SLEVING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 78.71 DEG.
CONE ANGLE OF THE CUT. HEAD : 60.19 DEG.



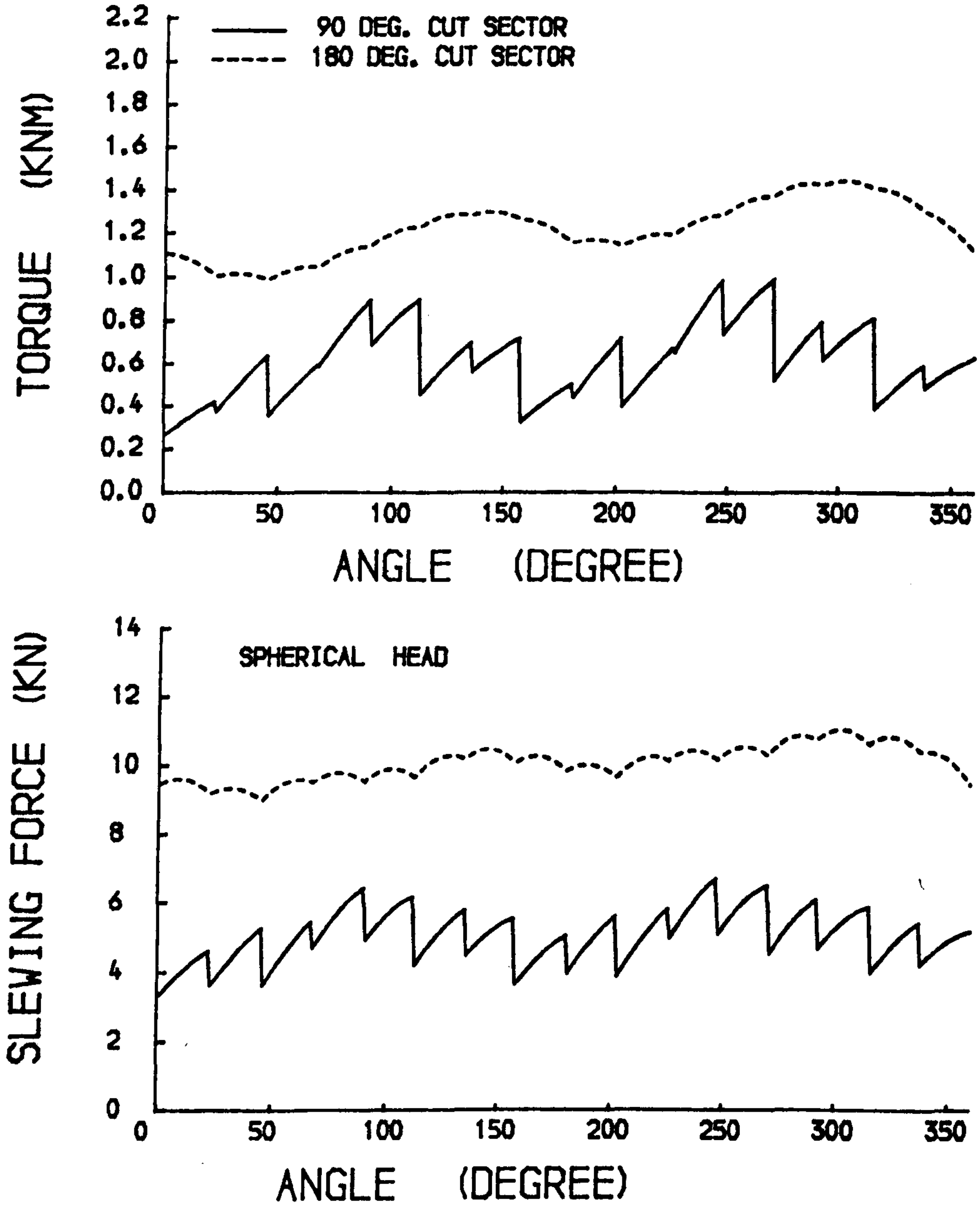
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 78.71 DEG.
CONE ANGLE OF THE CUT. HEAD : 64.82 DEG.



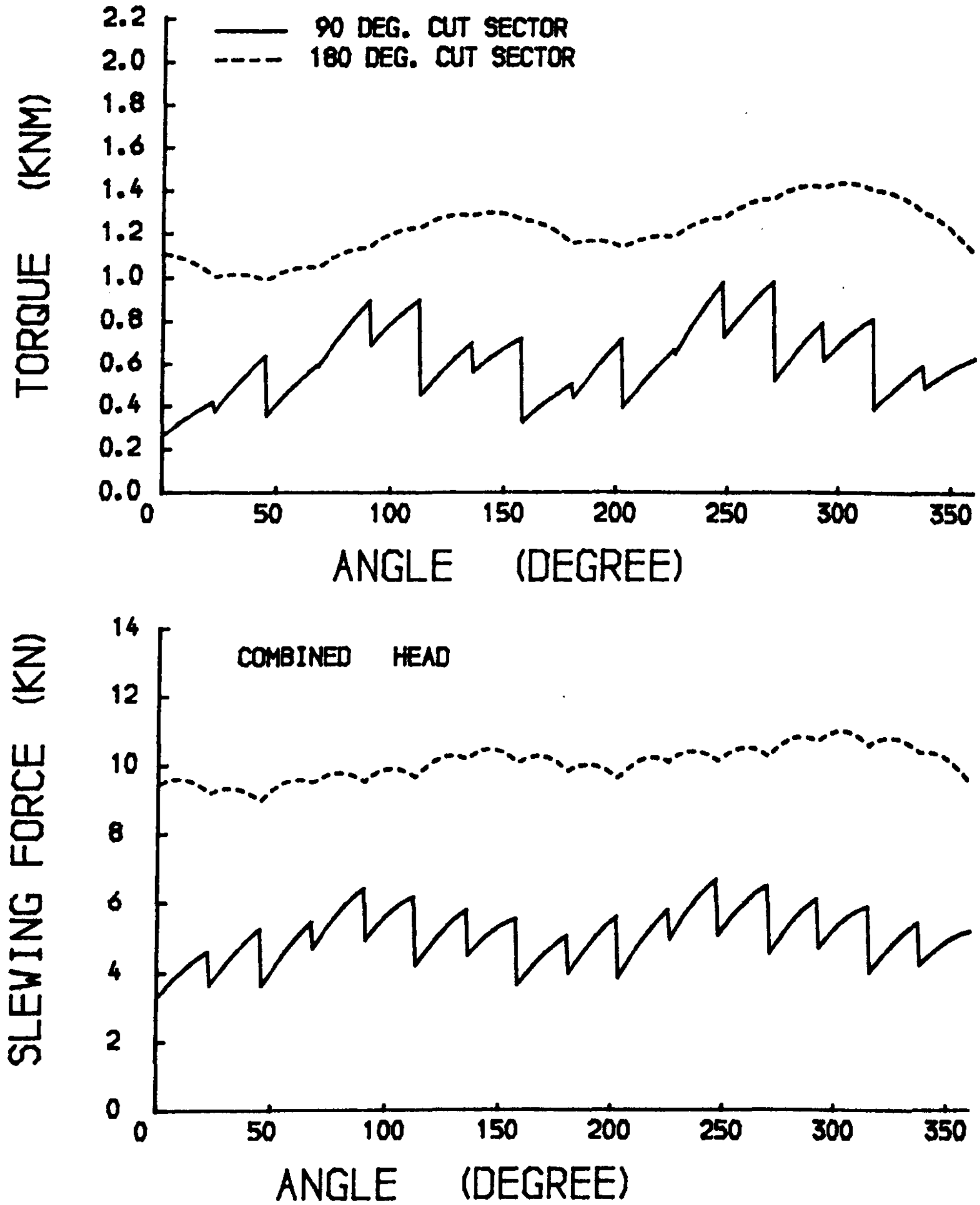
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 78.71 DEG.
CONE ANGLE OF THE CUT. HEAD : 69.45 DEG.



FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 78.71 DEG.
CONE ANGLE OF THE CUT. HEAD : 74.08 DEG.



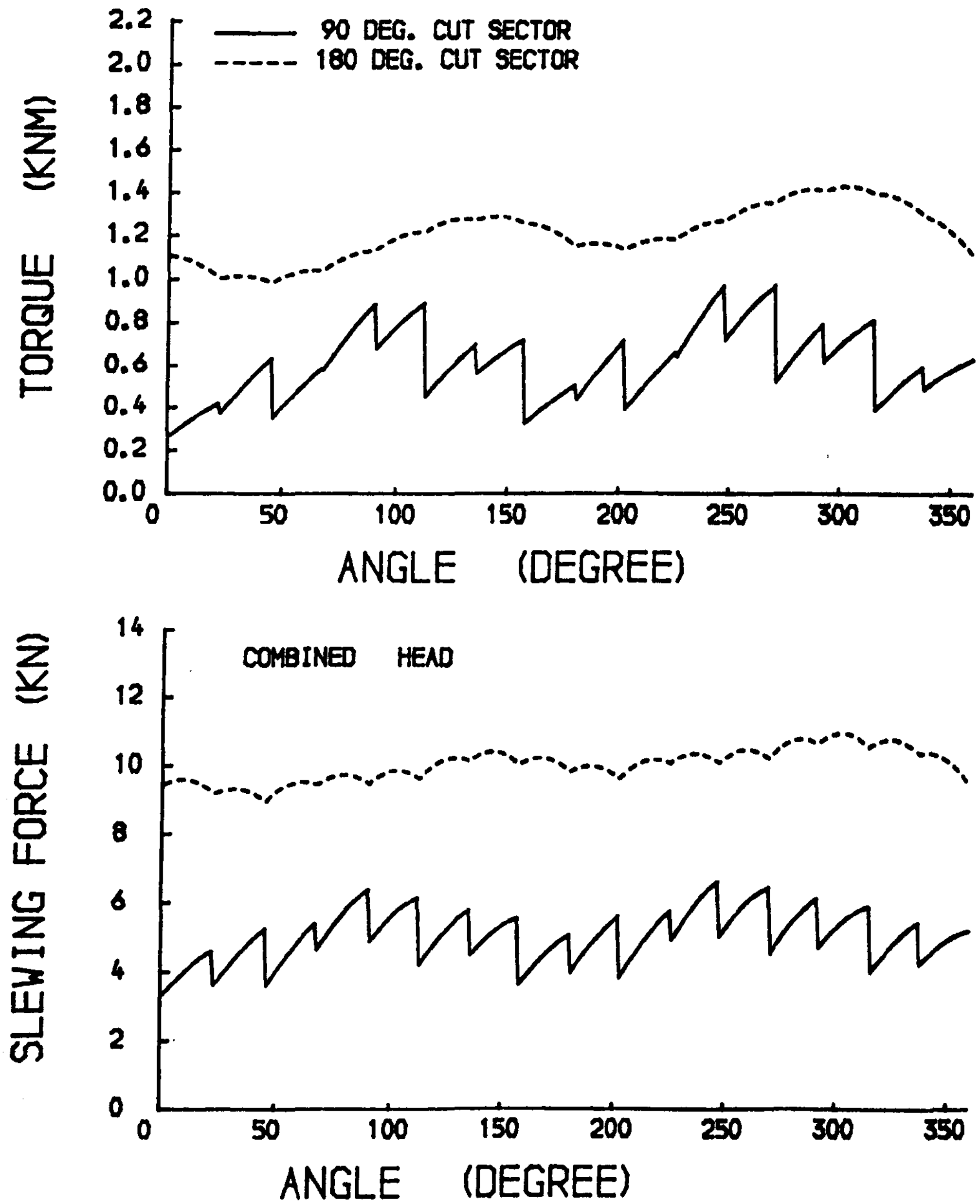
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 83.34 DEG.
TILT ANGLE OF THE FIRST TOOL : 13.89 DEG.



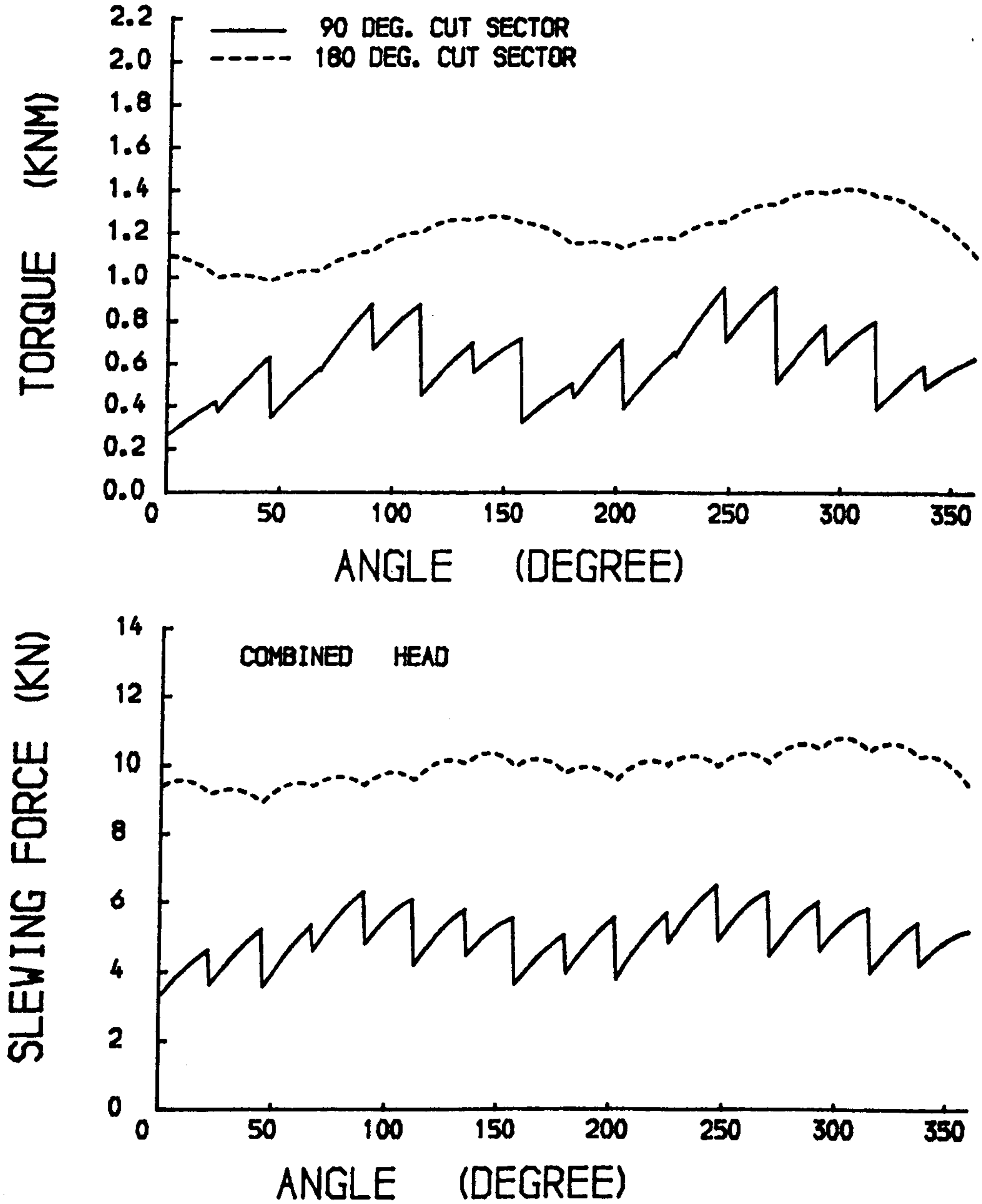
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,

TILT ANGLE OF THE CORNER CUT. TOOL: 83.34 DEG.

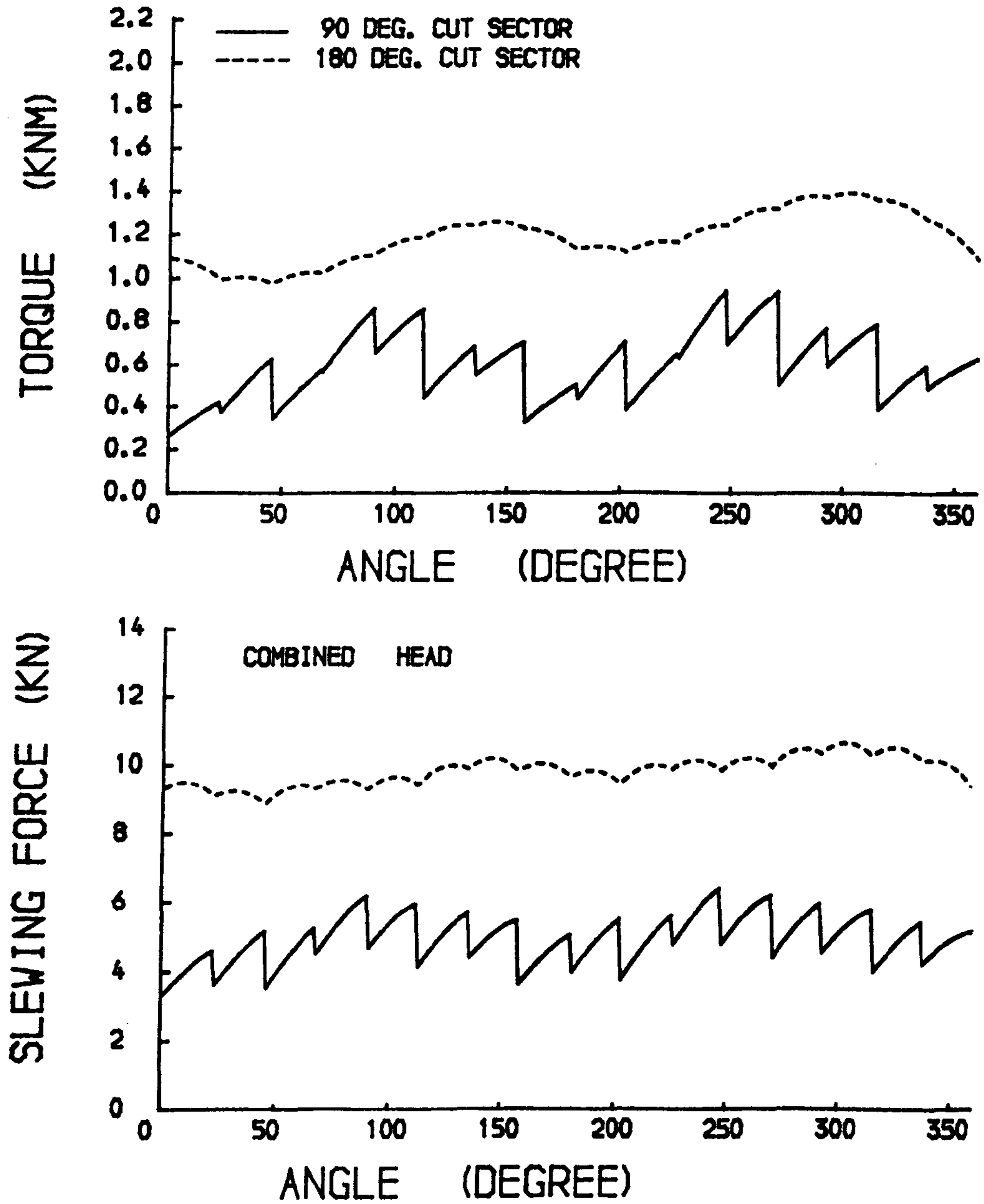
CONE ANGLE OF THE CUT. HEAD : 18.52 DEG.



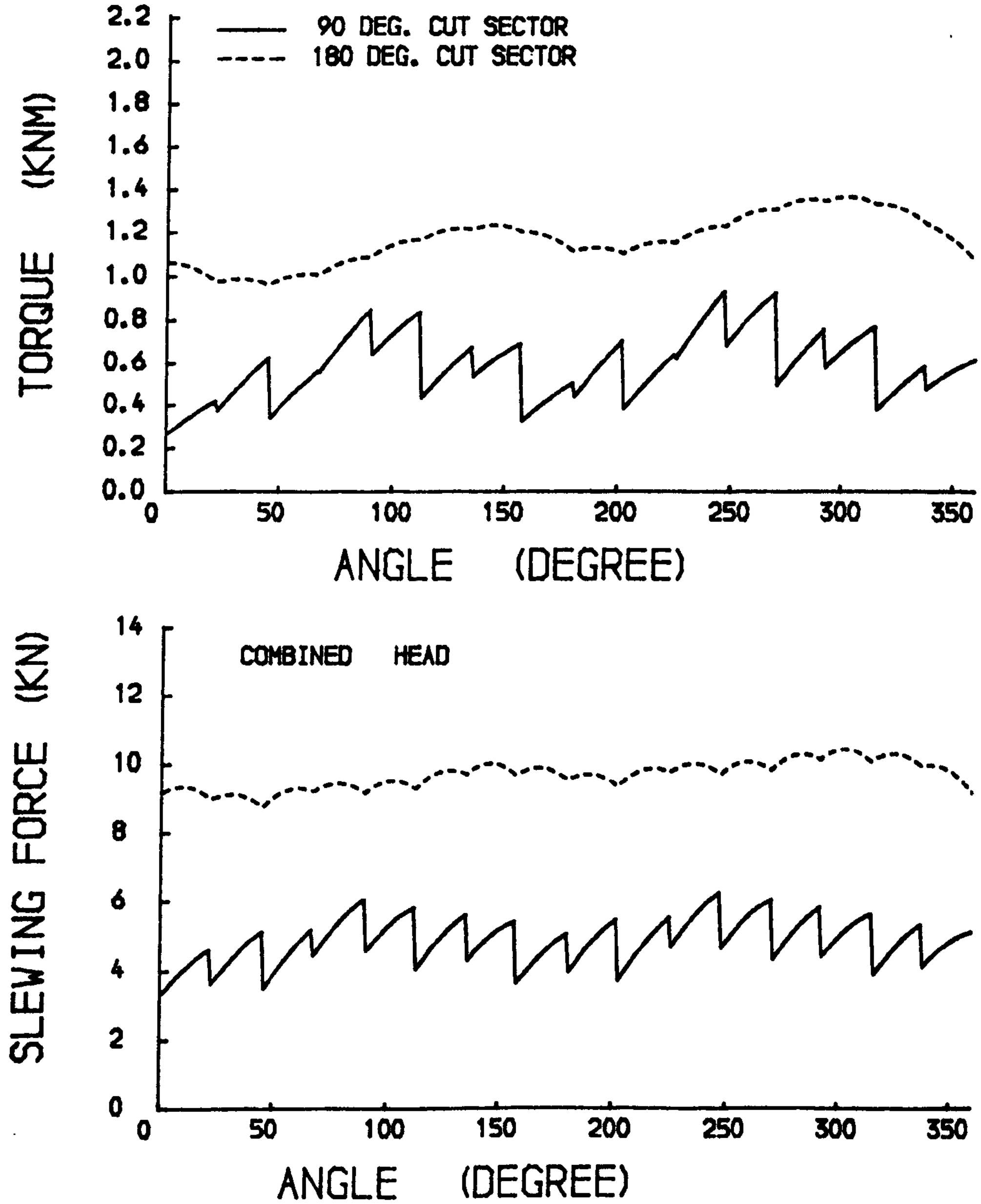
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 83.34 DEG.
CONE ANGLE OF THE CUT. HEAD : 23.15 DEG.



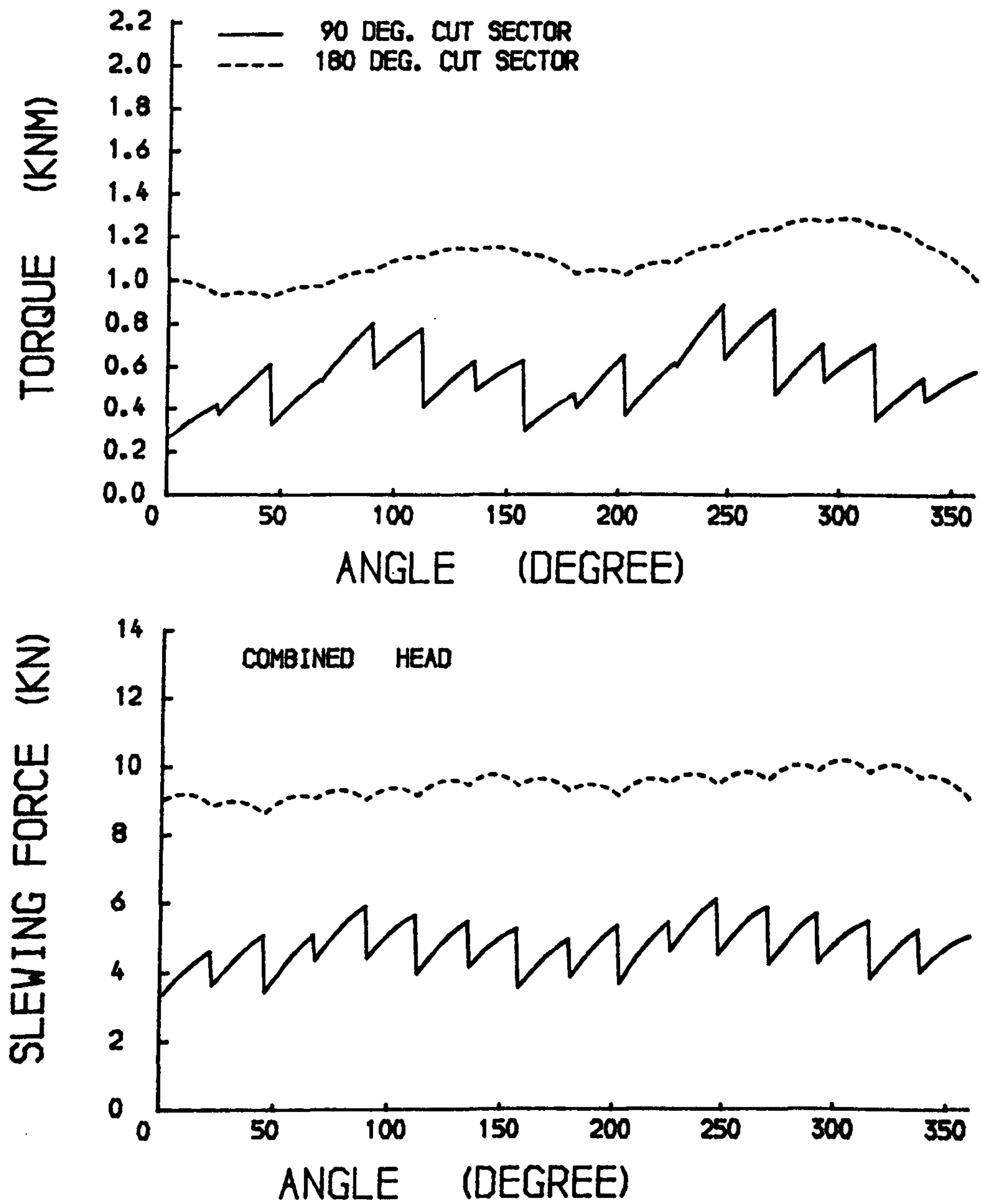
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 83.34 DEG.
CONE ANGLE OF THE CUT. HEAD : 27.78 DEG.



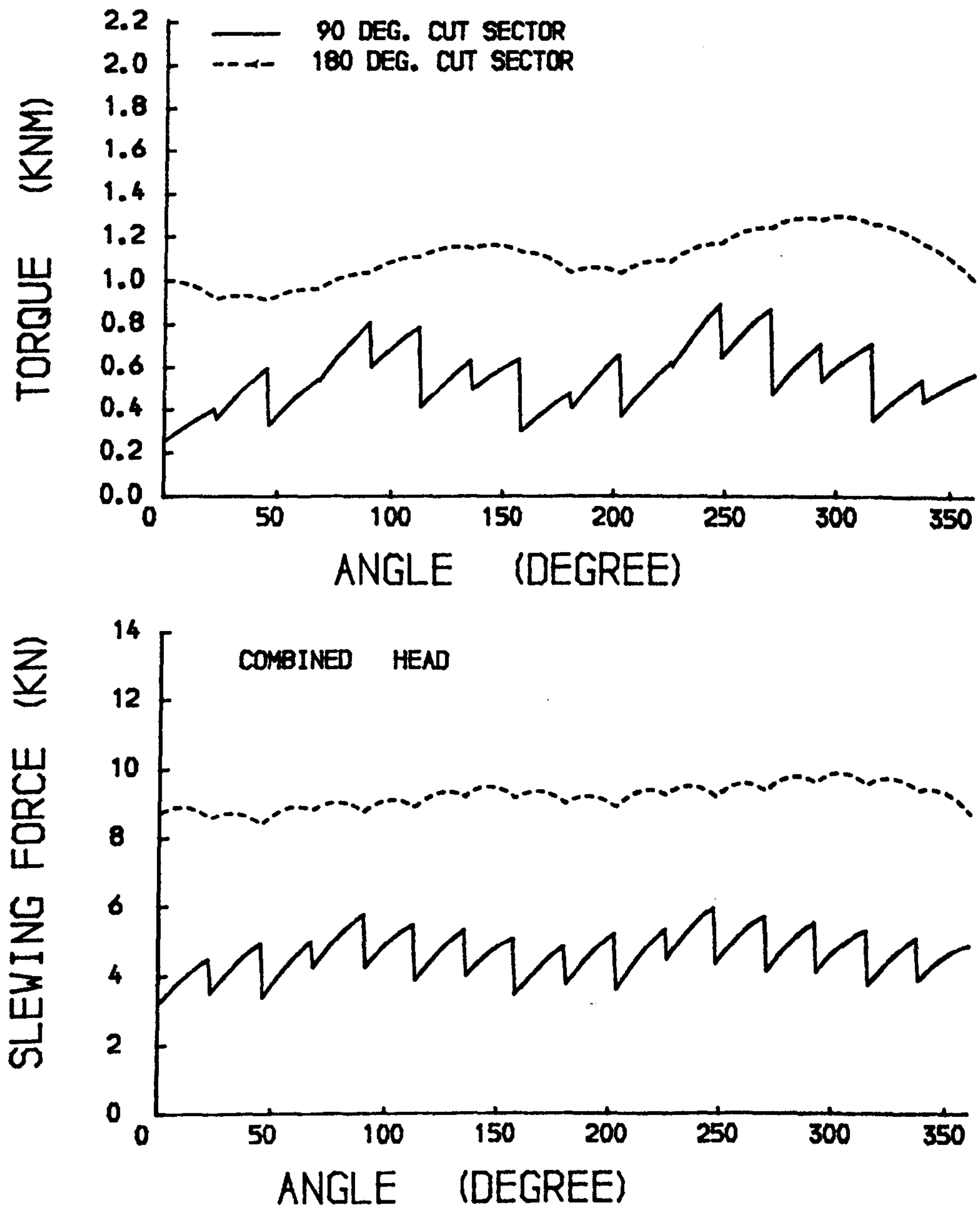
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 83.34 DEG.
CONE ANGLE OF THE CUT. HEAD : 32.41 DEG.



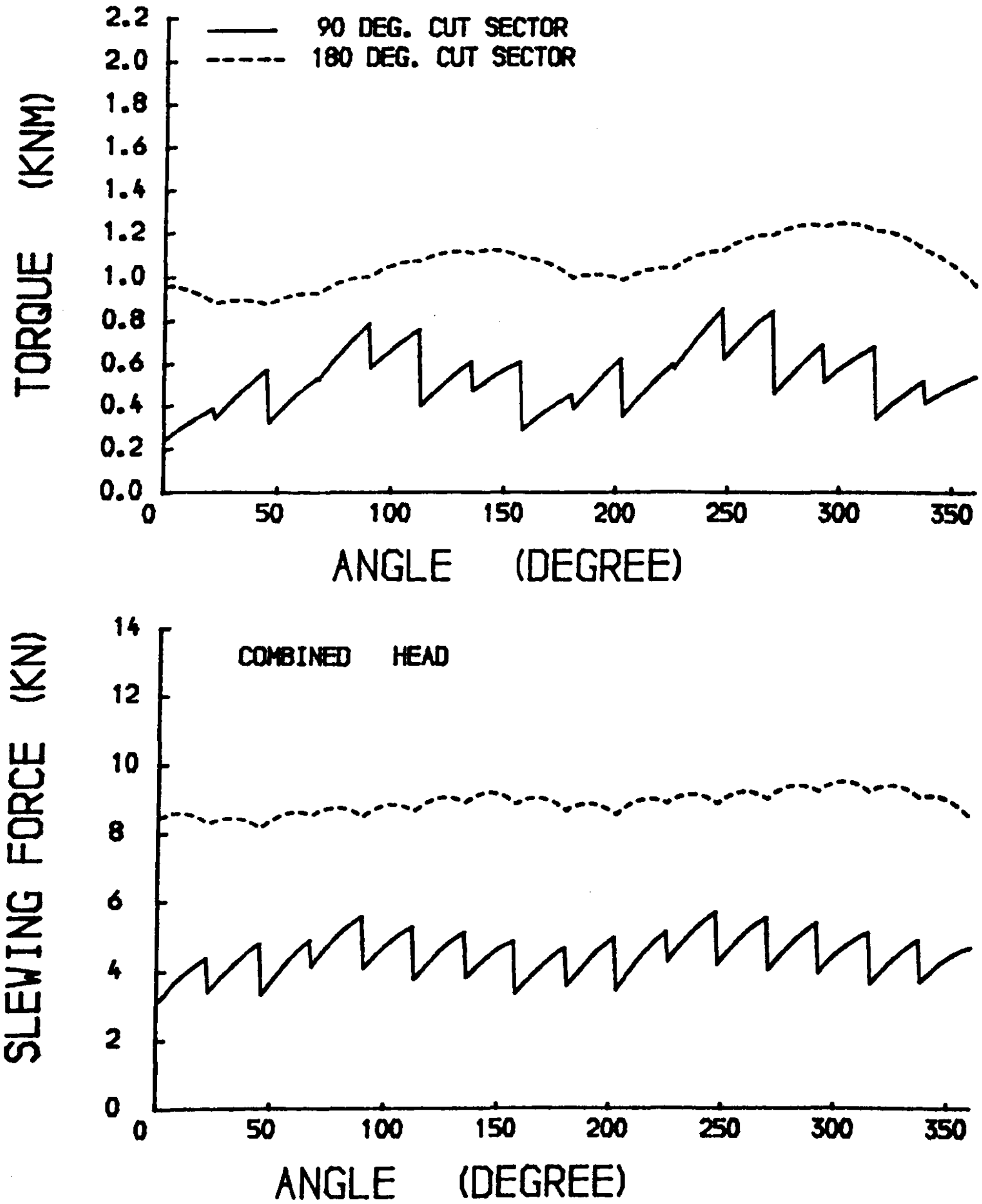
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL, 83.34 DEG.
CONE ANGLE OF THE CUT. HEAD , 37.04 DEG.



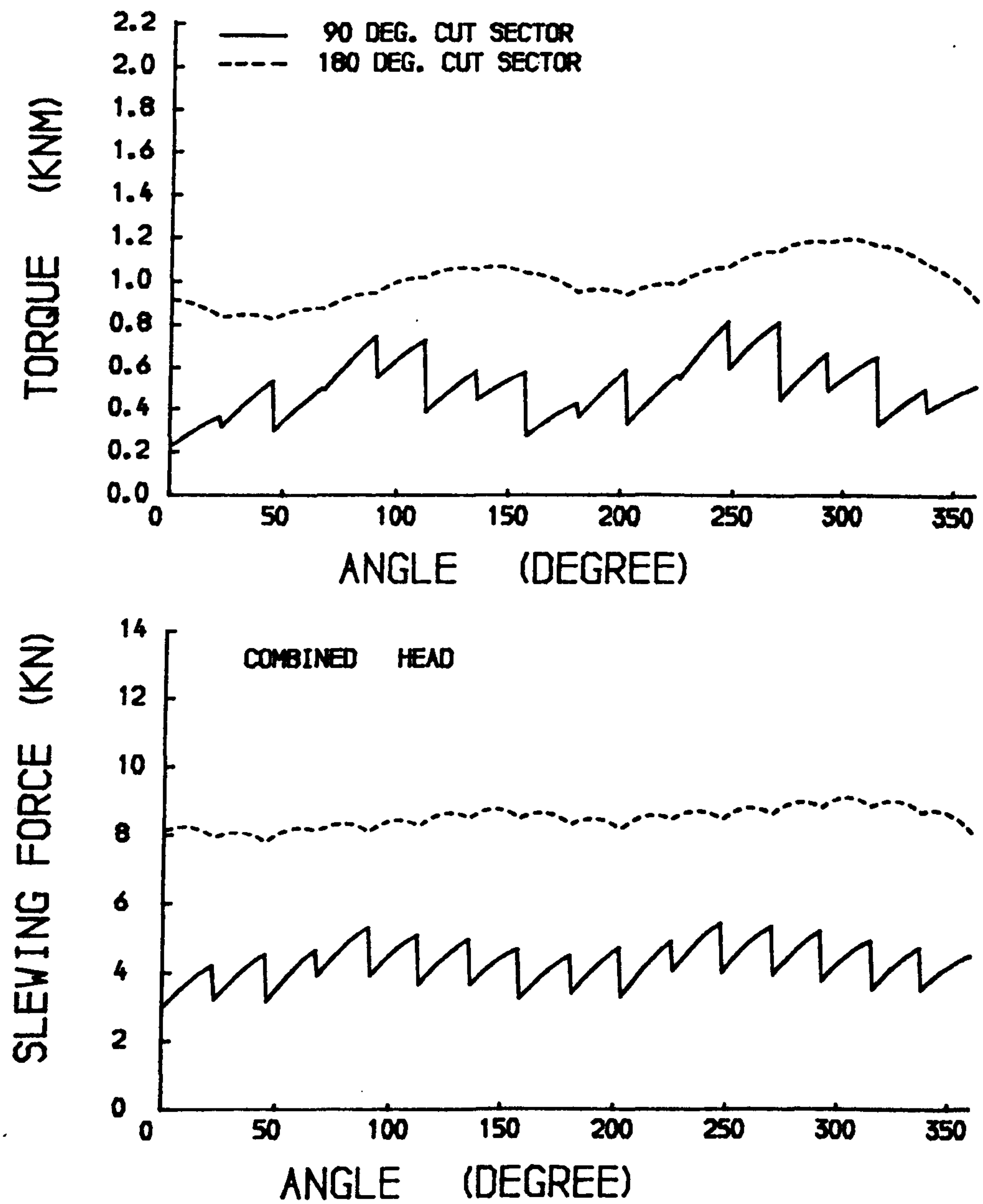
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 83.34 DEG.
CONE ANGLE OF THE CUT. HEAD : 41.65 DEG.



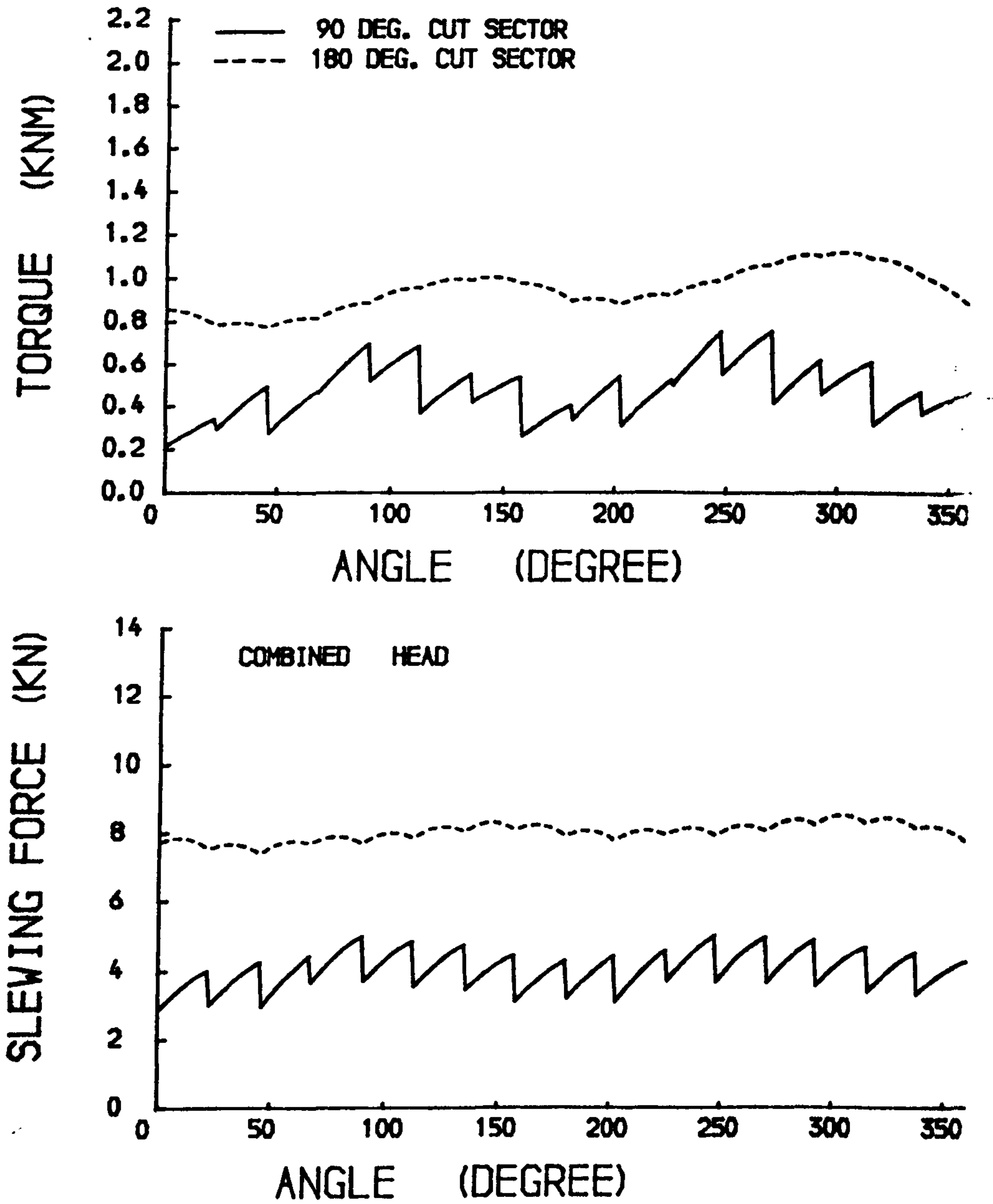
FLUCTUATIONS IN TORQUE AND SLEVING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 83.34 DEG.
CONE ANGLE OF THE CUT. HEAD : 46.30 DEG.



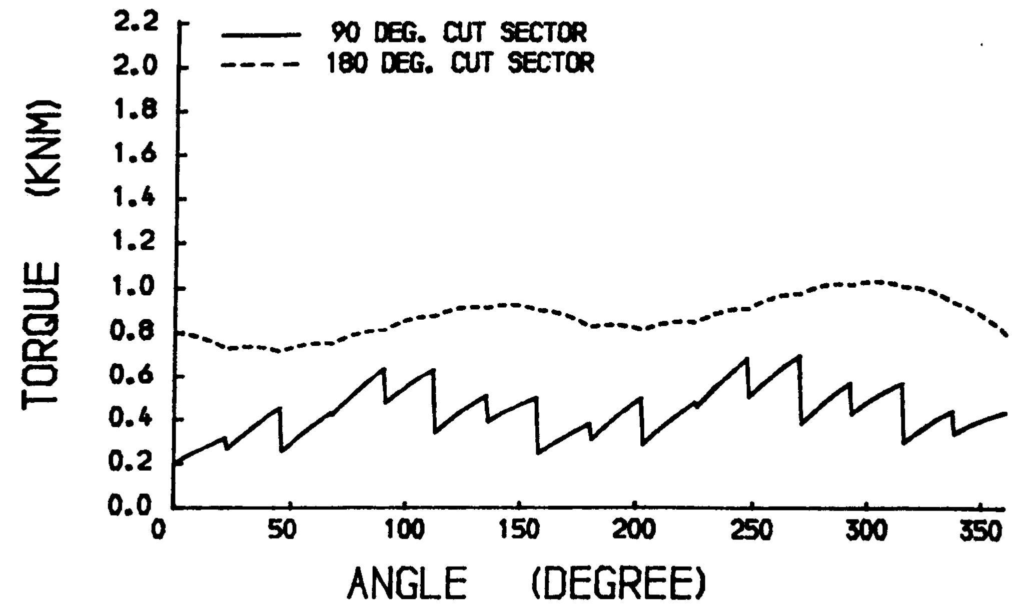
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 83.34 DEG.
CONE ANGLE OF THE CUT. HEAD : 50.93 DEG.

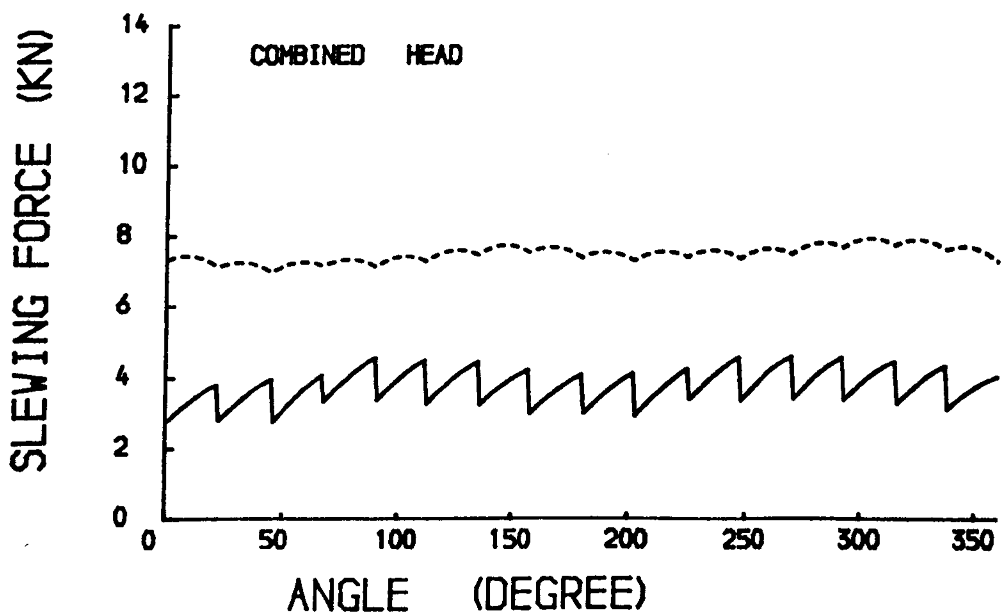


FLUCTUATIONS IN TORQUE AND SLEVING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 83.31 DEG.
CONE ANGLE OF THE CUT. HEAD : 55.56 DEG.

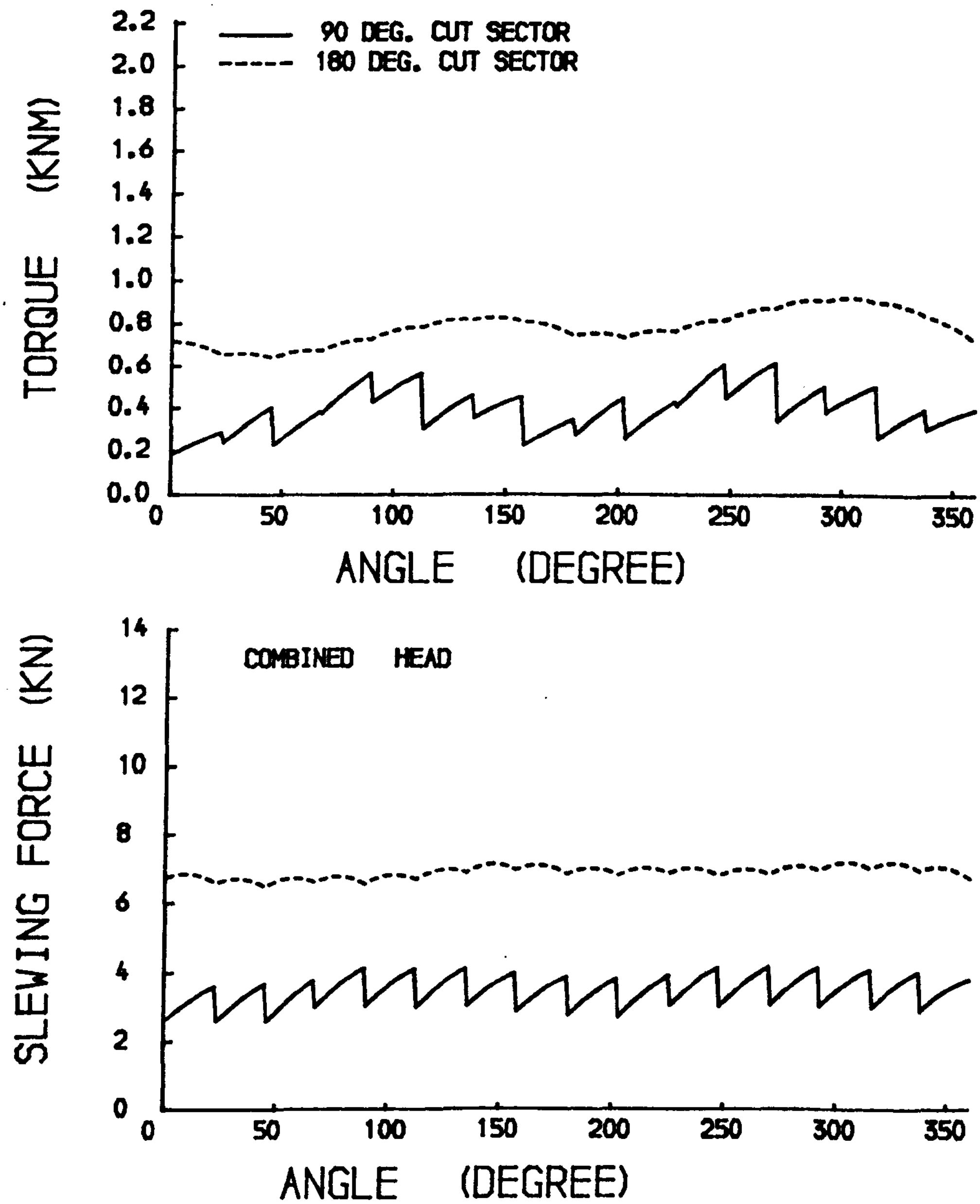


FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 83.31 DEG.
CONE ANGLE OF THE CUT. HEAD : 60.19 DEG.

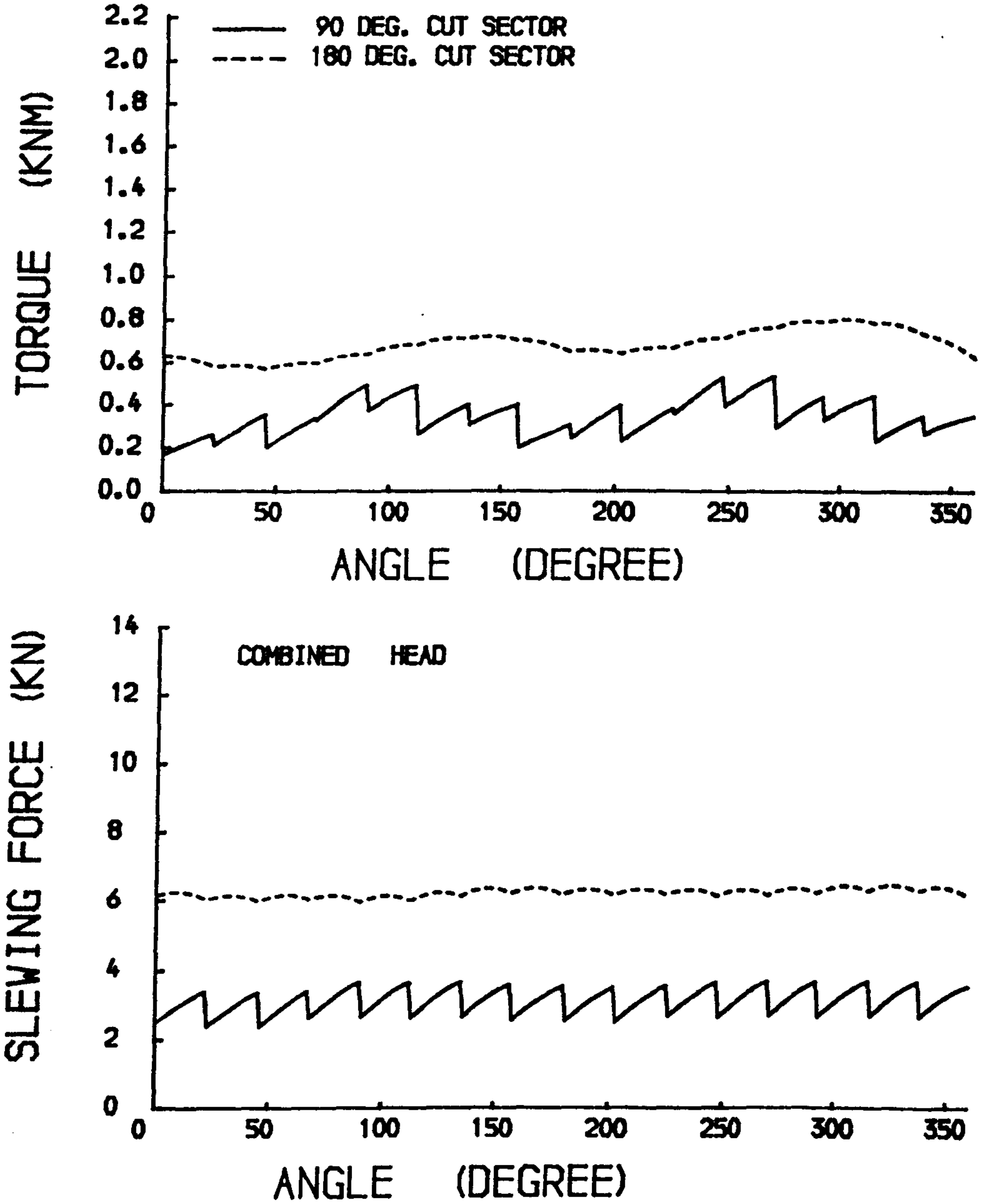




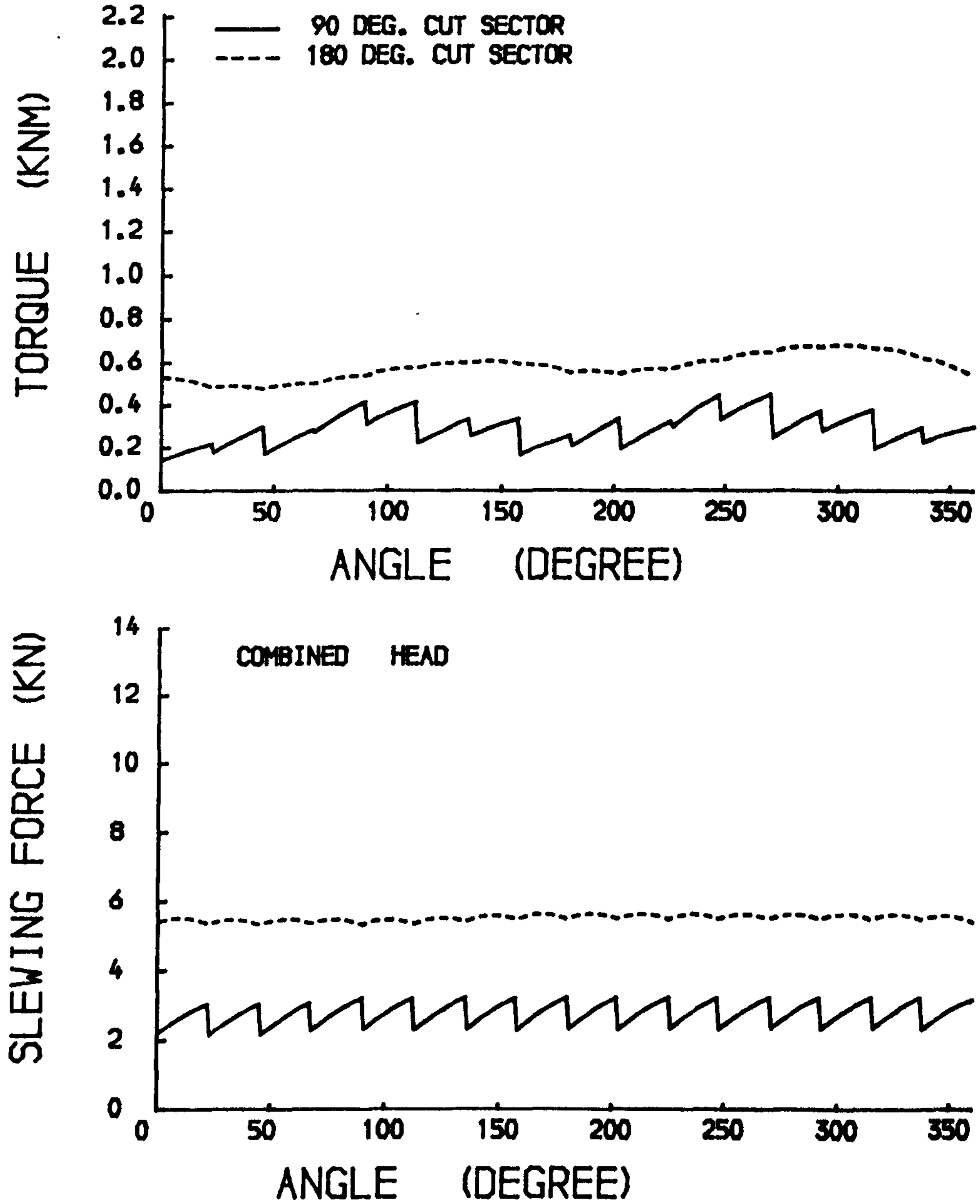
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 83.31 DEG.
CONE ANGLE OF THE CUT. HEAD : 64.82 DEG.



FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 83.31 DEG.
CONE ANGLE OF THE CUT. HEAD : 69.45 DEG.



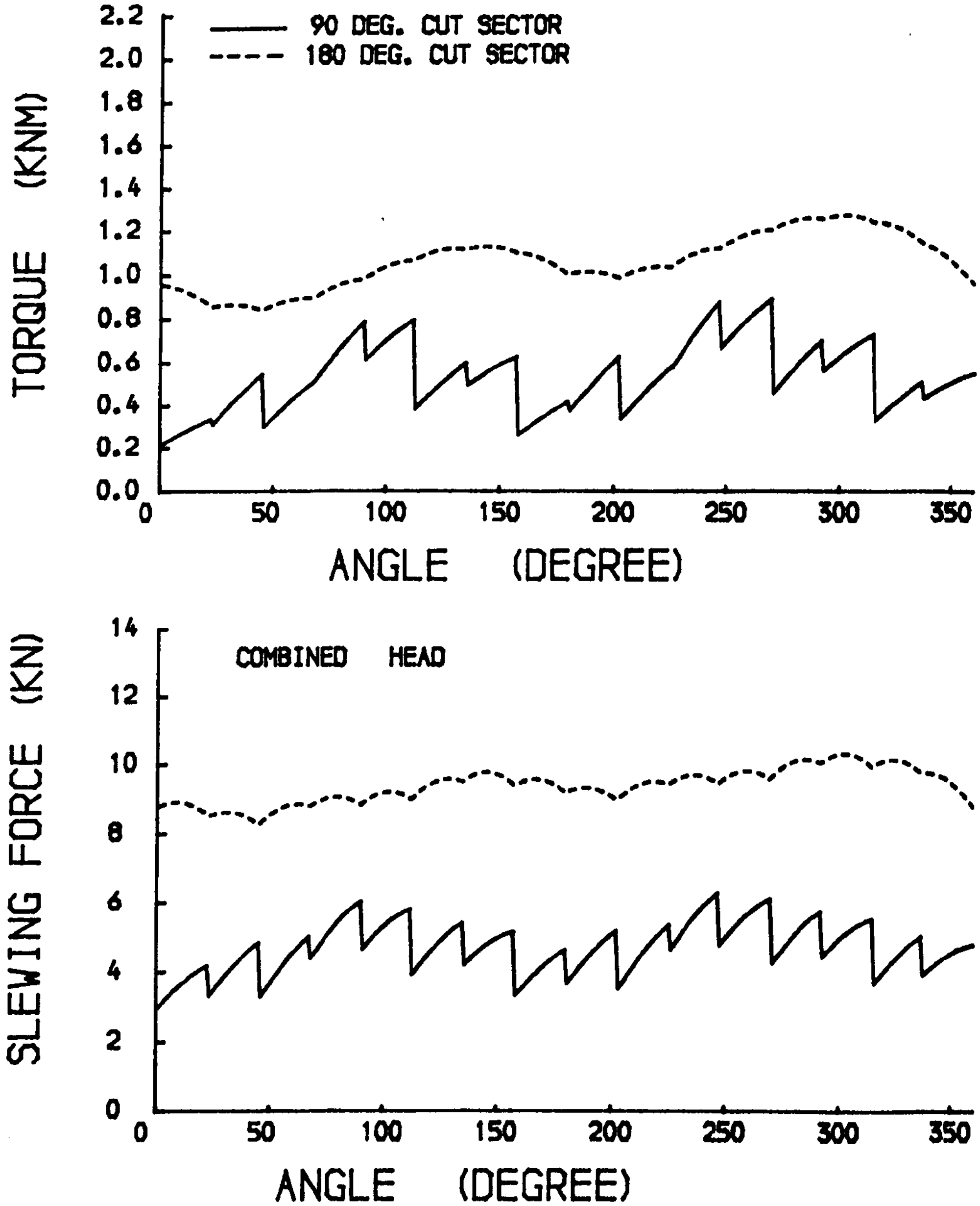
FLUCTUATIONS IN TORQUE AND SLEVING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 83.31 DEG.
CONE ANGLE OF THE CUT. HEAD : 74.08 DEG.



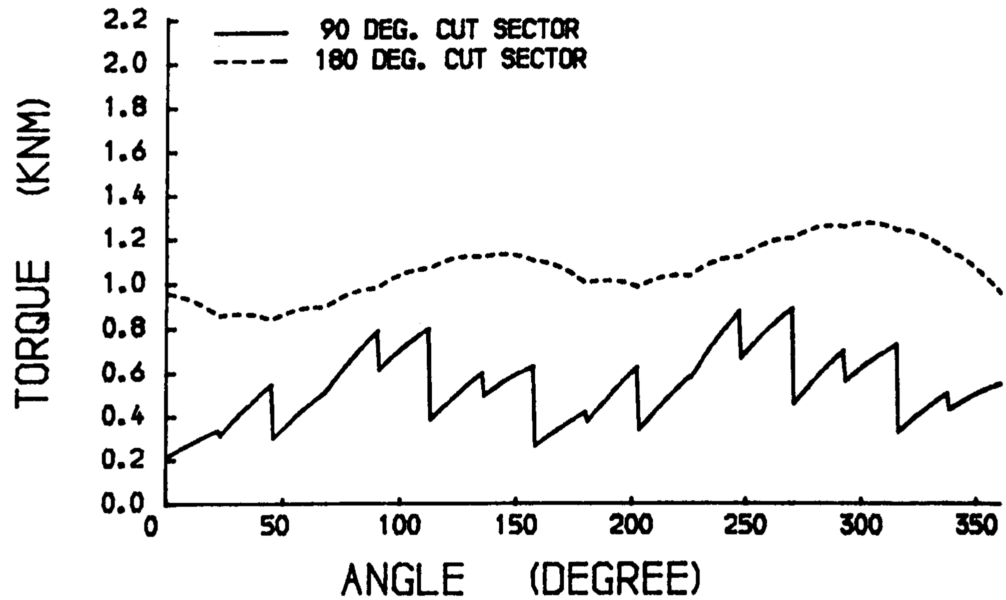
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,

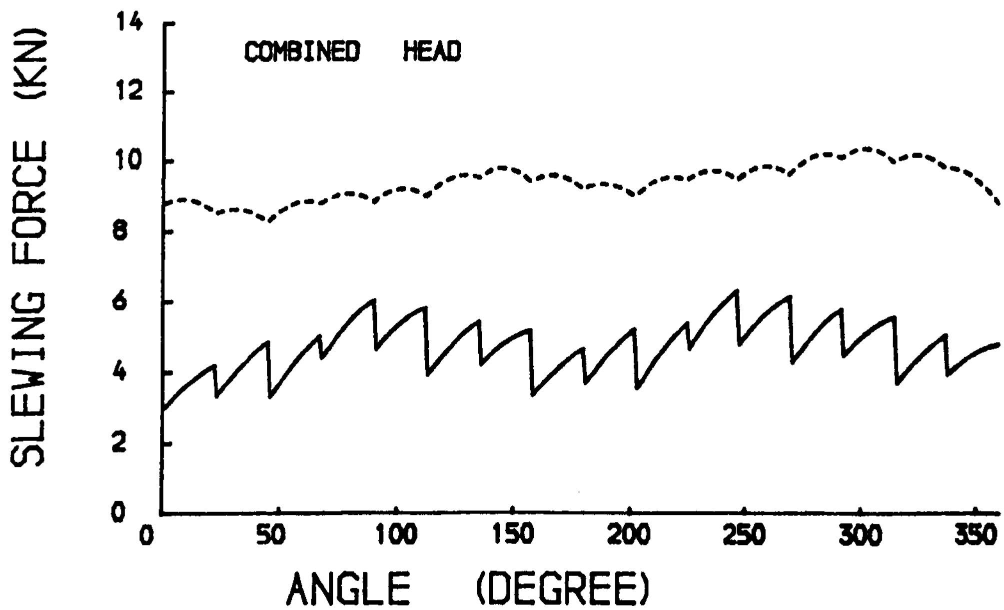
TILT ANGLE OF THE CORNER CUT. TOOL: 83.31 DEG.

CONE ANGLE OF THE CUT. HEAD : 78.71 DEG.



FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 87.97 DEG.
CONE ANGLE OF THE CUT. HEAD : 23.15 DEG.

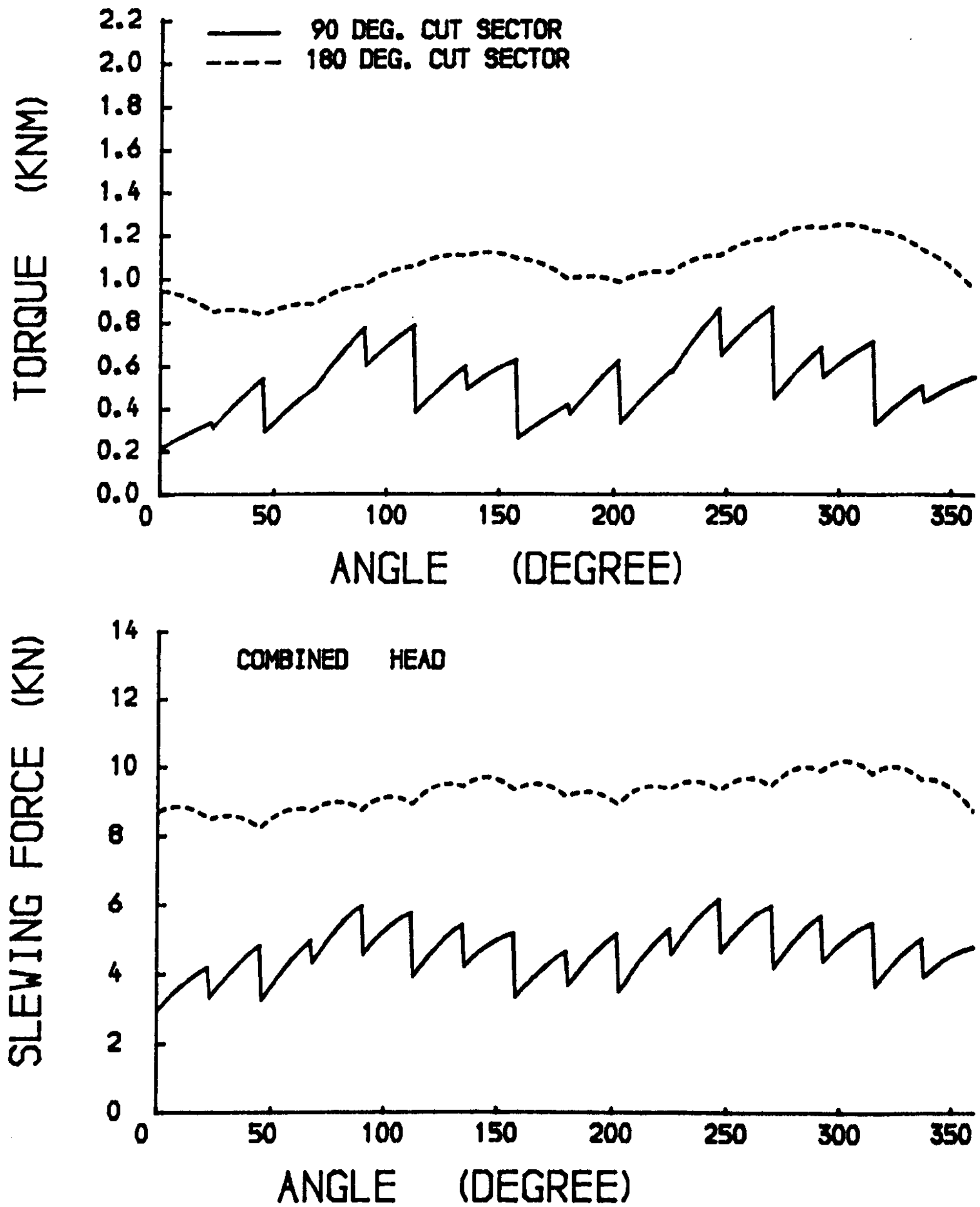




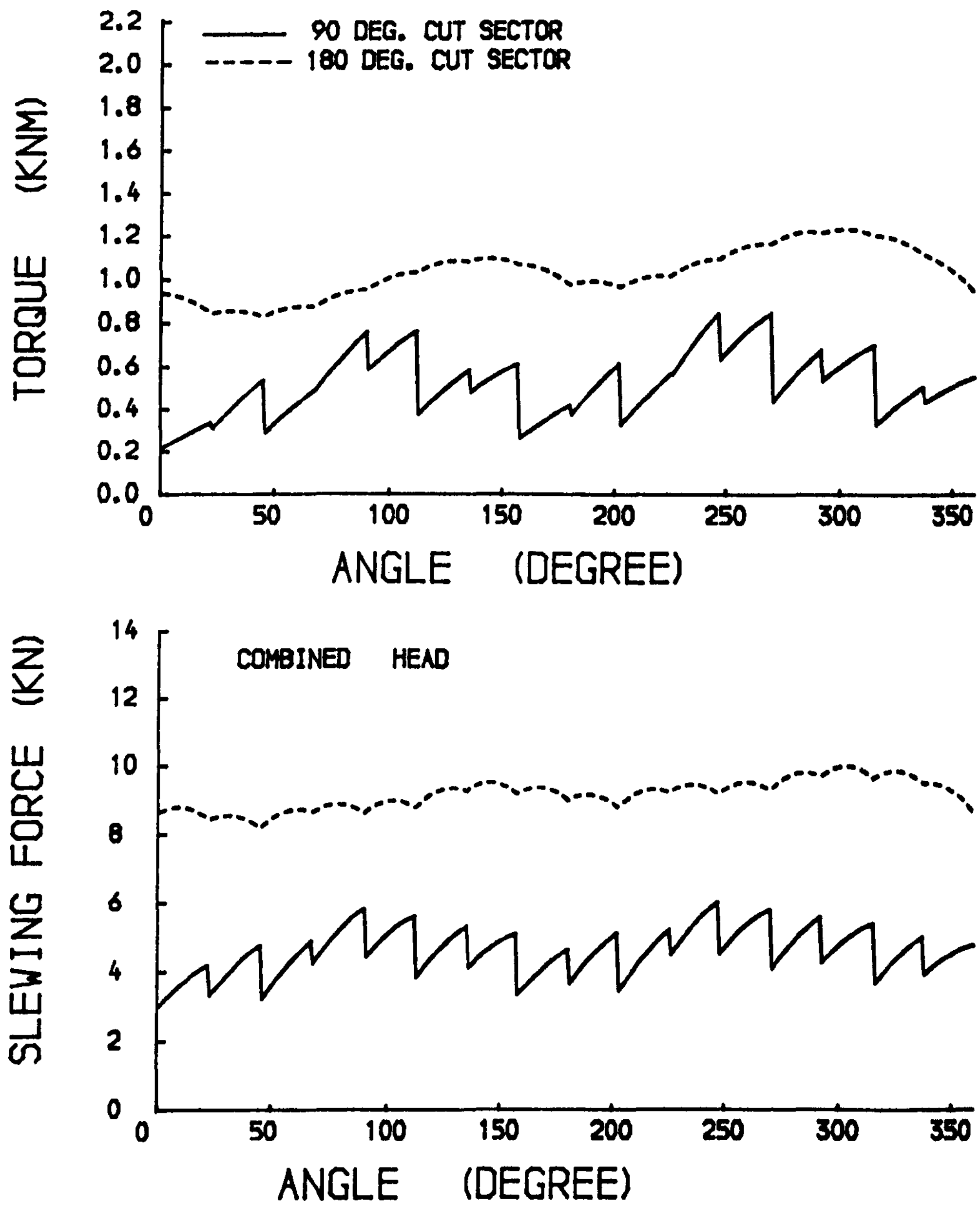
FLUCTUATIONS IN TORQUE AND SLEVING FORCE,

TILT ANGLE OF THE CORNER CUT. TOOL: 87.97 DEG.

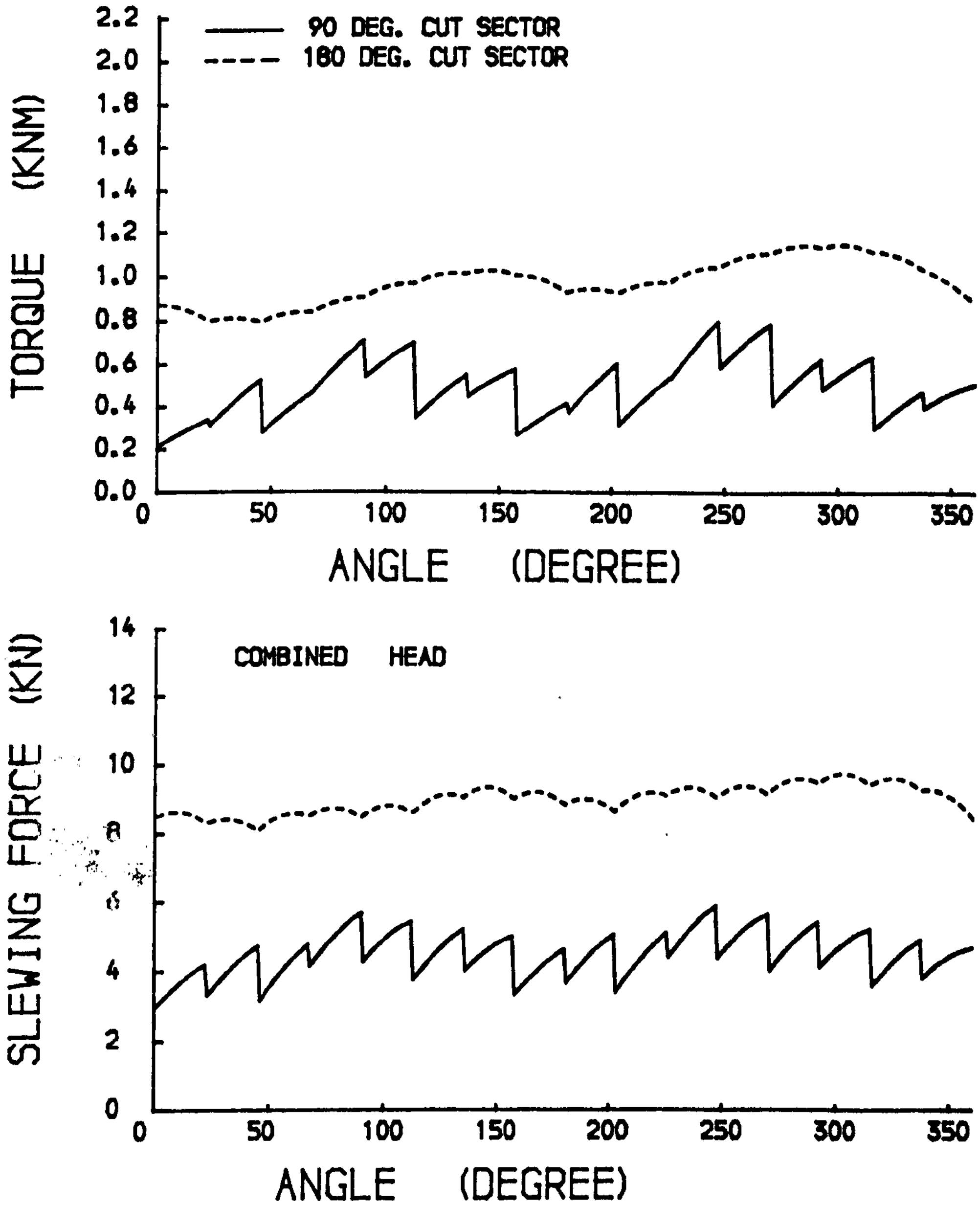
CONE ANGLE OF THE CUT. HEAD : 27.78 DEG.



FLUCTUATIONS IN TORQUE AND SLEVING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 87.97 DEG.
CONE ANGLE OF THE CUT. HEAD : 32.41 DEG.



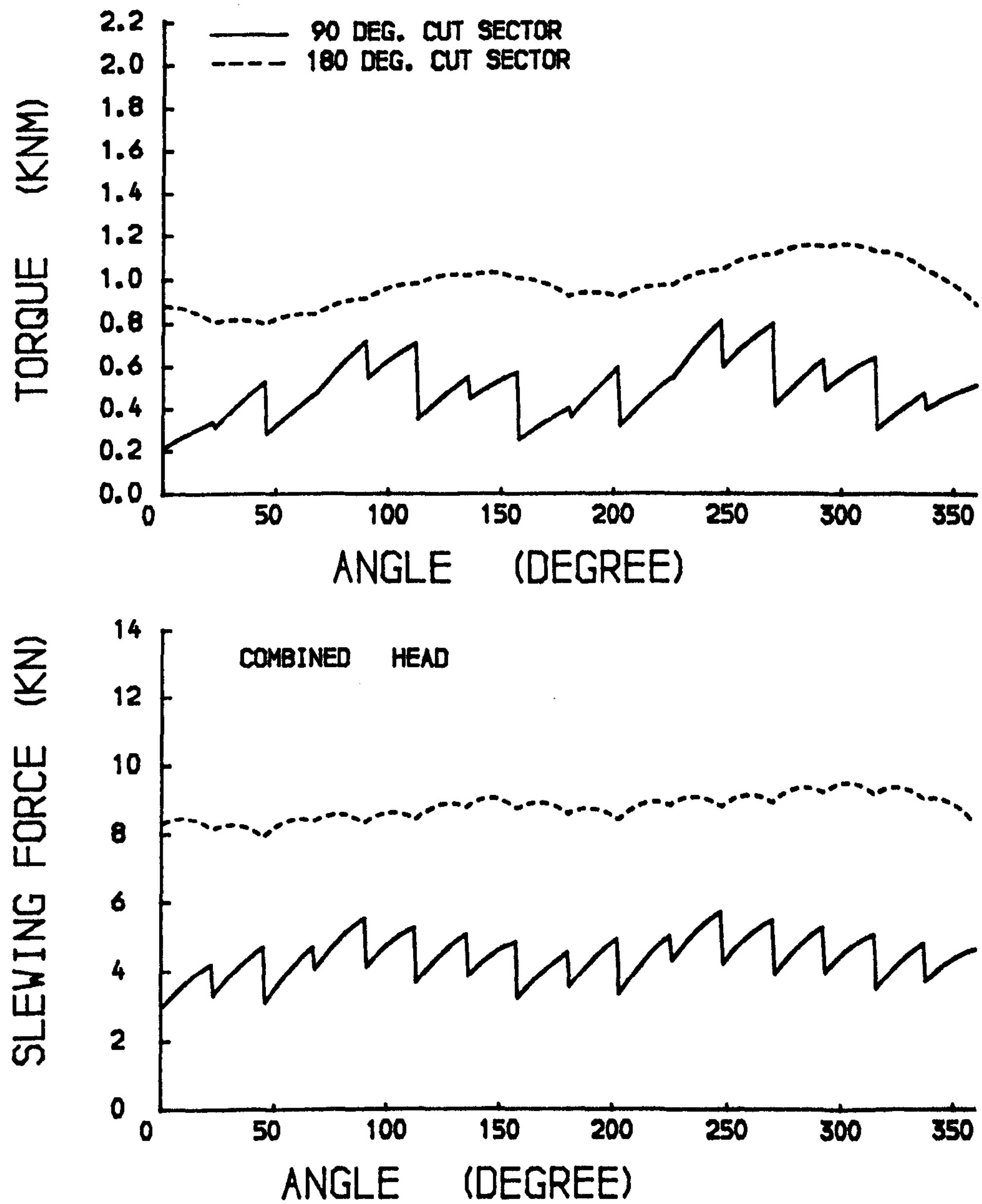
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 87.97 DEG.
CONE ANGLE OF THE CUT. HEAD : 37.04 DEG.



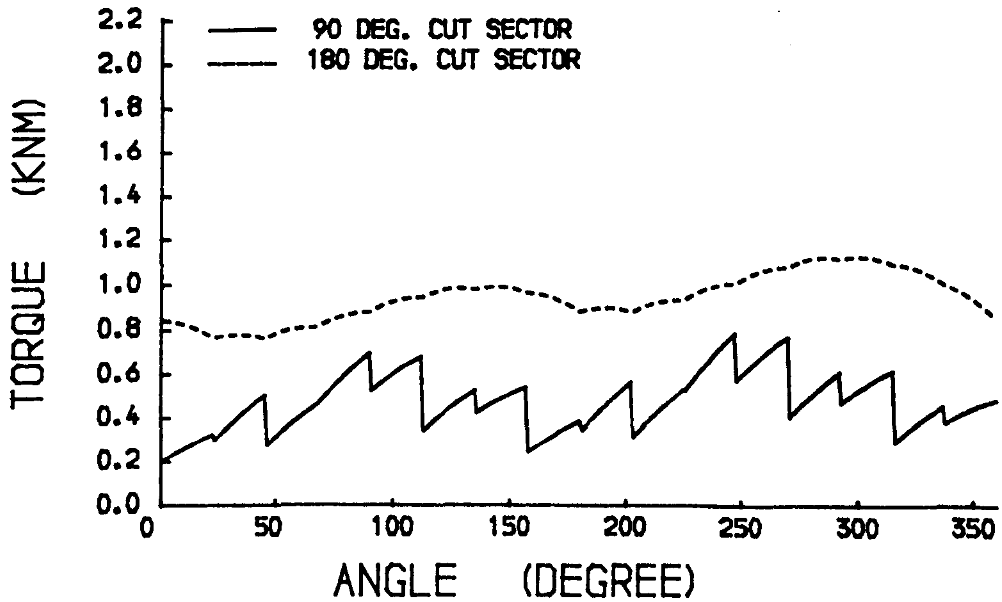
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,

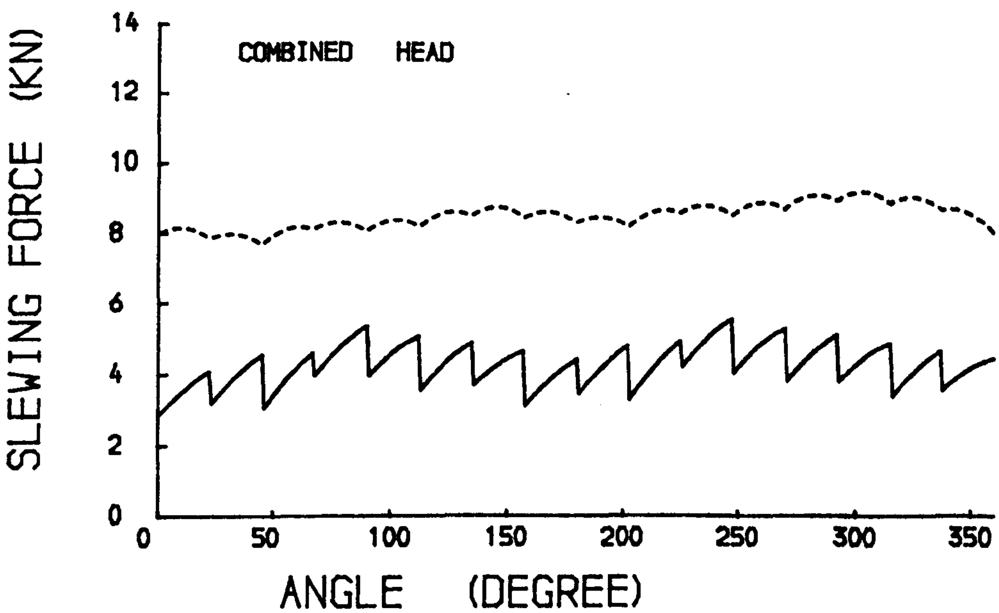
TILT ANGLE OF THE CORNER CUT. TOOL, 87.97 DEG.

CONE ANGLE OF THE CUT. HEAD , 41.65 DEG.

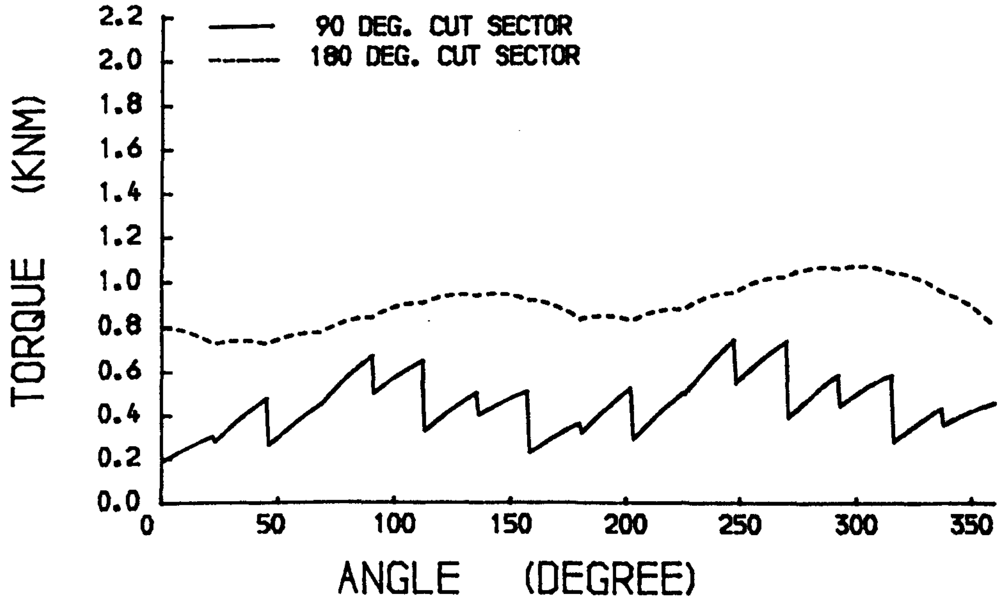


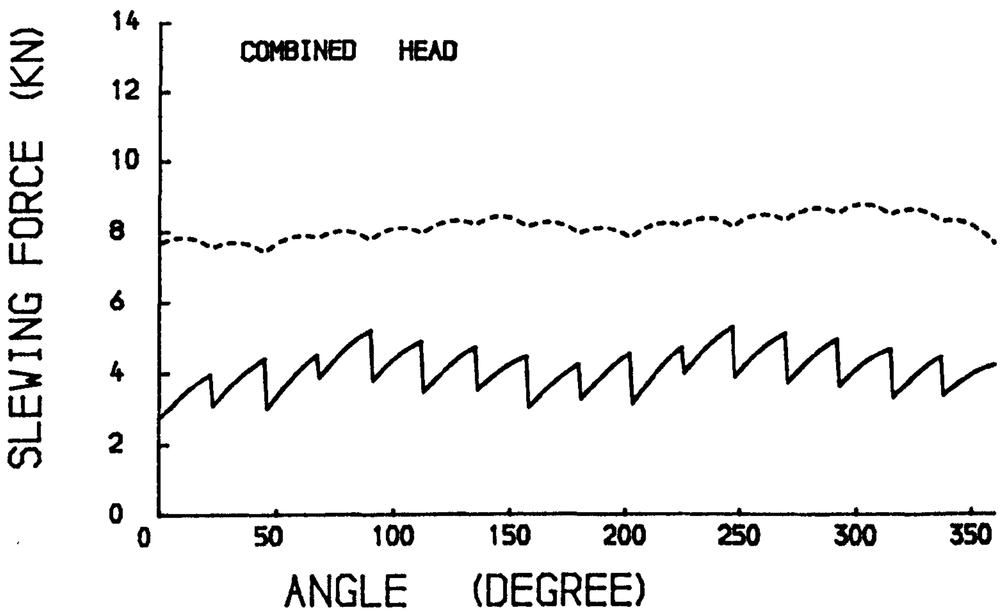
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 87.97 DEG.
CONE ANGLE OF THE CUT. HEAD : 46.30 DEG.





FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 87.97 DEG.
CONE ANGLE OF THE CUT. HEAD : 50.93 DEG.

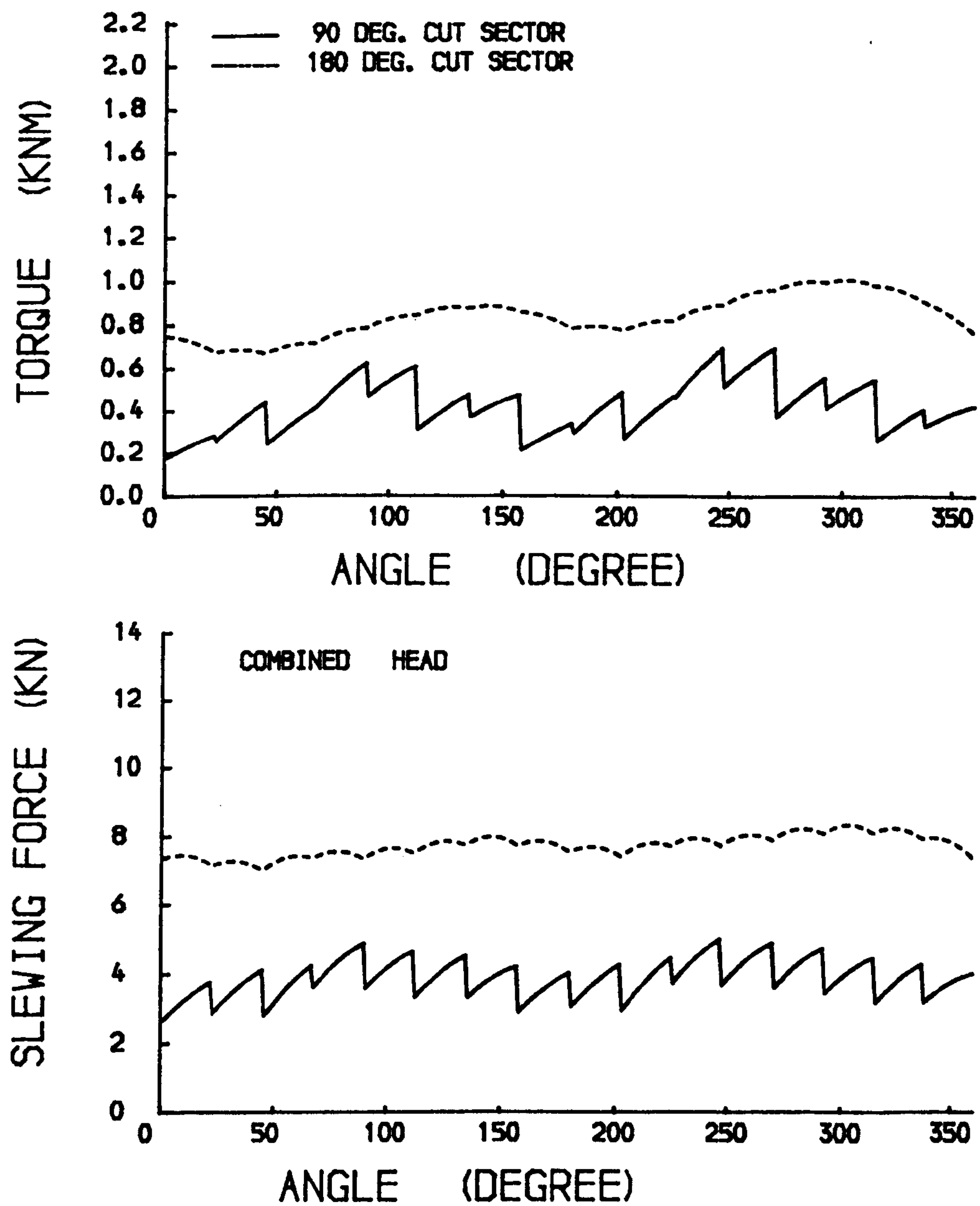




FLUCTUATIONS IN TORQUE AND SLEVING FORCE,

TILT ANGLE OF THE CORNER CUT. TOOL: 87.97 DEG.

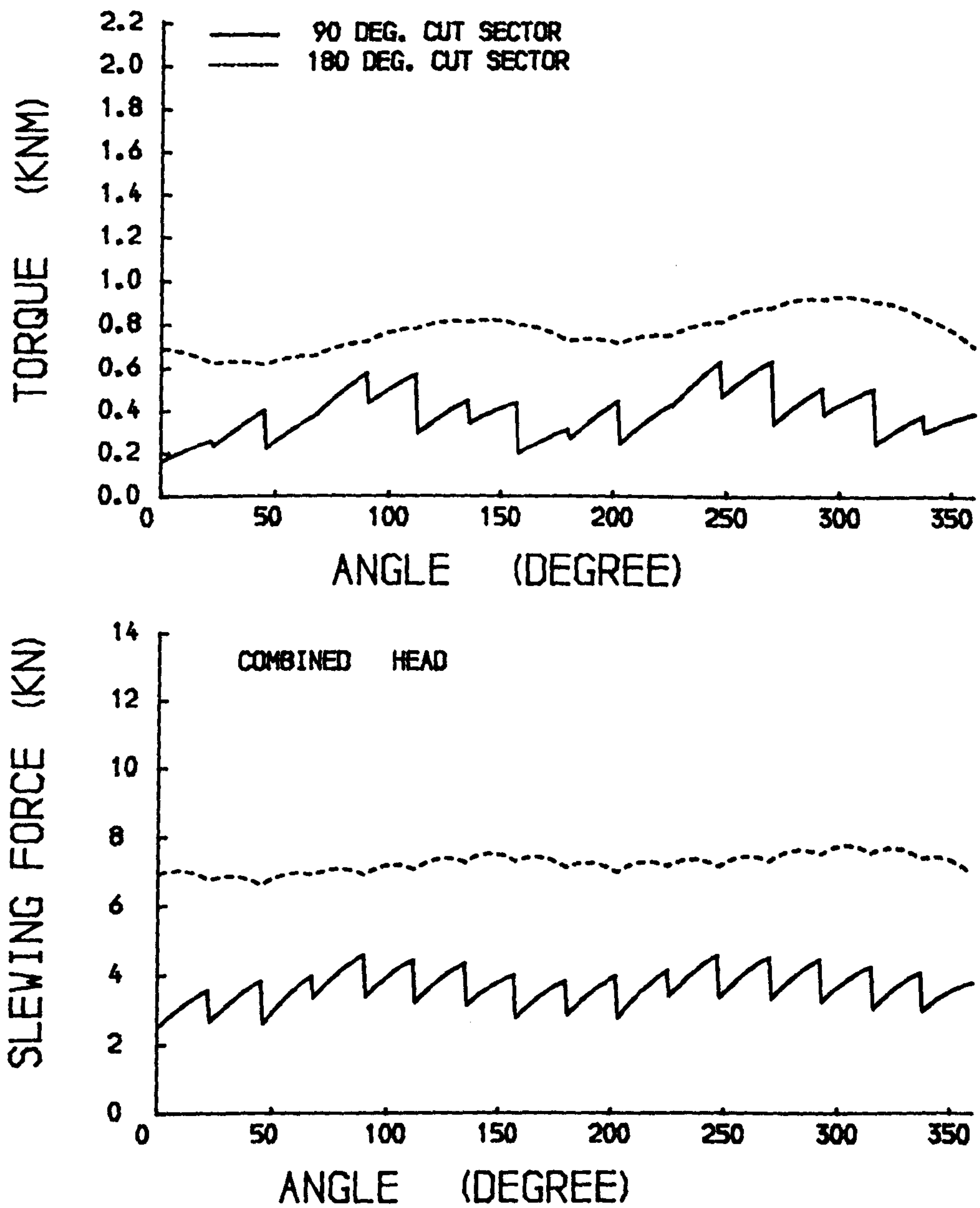
CONE ANGLE OF THE CUT. HEAD : 55.56 DEG.



FLUCTUATIONS IN TORQUE AND SLEVING FORCE,

TILT ANGLE OF THE CORNER CUT. TOOL: 87.97 DEG.

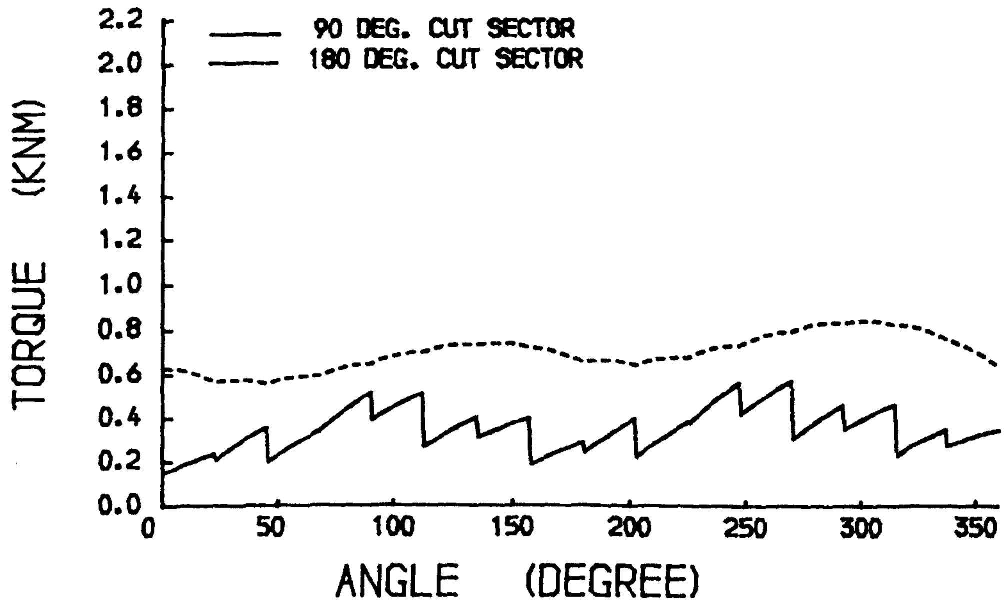
CONE ANGLE OF THE CUT. HEAD : 60.19 DEG.

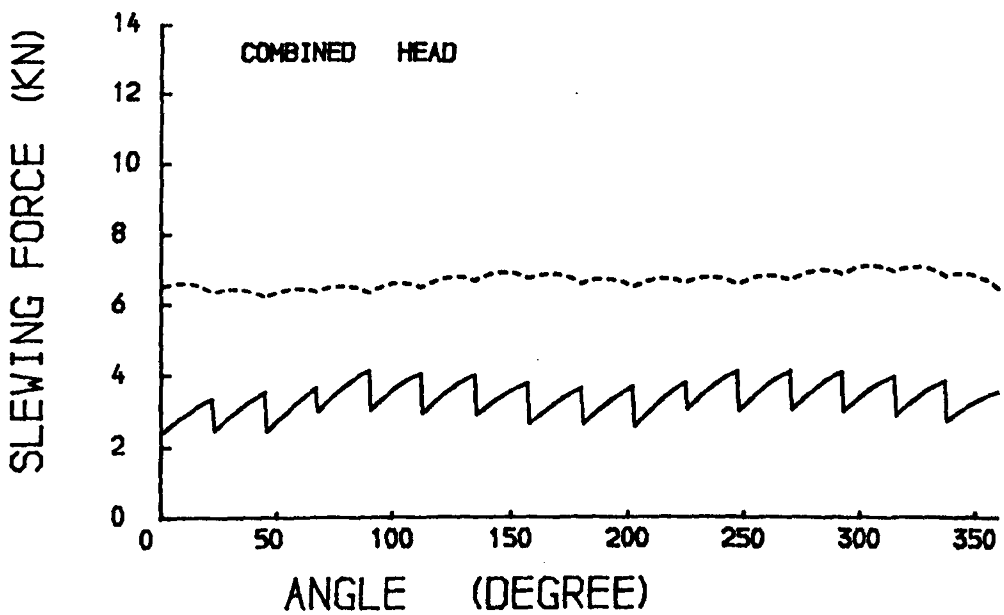


FLUCTUATIONS IN TORQUE AND SLEVING FORCE,

TILT ANGLE OF THE CORNER CUT. TOOL: 87.97 DEG.

CONE ANGLE OF THE CUT. HEAD : 64.82 DEG.

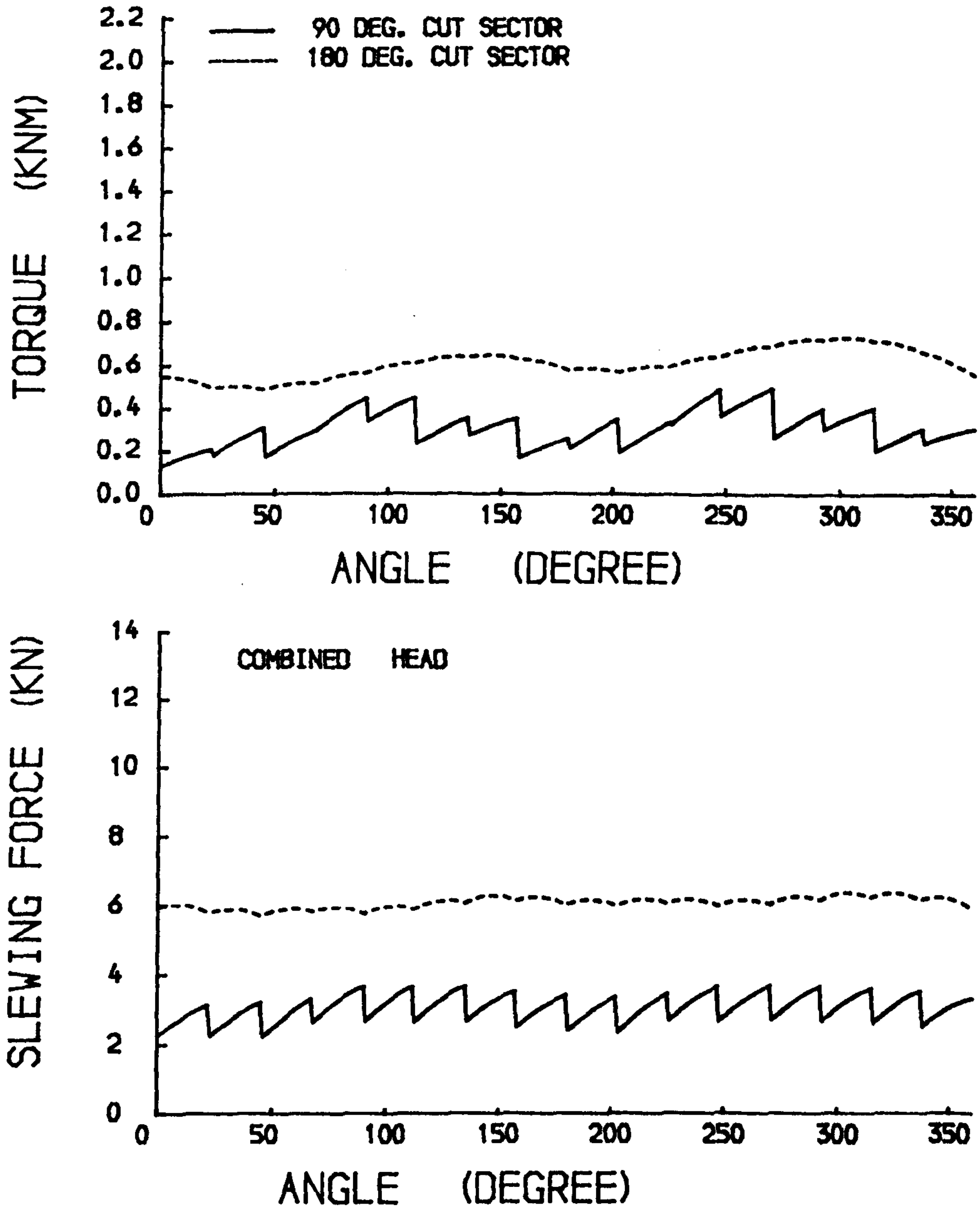




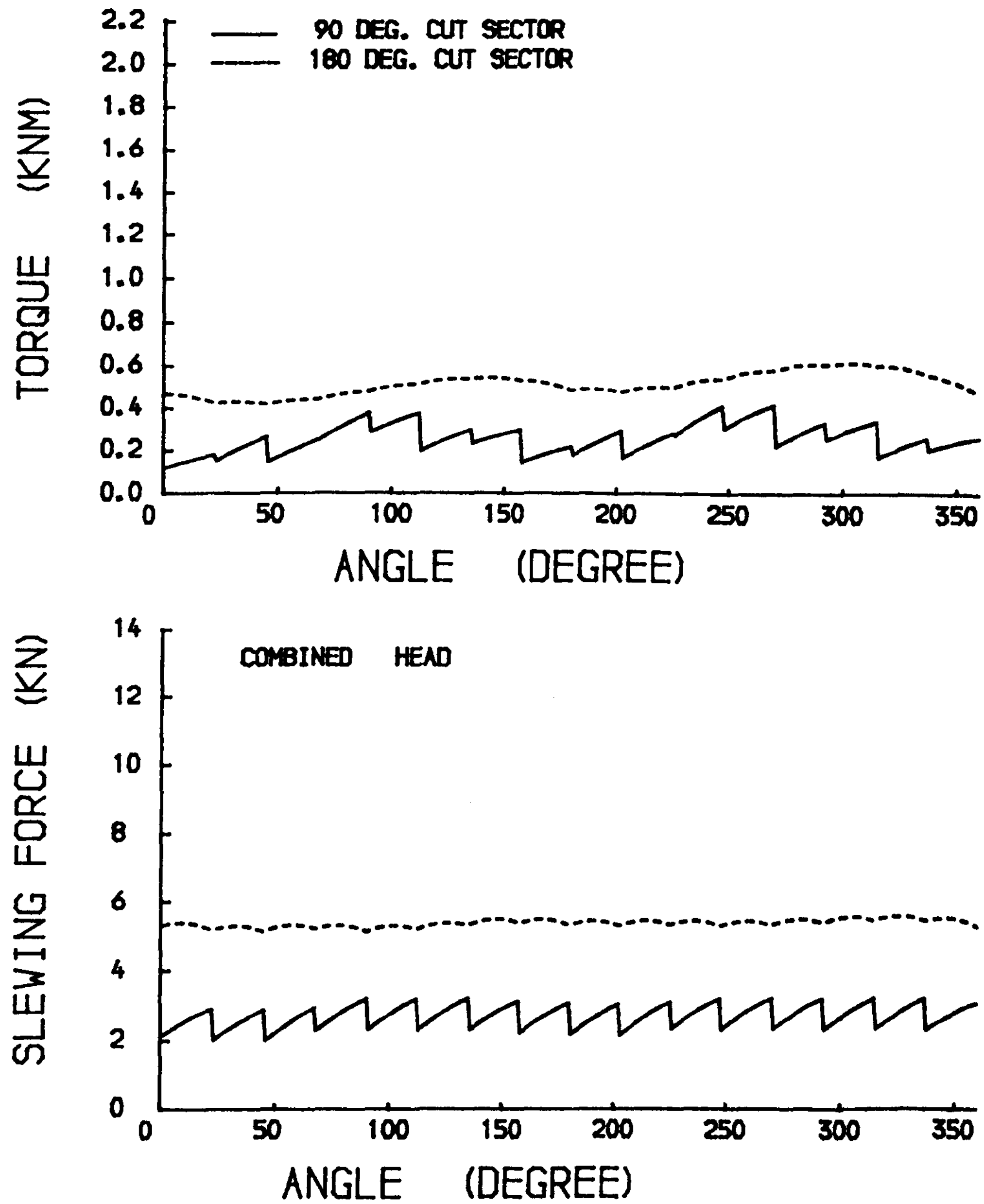
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,

TILT ANGLE OF THE CORNER CUT. TOOL: 87.97 DEG.

CONE ANGLE OF THE CUT. HEAD : 69.45 DEG.



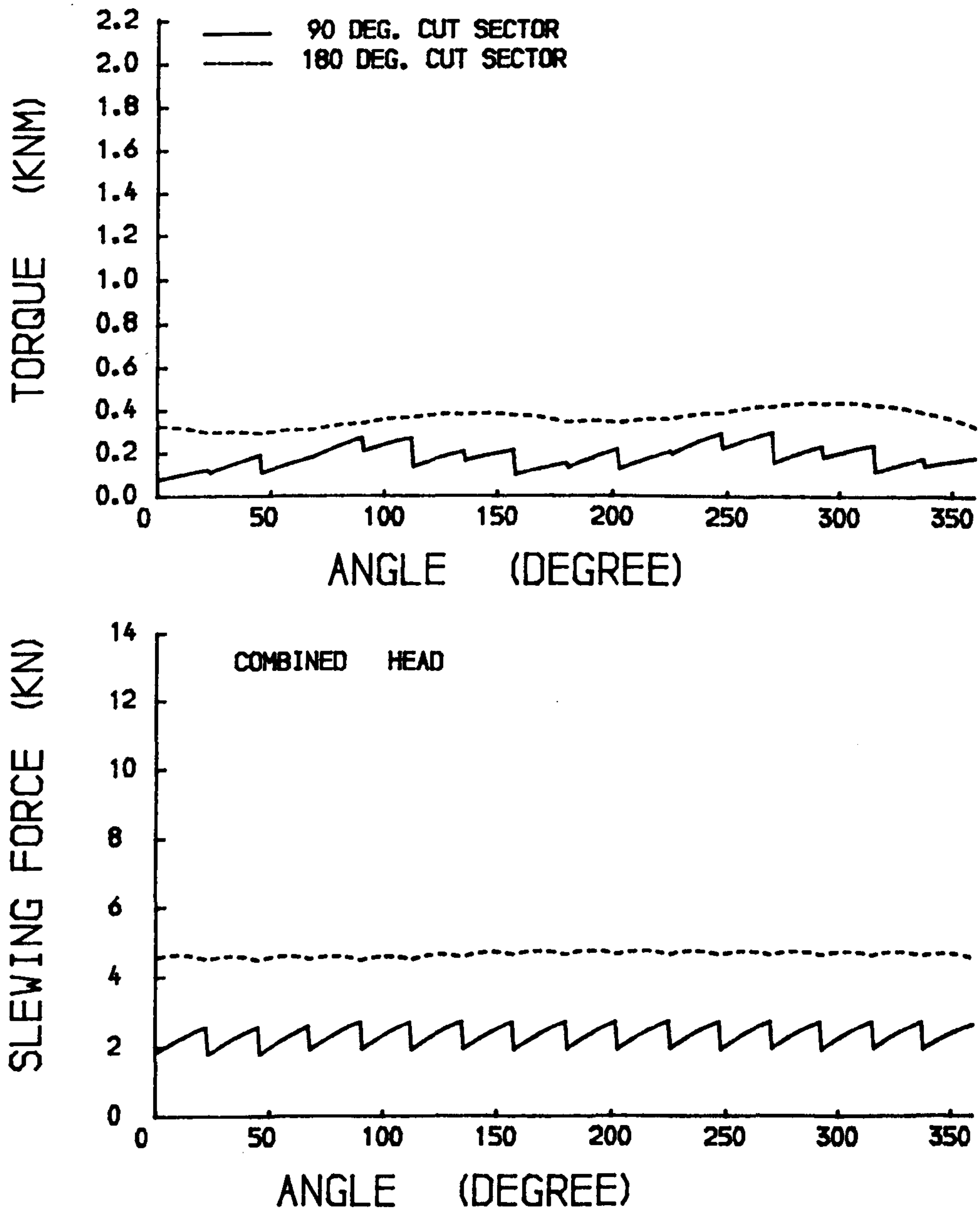
FLUCTUATIONS IN TORQUE AND SLEWING FORCE,
TILT ANGLE OF THE CORNER CUT. TOOL: 87.97 DEG.
CONE ANGLE OF THE CUT. HEAD : 74.08 DEG.



FLUCTUATIONS IN TORQUE AND SLEWING FORCE,

TILT ANGLE OF THE CORNER CUT. TOOL, 87.97 DEG.

CONE ANGLE OF THE CUT. HEAD , 78.71 DEG.



FLUCTUATIONS IN TORQUE AND SLEWING FORCE,

TILT ANGLE OF THE CORNER CUT. TOOL: 87.97 DEG.

CONE ANGLE OF THE CUT. HEAD : 83.31 DEG.

Spacing to Penetration ratios	Disc Edge Angle (Degree)	Parameters Measured						
		MRF (kN) ±s.d.	MPRF (kN) ±s.d.	MTF (kN) ±s.d.	MPTF (kN) ±s.d.	Qm (m^3/km) ±s.d.	Qc (m^3/km) ±s.d.	S.E. (MJ/m^3) ±s.d.
3	40	8.00 ±0.80	9.5 ±1.1	47.3 ±4.3	48.2 ±4.9	0.298 ±0.028	0.300	26.8 ±2.3
	60	8.97 ±0.69	10.75 ±0.96	62.25 ±3.95	67.25 ±3.59	0.253 ±0.029	0.300	35.75 ±6.18
5	40	10.0 ±0.40	11.5 ±0.06	48.2 ±0.9	53.1 ±1.5	0.478 ±0.023	0.500	20.9 ±1.6
	60	16.4 ±1.6	18.5 ±1.7	89.4 ±5.6	91.6 ±6.4	0.535 ±0.031	0.500	30.8 ±4.2
7	40	12.6 ±0.7	13.5 ±0.5	57.5 ±2.4	61.8 ±2.4	0.653 ±0.070	0.700	19.5 ±3.1
	60	16.5 ±1.45	18.2 ±1.2	92.6 ±7.6	98.3 ±3.6	0.721 ±0.138	0.700	23.5 4.1
9	40	14.4 ±0.5	15.8 ±1.1	63.6 ±2.9	69.5 ±1.9	0.994 ±0.296	0.900	15.7 ±5.7
	60	17.23 ±0.7	19.1 ±0.4	90.3 ±7.13	94.0 ±9.2	0.921 ±0.266	0.900	19.8 ±5.6
11	40	13.8 ±1.8	15.5 ±1.9	62.3 ±5.2	67.9 ±4.8	1.043 ±0.297	1.100	13.7 ±2.3
	60	20.4 ±1.1	22.0 ±0.9	105.5 ±7.1	108.4 ±7.3	0.988 ±0.407	1.100	23.0 ±7.84
13	40	15.6 ±0.5	17.4 ±0.5	73.5 ±4.1	79.8 ±6.5	1.544 ±0.514	1.300	11.1 ±4.6
	60	20.0 ±0.36	23.3 ±2.31	109.33 ±9.27	125.0 ±9.64	1.079 ±0.281	1.300	19.67 ±5.69

APPENDIX 7A1 Results for disc cutting experiments, groove deepening cuts, penetration = 10.0mm

Spacing to Penetration ratios	Disc Edge Angle (Degree)	Parameters Measured						
		MRF (kN) ±s.d.	MPRF (kN) ±s.d.	MTF (kN) ±s.d.	MPTF (kN) ±s.d.	Qm (m^3/km) ±s.d.	Qc (m^3/km) ±s.d	S.E (MJ/m^3) ±s.d
3	40	15.1 ±2.6	17.4 ±1.7	68.7 ±6.4	76.0 ±3.9	0.593 ±0.063	0.588	25.3 ±1.4
	60							
5	40	21.2 ±0.4	24.1 ±0.3	81.3 ±4.0	92.5 ±1.7	0.989 ±0.112	0.980	21.6 ±1.7
	60	23.7 ±1.4	27.0 ±0.7	113.3 ±1.4	121.5 ±7.7	1.023 ±0.054	0.980	23.2 ±0.1
7	40	24.7 ±2.4	27.0 ±1.9	101.5 ±2.7	112.4 ±2.1	1.895 ±0.189	1.372	13.1 ±1.1
	60	26.0 ±1.1	29.5 ±0.5	116.3 ±5.3	132.8 ±3.91	1.528 ±0.270	1.372	17.4 ±3.5
9	40	24.4 ±1.2	27.3 ±1.4	98.6 ±10.4	110.7 ±12.9	1.979 0.572	1.764	13.3 ±4.6
	60	26.8 ±0.4	30.2 ±0.6	124.3 ±9.4	140.5 ±11.3	2.020 0.776	1.764	15.0 ±6.8
11	40	21.7 ±1.4	24.5 ±1.4	85.3 ±6.1	95.3 ±6.4	2.527 ±1.746	2.156	11.5 ±6.7
	60	27.3 ±3.5	30.6 ±3.8	126.1 ±15.7	143.4 ±16.9	1.763 ±0.495	2.156	16.1 ±4.2

APPENDIX 7A2 Results for disc cutting experiments, groove deepening cuts, penetration = 14.0mm

Spacing to Penetration ratios	Disc Edge Angle (Degree)	Parameters Measured					
		MRF (kN) ±s.d.	MPRF (kN) ±s.d.	MTF (kN) ±s.d.	MPTF (kN) ±s.d.	Qm (m^3/km) ±s.d.	S.E. (MJ/m^3) ±s.d.
3	40	9.2 ±0.6	12.1 ±0.7	45.3 ±2.4	52.4 ±2.1	0.308 ±0.003	30.1 ±2.3
	60	11.8 ±0.8	14.1 ±0.9	68.9 ±2.5	80.6 ±2.2	0.293 ±0.028	40.0 ±3.1
5	40	14.1 ±0.7	16.0 ±0.4	56.4 ±1.2	62.5 ±1.7	0.514 ±0.010	27.4 ±1.9
	60	16.4 ±0.6	18.9 ±1.0	85.3 ±5.2	94.2 ±3.2	0.482 ±0.030	34.3 ±3.0
7	40	13.5 ±1.0	15.6 ±1.0	53.0 ±3.1	59.7 ±3.1	0.621 ±0.016	21.7 ±2.1
	60	19.1 ±0.1	20.1 ±0.7	88.0 ±0.3	94.6 ±4.2	0.613 ±0.069	31.3 ±3.7
9	40	14.5 ±1.2	15.9 ±1.3	57.1 ±4.2	63.0 ±5.5	0.516 ±0.132	29.0 ±5.2
	60	18.3 ±1.2	19.8 ±0.7	88.0 ±0.7	95.7 ±3.7	0.621 ±0.008	31.2 ±1.2
11	40	15.2 ±0.6	16.5 ±0.5	61.1 ±1.9	66.7 ±0.5	0.403 ±0.008	37.8 ±1.7
	60	18.5 ±0.5	20.1 ±0.3	84.9 ±0.6	96.0 ±5.8	0.394 ±0.014	46.9 ±0.7
Unrelieved	40	15.3 ±1.7	16.8 ±2.3	57.1 ±5.2	62.0 ±6.9	0.391 ±0.032	38.8 +3.2
	60	17.8 ±0.4	18.7 ±0.8	79.3 ±1.2	88.1 ±6.8	0.405 ±0.030	43.9 ±2.2

APPENDIX 7B1 Results for disc cutting experiments, skew cuts, penetration = 10.0mm

APPENDIX 8A1

```
C                *****  * PROGRAM HEAD *  *****
C
C  ***      THIS PROGRAM IS CONCERNED WITH THE KINEMATICS AND
C  ***    ENERGETICS  OF ROADHEADERS WITH LONGITUDINAL TYPE
C  ***    CUTTING HEADS.
C  ***      THE PROGRAM CARRIES OUT THE CALCULATIONS FOR THE
C  ***    CUTTING HEAD TORQUE, SLEWING FORCE, VOLUME SWEPT AND
C  ***    SPECIFIC ENERGY VALUES FOR AN ADVANCE PER REVOLUTION
C  ***    OF THE HEAD. THE CUTTING HEAD CAN BE OF SPHERICAL,
C  ***    CCNICAL OR COMBINATION OF THESE TWO GEOMETRIES AND
C  ***    EMPLOYS A TOTAL OF 16 TOCLS EXCLUDING THE SUMPING PICKS.
C  ***    IT FURTHER PRINTS OUT THE DETAILS OF THE INDIVIDUAL PICK
C  ***    FORCES AND THEIR CORRESPONDING TILT ANGLES AND CUTTING
C  ***    RADII.
C  ***      THE DATAS FOR THE INDIVIDUAL PICK FORCES WERE OBTAINED
C  ***    FROM LABORATUARY SIMULATION EXPERIMENTS. THE METHODS FOR
C  ***    THE CALCULATION OF THE ABOVE PARAMETERS ARE RELEVANT ONLY
C  ***    TO THE SPECIFICATION OF THE CUTTING HEADS GIVEN IN THIS
C  ***    WORK.
C  ***
C  ***************************************************************
C
      IMPLICIT REAL*8 (A-H,C-Z)
      DIMENSION A(16),RPR(16),FCAA(16),FNAA(16),M(16),ACI(16)
C
2000  TA=0.D0
      SA=0.D0
      TB=0.D0
      SB=0.D0
      THA=0.D0
      SHA=0.D0
      THB=0.D0
      SHB=0.D0
      D=0.012D0
      PI=4.D0*DATAN(1.D0)
      C=PI/180.D0
C ****** INPUT FORMATS ***********************
    9 FORMAT(2(F5.2,1X))
C ****** OUTPUT FORMATS **********************
  101 FORMAT(1H1,//)
  102 FORMAT(21X,'DETAILS CF THE CUTTING HEADS INVESTIGATED')
  103 FORMAT(21X,'-----------------------------------------')
  104 FORMAT(25X,'HEAD GEOMETRY   :   SPHERICAL')
  105 FORMAT(20X,'TILT ANGLE OF THE FIRST TOOL : ',F5.2,' DEGREE')
  106 FORMAT(17X,'TILT ANGLE OF THE CORNER CUTTING TOOL : ',F5.2,' DEGRE
     #E')
  107 FORMAT(25X,'HEAD GEOMETRY     :    CONICAL')
  108 FORMAT(25X,'HEAD CCNE ANGLE   :    ',F5.2,' DEGREE')
  109 FORMAT(25X,'HEAD GEOMETRY     :    COMBINED')
C ********************************************************************
  110 FORMAT(12X,':====================================================
     #=======:')
```

```
111 FORMAT(12X,':      CUTTING RADIUS AND FORCE LEVELS AT EACH CUTTING T
   #COL    : ')
112 FORMAT(12X,':-----------:------------:---------------:--------:--
   #-------:')
113 FORMAT(12X,':  TOOL NO. : TILT ANGLE : CUTTING RADIUS :  MCF    :
   # MNF    :')
114 FORMAT(12X,':           :  (DEGREE)  :      (M)       :  (KN)   :
   # (KN)   :')
115 FORMAT(12X,':===========:============:===============:========:==
   #=======:')
116 FORMAT(16(12X,':      ',I2,'    :    ',F5.2,'    :     ',F6.4,'
   #:  ',F4.2,'  :   ',F4.2,'  :',/,12X,':-----------:------------:---
   #-------------:--------:---------:',/))
117 FORMAT(7X,':=========================================================
   #===============:')
118 FORMAT(7X,':          CALCULATED              :              CUT   SECTOR
   #                 :',/,7X,':          PARAMETERS              :-------------
   #------:----------------------:')
119 FORMAT(7X,':        (ADV. / REV.)            :    180   DEGREE      :
   #90 DEGREE       :',/,7X,':=================================:=============
   #======:======================:')
120 FORMAT(7X,': TORQUE + S.D.   (KNM)       :',F8.5,' + ',F8.5,' :',F8
   #.5,' + ',F8.5,'  :',/,7X,':----------------------------------:----------
   #--------:----------------------:')
121 FORMAT(7X,': SLEWING FORCE + S.D. (KN):',F8.5,' + ',F8.5,' :',F8.
   # 5,' + ',F8.5,'  :',/,7X,':----------------------------------:----------
   #--------:----------------------:')
122 FORMAT(7X,': VOLUME SWEPT  (CUBM)       :       ',F9.7,'       :      '
   #,F9.7,'        :',/,7X,':----------------------------------:-------------
   #----:----------------------:')
123 FORMAT(7X,': SPECIFIC ENERGY (MJ/CUBM):        ',F7.4,'         :
   # ',F7.4,'         :',/,7X,':==================================:===========
   #========:======================:')
    READ(5,9) AL1,AL2
C **** READS THE TILT ANGLES OF THE FIRST TOOL AT THE MACHINE SIDE (AL1)
C **** AND THE LAST TOOL AT THE NOSE SIDE (AL2, BEING CORNER CUTTING TOOL)
C
    IF(AL2.EQ.0.D0) GO TO 2001
    RR=0.2229D0
    S=0.27D0-(2.D0*PI*RR*(AL2-AL1)/360.D0)
    SL=0.018D0*DSIN(AL1*C)
C ******* THIS SECTION DEALS WITH THE CALCULATION OF INDIVIDUAL
C ***  PICK FORCES. IN ORDER TO AVOID TEDIOUS PROCEDURES THE PICK
C ***  FORCES ARE OBTAINED FROM REGRESSED VALUES (FROM COS (AL1)
C ***  - FORCE RELATIONSHIP).
    AAAC=0.3511D0
    BBBC=1.9050D0
    AAAN=0.6395D0
    BBBN=1.4784D0
    ALF=AL2+4.63D0
    Z=0.D0
C ****************************************************************
    DO 501 I=1,16
    ALF=ALF-4.63D0
    IF(ALF.LE.AL1) GO TO 502
    FRR(I)=RR*DCOS(ALF*C)
    FCAA(I)=AAAC+(BBBC*DCOS(ALF*C))
    FNAA(I)=AAAN+(BBBN*DCOS(ALF*C))
    ACI(I)=ALF
    N(I)=I



    GO TO 501
502 FRR(I)=RR*DCOS(AL1*C)+SL*Z
    FCAA(I)=AAAC+(BBBC*DCOS(AL1*C))
    FNAA(I)=AAAN+(BBBN*DCOS(AL1*C))
    ACI(I)=AL1
    N(I)=I
    Z=Z+1.D0
501 CONTINUE
C *****  CALCULATION OF THE CUTTING RADII    ********************
```

```
      R8=RRR(1)
      R15=RRR(2)
      R6=RRR(3)
      R13=RRR(4)
      R4=RRR(5)
      R11=RRR(6)
      R2=RRR(7)
      R9=RRR(8)
      R16=RRR(9)
      R7=RRR(10)
      R14=RRR(11)
      R5=RRR(12)
      R12=RRR(13)
      R3=RRR(14)
      R10=RRR(15)
      R1=RRR(16)
C **************************************************************
      FCA8=FCAA(1)
      FCA15=FCAA(2)
      FCA6=FCAA(3)
      FCA13=FCAA(4)
      FCA4=FCAA(5)
      FCA11=FCAA(6)
      FCA2=FCAA(7)
      FCA9=FCAA(8)
      FCA16=FCAA(9)
      FCA7=FCAA(10)
      FCA14=FCAA(11)
      FCA5=FCAA(12)
      FCA12=FCAA(13)
      FCA3=FCAA(14)
      FCA10=FCAA(15)
      FCA1=FCAA(16)
C ************************************************************
      FNA8=FNAA(1)
      FNA15=FNAA(2)
      FNA6=FNAA(3)
      FNA13=FNAA(4)
      FNA4=FNAA(5)
      FNA11=FNAA(6)
      FNA2=FNAA(7)
      FNA9=FNAA(8)
      FNA16=FNAA(9)
      FNA7=FNAA(10)
      FNA14=FNAA(11)
      FNA5=FNAA(12)
      FNA12=FNAA(13)
      FNA3=FNAA(14)
      FNA10=FNAA(15)
      FNA1=FNAA(16)
C *******   CALCULATION OF THE VOLUME SWEPT   *************


      VOLSP=D*(RR**2.D0)*(PI*(AL2-AL1)/360.D0+(DSIN(2.D0*AL2*C)-DSIN
     @(2.D0*AL1*C))/4.D0)
      VOLCO=D*S*(RR*DCOS(AL1*C)*DCOS(AL1*C)+S*DSIN(2.D0*AL1*C)/4.D0)
      IF(AL1.EQ.0.D0.AND.AL2.EQ.60.19D0) VOLSP=VOLSP+(0.00009629)
      IF(AL1.EQ.0.D0.AND.AL2.EQ.64.82D0) VOLSP=VOLSP+(0.00004815)
      VOL=VOLSP+VOLCO
C *****************************************************************
      T=0.D0
  200 T=T+1.D0
      IF(T.GT.360.D0) GO TO  202
C*****THE REAL VALUE OF FC AT A DEPTH OF CUT ********
```

```
      FC9=DABS(FCA9*DSIN(T*C))
      FC8=DABS(FCA8*DSIN((T+22.5D0)*C))
      FC7=DABS(FCA7*DSIN((T+45.D0)*C))
      FC6=DABS(FCA6*DSIN((T+67.5D0)*C))
      FC5=DABS(FCA5*DSIN((T+90.D0)*C))
      FC4=DABS(FCA4*DSIN((T+112.5D0)*C))
      FC3=DABS(FCA3*DSIN((T+135.D0)*C))
      FC2=DABS(FCA2*DSIN((T+157.5D0)*C))
      FC1=DABS(FCA1*DSIN((T+180.D0)*C))
      FC16=DABS(FCA16*DSIN((T+202.5D0)*C))
      FC15=DABS(FCA15*DSIN((T+225.D0)*C))
      FC14=DABS(FCA14*DSIN((T+247.5D0)*C))
      FC13=DABS(FCA13*DSIN((T+270.0D0)*C))
      FC12=DABS(FCA12*DSIN((T+292.5D0)*C))
      FC11=DABS(FCA11*DSIN((T+315.0D0)*C))
      FC10=DABS(FCA10*DSIN((T+337.5D0)*C))
C ***** THE REAL VALUE OF FN AT A DEPTH OF CUT*************************
      FN9=DABS(FNA9*DSIN(T*C))
      FN8=DABS(FNA8*DSIN((T+22.5D0)*C))
      FN7=DABS(FNA7*DSIN((T+45.D0)*C))
      FN6=DABS(FNA6*DSIN((T+67.5D0)*C))
      FN5=DABS(FNA5*DSIN((T+90.D0)*C))
      FN4=DABS(FNA4*DSIN((T+112.5D0)*C))
      FN3=DABS(FNA3*DSIN((T+135.D0)*C))
      FN2=DABS(FNA2*DSIN((T+157.5D0)*C))
      FN1=DABS(FNA1*DSIN((T+180.D0)*C))
      FN16=DABS(FNA16*DSIN((T+202.5D0)*C))
      FN15=DABS(FNA15*DSIN((T+225.D0)*C))
      FN14=DABS(FNA14*DSIN((T+247.5D0)*C))
      FN13=DABS(FNA13*DSIN((T+270.0D0)*C))
      FN12=DABS(FNA12*DSIN((T+292.5D0)*C))
      FN11=DABS(FNA11*DSIN((T+315.0D0)*C))
      FN10=DABS(FNA10*DSIN((T+337.5D0)*C))
C ****CALCULATION OF TORQUE ****************************************
      A9=DABS(FCA9*R9*DSIN(T*C))
      A8=DABS(FCA8*R8*DSIN((T+22.5D0)*C))
      A7=DABS(FCA7*R7*DSIN((T+45.D0)*C))
      A6=DABS(FCA6*R6*DSIN((T+67.5D0)*C))
      A5=DABS(FCA5*R5*DSIN((T+90.D0)*C))
      A4=DABS(FCA4*R4*DSIN((T+112.5D0)*C))
      A3=DABS(FCA3*R3*DSIN((T+135.D0)*C))
      A2=DABS(FCA2*R2*DSIN((T+157.5D0)*C))
      A1=DABS(FCA1*R1*DSIN((T+180.D0)*C))
      A16=DABS(FCA16*R16*DSIN((T+202.5D0)*C))
      A15=DABS(FCA15*R15*DSIN((T+225.D0)*C))
      A14=DABS(FCA14*R14*DSIN((T+247.5D0)*C))
      A13=DABS(FCA13*R13*DSIN((T+270.0D0)*C))
      A12=DABS(FCA12*R12*DSIN((T+292.5D0)*C))
      A11=DABS(FCA11*R11*DSIN((T+315.0D0)*C))

      A10=DABS(FCA10*R10*DSIN((T+337.5D0)*C))
C**** CALCULATION OF THE SLEWING FORCE *****************************
      H9=DABS(FC9*DCOS(T*C))+DABS(FN9*DSIN(T*C))
      H8=DABS(FC8*DCOS((T+22.5D0)*C))+DABS(FN8*DSIN((T+22.5D0)*C))
      H7=DABS(FC7*DCOS((T+45.D0)*C))+DABS(FN7*DSIN((T+45.D0)*C))
      H6=DABS(FC6*DCOS((T+67.5D0)*C))+DABS(FN6*DSIN((T+67.5D0)*C))
      H5=DABS(FC5*DCOS((T+90.D0)*C))+DABS(FN5*DSIN((T+90.D0)*C))
      H4=DABS(FC4*DCOS((T+112.5D0)*C))+DABS(FN4*DSIN((T+112.5D0)*C))
      H3=DABS(FC3*DCOS((T+135.D0)*C))+DABS(FN3*DSIN((T+135.D0)*C))
      H2=DABS(FC2*DCOS((T+157.5D0)*C))+DABS(FN2*DSIN((T+157.5D0)*C))
      H1=DABS(FC1*DCOS((T+180.D0)*C))+DABS(FN1*DSIN((T+180.D0)*C))
      H16=DABS(FC16*DCOS((T+202.5D0)*C))+DABS(FN16*DSIN((T+202.5D0)
     #*C))
      H15=DABS(FC15*DCOS((T+225.D0)*C))+DABS(FN15*DSIN((T+225.D0)*C))
      H14=DABS(FC14*DCOS((T+247.5D0)*C))+DABS(FN14*DSIN((T+247.5D0)*C
     #))
      H13=DABS(FC13*DCOS((T+270.D0)*C))+DABS(FN13*DSIN((T+270.D0)*C))
      H12=DABS(FC12*DCOS((T+292.5D0)*C))+DABS(FN12*DSIN((T+292.5D0)*C
     #))
      H11=DABS(FC11*DCOS((T+315.D0)*C))+DABS(FN11*DSIN((T+315.D0)*C))
      H10=DABS(FC10*DCOS((T+337.5D0)*C))+DABS(FN10*DSIN((T+337.5)*C))
C ***************************************************************
```

```
      IF(T.GT.0.D0.AND.T.LE.22.5D0) GO TO 60
      IF(T.GT.22.5D0.AND.T.LE.45.D0) GO TO 61
      IF(T.GT.45.D0.AND.T.LE.67.5D0) GO TO 62
      IF(T.GT.67.5D0.AND.T.LE.90.D0) GO TO 63
      IF(T.GT.90.D0.AND.T.LE.112.5D0) GO TO 64
      IF(T.GT.112.5D0.AND.T.LE.135.D0) GO TO 65
      IF(T.GT.135.D0.AND.T.LE.157.5D0) GO TO 66
      IF(T.GT.157.5D0.AND.T.LE.180.D0) GO TO 67
      IF(T.GT.180.D0.AND.T.LE.202.5D0) GO TO 68
      IF(T.GT.202.5D0.AND.T.LE.225.D0) GO TO 69
      IF(T.GT.225.D0.AND.T.LE.247.5D0) GO TO 70
      IF(T.GT.247.5D0.AND.T.LE.270.D0) GO TO 71
      IF(T.GT.270.D0.AND.T.LE.292.5D0) GO TO 72
      IF(T.GT.292.5D0.AND.T.LE.315.D0) GO TO 73
      IF(T.GT.315.D0.AND.T.LE.337.5D0) GO TO 74
      IF(T.GT.337.5D0)  GO TO 75
C *************************************************************
   60 AA=A9+A8+A7+A6+A5+A4+A3+A2
      BB=A9+A8+A7+A6
      HA=H9+H8+H7+H6+H5+H4+H3+H2
      HB=H9+H8+H7+H6
      GO TO 76
   61 AA=A10+A9+A8+A7+A6+A5+A4+A3
      BB=A10+A9+A8+A7
      HA=H10+H9+H8+H7+H6+H5+H4+H3
      HB=H10+H9+H8+H7
      GO TO 76
   62 AA=A11+A10+A9+A8+A7+A6+A5+A4
      BB=A11+A10+A9+A8
      HA=H11+H10+H9+H8+H7+H6+H5+H4
      HB=H11+H10+H9+H8
      GO TO 76
   63 AA=A12+A11+A10+A9+A8+A7+A6+A5
      BB=A12+A11+A10+A9
      HA=H12+H11+H10+H9+H8+H7+H6+H5
      HB=H12+H11+H10+H9
      GO TO 76
   64 AA=A13+A12+A11+A10+A9+A8+A7+A6
      BB=A13+A12+A11+A10
      HA=H13+H12+H11+H10+H9+H8+H7+H6
      HB=H13+H12+H11+H10
      GO TO 76
   65 AA=A14+A13+A12+A11+A10+A9+A8+A7
      BB=A14+A13+A12+A11
      HA=H14+H13+H12+H11+H10+H9+H8+H7
      HB=H14+H13+H12+H11
      GO TO 76
   66 AA=A15+A14+A13+A12+A11+A10+A9+A8
      BB=A15+A14+A13+A12
      HA=H15+H14+H13+H12+H11+H10+H9+H8
      HB=H15+H14+H13+H12
      GO TO 76
   67 AA=A16+A15+A14+A13+A12+A11+A10+A9
      BB=A16+A15+A14+A13
      HA=H16+H15+H14+H13+H12+H11+H10+H9
      HB=H16+H15+H14+H13
      GO TO 76
   68 AA=A1+A16+A15+A14+A13+A12+A11+A10
      BB=A1+A16+A15+A14
      HA=H1+H16+H15+H14+H13+H12+H11+H10
      HB=H1+H16+H15+H14
      GO TO 76
   69 AA=A2+A1+A16+A15+A14+A13+A12+A11
      BB=A2+A1+A16+A15
      HA=H2+H1+H16+H15+H14+H13+H12+H11
      HB=H2+H1+H16+H15
      GO TO 76
   70 AA=A3+A2+A1+A16+A15+A14+A13+A12
      BB=A3+A2+A1+A16
      HA=H3+H2+H1+H16+H15+H14+H13+H12
      HB=H3+H2+H1+H16
      GO TO 76
```

```
   71 AA=A4+A3+A2+A1+A16+A15+A14+A13
      BB=A4+A3+A2+A1
      HA=H4+H3+H2+H1+H16+H15+H14+H13
      HB=H4+H3+H2+H1
      GO TO 76
   72 AA=A5+A4+A3+A2+A1+A16+A15+A14
      BB=A5+A4+A3+A2
      HA=H5+H4+H3+H2+H1+H16+H15+H14
      HB=H5+H4+H3+H2
      GO TO 76
   73 AA=A6+A5+A4+A3+A2+A1+A16+A15
      BB=A6+A5+A4+A3
      HA=H6+H5+H4+H3+H2+H1+H16+H15
      HB=H6+H5+H4+H3
      GO TO 76
   74 AA=A7+A6+A5+A4+A3+A2+A1+A16
      BB=A7+A6+A5+A4
      HA=H7+H6+H5+H4+H3+H2+H1+H16
      HB=H7+H6+H5+H4
      GO TO 76
   75 AA=A8+A7+A6+A5+A4+A3+A2+A1
      BB=A8+A7+A6+A5
      HA=H8+H7+H6+H5+H4+H3+H2+H1
      HB=H8+H7+H6+H5
C ***********************************************************
   76 TA=AA+TA


      AR=AA**2.D0
      SA=SA+AR
      TB=TB+BB
      BR=BB**2.D0
      SB=SB+BR
      THA=THA+HA
      HAR=HA**2.D0
      SHA=SHA+HAR
      THB=THB+HB
      HBR=HB**2.D0
      SHB=SHB+HBR
C *****  IN THIS SECTION THE INSTANTANEOUS VALUES OF TORQUE AND
C ***** AND SLEWING FORCE VALUES AGAINST THE CUTTING HEAD REVOLUTION
C ***** CAN BE LISTED OUT FOR SOME PLOTTING PURPOSES.
      GO TO 200
C ******************************************************
  202 TAM=TA/360.D0
      TBM=TB/360.D0
      THAM=THA/360.D0
      THBM=THB/360.D0
      DA=DSQRT((SA-(360.D0*(TAM**2)))/359.D0)
      DB=DSQRT((SB-(360.D0*(TBM**2)))/359.D0)
      DHA=DSQRT((SHA-(360.D0*(THAM**2)))/359.D0)
      DHB=DSQRT((SHB-(360.D0*(THBM**2)))/359.D0)
      VOLA=VOL*2.D0
      VOLB=VOL
      SEA=(2.D0*PI*TAM)/(VOLA*1000.D0)
      SEB=(2.D0*PI*TBM)/(VOLB*1000.D0)
C      DVB=DSQRT((SVB-(360.D0*(TVBM**2)))/359.D0)
      WRITE(6,101)
      WRITE(6,102)
      WRITE(6,103)
      IF(AL2.EQ.64.82D0.AND.AL1.EQ.0.0D0) GO TO 1449
      IF(AL1.EQ.AL2) GO TO 1500
      IF((AL2-AL1).NE.69.45D0) GO TO 1510
 1449 WRITE(6,104)
      WRITE(6,105) AL1
      WRITE(6,106) AL2
      GO TO 1520
```

```
C ***************************************
1500 WRITE(6,107)
     WRITE(6,108) AL1
     WRITE(6,106) AL2
     GO TO 1520
1510 WRITE(6,109)
     WRITE(6,108) AL1
     WRITE(6,106) AL2
1520 WRITE(6,110)
     WRITE(6,111)
     WRITE(6,112)
     WRITE(6,113)
     WRITE(6,114)
     WRITE(6,115)
     WRITE(6,116) (M(I),ACI(I),RRR(I),FCAA(I),FNAA(I),I=1,16)
     WRITE(6,117)
     WRITE(6,118)
     WRITE(6,119)
     WRITE(6,120) TAM,DA,TBM,DB
     WRITE(6,121) THAM,CHA,THBM,DHB
     WRITE(6,122) VOLA,VCLB


     WRITE(6,123) SEA,SEB
     GO TO 2000
2001 STOP
     END
```