INVESTIGATION OF THE APPLICATION OF MECHANICAL MINING OF OCEAN FLOOR POLYMETALLIC SULPHIDE DEPOSITS

by

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Abstract

This thesis focused on developing and understanding of the challenges of mining subsea polymetallic sulphide (PMS) deposits. The research presented starts from the concept of deposit identification through to prototype testing of an ocean mining excavator. The work presented builds on existing work in the field as well as relying heavily on the Solwara Ocean mining expedition case study carried out in conjunction with Barrick Gold and Nautilus Minerals.

The research demonstrates the mechanical cutting of PMS sulphide deposits in the Manus Basin and confirms the viability of mechanical excavation as a mining strategy. As well, knowledge was gained in the performance of an undersea excavator and potential design objectives for a future generation mining ocean machine. This thesis presents the results of 27 cutting dives in the Manus Basin as well as the results from surface cutting trials of PMS substitute materials. The result indicate that excavation of deep ocean PMS deposits is technically viable.

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Nomenclature

F_C=	Cutting force
S_T=	Rock tensile strength
S_C=	Rock compressive strength
d=	Depth of cut
β=	Cutterhead shape factor
ICR=	Instantaneous cutting rate
k=	Transfer function calibration factor
H_P=	Cutter head power
SE_{OPT}=	Optimal specific energy of cutting
P_H =	Hydraulic pressure
RMCI=	Rock Mass Cutability Index
RQD=	Rock quality designation
γ=	Specific weight
SE_{cor}=	Corrected specific energy
E_i=	Energy consumed during interval i
E_P=	Parasitic energy drain while cutting
Vol_i=	Volume excavated during interval i
Q_{aft}=	Aft cutter-head hydraulic flow
Q_{fwd}=	Forward cutter-head hydraulic flow
V_P=	Analog pressure voltage
V_F=	Analog flow voltage

Preface

The author, Richard Joseph Hunter, completed a Bachelor of Mining Engineering degree with the mechanical engineering option at Queens University in Kingston, in 2001. He started his work on the Master of Applied Science degree in the department of Mining Engineering, in 2001, under the supervision of Dr. Robert Hall. After completion of one year of study the author began a working sabbatical for Placer Dome at the Musselwhite Mine Operation.

Following this research absence the author was transferred to Placer Dome's Research and technology unit where he became involved with the rock cutting research as well as ocean mining studies. Following the merger of Placer Dome with Barrick Gold Corporation, he currently works in the Barrick Toronto Corporate office involved with mining technology integration and development.

Acknowledgments

I would like to thank Barrick Gold and Nautilus Minerals for their assistance in sponsoring the work in this thesis, without their assistance this work would have not been possible. In addition I would like to thank my advisor Dr. Robert Hall for his dedication throughout the progress of this extended project.

I would also like to thank the DOSS build team for their assistance in interpreting the sensor readout and their support both on the expedition and after. Special regards to Kelvie Wong from Cellula Robotics in his work with the mass processing of the bulk amounts of data.

Lastly, I would like to thank my parents, whose support has sustained me throughout the thesis process.

1. Introduction

1.1. Ocean mining

The oceans cover over 75% of the earth's surface, these watery depths contain vast material wealth awaiting exploitation. The high pressure caused by hundreds of metres of water causes many unique chemical processes to occur on the sea bottom. The high pressure causes manganese to precipitate out and form metal rich nodules covering the deep ocean floor. Volcanic ocean vents spew mineral rich solutions which solidify into large pipes of mineral rich columns. Surface river action deposits vast amounts of sediments into submerged ocean deltas which act as large preconcentration operations. Methane gas is trapped deep beneath the ocean floors in complex hydride structures, which could provide the fuel for generating vast amounts of electricity to service future energy demands. If the dissolved mineral content of the ocean itself is also included with the previously mentioned items the potential riches are enormous, but these riches are not free, for both technical and legislative hurdles remain to be resolved.

Historically, as will be presented in chapter 2, ocean mining has focused on deep ocean manganese nodule research. The potential for rapid exploitation of the ocean led to the establishment of the International Seabed Authority (ISA 2006) under the United Nations Convention on the Laws of the Sea. The ISA currently governs the exploitation of the subsea resources that fall outside national boundaries. The ISA manages the international laws, including environmental protection standards, involved with exploiting mineral resources that fall within its jurisdiction. The ISA is adapting new laws and standards as more information becomes available; mineral title under its jurisdiction remains difficult to obtain. To ensure clear title many explorers have focused on the areas within the national boundaries of sea bound countries.

Within country limits there remain many deposits which can still be investigated and due to recent changes in the commodities market, ocean mining is beginning to hold renewed promise. A problem with mining in the ocean at the depths most of the rich mineral deposits occur is the high hydrostatic pressure. This high pressure means that all the equipment must be operated under teleremote conditions. Ocean smoker deposits however are often located

closer to shore within national boundaries and are in shallower water than manganese nodule deposits. Ocean smokers form polymetallic surface (PMS) deposits, which are high in mineral wealth. These deposits do not appear to have a large layer of overburden and should be easy to extract. These types of deposits have been seen as the most promising deposits for exploitation. (Halfar, 2002)

To continue advancement in the field of ocean mining of PMS deposits, there are many questions which remain to be answered. This thesis aims to provide insight into:

- The machine demands for a deep ocean excavation system. These demands include the cutting strength of the deep ocean rock, information regarding the mechanical reliability, and lastly general knowledge regarding the strategy for continued development of ocean excavators.
- The mining conditions of deep ocean smoker deposits. Little is known about the operating conditions of mining at depth. What is the rock like to excavate? What mining approach is best to maximize recovery of PMS deposits?

1.2. Thesis overview

In order to begin answering the previous questions this thesis continues in the next chapter with a background overview of ocean deposits and of the previous ocean mining attempts to mine manganese nodules. Following that is an overview of mechanical rock excavation and performance predictions from rock dredging operations. In Chapter 3 a methodology is developed to investigate PMS mining, followed by Chapter 4 that introduces a case example of an investigation into deep ocean mining conducted by Barrick Gold Corp and Nautilus Mining. Chapter 5 outlines the test apparatus which was used to test the mining of the PMS deposits, the Deep Ocean Sampling Skid (DOSS). Chapter 6 outlines results and discussion of the mechanical excavation program. Lastly, Chapter 7 discusses the results of the cutting trials and presents some of potential engineering challenges which need to be addressed for the next phase machine. Chapter 8 presents conclusions from the work and presents recommendations for further study.

2. Toward Undersea Rock Cutting

To frame the ocean excavation challenge a review of some of the previous work in the field of ocean mining is presented. The mining system presented in this thesis is aimed at extracting poly-metallic smokers, so a brief outline of their formation is provided for reference. These smokers are believed to be quite friable allowing for mechanical rock excavation for their extraction. A review of surface mechanical rock mining theory follows, developing into a performance prediction of mechanical excavators. Lastly, although the designed excavation system resembles a surface excavator more than an underwater dredge performance prediction parameters studies from underwater dredging operations are presented.

2.1. Mining deep-ocean deposits

Exploiting the mineral wealth of the oceans has been a goal of the minerals industry for more than 30 years and is outlined in an excellent summary by Glasby (2002) on the historical failures of ocean mining and the potential outlook of the field. Glasby notes that the years 1972 to 1982 were the prime time for nodule research with over 2000 publications published by 1982. In 1998 the ISA, contracted UBC to conduct a patent review of the progress in deep sea mining, (ISA, 1998) and over 352 patents were identified in the survey. It was noted that the number of patents issued peaked in 1983, and has since dropped dramatically. One point of optimism is that these patents have now expired and future development work can proceed unhindered. The peak of the research concluded with the development and testing of a complete pilot system for nodule mining in 1978. The pilot system extracted 800 tonnes of material before the entire pilot system was lost over the stern of the mother ship. One area of concern for the promotion of ocean mining research, was the incident of the Hughs Glomar Explorer billed as an ocean mining vessel, that was actually developed to recover k-127.[1] Glasby (2002) This led to an artificial sense of ocean mining's viability and the stigma of deceit remains.

[1] A Russian Submarine, which the CIA financed US$500 million to construct the Explorer in order to recover it.

Although current estimates indicate that there are 7.5 billion tonnes of manganese ore in one field alone, the advances in surface excavation and processing techniques have not rendered mining them economically viable. In addition many of the earlier studies underestimated the cost of ocean mining leading to gross overestimation of the profitability of extracting manganese from depth. Because of high unsubstantiated profitability estimates for these deposits, the International Seabed Authority (ISA, 2006) was established under the United Nations Convention on the Laws of the Sea, and currently governs the exploitation of the subsea resources that fall outside of the international country boundaries. The ISA manages the international laws, including environmental protection standards, involved with exploiting mineral resources that fall within this jurisdiction. The ISA is adapting new laws and standards as more information becomes available; mineral title under its jurisdiction remains difficult to obtain. To ensure clear title many explorers have focused on the areas with national boundaries within that country's legal regulations. Its conditions for releasing tenements were so onerous that private interest in exploiting deep ocean manganese deposits ceased. This led to the interest in exploring within national boundaries. These exploration efforts lead to the discovery of numerous PMS deposits, of which the geology is described later in this chapter. Recently, some of the more onerous regulations have been rescinded and research in deep ocean mining continues. (Herzig, 2000)

2.1.1. Current ocean mining system

Figure 2-1 illustrates common approaches to an ocean mining system that are considered for manganese nodule and PMS mining. The two approaches (Ecker 1978, Schwarz 1999) outline a similar concept with a surface control vessel supporting mining operations below, and with a flexible riser system being utilized for material transport.

Figure 2-1 was removed due to copyright restrictions.
This figure illustrated a schematic of an ocean mining system. The original figure can be found as figure 1 in the paper "Handschuh, R., Grebe, J., Schulte, E., Wenzlawski, B., Schwarz, W., Atmanand, M.A., Jayamani, R., Shajahan, M., Deepak, R., Ravindran, M.; "Innovative Deep Ocean Mining Concept based on Flexible Riser and Self Propelled Mining Machines", *Proceeding of the Fourth Ocean Mining Symposium*, 2001".

Figure 2-1: Marine mining concepts (Handschuh, 2001)

The surface ship acts as a mobile mining camp, being required to process the ore, service the excavators, and house the personnel. The ship could be a conventional offshore vehicle such as a mobile drill ship, or could be simply a large support barge. The design of the surface vessel depends both on the total application space requirement as well as the sea state of the potential mining location.

A major challenge in ocean mining is the materials handling problem. It is easy to move material around the surface of the ocean, but bringing material up from the seafloor poses a more substantial challenge. Discrete approaches such as recovering material in a grab net can not yield enough material to be productive. Innovative approaches such as vertical conveyances have been proposed, but currently riser technology is recognized as the most viable method of vertical conveyance. (PDTS, 2005) Riser technology is a mature technology which has been used in the offshore oil industry for the last 30 years, and was used in the initial pilot testing of the nodule mining. In order to move material from the seafloor via a riser there are two choices, a submerged pumping system or an airlift system, two different pumping methods both using a pipeline connected to the surface. Using a submerged pumping system increases the complexity of the undersea infrastructure as the

pumps need to be located at the mining horizon. Submerged mining systems using displacement pumps have been tested to depths of greater than 500 metres. (Deepak, 2001) Conversely with airlift technology the air compressors are located on the surface and air is pumped to depth to lift the undersea material. This approach is commonly used in the diamond industry (Garnett, 2002) and was used in the original ocean mining trials. Air lift technology introduces its own set of issues as this is a multiphase slurry fluid problem in which the pumping conditions are dynamic. (Yoshinaga, 1996) Ocean riser theory is an in-depth field of research by itself and there are many additional sources of information in the literature. (Liang, 2005) (Samaras, 2005) (Wilson, 2003) (Xia, 2004a, 2004b) (Littman, 1995)

2.1.2. Marine mining

Although deep ocean mining for metal nodules has yet to be proven to be commercially viable, there are marine mining operations around the world that have been proven viable. The most common applications of marine mining currently being conducted are offshore diamond mines in southern Africa and tin mines near Indonesia.

Diamond production began in southern Africa (Garnett, 2002) in 1908 on the coastline and moved out into the beaches in the subsequent decade. Production, monopolized by DeBeers, increased over the years to exceed a current production of over 100Mct. The first offshore permit for diamond mining was issued in 1957 and production commenced in 1961, using simple airlift technology in shallow water. Production continued to be sporadic until DeBeers bought out the mining operator in 1980. New exploration results by Namdeb indicated that potentially more economic deposits were located in deeper water which would be more viable while providing a more consistent production profile. Offshore diamonds continue to be mined off the coast of Namibia, by Namdeb (Namdeb, 2006) joint venture between DeBeers and the Namibian government.

Currently, 510 mm diameter airlift technology is being used to transport seafloor material from a depth of approximately 200 metres to the surface. Unfortunately, the airlift alone is unable to mobilize the diamond from the seafloor, unless the conditions are optimal. To address this problem an excavation machine is located at the bottom of the airlift. These

machines have undergone many developments since the early 1960's from early dredge machines to the currently used Wirth Drill and Nam-2. (Garnett, 2002)

The Wirth Drill continues to be a mainstay in offshore diamond production, consisting of a 7 meter drill platform which mobilizes the seafloor with a rotational torque and a vertical motion. This drill is capable of extracting seabed sediments to base rock at 400 tonnes per hour. However, the Wirth drill is a vertical operating machine and lacks horizontal operating flexibility. During the development period, numerous skid and crawler mounted machines were trialed in the environment. Although skid mounted excavators like those patented by Fagervoid (2001) did not perform adequately, crawler mounted excavators such as those outlined in Jacobsen (2001), allowed operational flexibility that the Wirth drill lacked. The NAM-2 (Smart 1998) is the latest in the series of crawler mounted excavators. The NAM-2 has a dredge head mounted on an articulated arm. Due to improved control a crawler mounted excavator outperforms the Wirth when the deposit is high grade or the bathymetry is irregular.

In addition to diamond mining, another area of ocean mining is the use of bucketwheel dredges to mine tin off the coast of Indonesia. Because of the high specific gravity of tin ore, bucket wheel dredges are used due to the performance inefficiencies of the suction dredges used in the diamond applications. Unfortunately bucketwheel dredges are further limited in their depth of operation. The ore is transported from the submerged bucketwheel to surface via a ladder conveyer. This method is only viable for depths less than 50 metres due to the structural stability of the conveyor system. Unfortunately, the deposits which can be mined by this method are almost depleted and new advances must be made. Alabar (2002) outlines a design plan to increase the viable depth that the bucketwheel dredge can be successfully used, by utilizing a submerged staggered pumping to transport the material to the surface. This is similar to the riser concepts presented earlier, but the submerged pumping system increases complexity as the depth increases beyond the shallow depths required for tin mining.

2.2. The geology of the polymetallic massive sulphide (PMS) deposits

Subsea polymetallic sulphide (PMS) smoker deposits have peaked industrial interest as they are potentially easier to extract as they are found at shallower depths than manganese nodules, in addition they are rich in valuable minerals such as gold, silver and copper. (Halfar, 2002) PMS deposits have been investigated intensively over the last 15 years as summarized by Herzig. (Herzig, 1995) including the Pac-Manus Basin which has been researched continually since its discovery in 1991. (Wheiler, 1992)

Figure 2-2 illustrates a typical schematic of a seafloor smoker. Below the active smoker, seawater percolates through the pores in host rock. This water is heated by an active volcanic source, and the seawater leaches metals out of the host rock. This superheated water percolates to the surface of the seabed, where it is vented out and the dissolved metals precipitate out. The solid precipitates are a function of the ocean depth. These solids form a ring around the discharge vent, which gradually grows into a pipe. Eventually as more material precipitates out the pipe is clogged off with precipitate and the cycle begins again. It is estimated that a single black smoker can produce 250 tonnes of sulphide material per year. The mineralogy of the PacManus Basin smoker material consists of chalcopyrite, bornite, sphalerite and other minerals. The high gold content in this area is believed to be due to the leaching of gold enriched rocks of the PacManus Basin below the seafloor by circulating hydrothermal fluids which then precipitates out upon the chimney material. (Moss, 2001)

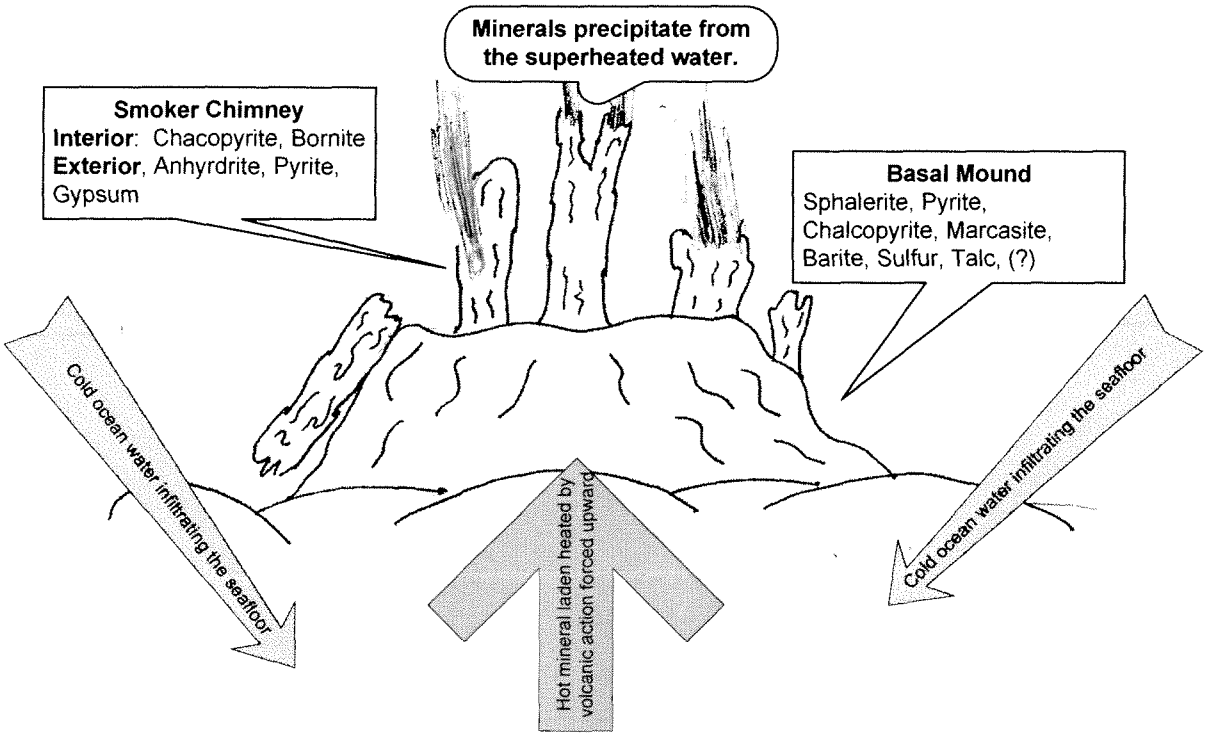

Figure 2-2: Schematic of hydrothermal chimney formation

2.3. *Mechanical rock cutting*

Due to the depths involved with PMS deposits and environmental issues explosive rock breaking of the chimney material was not deemed to be a viable solution. This is also due to the logistical problems involved with getting explosives to the ocean floor. As an alternative, mechanical rock cutting was deemed to provide the best option for excavation for initial consideration. The fact that the ocean chimney material is believed to be primarily formed by consolidation by precipitation indicated that PMS deposits would be particularly suited to mechanical cutting. Mechanical rock breakage has been extensively used for the last 40 years as the principal method of mining coal, salt, and other soft materials. Due to this there are numerous references outlining the advances in the field. (Fowell, 1993) (Nichimatsu, 1993) (Copur 1998) This review begins with the basic theory of rock fragmentation by mechanical means of a single cutter, then progresses into the analysis of cutting requirements with a full cutterhead. Lastly, performance of mechanical dredges is reviewed as well as literature which predicts the expected energy requirements of deep hydrostatic rock cutting.

2.3.1. Types of rock cutting

Mechanical rock cutting can be divided into two main indentation cutting modes: drag pick cutting or disk cutting. While both cutting modes rely on indentation of the rock mass, the difference between the two modes is illustrated in figure 2-3. (Fowell, 1993) Drag pick cutting in general relies on the pick or cutter impacting and dragging a furrow of chips from the rock. This dragging motion causes the rock to break in tension and shear off. This is particularly useful in soft rock (less than 50 Mpa) such as coal and salt as the picks readily penetrate the rock. Once the rock hardness increases, the picks are no longer able to penetrate the rock as readily and wear increases due to increasing heat. The increased wear rapidly decreases the viability of these cutters. Instead for harder rock applications, the disk cutter was developed. The disk cutter is forced into the rock with forces greater than the compressive strength of the rock which generates lateral chips as the disk is rolled across the rock surface. Unfortunately the force required to overcome the compressive strength necessitates a large power source and rigid structure. Disk cutters are commonly used in tunnel and raise boring machines in hard rock applications. Further discussion on Disc cutter theory is beyond the scope of this review, but valuable initial research in work by Roxborough (1975), Sanio (1985), and a review of the research in the field by Clark (1987) will provide the reader with a good understanding in work on this cutting mode. Although generally concerned with full scale research the Colardo School of Mines also has contributed to disc cutter knowledge with work by Rostami, (1993) and Asbury. (1998)

Drag pick cutting as mentioned is more efficient in terms of energy requirements, but is limited in its application to softer material. However, within its application range drag pick cutting is used in diverse mining systems including continuous miners, longwall shearers, and road headers.

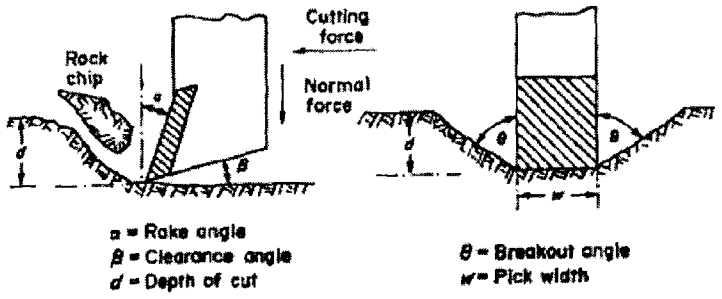

Figure 1 Drag pick

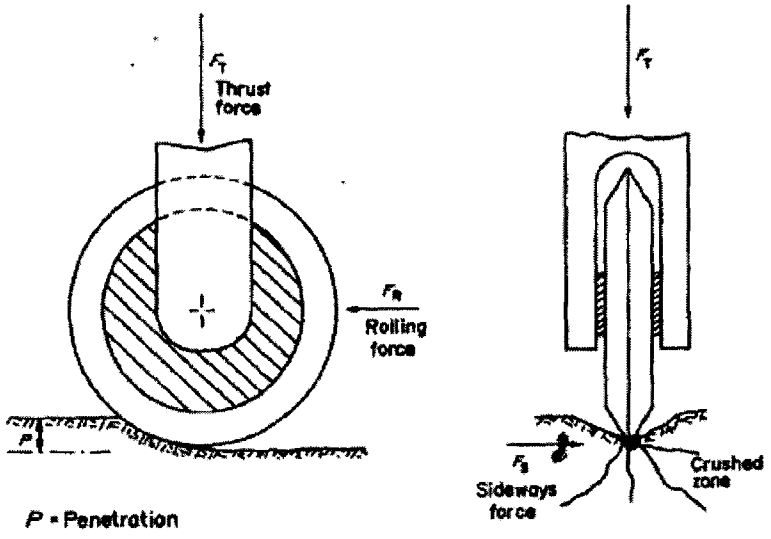

Figure 2 Disk cutter

Figure 2-3: Two different indenter cutting modes (Fowell, 1993 reproduced with permission from Elsevier)

2.3.2. Pick cutter theory

In an excellent review of the development of the theory of rock cutting Nichimatsu (1993) provides an overview of 20 years of indentation excavation theory research. An initial explanation of the dynamics of pick cutting was provided by Evans (1967) and is still commonly used as a simple example model. Evans models a wedge shaped cutter pressed into a block of coal. This causes a failure along a circular tension surface defined by the material strength properties. The theoretical models have advanced into complex geometric models with analysis primarily consisting of simple mathematical physics models to describe laboratory testing.

The cutting force (F_C) (Nichimatsu, 1993) for a point attack pick can is generalized in equation 2-1. This force is a function of the cutting pick shape and orientation (β), the rocks tensile(S_t) and compressive strength (S_c) at the point, and lastly the depth of cut (d).

$$F_c = \frac{16\pi}{\cos^2\beta}\left(\frac{S_t}{S_c}\right)\cdot S_t \cdot d^2 \qquad [2\text{-}1]$$

Lindqvist (1983) investigated the performance of an indenter while it is pressed into rock. The indentor crushes the rock immediately beneath the indenter causing plastic deformation of the rock which then causes tensile forces on the surrounding rock resulting in chips of rock forming. As the indentor continues to descend into the rock, the zone of plastic deformation increases and further chips form. This has been confirmed in further experimentation by Momber (2004) who analyzed the cracking in both plate glass where hertzian cracks formed and in limestone where the cracks were irregular due to heterogeneous mineral matrix

Ranmens (1985) investigated unsuccessfully using a geometrical model to model the rock failure process. When cutting along a line, it was concluded that time between rock failures and chip formation follow a Poisson distribution, thus each chip failure is independent of one another. Due to this a model dealing with the single chips formation is not sufficient to describe the cutting process and a statistical method must be used. It is important to note the strength properties of the rock are dynamic and change as the cutting progresses. Previous cutting passes induce cracking into the rock mass weakening both the compressive and tensile strength of the rock. Because of this dynamic process and the need for a more statistical approach to rock cutting modern investigations have moved to computer modeling of cutting rather than geometrical interpretations.

2.3.3. Modeling of pick cutting

The advent of computers has lead to a long history of cutter modeling to better understand cutting dynamics without resorting to lab experimentation. Most of the major modeling techniques developed from initial fracture mechanics theory (Lindqvist, 1984) to more advanced techniques such as boundary element modeling (Chen 1998), displacement discontinuanity approaches (Tan 1998), and finite element modeling (Jonak 2001). The

latest approaches use discrete element techniques for modeling the tool rock interaction as they model chip formation as well cutting forces. (Lui, 2002) (Onate, 2004)

The author was involved in another project where Placer Dome commissioned the development of a 3 dimensional rock cutting model using particle flow code PFC from Itasca consulting group based on the initial 2 dimensional model by Kiatkay. (2002) This PFC model modeled the cutting interaction in 3 dimensions, (Itasca, 2005) unfortunately due to the size of the models it failed to perform as expected with excessive runtime for modeling.

All of these modeling techniques share the same problems in that the base modeling code structure influences the results of the model. With discrete element models the smallest size particle influences the crack propagation properties, decreasing the speed of the model's runtime. In addition most of the earlier models are 2 dimensional models attempting to model a 3 dimensional problem. Lastly, all the models only simulate a few cutting tools rather than a complete cutterhead. Computer modeling currently can only provide at best an indication of the cutting interaction and currently empirical methods are still used in the development of rock cutterhead, rather than advanced numerical modeling.

2.3.4. Specific energy of pick cutting

Due to the difficulties in defining the cutting force by theoretical methods, most of the design work for excavation machines is based on linear cutting machine (LCM) trials. A LCM, described in Bilgin, (2006) is a rigid hydraulically actuated machine used for testing rock cutting. The LCM is able to cut blocks of rock using full sized cutters allowing for a prediction of the cutting force requirements. In addition multiple lines of cutting can be conducted on a single sample allowing for testing of three key parameters for rock cutting, namely depth of cut, line spacing, and rock type. From these three parameters, cutting forces and energy requirements for a full sized excavation machine can be predicted. The force required to cut the rock provides information on the strength requirements for the cutting teeth, and the requirements that the full sized machine is required to deliver. In some cases, due to a defined machine configuration the available force has already been set. In this case the energy requirements for excavating rock, in particular the specific energy is of greater importance. The specific energy is the energy required to excavate a unit of rock. Specific

energy as a criterion for determining the cutability of rock has recently been reviewed by Copur (2001)

One of the most difficult issues with modeling rock cutting and other mining practices is the variability in rock parameters. The strength, and geotechnical properties as well as the friction angle correspond well to the required specific energy requirement for rock cutting. Bilgin (2006) reviews many of the common (and not so common) geotechnical tests and their correleation to specific energy for rock cutting. As expected there are strong correlations between the specific energy and the unconfined compressive strength and the tensile strength. Interesting, the results of the Schmidt hammer tests were found to correlate to the cutability, possibly due to the similar mechanical action that an indentor cutter performs.

2.3.5. Cutterhead design

Cutter spacing is one of the key design parameters for cutterheads. As outlined in Copur, (2001) Clark, (1987) and Fowel (1993) for a given rock type and penetration depth there is an optimal spacing which the energy required to break the rock is at a minimum. The greatest amount of energy for breaking rock is found with a single cutter cutting a virgin rock surface (unrelieved cutting). When a cutter is cutting beside a previously cut path (relieved cutting) the chips will form to the base of the other pass, which requires less energy than cutting the original path. As the cutter spacing closes the specific energy will decrease at the optimal spacing distance, but then will begin increasing as the spacing continues to close as energy is being wasted in inefficient cutting.

Now as the cutting force is a function of depth[2] the optimal cutting spacing is also related to depth. For a given rock type there is an optimal spacing to penetration ratio which will give minimal cutting energy. This is important as the depth of penetration is dependent on the excavation machines ability to overcome the rock strength. With the knowledge of the optimal cutter spacing, the overall pick layout can be designed to deliver this spacing and penetrate to the desired depth that the machine can deliver, whilst balancing the cutterhead to minimize vibrations. (Hekimoglu, 2004) This design is done using computer software to

[2] The depth must be great enough to allow chips to form.

ensure that the lacing pattern performs as designed and does not require excess forces due to inefficient design. (Somanchi, 2005) An optimal design is analogous to electronic impedance matching too little energy and the cutter will not penetrate the rock, however too much energy and the rock will cause the cutterhead to stall. Previously, it has been noted the optimal specific energy is analogous to blasting, where a given unit of explosive has an optimal burden in which it will perform. (Khalaf, 1980)

2.3.6. Mechanical excavation systems and performance

There are various machines used for mechanical rock excavation depending on the application. For soft rock production, continuous mining machines and long wall shearers are prevalent and for hard rock tunnelling, disc cutting tunnel boring machines, are finding increased utilization. However, for maximum flexibility roadheaders are one of the more common machines for mechanical excavation of rock. Their primary application is in the soft rock industry with a rock UCS of less than 100 MPa. (Rostami, 1994)

CSM has developed software (Copur 1998) for predicting the performance of road headers based on empirical methods outlined by (Neil, 1994). Roadheaders are manufactured by various global manufacturers; three of the more prominent are Dosco, Wirth and Voest-Alpine. Figure 2-4 shows a T4.30 road header manufactured by Wirth which is typical of heavy duty road header construction. It features a slewing telescopic arm with a cutting head mounted on the end. To develop into a rock face the cutter sumps (penetrates) into the face then cuts in a slewing motion. The muck drops onto a feeder apron and is transported thru the machine to a discharge conveyor.

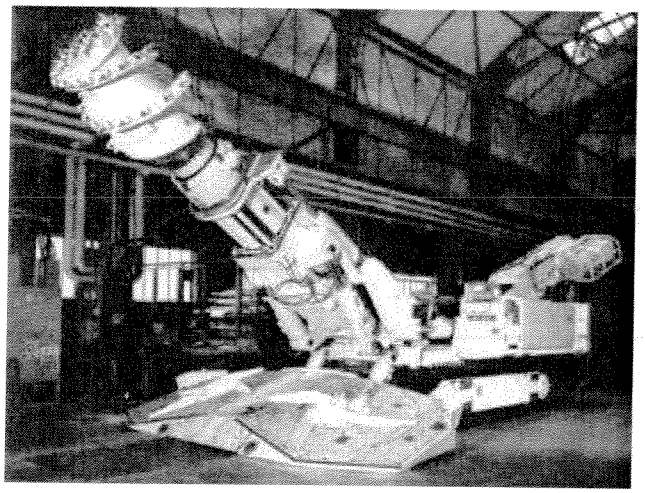

Figure 2-4: A Wirth T4.30 Roadheader

Cutting machine performance is characterized by geological properties (such as RQD and UCS) and machine parameters (such as head geometry and machine dynamics.) Thurgo (1999) presents a review of the factors in tunnelling with roadheaders as well as some key problems encountered. As roadheaders have been widely used in the soft rock industry it is possible to compile the data to predict how a roadheader will perform in a given rocktype. Laboratory LCM testing can be converted to an instantaneous cutting rate (ICR) for full sized Roadheaders by the following equation [2-2]. (Rostami, 1994)

$$ICR = k\frac{H_P}{SE_{opt}} \qquad [2\text{-}2]$$

ICR is in m^3/hr and H_P is the power of the cutting head in kW and SE_{opt} is the optimal specific energy for cutting in kWh/m^3 as determined by LCM testing. Through a wide series of tests on full sized machines k has a value of 0.45-0.55 for roadheaders Bilgin (2005) came up with a different criteria relating the ICR with the rock parameters in equation 2-3 and 2-4.

$$ICR = 0.28 \cdot H_P \cdot (0.974)^{RMCI} \qquad [2\text{-}3]$$

$$RMCI = S_c \cdot \left(\frac{RQD}{100}\right)^{2/3} \qquad [2\text{-}4]$$

In equation 2-4 the Rock Mass Cutability Index (RMCI) provides a measure of the cutability of the rock as it relates to the cutting force. Unfortunately both these prediction methods rely on knowing detailed rock properties prior to design (such as the rock mass

quality designation RQD.) An additional factor in roadheader cutting performance is the cutting mode. If the roadheader is attempting to collar or sump into a new face the specific energy for cutting has been observed to be approximately 3 times the energy for cutting with a free face (Fowell, 1993).

The main cost component for roadheader mining is tool consumption. Consumption is measured in bits per volume of rock excavated. Typically field bit consumption is roughly 0.29 picks per mg/m of cutter wear experienced in the laboratory. (Mc-Feat-Smith, 1991) Unfortunately the previous relation is for conventional linear wear and pick consumption rapidly increases under impact loading. Thruo (1998) characterized the different types of bit wear from the compilation of the wear information from 4 different German case histories. He notes that peak UCS of the component geological matrix should be considered rather then the average UCS. He noted in one fanglomerite deposit the rock mass UCS ranged from 40-60 MPa, which is within the operating range of roadheader technology. Unfortunately the rock mass contained interlaced quartzite nodules (UCS 200 MPa) which resulted in extreme bit wear. These nodules are well into the hard rock region as well as highly abrasive.

2.3.7. Performance of rock dredges

Rock dredging is not commonly practiced due to the high costs involved. Most dredging is conducted with soils and extremely soft material. Dredges have been used in mining operations such as the diamond and tin operations mentioned in section 2.1 and in placer gold mines and phosphate mining in the United States. Unfortunately, there is little literature available on the design of rock dredges. This is due to the size of the industry. As the industry is so small, dredges for rock excavation are designed for a single application and the knowledge is kept as proprietary company information. In addition, due to the cost of rock dredging operations, explosives are often considered as a more viable alternative for removal of large rock formations. (Tarbotton, 2006) However, when conditions are not suitable for explosives due to poor rock mass, or interbedded clay seams rock cutting machines are used.

Deketh (1998) outlines a systematic comparison of previous surface rock cutting studies with the performance of an underwater trenching machine based on numerous rock trenching sites. The sites were typically soft limestone deposits intersected with jointing and

numerous discontinuities. In general it was found the amount of cuttings generated corresponded to the advance rate, which is a function of the rock mass. In general when the rock mass is prefractured with closely spaced discontinuities, the trencher had a larger excavation rate, as it would dislodge block of rocks from the host matrix. Conversely, where the rock mass is more consistent the trencher had to cut the rock mass resulting in a lower rate of production. Lastly, in a condition, where the trencher could not deliver enough force for the cutters to penetrate the rock, it scraped across the surface, resulting in the lowest production rate, but high levels of wear on the cutters. The scraping cutting was also associated with ductile cutting found as previously mentioned when there is not enough force generated to cause chipping.

Vervoort (1997, 1997) provides another case study investigating the relations between dredging performance and mechanical rock properties, using a case study of a cutter dredging operation in Qatar. The site was drilled and tested using the standard geotechnical parameters, such as UCS, tensile strength, RQD, penetration rate, geological mapping, as well as numerous other tests. It was noted that where there are numerous fractures, the effect of rock strength on productivity becomes negligible, but the spacing must be referenced to the cutterhead size. In general it was found that the higher the RMR the lower the productivity. Although discontinuanities and fractures aid in improving performance, bands of strong material can cause significant wear and productivity problems as they cause impact failure on the cutterhead.

In general both the studies presented, expressed concern about using drilled data to qualitatively predict dredging performance due to the small amount of data being tested. In addition the authors felt that although the various cutting data did correlate to the equivalent surface activity, further work is required to develop an underwater testing standard for underwater excavator performance prediction.

2.3.8. Rock cutting under hydrostatic pressure.

As submerged rock cutting is not the preferred method of excavation compared to using other means such as explosives. There is little literature available to describe a systematic effort to understand the effect of hydrostatic pressure on cutting forces.

Typically, problems requiring a mechanical excavation solution are conducted on a specific project basis, by companies who keep this knowledge within the corporate domain.

One example, Kaitkay (2005) investigated the effect of hydrostatic pressure on rock using a single polycrystalline diamond cutter (PDC). The results presented illustrate 3 different confinement pressures, 0, 10, and 35 MPa. It was determined that that confinement generated an increase in normal forces of 3-5 times, with further increases in cutting forces as the pressure was increased. It was also observed that the confining pressure moved the cutting toward the ductile regime from a more brittle failure mode, which partly accounts for the higher cutting forces. Although a PDC cutter behaves slightly differently than a point attack cutter, as both cut with a standard indenter cutting mode the trends should remain the same.

In another drilling study Detourney (2000) looked at the response of pore pressure while drilling. It was found that undrained pore space increased the specific energy required to break the rock compared to a drained specimen. This suggests that under hydrostatic conditions it may have the effect of strengthening a porous rock matrix, increasing the resultant cutting force compared to surface tests.

2.4. Summary

A significant amount of work has been conducted to plan and develop a mining system for deep ocean deposits. However, most of the historical research is focused on extracting manganese nodules rather than poly-metallic chimney material. Many of the subsequent systems used in nodule mining are transferable, but there was no information found to provide an indication of the force requirements for rock cutting at ocean depths greater than 1000 metres. The formation of the poly-metallic chimney suggests that the material will be weak and conducive to mechanical excavation.

It became evident during the literature review that there are numerous complex relations developed to determine the specific energy of rock cutting, each dependent on both the site conditions and the machine configurations. The variability in rock conditions in a standard deposit generate large variations in the data recovered. Lab work that was conducted to support rock cutter modeling of diamond button cutters suggest that cutting under hydrostatic conditions will require more energy then in dry conditions, in addition to

increased cutting forces. Given the variability that mining data produces and the unknown nature of deep ocean PMS deposits, this thesis will focus on determining the cutting performance of a mechanical excavator in rock both on surface and in ocean conditions at depth.

3. Experimental Methodology

Not much is known about the insitu mechanical cutting performance of ocean sulphide deposits, so a complete research program is required to determine the mining properties of ocean chimney material. This program has been designed to test a cutter head which could be mounted to a conventional excavator. This chapter outlines a cutting program methodology to test the mining properties of PMS deposits by mechanical cutting. Following the research program is the data analysis plan a first pass analysis of the cutting data.

3.1. Program overview

A full program for studying the mining of ocean sulphide chimney material has been developed and is presented in figure 3-1. The program starts with an initial concept of sampling the ocean material and confirming that the approach for mining is sufficient and will meet the objectives of this research. Secondly, a series of dry land tests are required to be conducted to characterize the ocean excavator and to provide a benchmark for comparing the field data. Next, the excavator's systems need to be checked in a submerged environment to confirm that all subsystems are functional. Once the confirmations are complete, the cutting tests need to be repeated to provide a direct comparison of cutting similar test materials under different conditions. Once everything is operational the excavator is ready for ocean field trials, where the operational cutting measurements can be obtained.

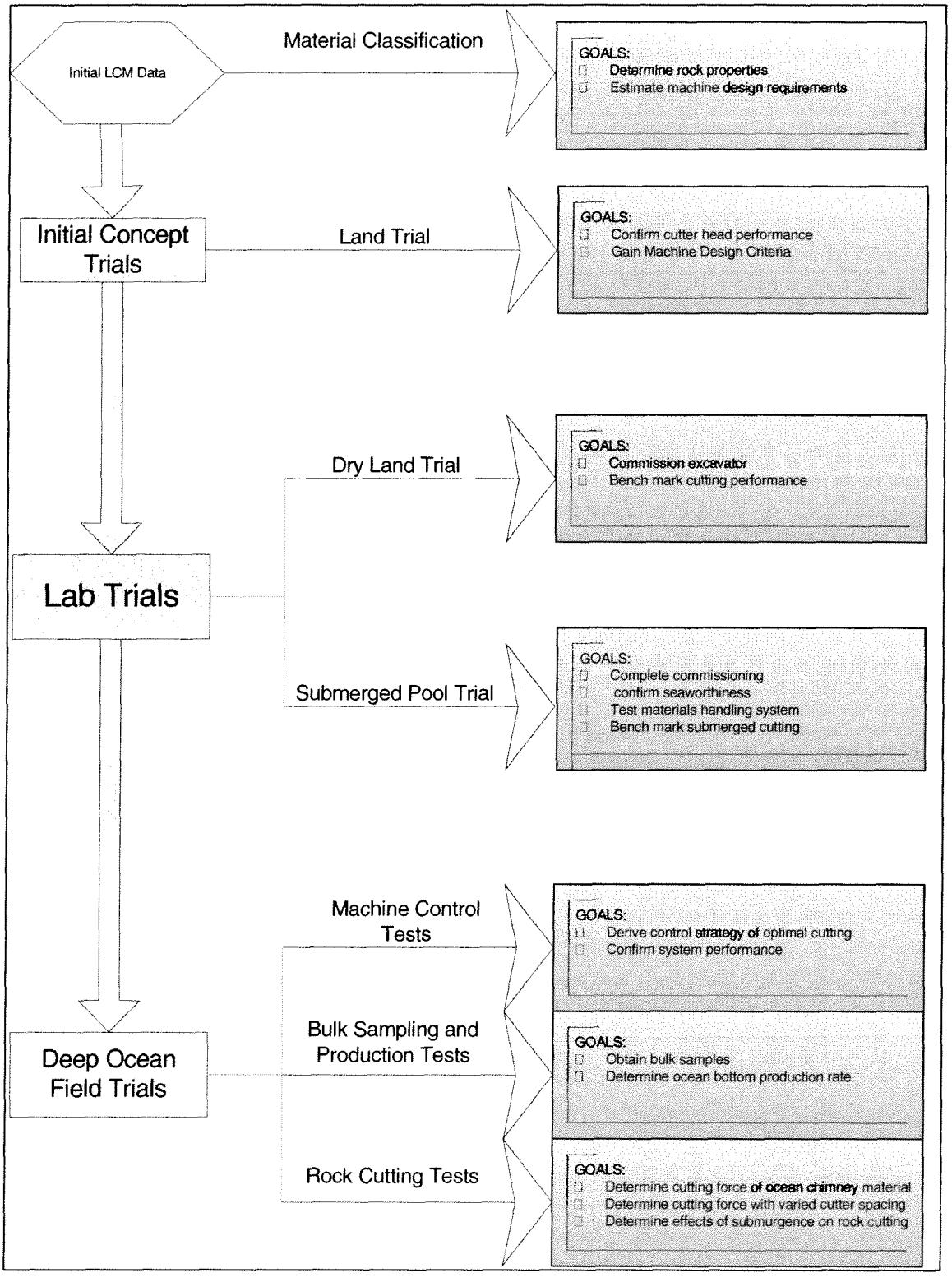

Figure 3-1: Ocean mining rock test program.

3.2. Initial characterization and concept trials

Prior to testing developing a testing process, sample ocean material must be characterized in such parameters as hardness, strength, abrasively, etc. As outlined in chapter 2, the rock hardness will determine whether point attack cutters or disc cutters should be used. This testing should include LCM testing to quantify the cutting characteristics of the rock and provide information for comparison with the field data. In addition by testing the rock properties a formula for creating substitute rock material can be created, in case there is not enough real material available on surface, which will be quite likely the case for seafloor material.

Following the initial determination of the design requirements, concepts for excavating ocean material can be developed. Once a suitable cutterhead is sourced it should be tested to confirm that it will meet the cutting demands, prior to the development of a complete mining excavator. Once the initial concepts have been confirmed the excavator can be designed and constructed and the actual testing program can commence. Although formal data is not generated from this concept trial it allows for an investment milestone which needs to be passed in order to make a decision whether to continue development of the concept excavator or to pursue other avenues of research.

3.3. Lab cutting trials

Once the mining excavator has been constructed, a suitable amount of test cutting substitute is required. At a minimum a 1.5 meter long by 1.5 metre width by 1 metre height of test substitute is required. In addition a second testing substitute should be prepared for the submerged trials. Prior to cutting, hydraulic sensors need to be calibrated to account for the variance in various hydraulic fluids. For a standard excavator four viable cutting modes were identified to be tested:

- Forward Cutting: While forward cutting the cutterhead is advanced perpendicular to the arc of motion and the cutterhead engages the rock solely in the forward direction.
- Aft Cutting: While aft cutting the cutterhead is advanced perpendicular to the arc of motion and the cutterhead engages the rock solely in the aft direction.
- Sumping: While sumping the cutterhead is advanced normal to the face of the rock.

- Transverse Cutting: While transverse cutting the cutterhead is advanced across the face of the rock.

A series of tests are planned to determine the cutting forces for each of above cutting modes. The excavator will cut the test rock for a planned 10 minutes with each of the modes and the cutting forces, torques, and power will be measured and logged. After each test the cuttings are collected and weighed to measure the amount of material excavated. In order to determine the effect of cutter spacing the tests are repeated with every alternate cutter removed from the cutterhead and a protective bolt installed in its places. A bolt is installed to protect the cutter pick blocks from damage.

3.4. Submerged pool trials

Following the land trails the excavator needs submerged testing. This testing serves two purposes one, it confirms the seaworthiness of the excavator, and two it, allows for a controlled comparison between the lab cutting tests and cutting tests under hydrostatic conditions. The seaworthiness tests allow for the testing of the instrumentation, to ensure that the pressure compensation system is functional.

A subsea excavator has pressure compensation circuits to compensate for the increasing hydrostatic pressure. These compensation circuits fill all the airspaces in the instrumentation and control with oil. This protects the excavator's control system when operating under extreme pressure. Part of the seaworthness trials is to ensure that the compensation circuits flow properly, and that there are no leaks in the instrumentation seals.

Once the excavator is submerged in a testing pool problems with instrumentation not related to the excavator become readily apparent, usually problems are identified within 3 metres of surface. Once these problems are corrected and identified the excavators cutting can be tested under submerged conditions to investigate the cutting forces and the materials handling system performance

Once the excavator is ready for testing, the second testing substitute, is lowered to the bottom of the testing pool and the cutting tests that were performed during land trials can be repeated. In this case, from the four cutting modes some of them are anticipated to be unviable. In order to develop a maximum amount of testing data, the trial durations, should be focused on maximizing the cutting time for the viable cutting modes. For each of the

viable cutting modes both pick configurations need to be tested. In addition during these cutting tests the materials handling system is monitored.

In order to recover material from the seafloor a materials handling system needs to be included on the excavator. This plan is developed to test a typical dredge setup with a pump located near the cutting head providing suction to capture the liberated cuttings. These cutting are then removed from the slurry thru the use of a cyclone separator in a setup similar to a vacuum cleaner. During the cutting trials the following materials handling system is tested:

- The nozzle design. The suction nozzle is designed to capture the maximum amount of cuttings. During the tests the liberated cuttings should be monitored to ensure that they are captured by the suction system.
- Production rate. The materials handling system should be instrumented to develop an indication of the amount of cuttings being captured. This can be integrated over time to determine the production rate.
- System lag. In addition to the production rate, a measure of how long the cuttings remain in the material handling system from the time they are cut to the time that they are captured. Because small particles will remain in suspension they may remain floating for a measurable period before settling out in the bottom of the hopper.
- Cyclone particle size cut. Since all the material cutting can not be captured, due to the volume of water sucked in by the suction pump, a cyclone or other scalping device must be used. These devices are rated on the size fraction that they will allow to pass and the performance can be tested by measuring the size distribution of the captured cuttings.

Once the excavator has been tested for seaworthiness, benchmarking data has been captured and the material handling system has been checked, the excavator is ready for field trials.

3.5. Field trials

Once the excavator has been constructed it must be tested in the field. These tests allow for the determination of the cutting requirements of insitu rock material. These tests are anticipated to be much longer in duration lasting until the sample collection hopper is full or there are mechanical problems with the excavator. These trials need to have:

- Controlled cutting conditions. Since the duration of field trials is long, there will be numerous operators, running the excavator. In order to minimize operator induced variability, the operators should maximize their amount of control time, before switching. This will allow the comparison of time induced trends.
- Maximum data collection. Due to future research efforts, the data will be sampled at a much higher frequency than analyzed data required for this thesis. Although more expensive, the increased sampling rate and the data storage costs, are cheaper than repeating the testing dives.
- Optimal site variability. During the testing program it is important to maximize the testing conditions. Based on experience in conventional mining, ground conditions will vary over the testing area, and a general site picture is required to get a better understanding of the strength properties of the PMS field.

To determine the effect of altering the cutting head, half the field tests will be conducted with the half pick configuration and the other half with a full complement of picks. Observations of the cutting process and mining may be of more importance than the numerical data generated, so videos of the cutting will also be captured for future reference.

3.6. Analysis of the data: Volume and specific energy

3.6.1. Production rate and specific energy determination

By determining the unit production rate and measuring the energy input into the system, it should be possible to determine the specific energy requirements for mining ocean chimney deposits. The energy that the excavator uses to excavate the rock can be determined by measuring the pressure and flow of the cutterhead hydraulic circuit. The pressure and flow is directly proportional to the energy consumption (H_P) under common hydraulic fluid of specific weight (γ) equation shown in 3-1 (REA, 1999) (assuming no leakage and 100% efficiency) where Q is the flow and P_H is the operating pressure drop across the hydraulic motor.

$$H_P = \gamma \cdot Q \cdot P_H \qquad [3\text{-}1]$$

By measuring the mass of the material and accounting for the system lag, the specific energy of cutting can be determined.

3.6.2. Alternate production rate and specific energy determination

Unfortunately due to problems discussed later in the thesis, an alternative method had to be developed to measure the specific energy. Since the aim of the field trial is to maximize the amount of data collected data processing will be required. The high frequency will result in a large amount of data recorded during the testing, and the variable geology of the target material and the uncertainty of the excavation face will result in a high amount of noise. For an initial investigation a high level of analytical detail is not required, the raw field data is processed then summarized over one minute intervals for each of the tests in the program. The data will be analyzed in Excel for general trends and exported to SigmaPlot for presentation.

Due to problems using material handling systems to measure the production rate, a voxel method approach for measuring the material is used. An algorithm, outlined in figure 3-2 was developed[3] to determine the amount of material excavated. A 3 dimensional grid of 1 cm voxels is generated and if the excavator is cutting the cubic centimetre it is flagged as being excavated. The excavator is seen as cutting if 16 of the last 60 points has an energy consumption value greater than 1.1 kJ. This is done to smooth out the data and to aid in the volume calculation. One limitation in this method of analysis is that the excavator does not excavate the entire cubic centimetre of material within a one minute interval, resulting in a skewed production value. This results in energy being consumed while there is no record of production resulting in clearly erroneous high value specific energy values.

[3] Strategy developed by the author and the bulk numerical analysis technique was implemented by Cellula Robotics.

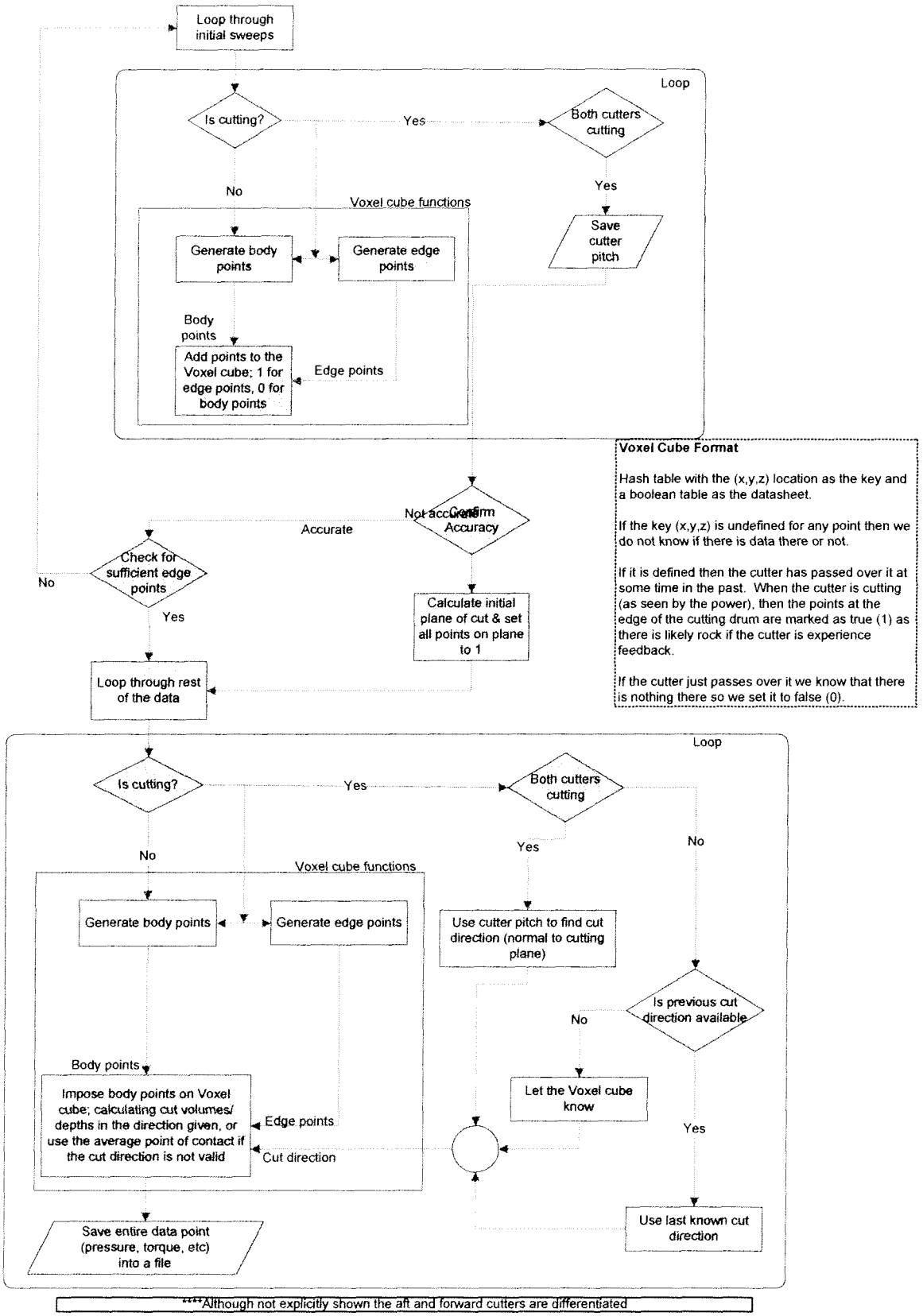

Figure 3-2: Voxel volume extraction method

To correct for this problem the total volume excavated was divided by the total energy consumed over the test, resulting in the average specific energy for the test. One problem with this method is the parasitic energy consumption caused by the cutters spinning, but not engaging in active cutting. The method used to compensate for this drain is illustrated in figure 3-3.

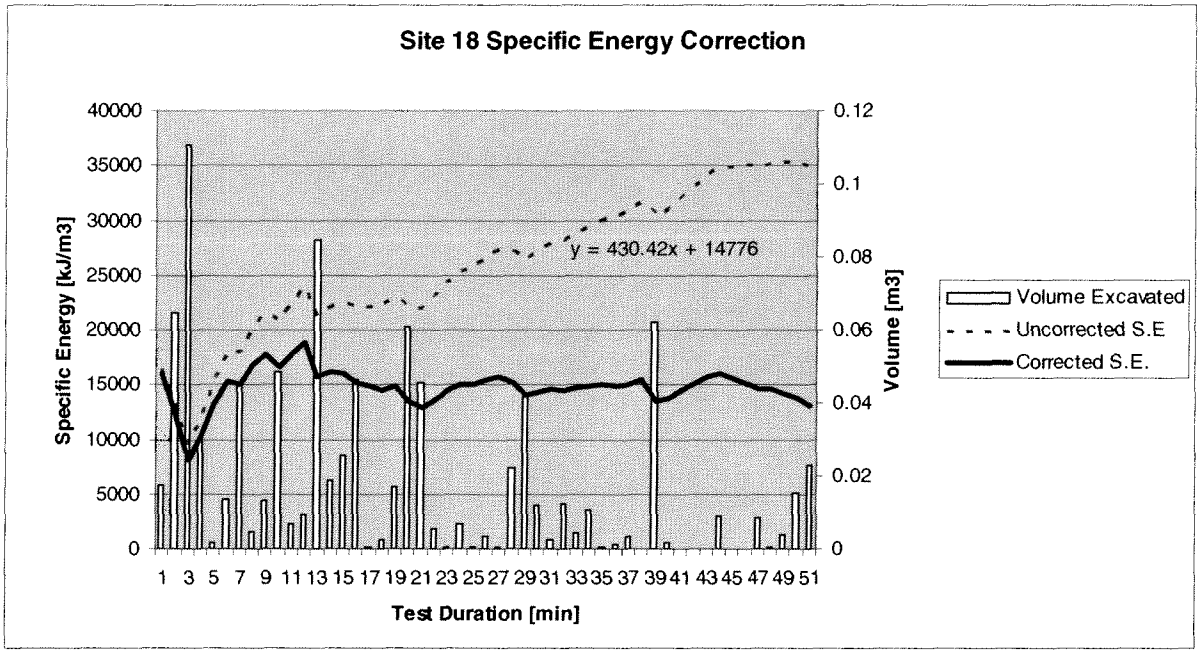

Figure 3-3: Sample specific energy correction

Shown on figure 3-3 is the calculated cumulative uncorrected specific energy of the test progress as the dashed line and the volume (Vol_i) of material excavated as a bar graph. There is a clear upward trend in the uncorrected SE, caused by energy used to spin the cutters which are not engaged in the rock. This energy is related to the engagement efficiency and the speed of the cutters, and is unique for each test. To find the corrected average specific energy an area of constant linear increase was interpolated to find the slope of the increase. In the case of the presented example there is a parasitic drain (E_P) or 420 kJ, per minute. This energy drain is then subtracted from the cutter energy as shown in equation 3-2, resulting in the corrected specific energy.

$$SE_{cor} = \frac{\sum_{1}^{n} E_i}{\sum_{i=1}^{n} Vol_i} - E_P \qquad [3\text{-}2]$$

Although the lab trials consist of much shorter tests, a standardized reporting scheme is used to ensure constancy of reporting. The units for equation 3-2 is in kJ/m^3 as the energy measured is in the amount of kilojoules consumed in one minute divided by the amount of material excavated (m^3) in one minute.

3.6.3. Cutting force determination

In addition to the analysis of the cutting energy using measurements from the hydraulic circuits in the cutterheads, it is possible to develop an understanding of the downward force placed on the cutterhead by using Jacobian analysis, based on the standard robotic analytic techniques using the excavator's arm configuration and the inertial components of the cutting arm. In optimal conditions, this provides an indication of the normal force and using the cutterhead torque the resolved cutting force can be determined.

4. Case Study Solwara expedition Feb 2006

The next progression of the research continues with the introduction of a case example in the mining of deep ocean PMS deposits with the Solwara 1 expedition in the Manus Basin, Papua New Guinea, February 2006. This expedition was a joint venture between Nautilus Minerals and Barrick Gold Corporation's wholly owned subsidiary Placer Dome. This chapter outlines the background of the study and the integration of the methodology presented in Chapter 3. The author was a member of the project team providing mining analysis and rock cutting expertise.

4.1. Placer Dome and Nautilus Minerals

In 1997 Nautilus Minerals Inc. secured the mineral rights to explore 15,000 square kilometres of tenements within Papua New Guinea's national boundaries. Included in this field is the PacManus Basin Poly-metallic sulphide (PMS) field identified by Australia's CSIRO mentioned in Chapter 2. Nautilus then proceeded to organize a consortium of deep ocean equipment companies and engineering design professionals to develop a methodology to exploit these potential resources. The Manus Basin tenements are located in the Bismarck Sea, west of the province of New Ireland and north of the town of Rabaul, in New Britain, shown in Figure 4-1

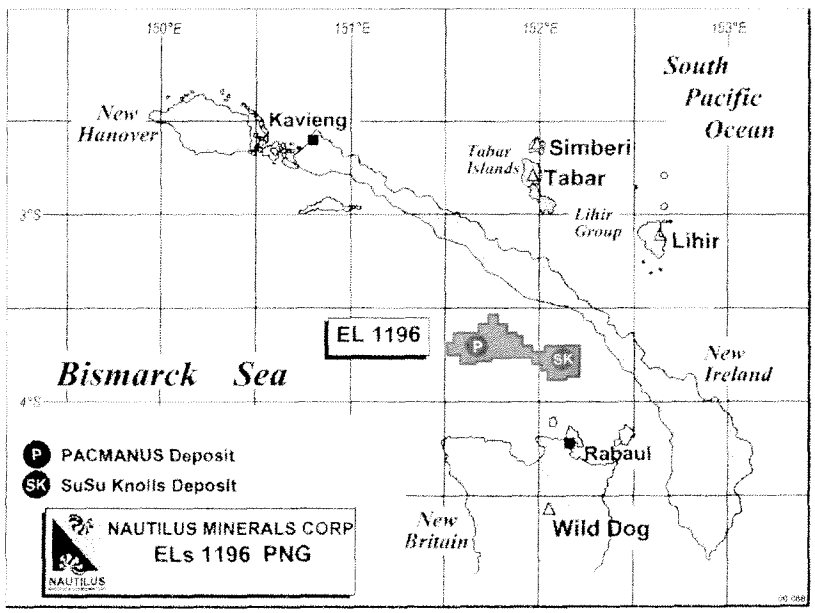

Figure 4-1: Location of Project site (reproduced with permission from Nautilus Minerals Inc)

Nautilus approached Placer Dome, to discuss establishing a joint venture agreement to explore some of the Nautilus tenements. After conducting their own economic analysis of the potential for exploitation, Placer Dome entered into an alliance to explore the mineral content of the Manus Basin's inactive PMS deposits. Under the joint venture agreement Placer Dome obtained a 75% interest in the gold content discovered in these mineral rich deposits once adequate exploration funding was expended.

4.2. PDTS ocean mining program

As part of Placer Dome's involvement in advancing ocean mining science Placer Dome Technical Services (PDTS) was mandated to investigate the technical viability of ocean mining and to develop technology to exploit the Manus Basin's riches. PDTS assembled an international team of experts to develop an integrated research program to investigate the viability of ocean mining. Figure 4-2 illustrates the 6 year research program timeline (PDTS, 2005) and goals developed. The research program began with the testing of rock samples dredged from the Manus Basin and is aimed at the final stage of trialing a million tonne per day ocean mining operation.

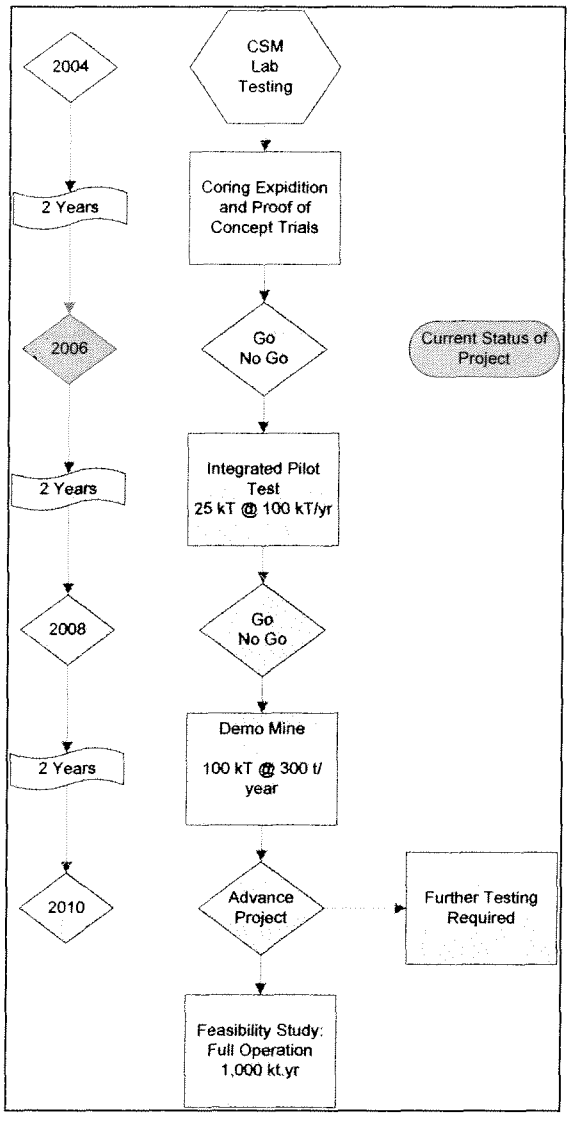

Figure 4-2: Ocean mining research program overview (PDTS, 2005)

In 2005, Placer Dome funded an exploration campaign of the Manus Basin, which included a wide scan bottom sonar mapping, magnetic survey as well as resistively mapping. This successful program identified two major targets for further investigation, the Suzette field and the Craw Field. Dredge sampling from the Suzette field recovered 39 samples with an average grade of 15.5g/t gold and 12.2% copper. (Heydon, 2006) After the positive results from the geophysical cruise, in Feb. 2005, the planning for the 2006 Solwara drilling campaign accelerated. Seacore drilling and the vessel DP Hunter were retained to conduct the drilling program. A rear mounted remote operated vehicle was contracted from Canyon to support both the drilling campaign and the environmental sampling. To prepare for the

environmental impact assessment for mining this poly-metallic sulphide deposit four biologists were contracted to sample and study the various biota around the test sites. In addition oceanographers were retained to monitor turbidity and current data during the drilling and rock excavation. Thus in addition to providing an estimation of the mineral content of the deposit, a wealth of academic information would be obtained during the 2006 campaign.

Ocean research is capital intensive, and the rock excavation trials needed to be coupled with another expedition in order to financially justify the expenditure of conducting deep ocean trails. This expedition provided an opportunity for PDTS to test rock excavation at depth, gaining valuable information for developing a next generation ocean mining machine. Adding the cutting trials to the expedition meant that PDTS would have two weeks to test the rock excavation under field conditions.

4.3. Preliminary work

As part of their preliminary work study, PTDS had rocks from the Suzette field sent for evaluation of their suitability for mechanical rock excavation to the Colorado School of Mines [EMI 2004]. At CSM they conducted numerous tests including linear cutting testing and standard rock parameter tests and determined that the Manus Basin material was conducive to excavation by mechanical means. As part of the initial investigation on the viability of the research CSM was hired to predict, using standard knowledge of road header production, expected rates from a full sized mining machine excavating the Manus Basin material. (EMI, 2004) They found that a standard roadheader, if the deposit was on surface, could excavate the material, but may have difficulties meeting the production targets planned in the PDTS mining system.

Based on the results of the study, PDTS decided to develop a deep ocean test platform. Since the Solwara expedition was occurring in 2006, there was an opportunity to test rock excavation faster than originally planned. Figure 4-3 outlines the actual testing program for the methodology discussed in Chapter 3. A trial cutterhead was purchased and tested on a test rock in Langley BC. This test rock was constructed to match the mechanical properties of the ocean material, based on a concrete recipe provided by CSM. These initial concept trials were highly successful and a decision was made to continue with the testing

program and begin construction of the Deep Ocean Sampling System, (DOSS) a testing platform to study rock cutting insitu.

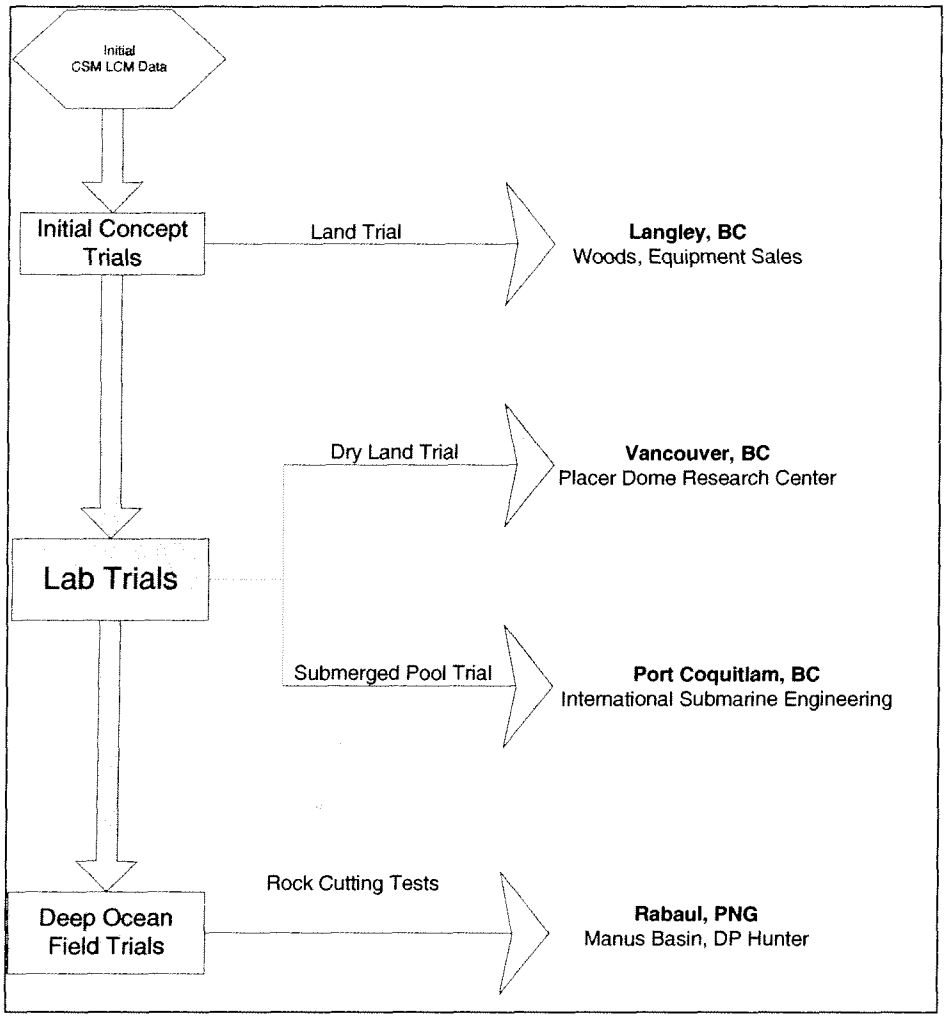

Figure 4-3: Rock cutting trial plan overview

4.4. Rock cutting trials

Using the results of the Langley trials the design of the DOSS was finalized and the testing program for the Solwara expedition was developed. PDTS assembled a team of top mechanical engineers, and subsea robotics professionals to construct the Deep Ocean Sampling Skid (DOSS) described in Chapter 5. Following the successful Langley trials a three phased approach for developing and testing the DOSS was developed. The unit would

be commissioned and tested in Vancouver, then it would be field tested on location in PNG. In Vancouver there were two phases of testing one at the Placer Dome Research Center (VRC) and submerged testing at International Submarine Engineering (ISE).

At the VRC the DOSS was assembled and commissioned. Once it was assembled, various design problems were identified and addressed over a period of three weeks. During this time the DOSS was powered by an external hydraulic control unit throttled to deliver the same hydraulic power as the ROV that would be used in the sea trials. Lastly, two days of rock cutting were conducted to test the cutting system. The unit was transferred to ISE where any problems with seaworthiness were addressed. Following the correction of these deficiencies, two days of submerged rock cutting trials were conducted and after these were complete the excavator was shipped by sea to PNG. In PNG the DOSS was integrated with the ship's ROV and the DOSS' subsystems were tested and the sensors were calibrated. Following the calibration activities 10 days of rock cutting trials and bulk sampling were conducted at various locations.

4.4.1. Vancouver trials program

Figure 4-4 outlines the DOSS' configuration for the Vancouver trials. The DOSS was attached to an external hydraulic power unit and a large concrete[4] block was cast as a cutting substitute for PMS material. The DOSS was weighed with steel ballast to deliver the same magnitude of negative buoyant force that the excavator would experience when submerged. The large concrete block was located to the front of the excavator allowing a full range of cutting motion to be tested. In order to determine the insitu cutting requirements the cutting torque to turn the cutting head was measured using pressure and flow sensors in the hydraulic circuit. This provides an independent measurement from the cutting force measurements. This is important as the force measurements obtained from the Jacobian translation algorithm relies on detailed inertia calculation, and if there is error in the position sensor readings the force data could be compromised. The cutting force is inferred from the geometry of the excavator arm and the pressure readings from the arm cylinders.

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[4] CSM's concrete recipe to mimic the properties of the seafloor material includes 25 Mpa sand topping mix with a max 2" sump (Water, Cement, Sand)

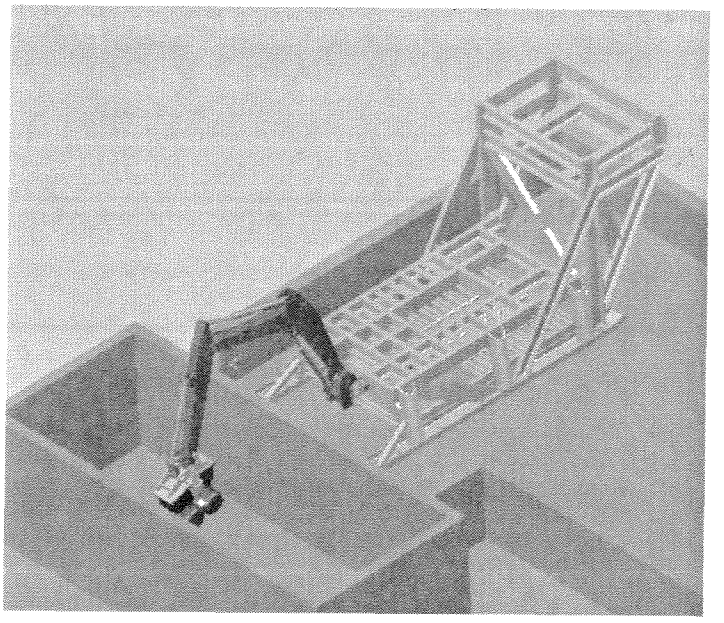

Figure 4-4: Vancouver test setup

4.4.2. Vancouver ISE trials program

Once the land trials portion of the surface cutting was complete the DOSS was mobilized to International Submarine Engineering in Port Coquitlam. The submerged testing allows for the cameras to be positioned for teleremote control as well as the calibration of the sensor system. During these trials the operators for the ocean cutting dives were trained in the operation of the DOSS and their cutting performance was matched to the VRC trial results to confirm consistancy.

4.4.3. PNG ocean cutting dives

The aim of the ocean cutting trials was to obtain an understanding of the dynamics of sub sea rock excavation. Although this is a prototype testing platform that is much smaller than the perceived final prototype mining machine, it should be possible to gather information to gauge final achievable production rates. A valid estimation for the steady state production rate is key in determining the profitability of the future operations. The Rebaul sea trials consisted of testing rock cutting at a variety of test locations to determining the cuttability. From these trials the main goal was to determine the insitu cutting requirements and to gain an understanding of the principles of rock cutting at depth. The data from these trials can be used to investigate the correlation between cutting forces on

surface to the cutting forces under water. If a strong correlation exists then it will be possible to use conventional knowledge to design the next generation excavator with allowances given for the submerged cutting conditions.

5. Deep Ocean Sampling Skid (DOSS)

In order to properly test the viability of ocean mining, PDTS needed to design and develop a test platform to monitor the cutting forces and collect the cuttings. It was determined that it would be more cost effective to develop a subsea skid which mounts on a conventional ocean remote operated vehicle (ROV) rather than a self contained unit. The DOSS has been designed as a complete teleremote unit with multiple cameras mounted for command and control. The ROV provides the hydraulic power and command and control infrastructure to the surface in an independent package, while the main cutting and test platform is a separate unit. The DOSS is designed as a self contained excavation and material recovery unit, shown in figure 5-1. A dual drum cutterhead is mounted on a standard excavator arm which has a suction system mounted above the cutters. The suction system (not shown) discharges at the rear of the skid into a hydrocylone, which captures material greater than 35 microns. As the DOSS is designed as a research tool it is equipped with a full sensor and data acquisition system.

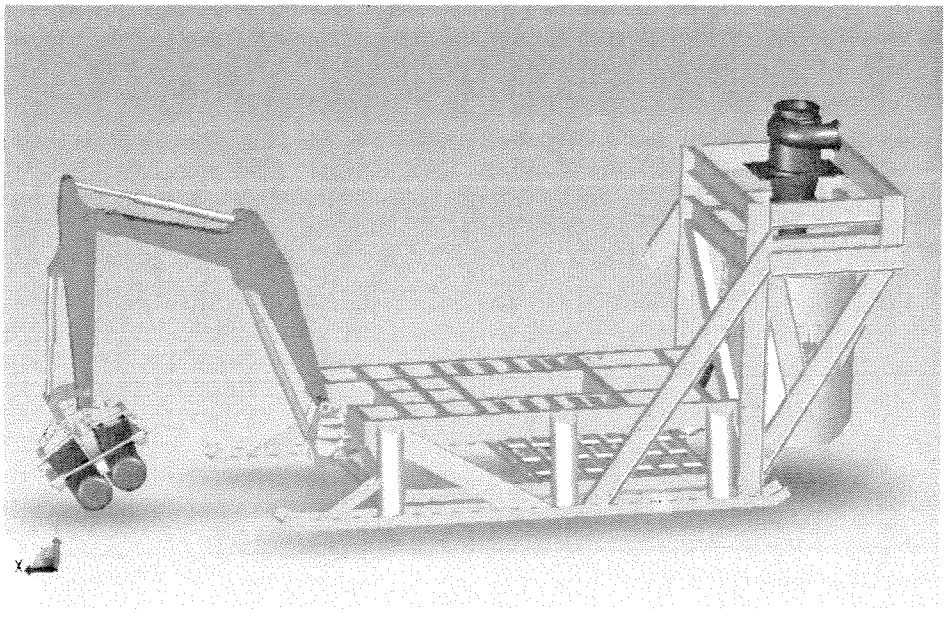

Figure 5-1: The Deep Ocean Sampling Skid

PDTS contracted top engineers from various firms to design the DOSS subsystems. Convergent Robotics was retained to develop the software interface including the data

logging and control software. Mechanics Design and Tandem Technologies supplied the primary mechanical engineering talent, designing both the mechanical frame of the test platform as well as the materials handling system. Finally, Trinity Offshore designed and integrated the instrumentation and telemetry systems. This team of designers were also experienced in the operation of teleremote submarine equipment and continued to act as the operations team during the testing program. The author as a mining specialist defined the sensor requirement for the testing of rock cutting and ensured that the sensor selection for the DOSS would meet the research aims. This was important as the DOSS design team consisted of a team of submarine robotics designers who selected the sensors with a focus on studies in subsea motion control and environmental monitoring. This section mainly discussed the work of the machine design team and is included to provide background reference on the testing apparatus. The authors main contribution to the research continues in the following chapter.

5.1. Cutter head

As rock excavation cutting by mechanical means is a key portion of the testing trials, considerable time and effort were spent analyzing the various cutterhead design options. The numerous options included custom made heads from suppliers such as Robbins, Atlas Copco, or Schaeff-Terex, however a custom made solution, was much more costly for this initial study, so premade cutter heads were investigated. The readily available Schaeff-Terex WS-15, (Terex, 2006) shown in figure 5-2, was chosen as the best option for these trials, as WS-15 is commonly used in civil construction applications in Europe and is used in concrete trenching operations. Since this cutterhead was designed to attach to a standard construction excavator, integration testing became simpler and less costly. In addition the WS-15 has been used in surface environments cutting material harder than that which was anticipated at the PNG test site. Lastly, this cutterhead was available to be shipped to the DOSS manufacturing site in order to meet the testing schedule.

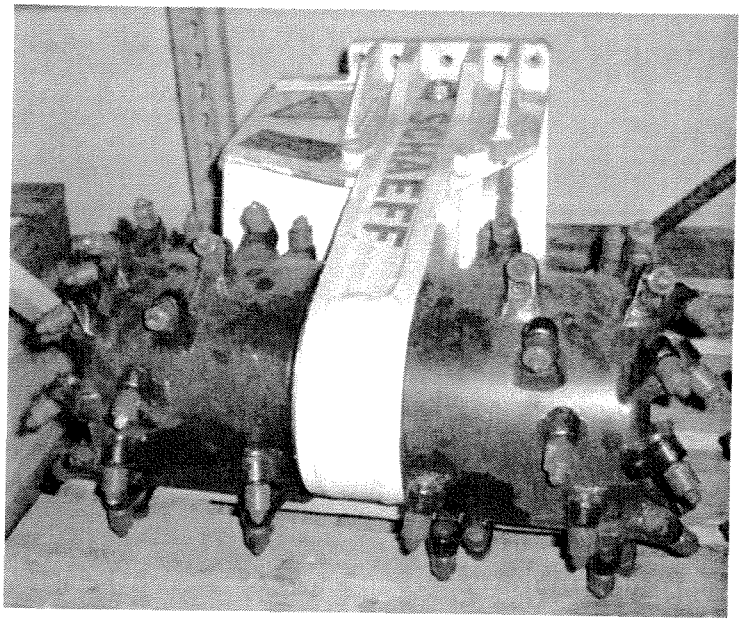

Figure 5-2: Shaeff-Terex WS -15 transverse cutter head

The WS-15, consists of two transverse heads with a cutting diameter of 29.4 cm spaced 8.7 cm apart mounted on a gear box. The drum cutter lacing consists of 2 lines of cutters spaced 180 degrees apart with an offset of 10 mm. Each line of cutters has the picks spaced 20 mm laterally with a 15 degree angular offset. Since each head has 29 picks there is a lateral spacing of 10 mm between cutting lines. The entire cutter head is rated with a maximum hydraulic power of 15 kW. To test the performance of using this particular cutterhead, one WS-15 was mounted on a 15 kW Takeuchi excavator and used to cut a cement block designed with similar rock characteristics as the seafloor chimney material. It was observed during this test that the cutting action mobilized a large amount of cuttings and tossed them into the air. From these observations it was decided to add a second counter rotating cutter head mounted as shown in figure 5-3.

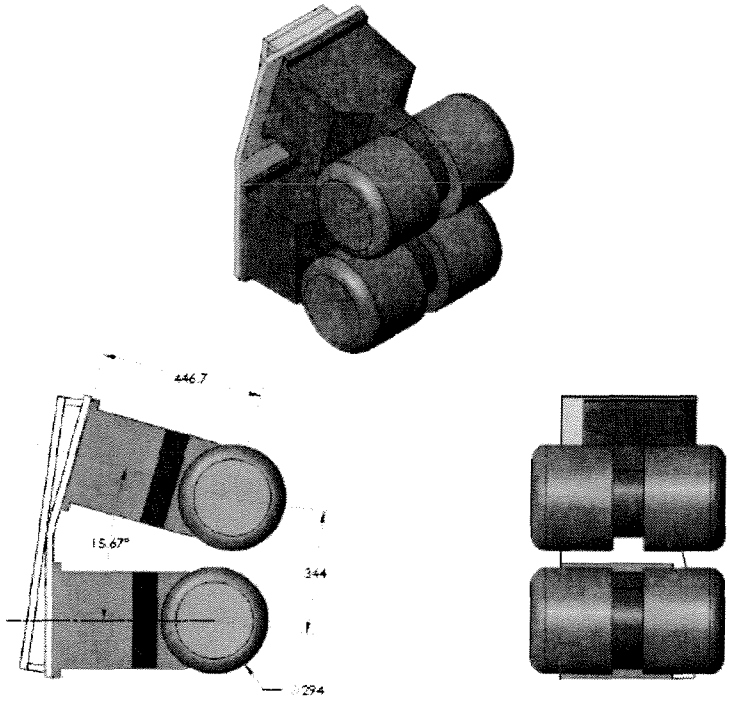

Figure 5-3: Cutter head mounting configuration

Between the two WS-15 cutterheads a large suction nozzle was placed to capture the liberated cuttings. It was anticipated that this would act as an open faced rolls crusher, and prevent oversize material from blocking the suction nozzle. The suction nozzle was mounted at a distance of 447 mm from the centroid of the cutterhead. Mounted in the throat of the suction nozzle were steel bars to act as a last preventative measure to keep oversize material from entering the materials handling system.

5.2. Materials handling system

After cutting the ocean chimney material is captured by the material handling system on the skid. As shown in figure 5-4 the cut material is captured via a suction nozzle mounted between the two WS-15 cutters. Material is sucked via a reinforced rubber hose to a 10 HP Thompson centrifugal pump. The material is then transferred under pressure to a Krebs hydro-cyclone for dewatering. The Hydrocyclone is designed with an involuted feed entry configuration with an apex diameter of 10.0 cm and a vortex finder diameter of 7.5 cm.

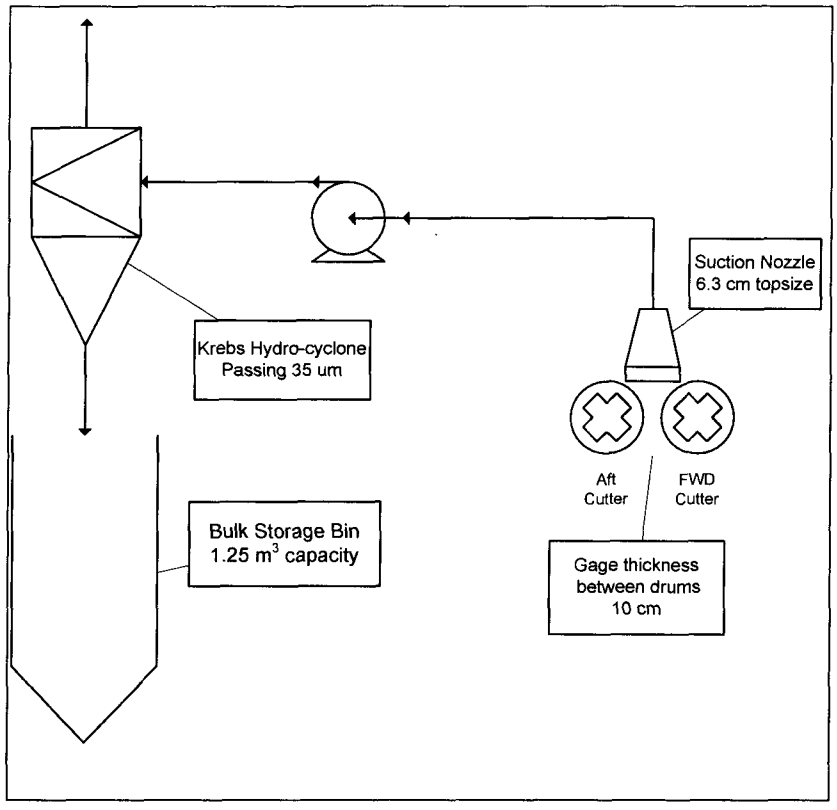

Figure 5-4: DOSS materials handling schematic

5.3. Instrumentation on the sampler

As the DOSS is designed as a research tool, a complete sensor and actuation system was specified. Each of the hydraulic cylinders was equipped with pressure sensors to measure the delivered cylinder force and then each of the cutterhead hydraulic circuits was independently measured with a flow and pressure sensor to determine the cutterhead performance. To determine the position of the cutting arm all the joint angles were measured. Lastly, all the measurements were processed on the DOSS and transmitted to a surface logging computer for data storage.

5.3.1. Pressure sensors

The hydraulic pressure was measured using a MSP-600 high accuracy digitally compensated pressure transducer. This 0 to 34.5 MPa (5000 PSI) sensor was used to measure the pressure in all the hydraulic circuits on the deep ocean sampler. The sensor itself has an error band of 0.25% FS or 86.1 kPa. (MSI, 2006) It produces an analog output connected to the telemetry system via a 12 bit A/D converter. To convert the analog voltage

reading to pressure the following calibration equation was used based on calibration with a reference gauge.

$$P_H = (V_P - 2) \times 0.090649 \qquad [3\text{-}1]$$

The sensor is a piezoelectric strain sensor, which is isolated from the housing via high temperature glass fused to the external steel diaphragm. To compensate for the hydrostatic pressure of working at ocean depths a hole was drilled into the top of the transducer, so that the sensor would reference ambient ocean pressure rather then absolute pressure. This technique is standard practice at ISE and allows a much more cost effective transducer to be used rather than custom made deep ocean pressure cells.

5.3.2. Turbine flow meters

The hydraulic flow in the forward and aft cutterhead circuits was measured using a Hoffer subsea turbine flow meter. (Hoffer, 2006) The flow meter integrates over one second the number of pulses from the flow turbine and outputs the flow value to the data acquisition system. The flow meters were calibrated for the hydraulic fluid prior to the testing to account for the non-linearity in the flow regime, which was found to be minimal in the operating range of the circuit. The following calibration relation was derived for the forward and aft cutter-head circuits by the design team prior to testing.

$$\begin{aligned} Q_{fwd} &= 13.7792597 \times V_f - 28.5145192 \\ Q_{aft} &= 12.9715769 \times V_f - 25.8606833 \end{aligned} \qquad [3\text{-}2]$$

5.3.3. Angle measurement

Each of the joint angles on the excavator arm is measured using a Sentron 25A-10 Hall Effect Dim chip (GMW 2006) mounted in a custom designed housing. The housing was designed and constructed by Convergent Robotics specifically for this application. Testing by the designers of this sensor's angular sensitivity resulted in an instrumentation error of approximately 5 degrees resolution error for absolute angle measurement, but less than 1 degree resolution error for a relative angle measurement.

5.3.4. Load cells

Prior to the land testing of the DOSS it was proposed that to measure the mass of the material retrieved, 4 load cells would be attached to the four support points of the catch bin. Although testing of this sensor system for mass measurement was sound in the controlled lab conditions, once the DOSS reached the field this strategy for mass measurement was unsuccessful and the load cells failed to function as designed. It is believed that the load measurement failure was due to unbalanced loading caused by the DOSS being operated off level.

5.3.5. Servovalve control

The DOSS was designed by incorporating high speed MOOG Series 7772 hydraulic servo valves. (MOOG, 2006) Jackson (2007) demonstrated, during PDTS experimental program into narrow vein hard rock excavation, that high speed hydraulic control can allow a reduction in the required machine stiffness during cutting activities. The high speed servo control valves allow the command and control team to tune the excavator to reduce the vibration caused by the cutterhead by using active control loops. The excavator is able to be programmed to be controlled using this high-speed position control system or the valves can be operated as conventional hydraulic valves in a default rate control mode.

5.3.6. Data acquisition

Installed on DOSS' telemetry control unit were 3 ICS Advent ADIO 1600 multifunction Analog and Digital I/O cards. These cards provide 16 channels of single ended analog input with 12 bit resolution and are capable of taking a total of 100,000 samples per second. The card uses successive digital approximation. For the command and control algorithms the data was sampled at 250 hz., then processed by the subsea processor and communicated with the logging computer at 50 hz. This allowed the onboard sensor data to be logged at the same time interval as the teleremote control signals being transmitted from the surface to the subsea processor. In total 79 unique data points were collected relative to the following variables:

- Time
- Operator control commands
- Hydraulic valve commands

- Excavator arm cylinder pressures
- Pitch and roll of skid
- Acceleration of skid
- Excavator arm joint angles
- Excavator arm swing angle
- Forward and aft cutterhead flow
- Forward and aft cutterhead pressure
- Load cell values

5.4. Coordinate frame of the excavator cutterhead

To ensure a common point of reference for the various studies being conducted a common reference frame shown, in figure 5-5, was defined for the cutterhead. The reference frame is a moving reference which is referenced to the centroid location between the two WS-15 cutterheads. The plane defined by the x and y-axis is a rotating plane that rotates with the cutterhead and ensures that the applied normal force is perpendicular to the cutting arc. The z-axis passes though the centroid and is normal to the x-y plane. The x and y-axis remain fixed on the cutterhead and rotate with the cutterhead. The y-axis is parallel to the arc of swing and the x axis is normal to this motion.

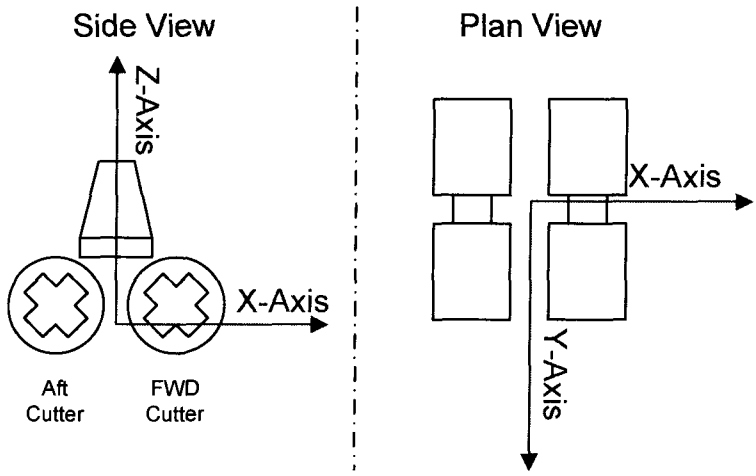

Figure 5-5: DOSS cutterhead axis reference

Based on this frame of reference and using the sensors included in the DOSS, the design team developed a Jacobian translation algorithm to resolve force data to the coordinate frame axis.

6. Experimental Results

This chapter will explore the investigation into the fundamental cutting results of mining PMS deposits. The results from various testing are presented and discussed in this chapter. Results conducted to benchmark the DOSS in Vancouver are presented in Section 6.2. Results from the PNG field trials of both the cutting program and geotechnical observations are presented in Section 6.3.

6.1. CSM data

Prior to the commencement of this project the project samples were sent from the Manus Basin to Colorado School of Mines to determine if they were suitable for excavation by mechanical means. CSM prepared two reports (EMI 2004) outlining the material proprieties of the chimney material and the result of linear cutting trials. The small rock samples were cemented into a testing rig and cut using a full sized linear cutter machine. Table 6-1 outlines the results from these surface cutting tests. In general the optimum specific energy obtained with cutting the chimney material is between 2000 and 6100 kJ per cubic metre.

Table 6-1: CSM 2004 Manus Basin LCM test specific energy LCM test [EMI 2004]

Rock Type	SP Ratio	SE Hp-hr/yd3	kJ/m3
Dark Green	10.0	1.61	3,305
Dark Green	5.0	0.79	1,622
Dark Green	3.0	0.56	1,150
Dark Green	10.0	1.81	3,716
Dark Green	5.0	1.55	3,182
Tan	10.0	2.73	5,605
Tan	5.0	1.61	3,305
Tan	3.3	0.69	1,417
Tan	10.0	2.89	5,933
Tan	5.0	1.43	2,936
Grey/Black	10.0	1.8	3,695
Grey/Black	5.0	1	2,053
Grey/Black	3.3	0.7	1,437
Grey/Black	10.0	4.84	9,937
Grey/Black	5.0	1.79	3,675
Beige Brick	10.0	3.68	7,555
Beige Brick	5.0	1.93	3,962
Beige Brick	3.3	0.97	1,991

Optimum SE predicted by CSM is between 2053 and 6159 kj/m3[1 and 3 HP-hr/yd3]

6.2. *Vancouver trials results*

As mentioned in the Chapter 3 the Vancouver land trials were aimed at confirming the DOSS' sensor and functional performance. In addition this series of tests was used to characterize the cutter's performance using a known rock sample. Two series of tests were performed. The initial dry land performance tests were conducted at the PDTS Research Center from late October 2005, to the final logged trials on Nov 3rd 2005. The DOSS was then relocated to International Submarine Engineering to test the underwater performance from November 9 to November 11, 2005. The formal trials were logged and are summarized in Table 6.2[5] provides a summary of the tests performed.

[5] Graphs of the Normal Force, Energy Consumption, Inferred Volume and Specific Energy for each of the trials are included in Appendix A.

Table 6-2: Summary of VRC cutting program results

Lab Test #	Test Duration [min]	Front Cutter Engaged	Aft Cutter Engaged	Nominal SE [kJ/m3]	Cutter Head Teeth	Notes
1103.000	3	100%	100%	23,500	Full	Transverse cutting test
1103.001	6	96%	96%	20,000	Full	Transverse cutting test
1103.004	4	99%	96%	6,000	Full	Sump Test w/small transvers Motion @ free face
1103.005	6	61%	78%	60,000	Full	Face cutting along free face
1103.007	6	89%	84%	5,000	Half	Transverse (chattering evident)
1103.008	5	97%	97%	7,000	Half	Transverse cut along outer edge
1103.010	5	98%	98%	40,000	Half	Sump w/small transverse
1103.011	6	71%	67%	40,000	Half	Face cutting
1103.012	5	77%	56%	11,000	Half	Transverse
1103.013	5	71%	45%	17,000	Half	Trimmed ridges then transverse
1103.014	3	76%	74%	9,000	Half	Transverse
1109.000	5	58%	63%	10,000	Half	Transverse Pool cutting trial
1109.001	14	96%	95%	60,000	Half	Transverse pool cutting trial
1110.000	23	85%	82%	60,000	Full	Long duration pool cutting trial

Table 6-2 contains test information such as the duration, cutting parameters of the test and notes about the trial. The cutting parameters include the cutter engagement, which represents the percentage of time each of the cutterheads were engaged during the tests duration. If there was a poor cutter engagement such as 1109.000 then the cutters were spinning in air (or water) during most of the test indicating poor cutting performance. Lastly, the cutter head teeth illustrates whether all the teeth were in the cutterhead or only half of the teeth, used to assess the effect of pick spacing on cutting performance.

There were some delays during the construction of the DOSS and due to shipping requirements; the time available for testing was shortened. The DOSS was ready for testing by Nov, 1 2005, and needed to be packed and loaded for shipping to PNG by the 15th of November 2005 in order to arrive in PNG to make the Solwara expedition. This meant that there was less than 2 weeks to test and commission the DOSS in Vancouver.

6.2.1. Vancouver cutting trials

On November 3, 2005 a series of tests were conducted to test the rock cutting performance of the DOSS. The test logs were numbered with the date (1103) followed by the individual test number starting at 000. The Tests 1103.000 to 1103.006 included a full complement of picks on the cutter head, but for the remainder of the day's tests half of the picks were removed and replaced with bolts. The bolts were inserted to protect the pickblocks from damage.

The first two tests 1103.000 and 1103.001 tested the transverse cutting mode, the cutterhead was engaged in the cement and a primarily swing motion was used to move the cutterhead across the test rock. Small adjustments with the arm actuators were required to ensure the cutterhead remained in contact with the rock for the duration of the test. Test 1103.002 a single transverse pass was conducted to obtain size analysis data of the fines for cutting with a full complement of picks. In test 1103.003 (data not included) a 5 minute trial of the sumping functions of the excavator was planned. With this test the cutterhead was engaged in the cement and the boom joints were used to sink the cutterhead along the z axis. After 1 minute the gearbox hit a central ridge of rock and the test was discontinued. The data for these past two tests was not included as the data was not representative of nominal cutting actions. In 1103.004 to test sump cutting a 20 cm of transverse motion along the y axis was included to remove this ridge of material, whilst the cutterhead penetrated into the concrete. Vertical sumping or face cutting was tested in test 1103.005, where the cutterhead was driven into the vertical face of the test rock, (with a small transverse motion) to simulate cutting into the chimney mound material. During this test the DOSS frame experienced lateral movement and the camera mounts on the side of the cutterhead became damaged. This test resulted in the camera mount being reinforced and illustrated a potential hazardous mode of operation. Finally, a forward and aft motion in the x direction was attempted in test 1103.006 to remove the ridges of material caused by the earlier transverse cutting trials. Due to the complex 4 joint motion required to move the cutterhead accurately in this direction, this data is not included as there was not consistent cutting performance.

For the next series of tests, every other pick was removed to investigate the effect of modifying pick spacing and the transverse and sumping cutting tests were repeated. For tests 1103.007 and 1103.008 a 5 minute transverse cutting test was conducted. In test 1103.007 a significant amount of vibration was evident and the cutter head bounced out of the groove 90 seconds prior to the end of the test. 1103.008 conversely was a model smooth test, where the cutterhead had ideal engagement with the rock. In test 1103.009 (data not included) a single transverse pass was conducted to analyze the size distribution of the cuttings. In tests 1103.010 and 1103.011 a repeat of the sumping and face cutting trials was conducted. For the remainder of the day, tests 1103.012 to 1103.014, the alternate operator conducted

transverse cutting test to gain skill in operating the DOSS under cutting conditions, as well as to destroy the remainder of the test slab.

6.3. ISE trials

After the land trials the DOSS was shipped to ISE for submerged pool trials. During these trails it was noticed that the injector pump which was sourced for the material handling system did not function and would not provide sufficient suction to recover any material. An emergency centrifugal pump was located and sourced locally, but because of this the materials handling system was not able to be tested as a whole prior to the field tests. The pool tests revealed other typical commissioning problems inherent with creating a submersible machine, including problems with the compensation circuit and water leakage. Once these problems were overcome, the excavator was used to continuously cut another concrete substitute in the pool. For the entire pool trial, it operated in a transverse cutting mode as that is the most common method for cutting, and the only mode that time permitted to be tested. These cutting tests were of longer duration and more indicative of the actual field cutting conditions.

Test 1109.000 and 1109.001 the DOSS was tested with only half the picks mounted on the cutterhead. As seen with the engagement numbers, in test 1109.000 the operators required some time to become familiar with operating the excavator in an aqueous environment. By the second test it is clear the operators have improved their control as there is much less skipping of the cutterhead resulting in much more energy entered into the concrete. Lastly the following day the picks were replaced in the cutterhead and the DOSS cut transversely 23 minutes in test 1110.000. During these tests the future visibility problems which would plague the ocean test became apparent. Once the DOSS began cutting visibility with the cameras rapidly diminished, this was accentuated by the non functional suction system. Figure 6-1 shows the remains of the pool slab after 2 days of testing. Note the cutting trough formed by the dual cutterheads.

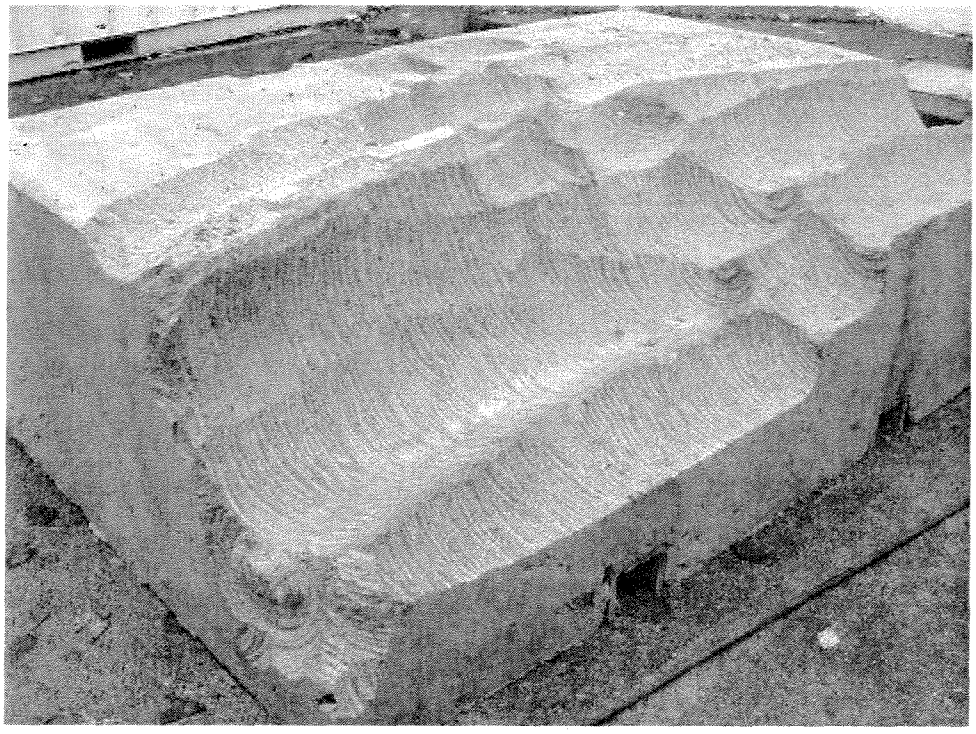

Figure 6-1: Test slab after ISE trials

It was discovered after analyzing the results from these Vancouver trials that the configuration of the pressure sensors and the hydraulic valves resulted in the pressure reading for the arm cylinders to be invalid when the excavator was operating in a manual rate control mode. This was due to one sensor being located in a line which drains to the hydraulic tank, and once the cylinder position move is completed the control valve closes and this side slowly depressurizes giving erroneous forces measurements. As this problem was not discovered until the DOSS was already in transit, it was not possible to correct this minor problem prior to the PNG trials. A work around solution was to program a position control system, which kept the servovalves open allowing valid force measurements to be recorded.

6.4. PNG trial results

Prior to the commencement of the subsea cutting trials, as part of the initial site investigation a detailed bathymetric model was made of the sea floor. The model was used to identify the potential drilling targets as well as located potential cutting sites. A graphical plot[6] of the test

[6] The contours are on 10 metre intervals and the grid lines are on a 250 metre spacing.

area is presented as figure 6-2. Based on the drilling campaign, 8 main cutting locations were tested with 27 different dives.

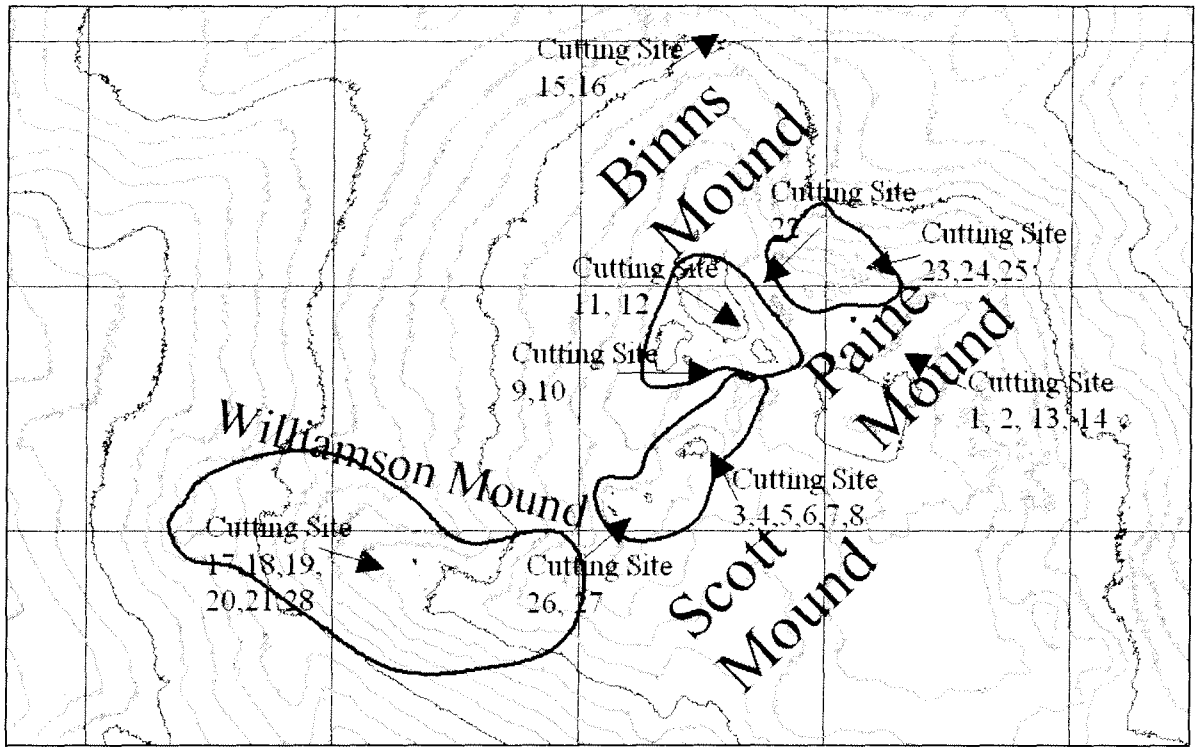

Figure 6-2: Detailed bathymetric contour of the Solwara project site

6.4.1. Geo technical information from drilling results

Prior to the cutting trials the drilling results from the drilling portion for the expedition were analyzed to determine the geotechnical properties of the cutting trial test sites. The attempts to use intact core to obtain a measure of the rock strength were unsuccessful. The average core recovery for the entire cruise was less than 41% with many of the initial holes averaging less than 30 %. In general there was better core recovery in the host volcanic rock and poorer recovery in the sulphides, as they were more friable. Important to rock cutting is the strength properties of host rock such as the unconfined compressive strength (UCS) and tensile strength. The standard measure for determining the USC is the triaxial test, but it can also be inferred from other tests such as independent point load testing or impact testing with a Schmitt hammer (Aydin, 2005). It was proposed to use a Schmitt hammer to test the core recovered and correlate the data to lab testing. The impact hammer testing was used because it was a better indicator of cutting ability than point load testing, and a point load testing apparatus was not available for the cruise. For weaker

strength rocks the amount of core recovered also provides a good indication of the strength of the rock.

It was initially thought that the mound structure was a large cohesive unit. Initial observations indicated that the mounds might consist of a mass of fallen chimney material interbeded with silty sediment material. In general the mounds at most of the test cutting locations consisted of large toppled chimneys 30-40 cm in diameter and 3-4 metres in length. In general the structure is likened to the brush fall at the edge of a forest, large random diameter cylindrical structures randomly oriented.

6.5. Cutting data from PNG

Following 4 weeks of drilling the DP Hunter's ROV was integrated with the DOSS, shown in figure 6-3 and commissioned for sea trials. In all 27 cutting dives were undertake at the cutting locations shown in Figure 6-2. The results from the dives are summarized in Table 6-3. A sample calculation to develop the data on Table 6-3 is included in Appendix A. This table illustrates the derived cutting volume, power status of the DOSS during the dive, the amount of material collected during the dive, and the normalized specific energy that was required to excavate at that location. In addition, the conditions of the dive can be determined from notes on the material excavated, the test completion failure info, and the percentage of time that each of the cutters was engaged during the test duration.

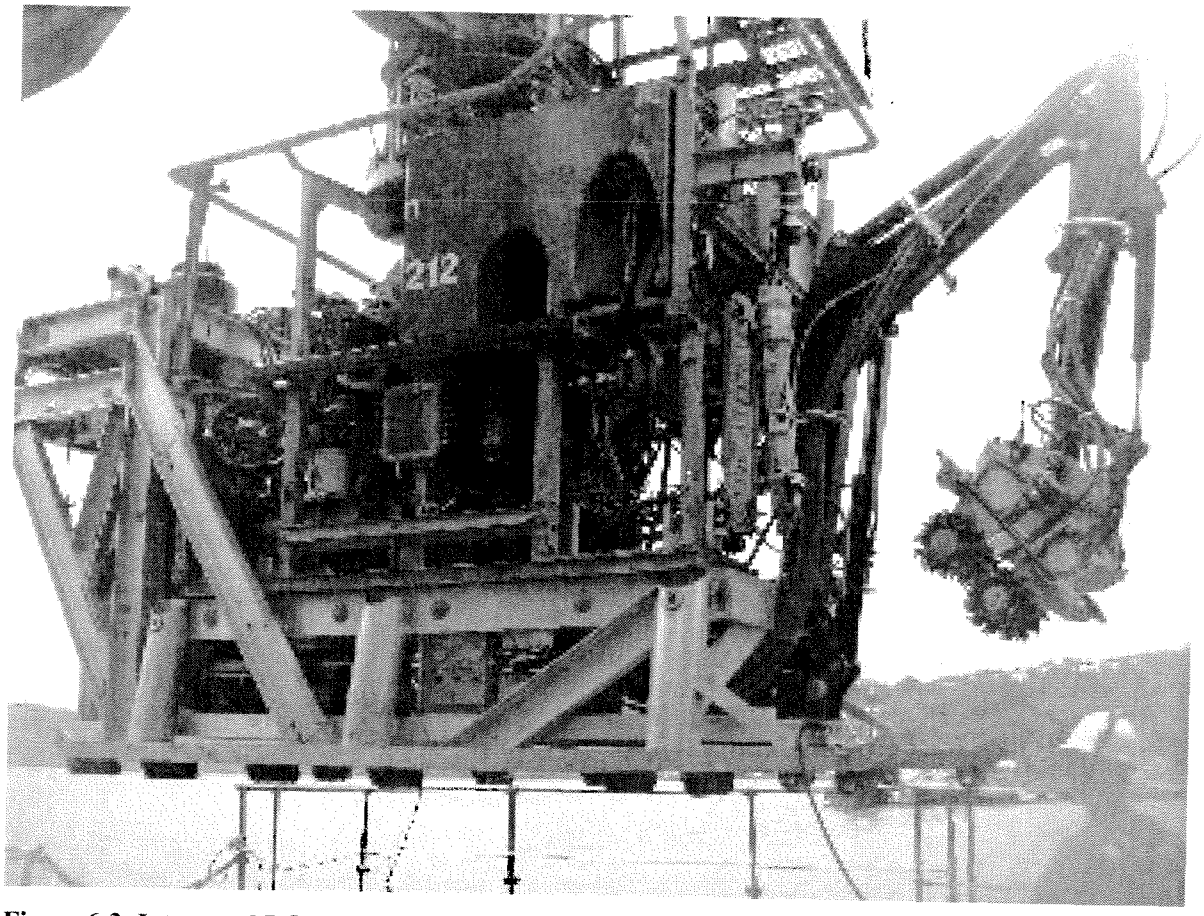

Figure 6-3: Integrated DOSS and ROV

Table 6-3: PNG cutting trial results

Dive	Test Duration [min]	Front Cutter Engaged	Aft Cutter Engaged	Derived Volume [m3]	Normalized S.E [kJ/m3]	Barrels	Area	Cutter Head Teeth	HPU Power	Test Completion	Notes
1	**65**	77%	89%	1.64	20,000	1	**Tumora**	Full	Full	Pump failure	Flat sulfide mound
2	**35**	14%	14%	0.15	57,000	0	**Tumora**	Full	Full	HPU	Andesite volcanics
3	**63**	36%	29%	0.22	80,000	3.5	**Scott**	Full	Half	Pump plugged	Sulfide chimney material
4	**128**	44%	30%	0.42	22,000	4.5	**Scott**	Full	Half	CH Jam	evident)
5	**40**	35%	27%	0.28	34,000	2	**Scott**	Full	Half	MH blockage	Minimal sulfides (lots of sediment evident)
6	**64**	47%	31%	1.30	10,000	2	**Scott**	Full	Half	Pump blockage	Sulfide chimney material
7	**17**	22%	21%	0.05	25,000	P.F.	**Scott**	Half	Half	Pump failure	No recovery
8	**85**	49%	31%	0.58	20,000	P.F.	**Scott**	Half	Half	Suction hose	No recovery, Top of mound
9	**89**	47%	15%	0.21	60,000	P.F.	**Binns**	Half	Half	Suction hose	No recovery
10	**79**	40%	33%	0.81	30,000	P.F.	**Binns**	Half	Full	No failure	No recovery
11	No data					P.F.	**Binns**	Half	Full	No failure	No recovery
12	**15**	13%	13%	0.07	75,000	P.F.	**Binns**	Half	Full	Cutter head	No recovery
13	**24**	24%	22%	0.26	8,000	P.F.	**Tumora**	Half	Full	Oil leak	Hard volcanics outcropping, poor visability
14	**110**	29%	14%	0.41	80,000	P.F.	**Tumora**	Half	Full	Oil leak	Hard volcanics
15	**47**	5%	12%	0.11	Inf	P.F.	**Other**	Half	Full	No failure	Hard volcanics
16	**47**	10%	4%	0.08	inf	P.F.	**Other**	Half	Full	CH jammed	Hard volcanics
17	No data					P.F.	**Williamson**	Half	Full	CH jammed	No recovery
18	**51**	32%	31%	0.92	15,000	P.F.	**Williamson**	Half	Full	No failure	No recovery
19	No data					1	**Williamson**	Half	Full	Suction hose	Sulfide chimney material
20	**22**	17%	7%	0.03	40,000	0	**Williamson**	Half	Full	Oil leak pump	No recovery
21	**46**	43%	19%	0.62	20,000	2	**Williamson**	Half	Full	Oil leak pump	Sulfide chimney material
22	**175**	37%	4%	1.93	20,000	2	**Binns**	Full	Full	No failure	Sulfide chimney material
23	**120**	50%	38%	1.16	40,000	2	**Paine**	Full	Full	Suction hose	Sulfide chimney material
24	**165**	44%	30%	0.63	40,000	1	**Paine**	Full	Full	Oil leak	Sulfice Mound Material
25	**78**	27%	30%	0.54	40,000	0	**Paine**	Full	Full	Suction hose	No recovery
26	**29**	28%	22%	0.24	20,000	2	**Scott**	Full	Full	No failure	Sulfide mound materail (lots of sediment)
27	**64**	37%	23%	0.94	45,000	3	**Scott**	Full	Full	No failure	Sulfide mound material

During the excavation tests on the Scott mound and the Binns mound the pick spacing was changed. In analyzing the data in table 6-3 there does not appear to be a noticeable effect on the normalized specific energy for excavation. Theoretically there should have been a noticeable change; this may be explained by 3 different factors. First although the locations for these tests are in close proximity, there may be large geological variances between the tests. Secondly, the penetration as mentioned above is quite small resulting in a large S/P ratio. This may minimize the effect of adjacent picks i.e. each pass is cutting independently, regardless of the spacing. Lastly, there was evidence of significant wear on the keeper bolts installed to protect the pick blocks. These bolts may have been acting as very poorly designed indent cutters; however the lack of a large increase in force, shown in the force data included in Appendix C, indicates that they probably caused resistance by mobilizing liberated cuttings. From this set of tests it is not prudent to conclude that the altered pick spacing had a positive or negative effect and further testing in a controlled environment is required. Moreover, it is essential to ensure that the next generation excavator is able to generate enough force to fully penetrate the rock to the optimal depth for which the cutter is designed.

Do to the earlier mentioned problems in the materials handling system, it was impossible to get a measure of the material excavated during the pool tests. As a result the Voxel method was developed to determine the production of the excavator while submerged.

As shown in table 6-4 for the initial trials the samples were collected and weighed. It appears that the derived volume method functions adequately when the cutter is operating in a smooth longer duration test, such as dives 3, 4, 5 26, and 27. When the excavator was functioning in alternative excavation modes such as cutting forward and aft, or excavating the front face of test slab the derived volumes showed a considerable variance. In the longer duration marine tests this error should be minimized, but very poor cutter engagement values indicate that the cutters are chattering across the surface of the rock rather then cutting, as this value is a measure of how much time the cutterhead is in contact with the rock. Table 6-4 shows the variance observed from the voxel approach for volume estimation compared to the amount of material recovered.

The large variances in the estimation show two trends, where there was a lot of sediment evident, there tends to be an over estimation of the volume excavated compared to the sulphide chimney material where the volume is underestimated. This is probably due to inefficiencies in the material handling system and the pump problems encountered. Due to this, the specific energy calculated from the derived volume should be used for order of magnitude trending. Although not ideal this method creates specific energy which appears overtime to trend to reasonable values based on the literature. Since the cutter parameters change due to operator adjustment, and given the error inherent with the voxel method of approximation, it is felt that it was not beneficial to develop a more automated analysis approach and the corrected specific value should give a reasonable order of magnitude approximation. Due to the high level estimation of the results and the variability a detailed statistical analysis was not conducted.

Table 6-4: Volume variance

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Test	Volume Excavated [m3]	Derived Volume [m3]	Percent Variance	Test Notes
1103.000	0.29	0.09	70%	Transverse Cutting Test
1103.001	0.25	0.26	-5%	Transverse Cutting Test
1103.004	0.25	0.26	-6%	Sump Test w/small transvers Motion @ free face
1103.005	0.27	0.03	91%	Face Cutting allong free face
1103.007	0.23	0.42	-82%	Transverse Chattering evident
1103.008	0.26	0.24	7%	Transverse Outer Edge
1103.010	0.32	0.06	80%	Sump w/ Small transverse
1103.011	0.29	0.04	88%	Face cutting
Dive 1	0.25	1.64	-555%	Flat sulfide mound
Dive 2	0.00	0.15	N/A	Andesite volcanics
Dive 3	0.88	0.22	75%	Sulfide chimney material
Dive 4	1.13	0.42	63%	Sulfide chimney material (lots of sediment evident)
Dive 5	0.50	0.28	44%	Minimal sulfides (lots of sediment evident)
Dive 6	0.50	1.30	-160%	Sulfide chimney material
Dive 21	0.50	0.62	-23%	Sulfide chimney material
Dive 22	0.50	1.93	-286%	Sulfide chimney material
Dive 23	0.50	1.16	-132%	Sulfide chimney material
Dive 24	0.25	0.63	-151%	Sulfice Mound Material
Dive 26	0.50	0.24	51%	Sulfide mound materail (lots of sediment)
Dive 27	0.75	0.94	-26%	Sulfide mound material

Figure 6-4 shows the distribution of the production rates logged for each of the cutting dives. Clearly, as well as a lower percentage of actual cutter engagement during a minute of cutting, there is a significant amount of time (often 35%) during a dive where the cutter is not producing at all. Some of these low production values can be attributed

to the derived method of determining production rate, but these values correspond to the video logs of the dives. During a cutting dive there were periods of time when the cutter head would become jammed with a large piece of chimney material. On average it took in excess of 5 minutes to clear most blockages. This was caused by both the design of the dual counter rotating cutter heads and the power rating of the WS-15.

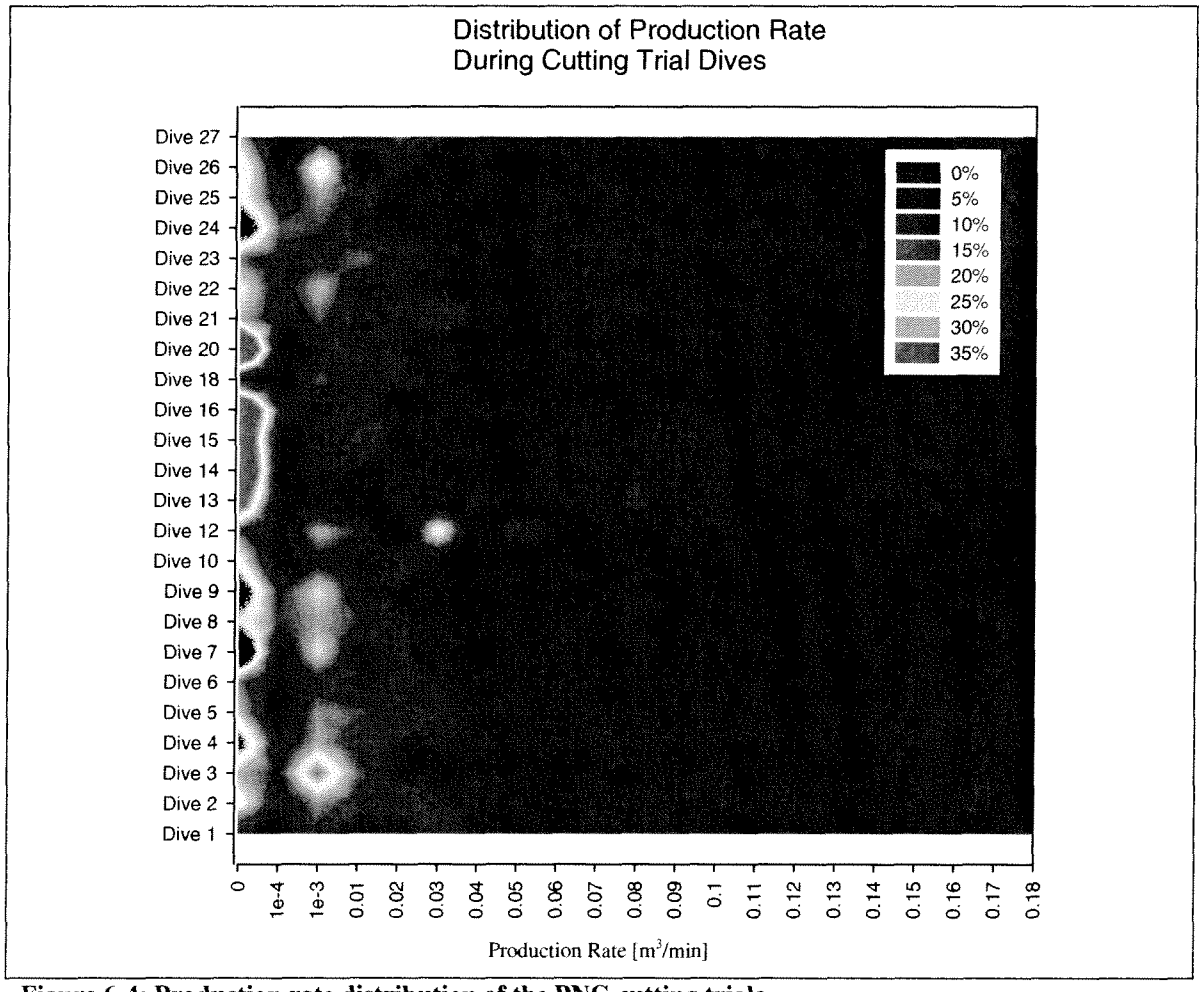

Figure 6-4: Production rate distribution of the PNG cutting trials

Figure 6-5 show shows the energy consumption distribution of the DOSS during the cutting dives showing the variability in the cutting sites. Clearly, where the system power was limited due to a hydraulic power unit failure, in dives 3 to 9, the energy distribution is centered around a lower 550 kJ compared to roughly 700 to 800 kJ in the subsequent tests. The spread on the energy input indicates the proportion of valid times that the excavator is actually in contact with the rock versus spinning in water. As confirmed in table 6-3 the energy distribution also clearly indicates effective cutting dives

such as dives 2-5 and dives 20 to 26 where in general the percentage of time that the cutters are engaged is quite high.

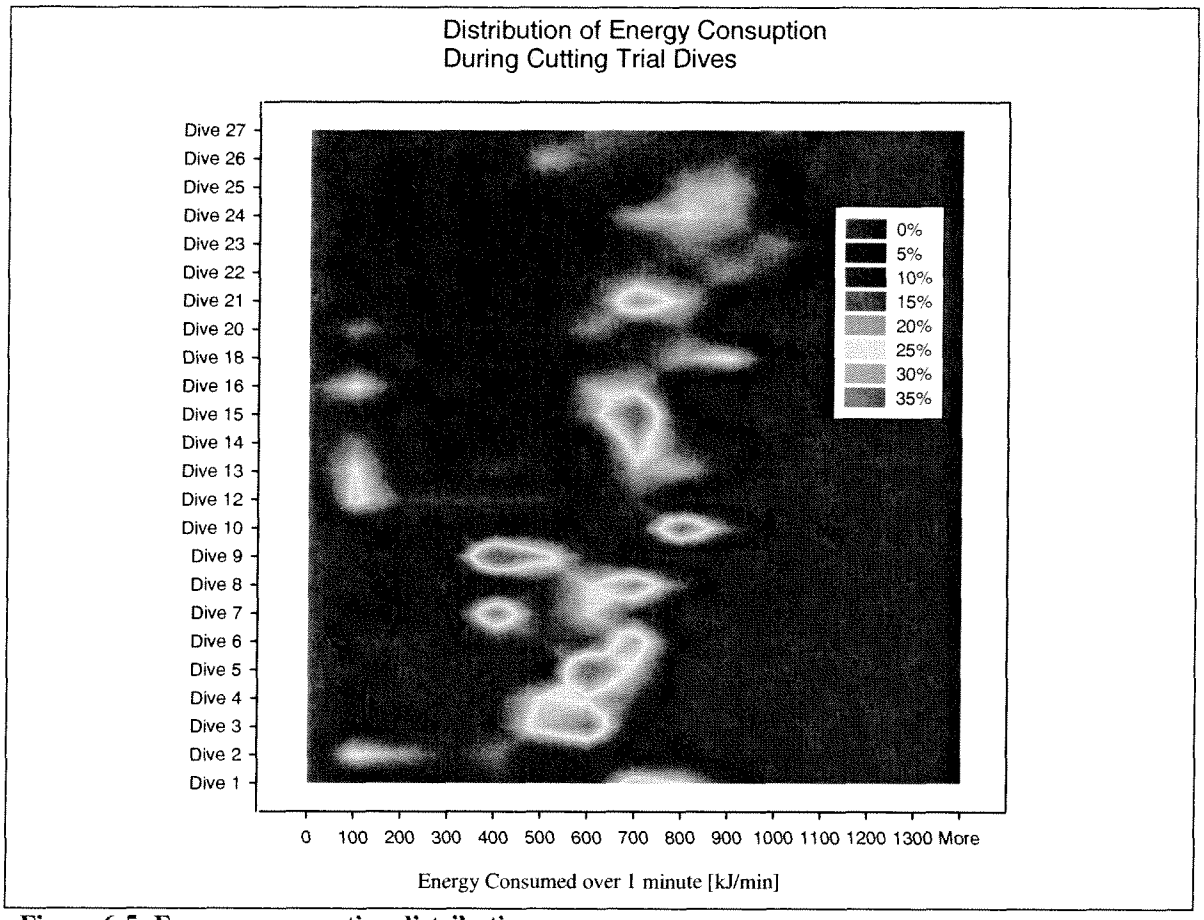

Figure 6-5: Energy consumption distribution

For both figures 6-4 and figures 6-5, the graphical presentation of the data is shown as continuous between the various tests. This however is a function of the graphing program which uses a smoothing algorithm, similar to krigging, which highlights the data points which are similar between the two tests. This allows for a graphical presentation of any similar trends between the trials.

Individual site data for each of the dives is included in Appendix C, and an example of this data is shown in figure 6-6. The data is presented in a time strip fashion outlining the values of the normalized specific energy, the energy consumption, the volume excavated and the normal force at the cutterhead. Below the time data the distribution of the specific energy, the energy consumption and the production rate values are displayed. For all the strip plots included in Appendixes B and C the scale the of

determinate axis have remained constant to allow for consistent presentation of the test data.

One interesting thing to note is that there appears to be no observed pattern to the time dependent data, as one might assume, there are two explanations for this. First the voxel method of approximation smoothes out any trends in the volume estimation, as the volume extracted is only registered the first time the cutterhead passes through the three dimensional space while cutting, and it could take more than a minute to excavate all the material represented by that voxel cube. The second explanation is that a majority of the energy consumption is used just to spin the cutterhead. A majority of the parasitic energy values were between 500-1000 kJ/min, and for example the parasitic energy consumption in figure 3-3 was 430 kJ/min. Thus the amount of flow into the cutterhead has much more impact on the energy consumption than the actual energy component attributed to the actual cutting of the rock. This energy component is lost in the noise floor caused by spinning of the cutterhead.

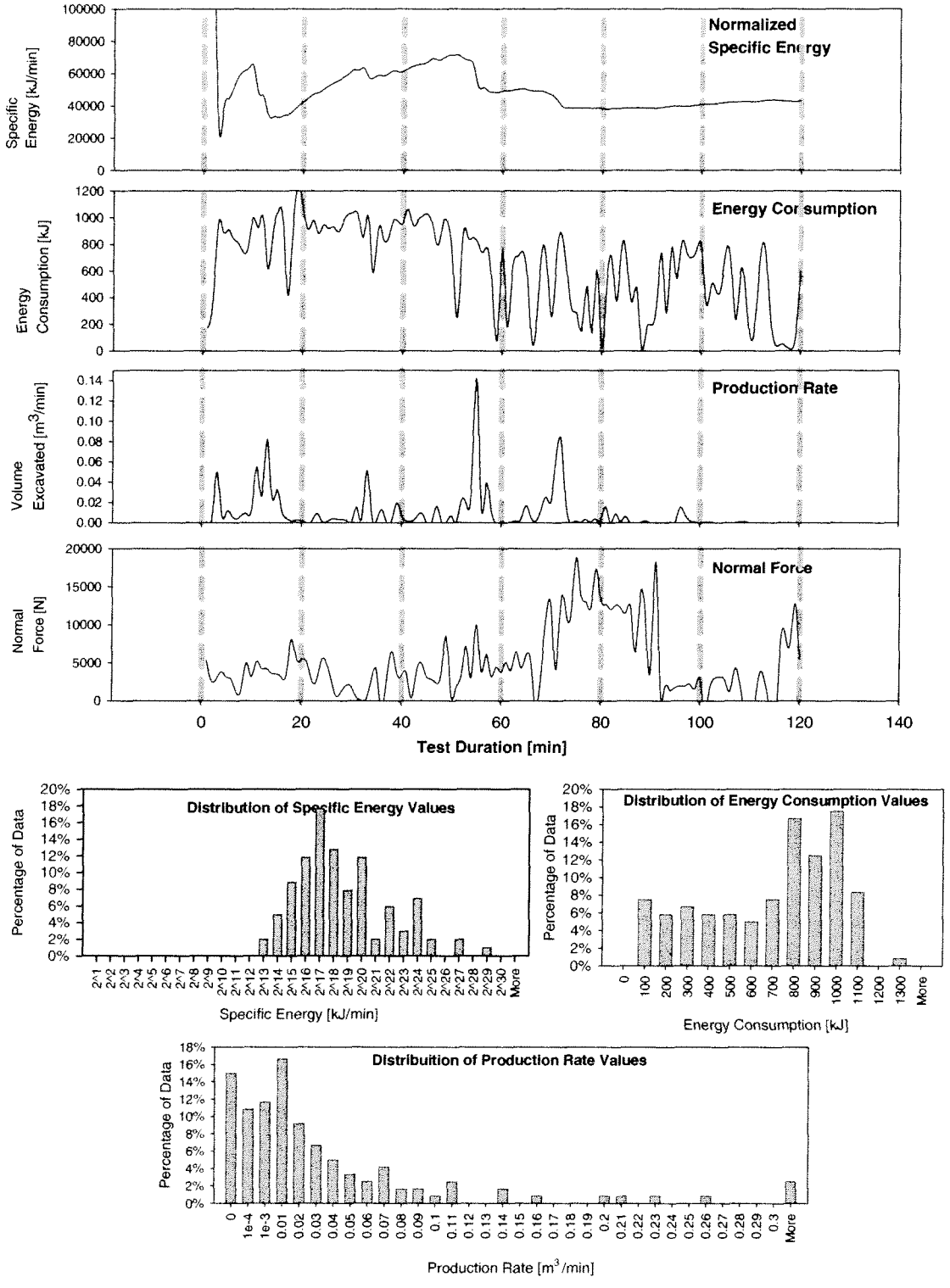

Figure 6-6: Site 23 data

6.5.1. Force analysis of the data

A Jacobian translation algorithm developed by Celula provided a measure of the normal penetration forces the cutterhead experienced. However because of the sensor configuration, the forces were only resolved to a centroid between the two cutterheads. Due to this when both cutterheads are engaged in the rock the problem to determine the normal force for a single cutterhead becomes indeterminate, as a result, the force information did not provide any readily available insight into rock cutting forces and remains to be further investigated. The author questions the validity of the normal force data and did not use it in the analysis, due to the mass sensor problems, and at the time of writing not being able to account for the variability in the DOSS's three dimensional orientation. Further investigation of the force information remains to be investigated, and is of more use in the DOSS robotic controls studies.

6.6. Summary

This chapter presents the results of the Solwara rock cutting trials from the initial proving trials in Vancouver to the deep ocean field trials in Rebaul, Papua New Guinea. The overall goal of the program was to confirm that the chimney material could be excavated and to obtain bulk samples for metallurgical testing. Extending from actually confirming that the material could be excavated was the goal of understanding the cutting forces and energy requirements for rock excavation in this environment.

Unfortunately, because of sensor failure it was not possible to obtain an online mass reading to determine the excavation cutting rate, so estimation for the volume had to be made. Do to the limited accuracy in using voxel approximation for specific energy, definite conclusions can not be made about the data obtained during the cutting trials. However, even with this point, the experimental program was a success as the DOSS successfully cut and recovered over 15 tonnes of material.

As a final note the due to the time constraints in the development of the DOSS and the necessity of meeting the Rabual expedition, although there was a much more detailed pretest cutting program developed by the author to determine the performance of

the excavator, these tests had to be curtailed to a bare minimum, in order to meet the greater goal of conducting bulk sampling.

The results from this chapter illustrated that it is viable to extract PMS materials from the seafloor, the energy required to cut PMS materials appears to be higher than on the surface, but is consistent with typical mechanical excavation values for rock cutting. From these tests it is clear that further controlled experiments are required to properly characterise the cutting requirements for deep sea PMS deposits.

7. Challenges of Ocean Mining

The Solwara expedition provided the author and the project team with a rare opportunity to validate concepts for ocean mining and to provide information for the design of the next generation excavation machine required for the ocean mining program. The ocean trials consisted of a geological survey, a baseline environmental survey, and excavation proving trials. The excavation trials were aimed primarily at verifying that sea floor ocean sulfide material could be excavated by mechanical means. A secondary goal of the cutting trial was to develop control strategies for a seafloor excavator. The results from control system analysis are outlined elsewhere, (Jackson, 2006) this discussion concentrates on the mineral excavation challenges. These challenges include the issues with fundamental mechanical rock breakage, bulk production, and finally overall ocean mining excavation strategy.

This chapter begins with discussing the machine cutting parameters from the experience of mining with the DOSS, leading into the energy requirements then production issues. This discussion leads into the design considerations for the future development stages of sub sea mining excavators. The discussion continues with observations and issues with mining PMS deposits and the maintainability of an ocean mining excavator.

7.1.1. Mechanical rock breakage

The primary goal of this test program was to demonstrate that ocean chimney material could be excavated from the ocean depths. Current and past mining efforts discussed in Chapter Two consisted mainly of conventional soil dredging techniques. In civil construction there is some specialized excavation equipment being utilized, but these applications are in shallow depths. There is no evidence in the literature to indicate the application of conventional surface methods to mechanically excavate back arch chimney material.

7.1.1.1.Cutting modes

The VRC trials played an important role in determining which of the cutting modes were viable for testing in the field conditions. From the initial four cutting modes identified during the Langley trials, transverse cutting was the most efficient and principal mode of cutting identified.

It was quickly apparent that without an integrated control system, slewing the cutter forward and aft as a primary mode of cutting was unviable. This is due to the joint configuration of the arm. Under normal operator control the operator had to manipulate four joint actuators simultaneously in order to move the cutter along the x-axis. Although a position control algorithm could be (and was for the ocean trials) developed. This mode of cutting was seen as inefficient and not tested beyond test 1103.006. In addition when this mode was trialed there was a lot of impact loading on the cutterhead as the cutters could not collar into the rock, rather they skidded across the surface.

Not surprisingly, since the cutter head is designed as a transverse cutterhead, this cutting mode was the most productive and efficient. Operating the swing articulation, the cutterhead travels in a path which defines the y-axis. Due to this, the operator was able to excavate rock by adjusting the swing angle, and sinking the cutter using minor adjustments to the boom. The counter rotating drums worked surprisingly well with the rotational torque generated by the forward head being counteracted by the torque generated by the aft head. Additionally, the dual cutter-heads aided the neutralization of the normal reaction forces at the head resulting in less vibration while cutting.

Lastly, the design of the WS-15[7] quickly illustrated a flaw with sumping solely in the z-axis. The gearbox of the WS-15 is only 63 mm below the cutting horizon, which is the limit the head could sump without bottoming out. By articulating the swing angle 5 degrees while engaging the boom angle it is possible to obtain a mainly sumping action. This however is principally a very short length transverse cutting action instead of a unique cutting mode.

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[7] There is a modification of the WS-15 design for trenching which includes a device to remove this central ridge.

During the ocean trials the DOSS was advanced into contact with the rock then engaged the rock with a transverse cutting action. Refinements in the control system during the course of the trials led to a more effective cutter engagement at the cutting face. These refinements lead to better cutting performance. These refinements primarily consisted of a force feedback mechanism which prevented the cutter from stalling at the cutter face, by minimizing the normal force as the rotational torque increased. Refinements in the end effector control were developed during the course of the ocean testing.

7.1.1.2.Specific energy requirements

During the trials the target subsea chimney material cut as expected, being on average more friable than originally estimated. As indicated in the original CSM studies the rock failed in a ductile fashion rather than in a more conventional brittle mode. The various geological studies of this region indicated that the chimney material, and in some cases the mound material, was formed by percolation of mineral laden fluids. This resulted in a framework of barite and silica being created followed by a continuous deposition of sulfide minerals within the resultant cavities. This leads to a very weak discontinuous structure which is not conducive to crack propagation. Due to the ductile mode of failure of the rock a greater amount of fines were generated than would be found with tensile fracturing. This indicates that a closer than standard pick spacing is required. This closer pick spacing will require either a smaller head or more energy due to a greater number of picks in contact with the rock. Conversely, the finer particles will require less energy to hydrotransport.

Comparing test 1103.001, 1103.008, and 1110.000 which all had the same operator[8] and cutting mode, it is clear that operating the excavator in a marine environment reduced the amount of time the cutters were engaged by 15% compared to the surface tests. Tests 1110.000 and 1103.001 tend to agree with Kaitkay (2005) of suggesting a 3-5 fold increase in the specific force required for sub sea applications. With the modified pick spacing there was no evidence of an increase or decrease in

[8] Test 1103.012 and 1103.014 the excavator was operated by a different operator.

energy consumption. The large amount of wear on the keeper bolts would indicate contact with the host strata contaminating the results. In addition, it is suggested that a majority of the cutting occurred with the gage cutters, which are the outer cutters on the cutting head.

As mentioned in Chapters 2 and 6, although the sulphide materials are extremely friable and present no problems to excavation, dives 13-16 conducted around the Tumora mound, illustrated that the sulfide materials rest upon a volcanic base. Confirmed with the drilling program, the volcanic material has an estimated strength of greater then 100 MPa, beyond the design capacity for point attack picks. Luckily, at this time, there is no evidence that volcanics are overlying the sulphide material. During these tests the volcanic material caused the cutterhead to stall or bounce off the face of the formation, since the DOSS lacked sufficient power it did not self destruct upon contact with this high strength material. This is a key point as in mechanical excavation the forces involved to drive multiple picks through weak rock, exceed the breaking strength of an individual pick. This can result in a high pick consumption if the volcanic surface is irregular. Luckily, the geological evidence for this deposit indicates that the volcanic material consists primarily of pillow lava, which for this application is a relatively smooth surface, maximizing potential mining recovery.

7.1.2. DOSS production

7.1.2.1.DOSS cutting performance

From the CSM study and the results presented in the last chapter it is clear that mechanical excavation is a technically viable method for excavating the Manus Basin Ocean material. However, as noted previously, operating in a hydrostatic environment requires more energy due to the impediment of crack propagation, and hydrodynamic effects on the cutterhead. However, the cutterhead used in this trial is not sufficient to excavate rock at commercial production volumes. Throughout the duration of the trials only 5.2 cubic metres of material was returned to surface after 18.3[9] hours of test work. To put this in perspective to achieve the final goal of 1 million tonnes of material

[9] These minutes refer to the time when the suction system was functioning.

excavated a year, assuming an insitu specific gravity of 3, a production excavator would have to be able to excavate 706 cubic metres of material during the same trial duration. With the next milestone phase of the ocean mining project, the second generation excavator is planned to have a design excavation rate of 100,000 tonnes per year, which would result in 70 cubic metres of material being excavated over the same period of time. Note that neither of these cases address the mechanical availability issues which are discussed in the next section. From these figures, it is clear that a considerable amount of design scaling is required. However, from the Terex commercial literature, the WS 15 is the smallest cutterhead provided for conventional 2 tonne excavators. The largest Terix cutterhead, the WS 120 designed for a 45 tonne machine has a cutting diameter 1.6 times greater than the WS-15's, 5 times the power, and 2 times the width. This implies that simply expanding the size of the cutterhead and increasing the power of the excavator it should be possible to achieve the next phase of design.

An increase in size may lead to greater problems with the hydrodynamic effects of the cutterhead. At the beginning of the test program it was anticipated that there would be an increase in power requirements due to the hydrodynamic drag effects of the cutterhead. In analyzing the performance of the cutterhead both on surface and submerged, there was no indication of a velocity dependent drain on the cutterhead torque. There was an increase in power demand from 3kW to 5-6 kW once the excavator was submerged to excavation depth. This large increase in power most likely conceals any velocity effects. In addition, the cutterhead was operated at the design speed for most of the trials, and operating outside this range increases the non linear response of the hydraulic cutterhead due to increased leakage across the motor in the cutterhead. As in the lab trials the transverse cutting mode was the primary mode of rock excavation during the ocean campaign. The transverse cutterhead assembly mounted on the end of a manipulator arm performed adequately and provided the flexibility to adapt to the various ground conditions. The manipulator arm mounted on a central pivot may present problems as this design is increased in size. An increase in side loads on the cutterhead is expected as the size of the cutter head increases caused by the gage cutters interacting with the rockmass.

An increase in the available power would be very beneficial to the excavation of the chimney material. Although the rock is very friable, the existing dual drum design lead to numerous problems as during the trials the cutterhead jammed and stalled numerous times. This is a primary reason for the low cutter engagement during the field trials compared to the Vancouver tests. Figure 7-1 illustrates the 3 main modes of jamming encountered while cutting.

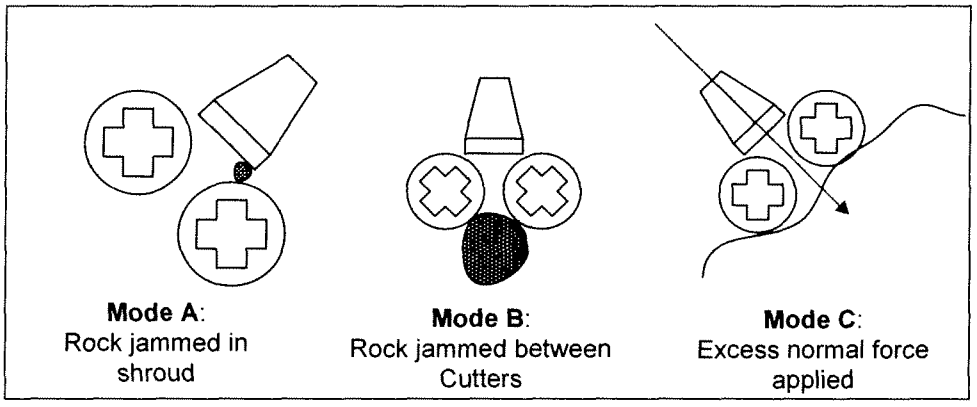

Figure 7-1: Stalling modes during rock breakage

Stalling mode A happens when an uncut rock becomes lodged between one of the cutters and the shroud of the cutterhead. These uncut rocks passed through the throat of the two cutters and either were forced into the nozzle head or, as mentioned, became lodged between the cutter drum and shroud. A stiff shroud was used for most of the tests as a more flexible material, such as rubber, would encounter more wear than higher strength steel. The initial shroud material constructed out of aluminium was destroyed during the first PNG trial dive. The shroud was then reconstructed with a hardened tool steel lip to minimize wear. By increasing the power in future designs, encountering stalling A mode should be minimized as the cutters act to crush the lodged particles. This was evident in dives 3-7, as one of the ROV hydraulic power units failed and less power was available to the cutterhead resulting in less cutting torque and more frequent jams

Under normal operating conditions the power allows the edge of the shroud lip to act as a crushing surface. One problem with this occurring is that the increased power could force unbroken rocks through the throat of the shroud. In three separate cases 10 cm. diameter rocks passed through the nozzle and entered the material handling system.

Most of the rocks that passed through the gape of the shroud were lodged within the nozzle impeding the suction flow. During the next phase of the cutter design, the nozzle must be able to allow large rocks to bypass the shroud and not get forced into the collection system. As the next generation system is coupled with a riser system to surface a large particle could cause serious problems unless it can easily be rejected prior to transport to the surface.

Two factors lead to the occurrence of failure mode B. The initial concepts of the undersea deposit and video footage lead to the assumption that the mounds consisted of large masses of sulphides. At the cutting sites, however, as the chimneys increased in height they became more unstable. Eventually, they collapsed under their own mass and a new chimney would begin to form. Although there is evidence from the drilling forces that there is sulphide cementation occurring at depth at the cutting sites, the fallen chimneys resemble the edge of a forest with loosely consolidated chimneys blanketed in sediment. When the DOSS attempted to cut one of these fallen chimneys it would fracture and the entire chimney would become lodged between the two cutters. Unfortunately, although the design of the cutterhead resembles an open faced rolls crusher, there was not enough power to crush the rock. The cutterhead was originally designed with a reversible hydraulic circuit powering the cutterhead, but there were hydraulic problems that were not able to be rectified prior to shipment to Rabaul and at the time this was not considered a serious issue. If the dual drum design, which was quite successful, is used in the next generation machine, enabling the heads to reverse is a key priority. Fundamentally, the chimneys are quite friable and if the cutter head contains enough torque to crush the unconsolidated chimneys, they should present minimal problems as the design is scaled.

Lastly, stalling mode C is encountered where the normal force, in this case caused by the boom, exceeds the cutting torque. This problem is a function of the head design and the rock properties. As previously mentioned there is an optimum specific energy for a given rock mass, which can be likened to the electrical impedance. The cutterhead can be tuned for a given rock mass using standard methods presented in Chapter 2. The combination of normal force and cutterhead design will have an optimal penetration based on the cutterhead torque and rock mass. Unfortunately as the rock mass changes

the effective impedance changes and a new cutterhead design is required. Because of this, a nominal design is chosen, which results in a suboptimal excavation performance, but still effective for excavation. As mentioned in Chapter 6, the effective spacing to penetration ratio experienced during the tests was inferred to be on average between 10 and 15. CSM in their initial testing concluded an optimal spacing to penetration ratio of 5. The significance of this is that operating this far away from the optimal spacing setpoint results in much higher energy consumption and poorer cutting performance. The WS-15 is limited in how much power can be applied to the drive motors without damage, which limits the amount of cutting torque it can deliver. This resulted in the cutter stalling if excess force was applied. Increasing available cutter power at the pick will reduce both this mode of stalling, and move the spacing to penetration ratio closer to optimal.

If the cutterhead drum is increased in size from the WS-15 to the WS-120 there is an increase of available rated pick force from 18 kN to 108 kN. Although, it would still be possible to stall the cutterhead even with a more robust drum, feedback control designed during these tests enabled the force applied by the excavator to be controlled by the torque generated by the cutterhead. However, increasing to the WS-120 size will require an increase in designed power 11.2 to 89 kW.

Many of the jamming problems are engineering in nature and there is no reason to believe that they cannot be overcome especially since increased power will solve most of the previously discussed issues. Unfortunately, increasing the power available creates other complications. The DOSS as designed had enough force to move it around the sea bottom. To clear the modes A and B jams from the cutterhead, the hydraulic pressure was released and the cutter drums were manually forced in reverse to free lodged particles. Often, considering the topology of the cutting sites, the DOSS would need to move due to the boom forces. In order to force the cutterhead into the rock the excavator must be able to provide an opposing reactive force. This can be accomplished with mass or hydraulics. Conventional, surface mechanical excavators have an enormous mass which acts to counteract the cutterhead forces. By utilizing a dual cutterhead design, half of the reaction forces are counteracted compared to operating a single cutterhead, based on the data from the Langley trials and the Vancouver trials. It is thought that the counter

rotating cutter action acts to pull the head into the rock, allowing the excavator to primarily supply swing and normal forces. However, the increased power and mass requirements in a larger excavator would require a larger winch and cable for moving the excavator, which increases the size of the support equipment required, increasing the capital costs.

7.1.2.2.Material handling system performance

The DOSS used a centrifugal pump to generate a suction system to capture the excavated material. Due to scheduling problems, this was not tested in Vancouver as extensively as desired, and most of the unreliability that the DOSS encountered could have been resolved with more extensive machine performance testing. In general the suction system performed as designed, maintaining enough fluid velocity to keep the excavated material in suspension and delivering it to the hydro cyclone. The dual cutterhead imparted enough velocity to propel the rock fragments into the suction nozzle as seen during Dive 15, when the suction system was disconnected, there is video evidence of cut material being ejected out of hose attachment area above the nozzle.

On dive 5 a large rock, potentially from the previous dive, became lodged in the junction just prior to the hydrocyclone. Because the surface area of the blockage was less than that of the line, material was able to flow, but was impaired. The impaired flow lowered the velocity within the discharge pipe causing sediment to begin to settle. Once the pump was shut down the remaining suspended solids settled and the entire discharge line became clogged. This highlights a serious problem which is common in slurry handling systems where there may be variable feed rates or feed inconsistencies, resulting in sanding of the line. To prevent large material from passing from the excavator to the materials handling system a more robust scalping screen is required

The only other main problem observed was caused by too much suction head collapsing the suction hose. This was alleviated by moving the pump to the front of the excavator shortening the suction line, and adding an overpressure relief valve to the suction side of the pump. The suction head mainly collapsed when the excavator was excavating a large amount of either rock material or sediment. This can be addressed by

an improvement to the design of the suction system, including reducing the suction hose length and improving the stiffness of the suction line.

7.1.3. Mining strategy and volume estimation

Prior to the actual cutting trials, there was little understanding of the geotechnical nature of the seafloor deposits, as prior research was conducted via remote survey and grab sampling. This was the first excavation trial of the Manus basin, with a focus on studying the geological properties of the deposit with reference to mining. Originally the deposit was envisioned as a large consolidated mound of sulphide material with large chimneys growing from the mound. The reality of the deposit is much more challenging. Figure 7-2, which is a scale display of the bathymetric model, illustrates the large vertical structure of the chimney deposits in relation to the size of the excavator.

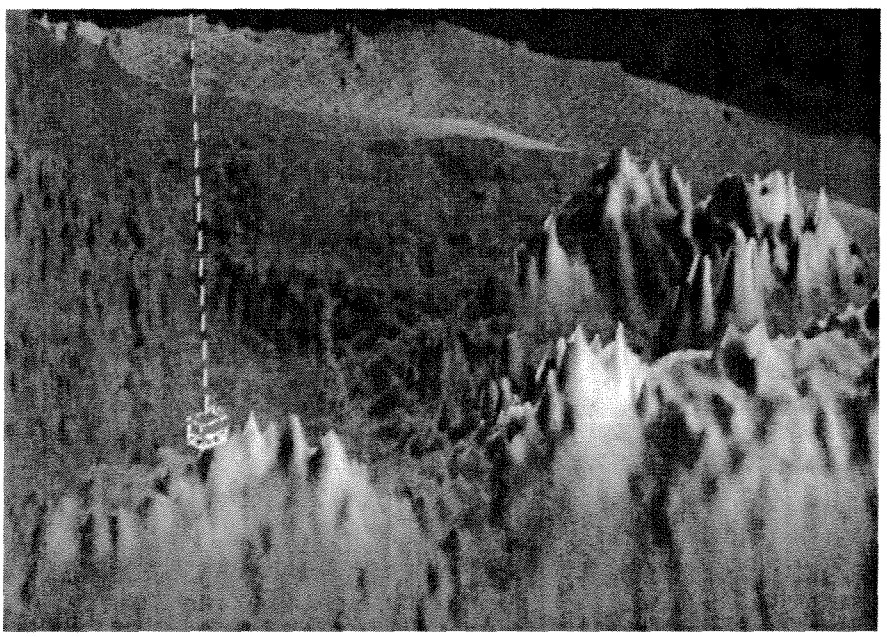

Figure 7-2: Bathymetric model of the Suzette field (Nautilus, 2006)

The deposit consists of fragile chimneys up to 15 metres in height and 5 metres in diameter towering above the mound; these are very fragile and prone to toppling. In addition the chimneys form as hollow structures and they slowly fill as material is deposited on the inner surface. Occasionally these chimneys become unbalanced and topple, and are subsequently crushed as the mound continues to grow. These crushed pieces loosely cement as the size of the mound increases. Whilst the mound is growing,

sedimentation and regional volcanic action deposits layers of silt and sand intermixed with the sulphide material. As a result of this, the mound, instead of being a large consolidated mass of sulphide, is a loosely cemented mound of toppled chimney material, interbedded with sediment.

This geotechnical structure caused some problems during the Solwara expedition, mainly due to the jamming of the dual drum cutter previously discussed. Assuming that this problem is resolved the next challenge for mining these types of deposit is the vertical extent. As shown Figure 7-2, attacking the deposit presented challenges for the DOSS due to the rugged bathometry. Since the chimneys grow vertically from the mound, there was concern that in working beside the chimney field, they would topple on the excavator resulting in its potential loss. Due to the risk of machine loss the optimal mining approach is to mine the mounds from the top rather than the side. Compared to a conventional mountain mining approach this is not as difficult as it first appears, since the excavator is attached to surface via an umbilical cord and is able to be raised from the seafloor quite readily and provides added stability. The main challenge faced during the Solwara trials, is developing a landing field for the excavator on the top of the mound. Due to the smoothing effects in the bathymetric data, Figure 7-2 does not capture the true vertical variations, exhibited at the mound. Indeed one of the researchers on the expedition likened lowering the DOSS onto the chimney field to lowering a transport truck into downtown New York. To solve this problem, there are numerous potential solutions, one proposal considered is to drag anchor chain across the chimney field knocking them over, while another is to use a wrecking ball approach to flatten a landing area and then excavate downward. However, all of these proposed solutions are still in the conceptual stage, but due to the friability of the chimneys either are technically viable. In order to mine the deposit from the top down the excavator will require enough flexibility to be able to sump into the deposit. This will need to be incorporated in the future excavator designs.

Ocean mining represents a paradigm shift in mining strategic thinking. Although the grades and production volumes are similar to an underground operation, the capital investment is in mobile infrastructure that is easily liquidized if the project becomes financially unviable. Ocean-going vehicles such as drill ships and barges are readily

liquid on the resale market, and unlike a conventional mining investment, if the deposit becomes uneconomic the mining assets can be sold or relocated to a new location easily. Indeed with the high cost of drilling and exploring individual mound deposits, it may become more viable to conduct bulk sampling of the deposits directly by relocating the excavation vessel. The technical challenges for mining ocean deposits are complex and will require a lot of design effort, but considering mines are developed around the world from the high Arctic to the tops of remote South American, mountains there is no reason to think that these challenge can not be resolved.

7.1.4. Visibility

Visibility is a measure of optical ocean clarity and allows the tele-remote operator to visually evaluate the excavation performance. It also provides a measure of the potential environmental impacts that mining activities will have downstream from the excavation site. Although the suspended particles are akin to suspended dust which is caused by surface operations, the increased density of water drastically decreases the settling rate of the suspended particles which increases their area of influence.

The presence of fine clay sediment overburden caused significant vision problems once the excavator commenced operations. At the ocean floor there was a fairly constant current which varied in magnitude from 0 to 6 metres per second. Although the current varied in magnitude during the tests, depending on the orientation of the excavator, if the current came from aft of the excavator there was no visibility. Conversely, if the current was from the starboard-bow of the excavator, it was possible to maintain reasonable visibility of the excavator arm as the silt was transported away from the DOSS. During these trials while the excavator was engaged it was possible to see sediment moving to the suction nozzle, but the actual cutting created vision problems which prevented a proper view of the rock cutting. In general the longer the duration that the cutters were engaged with the rock the more sediment would be mobilized and so the silt level would rise. In general when the current was from the starboard-bow the suspended sediment would clear from the field of view within minutes, giving a picture like that shown in figure 7-3. The poor visibility meant that the operator was operating the excavator blind most of the time and needed to use the onboard instrumentation to control the cutterhead.

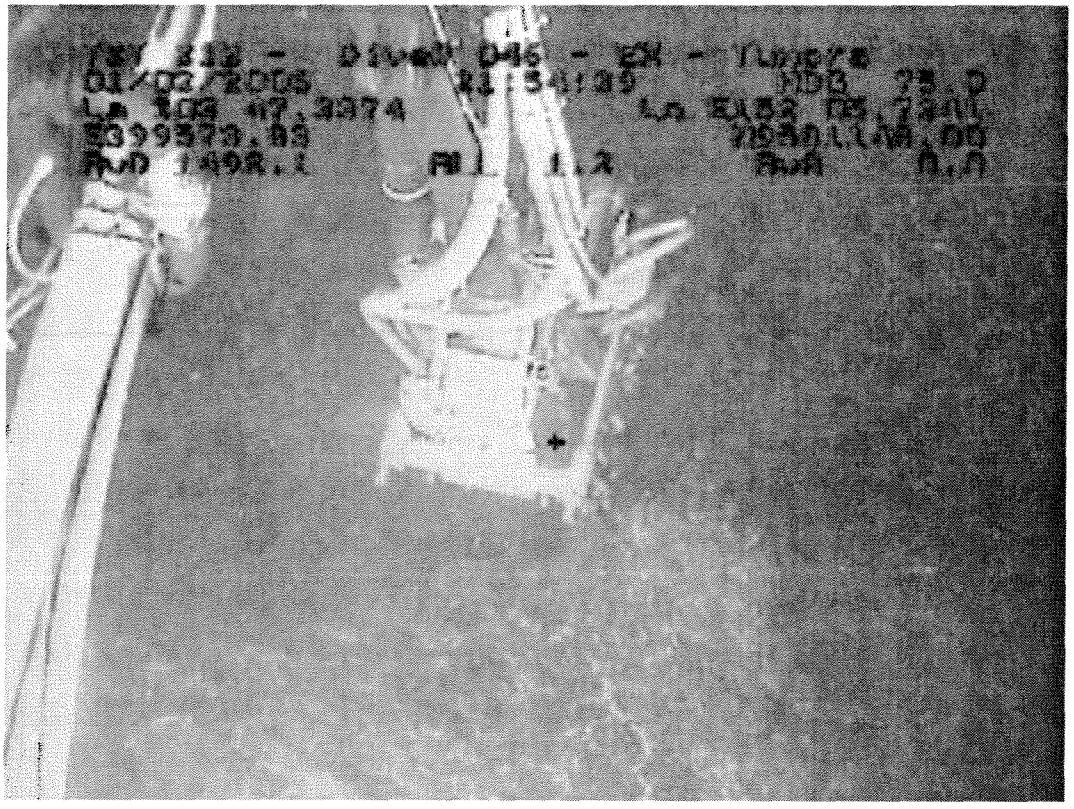

Figure 7-3: Teleremote display of ocean mining

Most of the time when the operators were controlling the DOSS in the field the cameras were blinded by sediment mobilized by the cutting actions. The only method of determining contact with the chimney material was to slowly lower the rotating cutterhead until the rotational torque increased, but did not stall. Due to this blind cutting an alternate vision system is required on future machines which may include sonar systems or ultrasonics.

At the aft of the excavator, the hydro-cyclone discharge highlights one of the potentially problematic areas which need to be addressed. The discharge plume that was generated contained a large amount of fine material and generated a large down stream plume. Because the discharge point was three metres above the seabed a 25 micron particle, of sediment material, with a specific gravity of 2 would take approximately 2.5 hours to settle back to the seafloor, assuming simple settling by Stokes Law. Given a current on the sea floor ranging from 0 to 6 metres per minute, the discharged particles 25 microns may migrate 880 metres from the discharge site, a smaller particle may drift even further before settling. This could have a detrimental effect on the ecological balance as the silt blankets the sources of nutrition and coats plant life. One positive

thing to note is the large sediment load being discharged into the area from both the active surface volcanoes and ocean bottom volcanic activities. Due to the poor visibility it was impossible to determine the amount of material passing through the hydro-cyclone and out the overflow. Visual examination of damage to the local strata both prior to cutting and after, indicates that a majority of the excavated rock material was captured. However, incidental refraction of light in the exhaust plume while excavating the chimney material indicates the presence of mineral crystals. This indicates that there is potential mineral loss in the fines fraction. While excavating clay sediment found around the ocean chimneys there was no light refraction.

Although sediment contamination is an environmental concern, it will be partially mitigated by capturing all the plume material and transporting it to the surface. The future mining system is proposed to be directly coupled to the material transport pipeline. This will reduce a significant portion of the sediment mobilization during mining. In addition the suction system will be stronger, which will capture more of the transient sediment.

Visibility concerns remain one of the serious challenges with mining at depth. The poor visibility caused by disturbing the bottom sediment, makes diagnostics of underwater problems complicated and masks the cutting operations. Complicated cutting operations will place additional pressure on achieving the required production rates for profitable mining.

7.1.5. Mechanical availability

A key function of performance of a successful mechanical system is its mechanical reliability. Mechanical reliability improvement is a serious focus of deep ocean engineering and is recognized as a major factor in determining whether undersea mining will be profitable or not. Due to the long transit times from the ocean bottom to the surface any repairs must be conducted remotely, or on surface causing significant time delays. An example from conventional mining is the transit time for maintenance that a piece of underground equipment requires to transit to a surface workshop. A typical transit time for both of these activities is, at the minimum, one hour. Since the vehicle must transit back to the excavation front, there is a significant time component for

every failure added on top of the actual repair time. Conventional sub-sea equipment is designed with this in mind and utilizes redundant systems to maximize the meantime between failures. Clearly the DOSS was a first prototype test platform and was not designed with a long mechanical life as a key priority. Schedule pressure minimized the amount of pre-trial machine testing which would have minimized the mechanical problems encountered during the ocean trials.

As shown in Table 5-3 during the trials of the 27 dives only 7 did not end with a mechanical failure. Of those seven dives, 3 of them were short duration trials where the site was not conducive to rock cutting. A majority of the failures were in the materials handling system and fifty percent of those failures were with the dredge pump. As mentioned previously the pump was replaced at the last minute, which resulted in a lack of replacement components. During the integration the hydraulic seals were damaged, resulting in numerous pump failures. Due to the remote location of the trials the replacement seal kit took a week to arrive. With a 10 day trial, this delay was very detrimental to the overall goals.

The problems with the pumping system were the major issues seen during these trials; however most of these stem from the failed seals. After the pumping system, the next major challenge is to address stress that the vibrations from cutting induce on the frame of the excavator. After every dive the excavator arm was inspected and the bolts were tightened. Due to the frequent pump failures the loosened bolts were not seen as a major cause for concern. If the pumping system's reliability were increased then the bolt loosening would cause major structural problems. This was observed during dive 11 when a bolt failure caused the support bracing on the cutterhead to fail ending the dive.

The problem with the failed hydraulic seal illustrates a key point with operating in a remote location such as PNG. The technological requirements of deep ocean mining exceed that of a standard mining operation due to the greater amount of the mining activity controlled by teleremote operations. This will necessitate a large investment in logistical support for an ocean mining system, as there are not local suppliers of the high technology equipment required. This is common in the offshore industry where a larger supply of inventory is kept on hand than is standard with a remote minesite, where parts can be sourced and flown to site in a couple of days. With the case of the pump seals, of

the 7 days shipment time only 2 days were spent in transit, with the remainder spent in various customs clearance processes. Clearly, having the excavator down for this reason during a production situation would be extremely costly. Unfortunately, due to the nature of ocean mining the currently proposed production system is a linearly coupled system, if the excavator is down there would be no production. One proposed solution is to have 100% redundancy by having a spare excavator which when there is a failure, the entire excavator is replaced, allowing for more time to repair any serious faults. To test this strategy, modeling is required to determine the optimal plan to maximize system reliability.

Prior to the next series of trials an extended period of water testing is required to minimize simple failures and maximize system availability. As mentioned above the short duration of the sea trials were not conducive to determining reliability performance as most of the failures are attributed to a single event. A series of long duration cutting trials to wear in the excavator are required to ensure that it will be able to sustain production over long periods of time. As the next generation system is proposed as an integrated pilot test designed to simulate a 100 000 tonne per year operation, a great deal of effort will need to be done to minimize excavator downtime. Luckily, experience in the design of undersea remotely operated vehicles has shown that increased reliability is possible if that is a design focus.

7.1.6. General comments

The dawn of a new frontier is upon us. As minerals on surface become more scarce the vast wealth of the ocean floor is calling. As with the ocean nodule experiments of the late 1970's PDTS and Nautilus have shown that it is possible to excavate ocean material using conventional means. Clearly, there are many issues that remain to be resolved but at this time mechanical excavation of back-arch hydrothermal material is not only viable, it remains the most promising method to extract the volumes required for a continuous production system. From these trials, the isolated nature of the site illustrates the logistical and mechanical problems which must be overcome as the project continues from this proof of concept stage, developing to a full production ocean mining system.

This thesis focused mainly on the rock excavation challenges with the ocean mining system. As mentioned earlier PDTS had developed an integrated research plan and commissioned numerous studies to investigate the various aspects of ocean mining. With the merger of Placer Dome and Barrick Gold, all the scientific knowledge gained from this expedition has been transferred to the joint venture partner Nautilus Minerals which is actively advancing the ocean mining frontier. Concurrently with the research presented in this document there is an entire research program dedicated to modeling, designing and testing the riser system to bring the material to surface. The riser system remains a critical flag to the viability of ocean mining. However, risers have been used in the offshore oil industry for twenty years, so the risk of a critical failure remains low. Finally, not addressed in this document are the large amounts of environmental and sustainability efforts which also were part of this research program. The social action team used this cruise to begin monitoring and classifying the biota and environment. Sediment contamination control remains a key focus for the ocean mining team and a concerted effort is being undertaken to minimize sediment mobilization while developing mining solutions for this new frontier of mining.

8. Conclusions and recommendations

This thesis focused on the challenges of mining deep ocean PMS deposits. Ocean mining becomes more attractive as conventional mining deposits become depleted and the mining industry needs to explore new and innovative frontiers to meet the demand for mineral resources. The research was presented using the Solwara expedition case study, a proof of concept experiment on the excavation of ocean sulphide materials from the sea floor. From a mining point of view, the results from this campaign do not present any major road blocks to developing an excavation system to exploit the Manus Basin sulphides. The results from the cutting program generated over a terabyte of data which remains to be analyzed in greater detail.

Although much of the work presented in this document is the work of a consorted design and research team. The team members consisted of primarily mechanical and robotics specialists, with the exception of the author, who is a practicing mining engineer and researcher. Along with designing a comprehensive rock excavation testing program, to characterize the cutting, performance of the undersea material the author also developed observations and strategies on how to further implement both this technology and the future aspects of this technology. Had this research program proceeded to the next phase of implementation, the more generic observations of the site structure would have been of great use. Compared to a conventional mining exploration program, this research provides a site review of the field conditions of the deposit and can be used to close the uncertainty in the future operating parameters of the mining project.

8.1. Contributions of the research

This thesis presents the findings from the Solwara expedition which is the first attempts at mining the Manus Basin PMS deposits. Some of information derived under the course of this research program has not been presented due to confidentially issues; however this primarily consists of detailed information, such as costs and mineral inventory. In general the study was enlightening and was a ground breaking investigation into the mining of poly metallic-massive deposits. A rock testing unit was developed from concept to ocean testing in less than a year.

This was the first experiment in rock excavation on the Manus Basin. It was demonstrated that the sulfide chimneys were amenable to excavation by mechanical means. Various sites in the Manus basin were tested in a total of 27 dives. Cutting the chimneys using point attack picks worked better than expected and presented minimal problems while excavating the target material. The chimney material appeared to be much weaker than the benchmark concrete specimen and has an estimated rock strength of between 5 and 10 MPa. One caveat to this conclusion is that the host volcanic rocks had a rock strength of approximately 100 MPa and were not conducive to excavation by mechanical means. The problems encountered with the cutting were of mechanical design in nature and can be addressed by a proper design

The trials illustrated the various mechanical problems that may be encountered and the effect on system reliability. The depths involved at the Manus Basin require at least an hour to either raise or lower the excavator from the ship to the sea floor. This necessitates a need to ensure the excavator will be able to function for extended periods of time without failure.

Material handling will be an issue unless steps are taken to ensure a robust suction system design. Throughout the test phase numerous dives were aborted due to problems with the suction system. The high specific gravity of the chimney material specifically chalcopyrite and bornite, presents a dangerous problem if the pumps are shut down. During the trials there were numerous cases when the system sanded out from pump failure.

A detailed bathymetric map of the ocean bottom is presented. The terrain was more rugged than expected and the final mining machine needs to be designed to tackle this challenge. Contour changes of greater than 10 metres were common and the unstable nature of the chimneys presents hazards unique to this environment.

Based on the production rates achieved whilst cutting, it is possible to design a machine to excavate at the required production rates. It was found that the production rate of the excavator was comparable to the benchmark surface tests. Modeling shows that based on the performance of surface excavators, a target goal of 10 tonnes per hour is obtainable if the utilization and reliability goals are achieved.

By the nature of ocean mining, and all deep seabed activities, teleromote operation is the only method of operation. However the bottom sediment excavator action resulted in a large amount of fine material becoming mobilized. This presents a visibility and sustainability challenge. Although most of the sediment will be captured, plume generation in the area remains a potential environmental road block as it may impact the local biota.

8.2. Recommendations for further study

Ocean mining is on the cusp of the new frontier. However as this is a first introductory cutting expedition, many details remain to be addressed as this research program advances to completion.

8.2.1. Machine design

The next phase of the project calls for an excavator that can excavate 100,000 tonnes of material in a 30 day period. In order to meet this objective a new excavator needs to be designed and constructed. The following points should be considered moving forward:

- Further controlled studies need to be undertaken to understand the nature of cutting rock at high hydrostatic pressures. This will allow a more robust cutterhead to be developed for this application.
- Improved information on the excavator's material handling system is required to reduce stoppages and improve recovery. This will allow a smooth transfer of the material from the excavator system to the surface riser system.
- The cutting log data contains vast amounts of valuable data on the cutting machine performance, which remains to be analyzed. This data can aid in the development of control algorithms needed for teleremote operation of the future excavator.
- The next generation machine needs to be designed to maximize reliability, and availability.

8.2.2. Geology

Following the next phase of the research program enough information needs to be compiled to allow a feasibility study of a trial mining operation to be developed. Although a lot of data was compiled during the drilling portion of the cruise, there are still many questions which need to be answered for a proper evaluation to be conducted.

- Core recovery needs to be improved to delimitate the volume of potential material to justify the capital expenditure to develop a mining system.
- Better core recovery is necessary to understand the geological structure of the deposit, which will lead to a better understanding of the rock units which make up the deposits. This will improve the extraction strategy, allowing a better estimation of viable production rates.
- A better understanding of the geological unit's rock strength properties is required to predict long term wear performance of the excavator, and excavator power requirements.

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Appendix A: Sample Calculation

The following provides a sample calculation on how the information presented in Appendixes B and C, as well as Table 6-3 is derived.

From as single Data Point from log file 20051110.000b at

time = 1131661849.392384000

The following data points involved in are used in calculation the energy and volume and measured from the DOSS' various transducers.

swingSinPosVolts=0.42358

swingCosPosVolts=-1.2146

boomSinPosVolts=1.23047

boomCosPosVolts=1.07056

stickSinPosVolts=0.6958

stickCosPosVolts=0.04883

bucketSinPosVolts=1.66016

bucketCosPosVolts=-0.41504

fwdCutterAPressureVolts=2.771

fwdCutterBPressureVolts= 2.04834

aftCutterAPressureVolts=2.8064

aftCutterBPressureVolts=2.07397

fwdCutterFlowVolts=6.32324

aftCutterFlowVolts=6.56372

The joint angles in degrees can be determined by taking the arc tangents of each of Sin and Cos voltage.

$$Ang_{Swing} = \arctan(\frac{\text{swingSinPosVolts}}{\text{swingCosPosVolts}}) * \frac{180}{\pi} = \frac{0.42358}{-1.2146} * \frac{180}{\pi} = -19.2$$

$$Ang_{Boom} = \arctan(\frac{\text{boomSinPosVolts}}{\text{boomCosPosVolts}}) * \frac{180}{\pi} = \frac{1.23047}{1.07056} * \frac{180}{\pi} = 48.9$$

$$Ang_{Stick} = \arctan(\frac{\text{stickSinPosVolts}}{\text{stickCosPosVolts}}) * \frac{180}{\pi} = \frac{0.6958}{0.04883} * \frac{180}{\pi} = 85.9$$

$$Ang_{Bucket} = \arctan(\frac{\text{bucketSinPosVolts}}{\text{bucketCosPosVolts}}) * \frac{180}{\pi} = \frac{1.66016}{-0.41504} * \frac{180}{\pi} = -76.0$$

As per equation 3-1 the pressure in the hydraulic circuit in Pascals

$$P_H = (V_P - 2) \times 0.090649$$

$$P_{FcutterA} = (\text{fwdCutterAPressureVolts} - 2) \times 4{,}389.1875 = (2.771 - 2) * 0.090649 = 0.06989$$
$$P_{FcutterB} = (\text{fwdCutterBPressureVolts} - 2) \times 4{,}389.1875 = (2.048 - 2) * 0.090649 = 0.00435$$

$$P_{AcutterA} = (\text{aftCutterAPressureVolts} - 2) \times 4{,}389.1875 = (2.807 - 2) * 0.090649 = 0.07315$$
$$P_{AcutterB} = (\text{aftCutterBPressureVolts} - 2) \times 4{,}389.1875 = (2.074 - 2) * 0.090649 = 0.00670$$

The pressure drop across the cutterheads can be determined by subtracting the A pressure from the B pressure.

$$\begin{aligned} P_{FWDcutter} &= P_{FcutterA} - P_{FcutterB} = 0.06989 - 0.00435 = 0.06554 \\ P_{AFTcutter} &= P_{AcutterA} - P_{AcutterB} = 0.07315 - 0.00670 = 0.06645 \end{aligned} \quad \text{[Pa]}$$

As per equation 3-2 the aft and forward cutter head flow in litres per minute is:

$$Q_{fwd} = 13.7792597 \times V_f - 28.5145192$$
$$Q_{aft} = 12.9715769 \times V_f - 25.8606833$$

$$Q_{fwd} = 13.7792597 \times \text{fwdCutterFlowVolts} - 28.5145192$$
$$Q_{aft} = 12.9715769 \times \text{aftCutterFlowVolts} - 25.8606833$$

$$\begin{aligned} Q_{fwd} &= 13.7792597 \times 6.32324 - 28.5145192 = 58.61528 \\ Q_{aft} &= 12.9715769 \times 6.56372 - 25.8606833 = 58.91481 \end{aligned} \quad \text{[lpm]}$$

From the cutterhead flow and pressure the power consumption can be calculated as follows [terex, 2006] in Watts.

$$H_P = 11.36 * Q * P$$

$$H_{PFWD} = 884.9 * Q_{fwd} * P_{fwd} = 884.9 * 58.61 * 0.06554 = 3399.4$$
$$H_{PAFT} = 884.9 * Q_{aft} * P_{aft} = 884.9 * 58.91 * 0.06645 = 3464.2 \quad [W]$$

As there was an enormous amount of data generated for each test the data was aggregated into 1 minute intervals as outlined in figure 3-2. From that algorithm the following data is calculated.

$T_{min} = 15$

$E_{cutters}$=796.98 kJ

V_{cut}=.003889 m^3

Eng_{fwd}=58.87 sec

Eng_{aft}=58.87 sec

And by the analysis method outlined in Figure 3-3 the parasitic drain is E_p=2062 kJ/m^3

The Eng term is a measure of the amount of time that the cutterhead was engaged in the rock and actually cutting. For example the amount of time that the cutterhead was engaged in the rock during the 15th minute of testing can be calculated by.

% engagement FWD cutter = Eng_{fwd}/60 * 100%= 58.87/60*100% =98.1%

% engagement FWD cutter = Eng_{fwd}/60 * 100%= 58.87/60*100% =98.1%

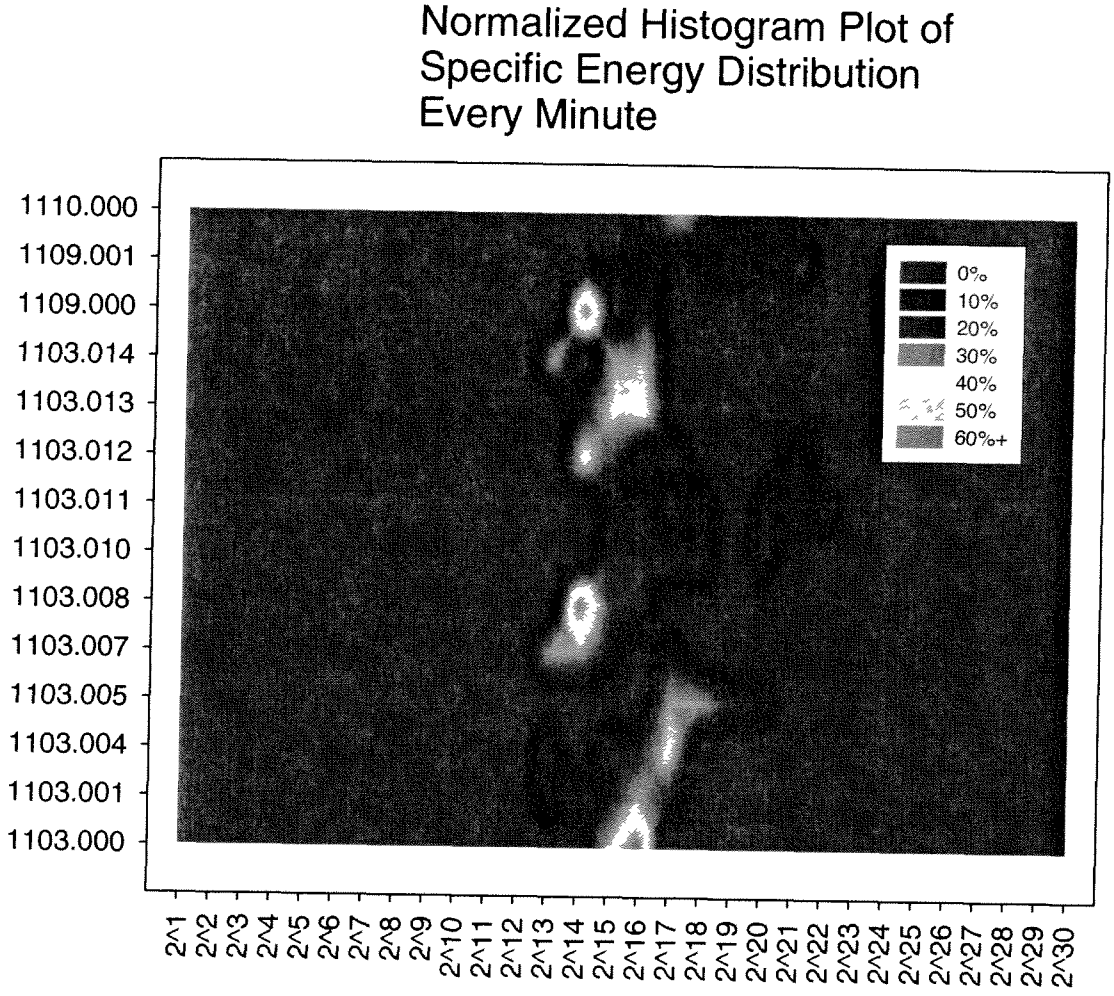
The corrected specific energy is calculated by using Equation 3-2 for the data set at minute 15 is:

$$SE_{cor} = \frac{\sum_{1}^{n} E_i}{\sum_{i=1}^{n} Vol_i} - E_P$$

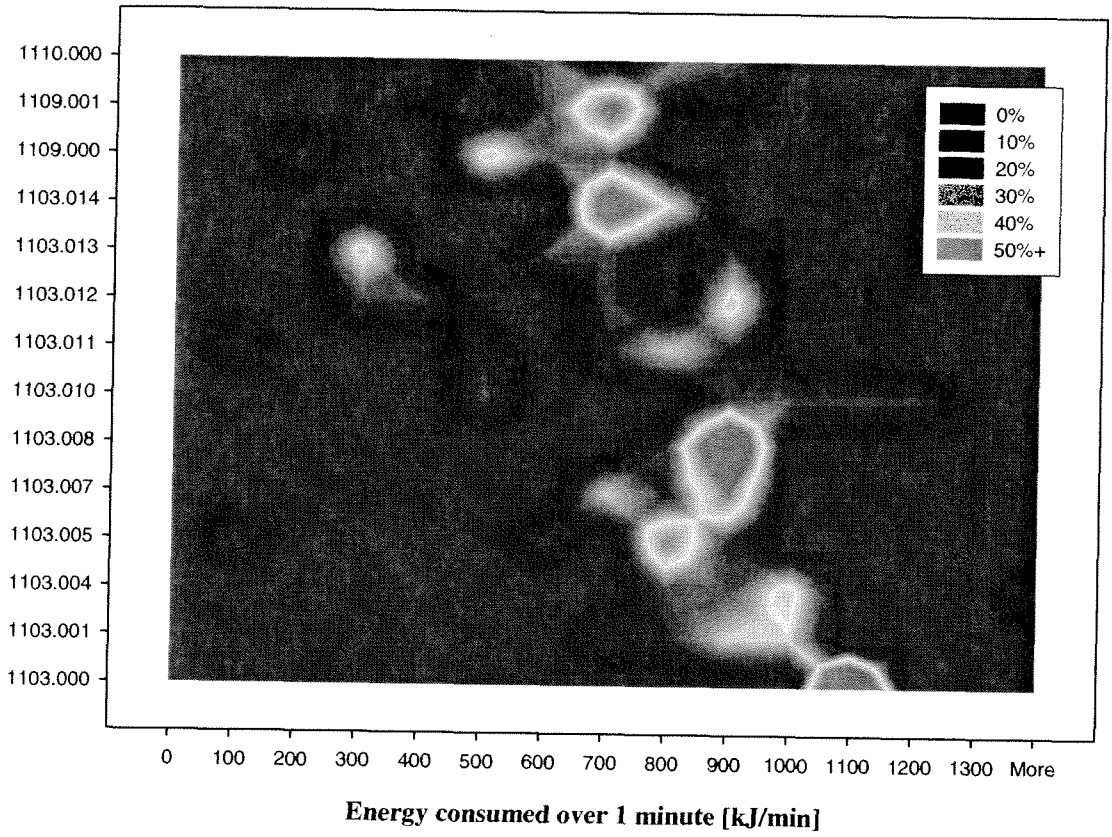
$$SE(15)_{cor} = \frac{E_{15}}{Vol_{15}} - E_P = \frac{796.98}{0.003889} - 2062 = 202{,}869.8 \quad [\text{kJ/m}^3]$$

Appendix B: Lab Trial Data

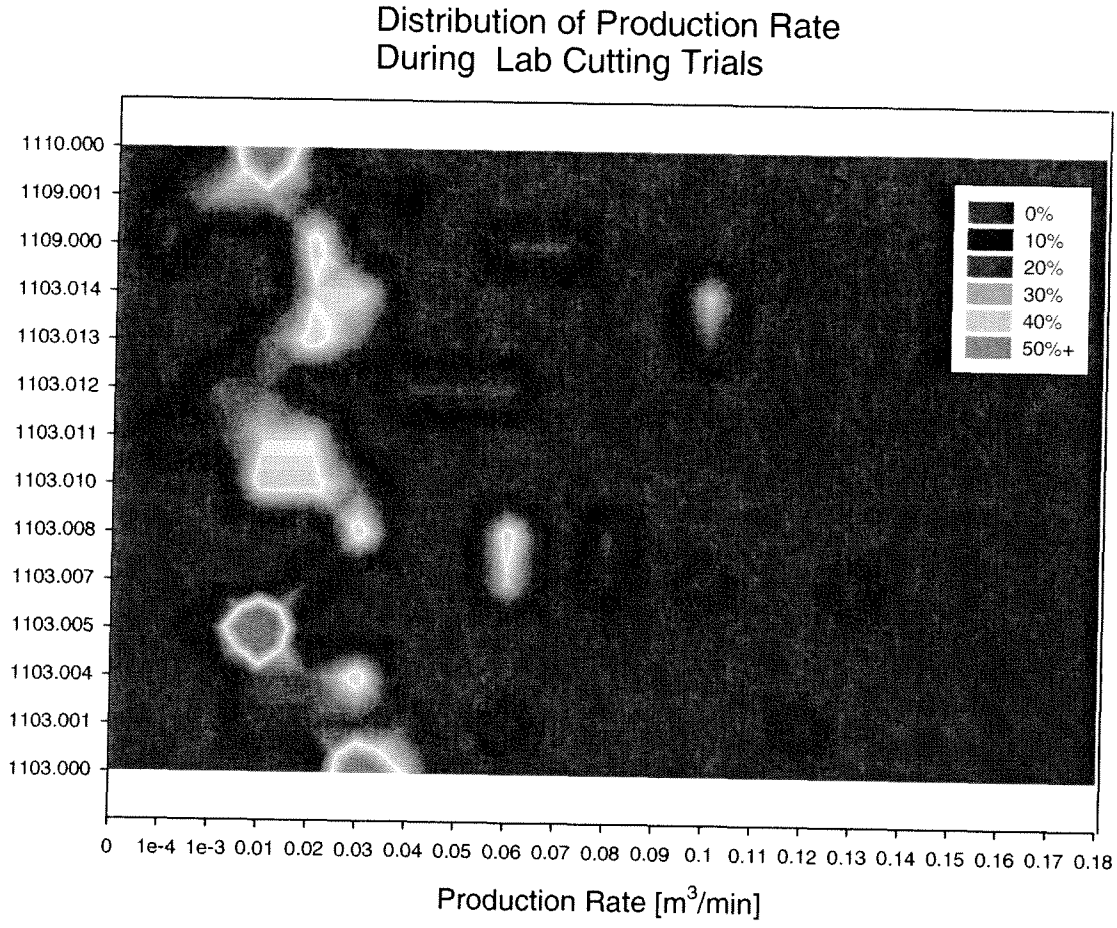
Contour Plot of Specific Energy Distribution During Lab Trials



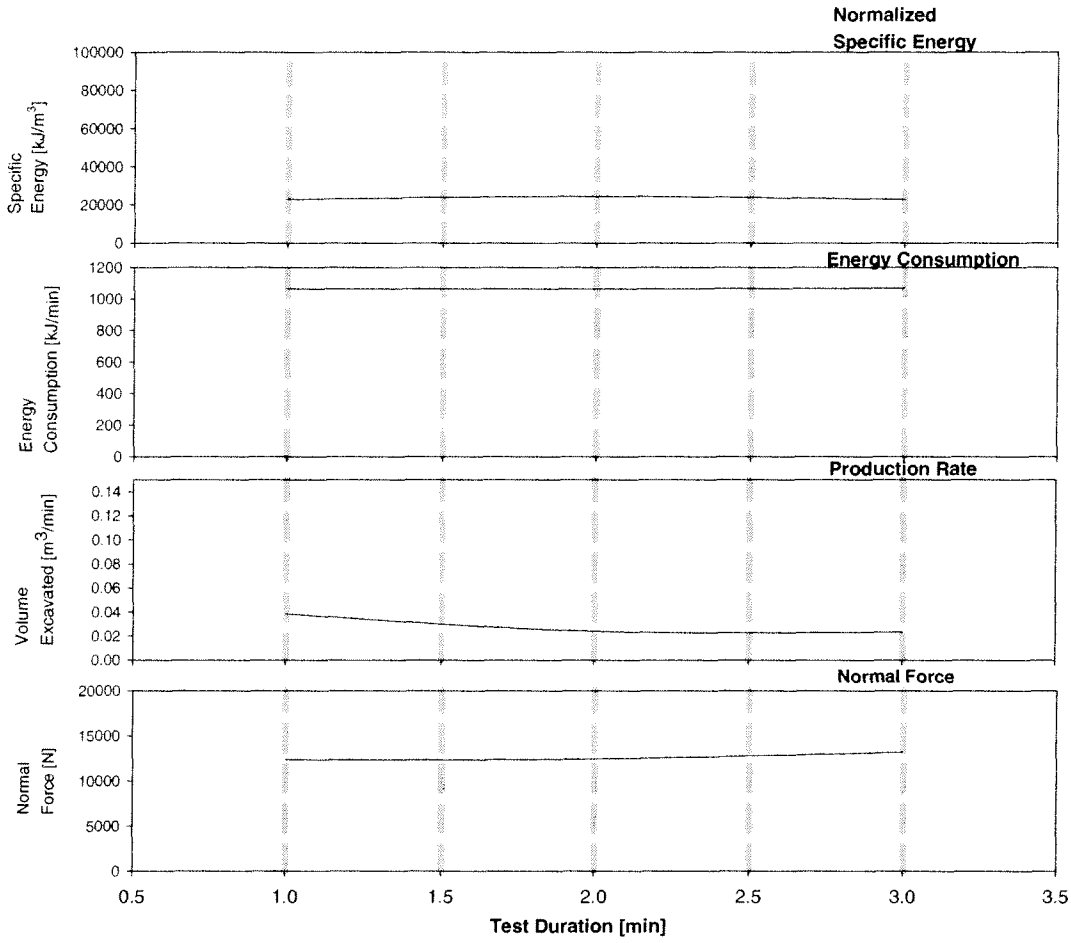
Contour Plot of Energy Consumption Distribution During Lab Trials

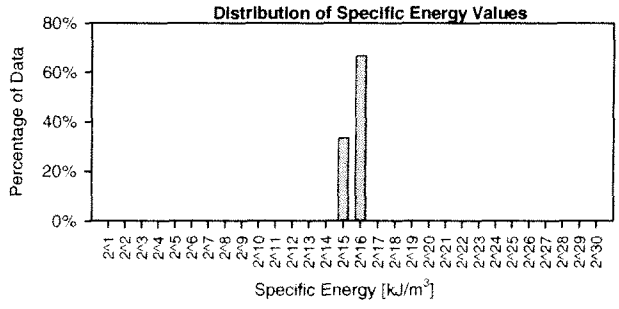


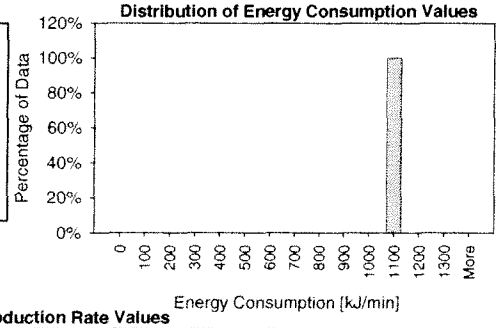
Contour Plot of Production Rate Distribution During Lab Trials

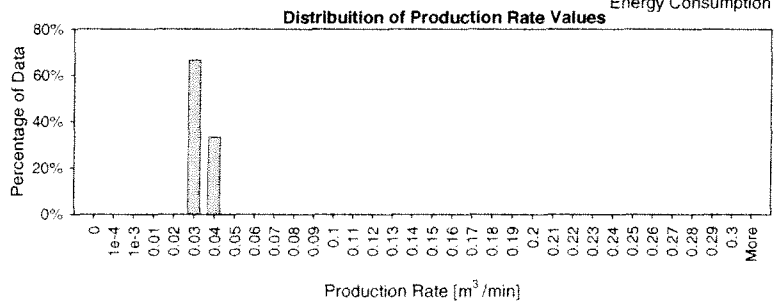


Test 1103.000 Data









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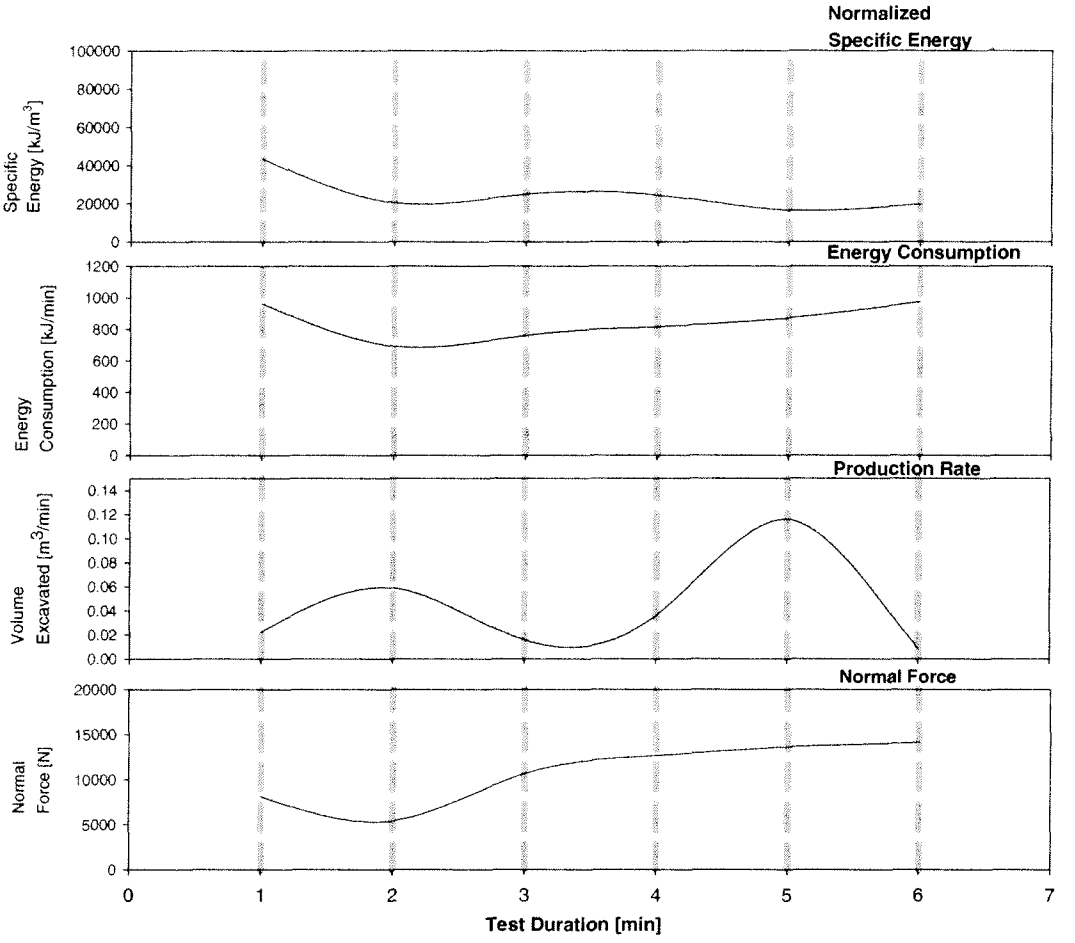

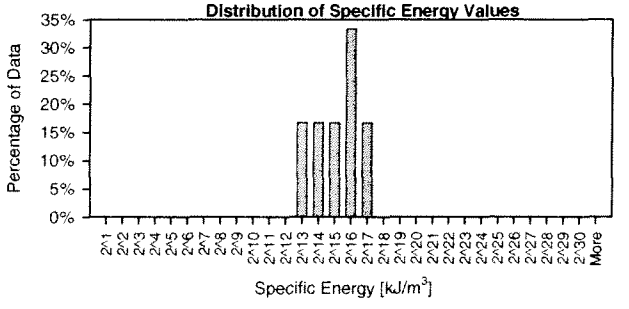

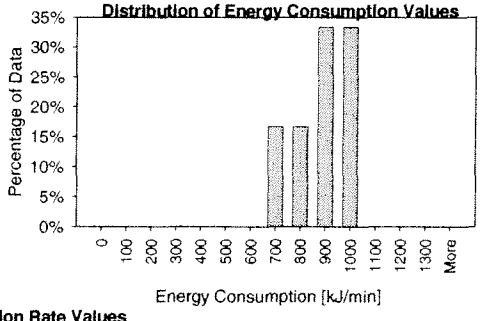

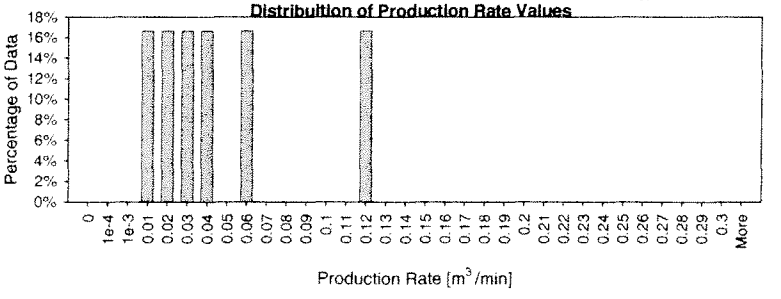

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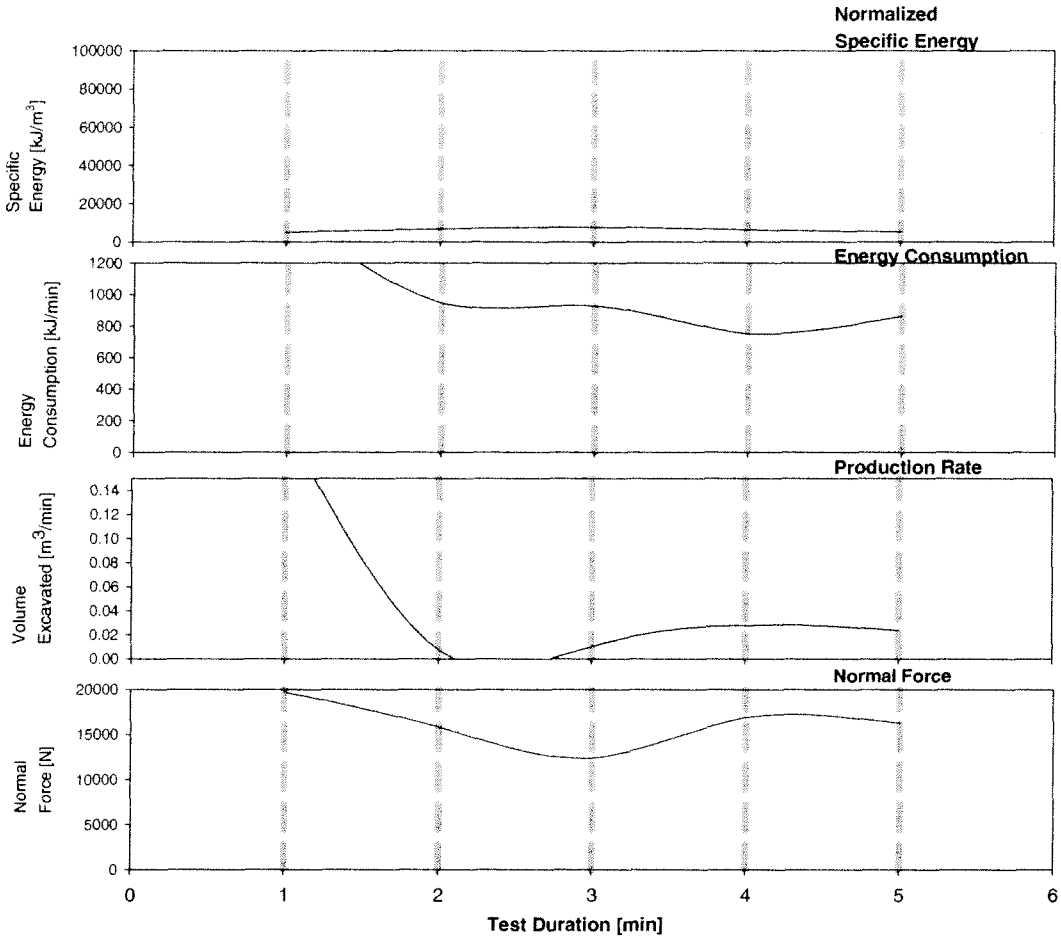

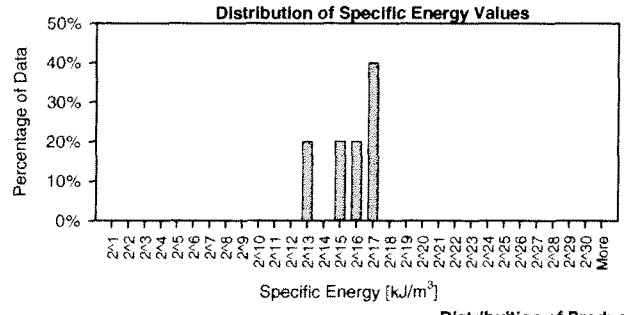

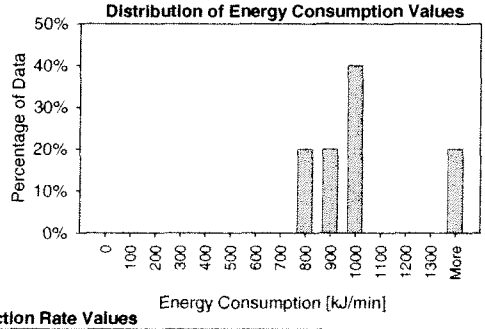

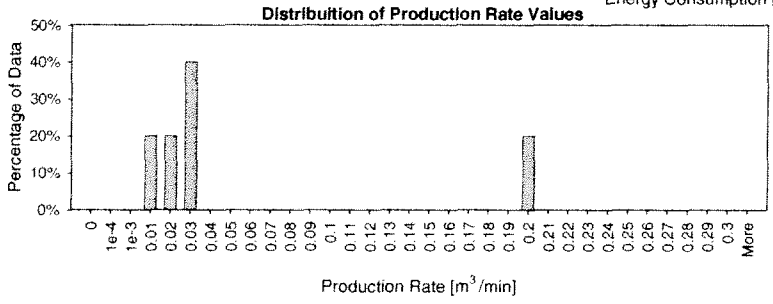

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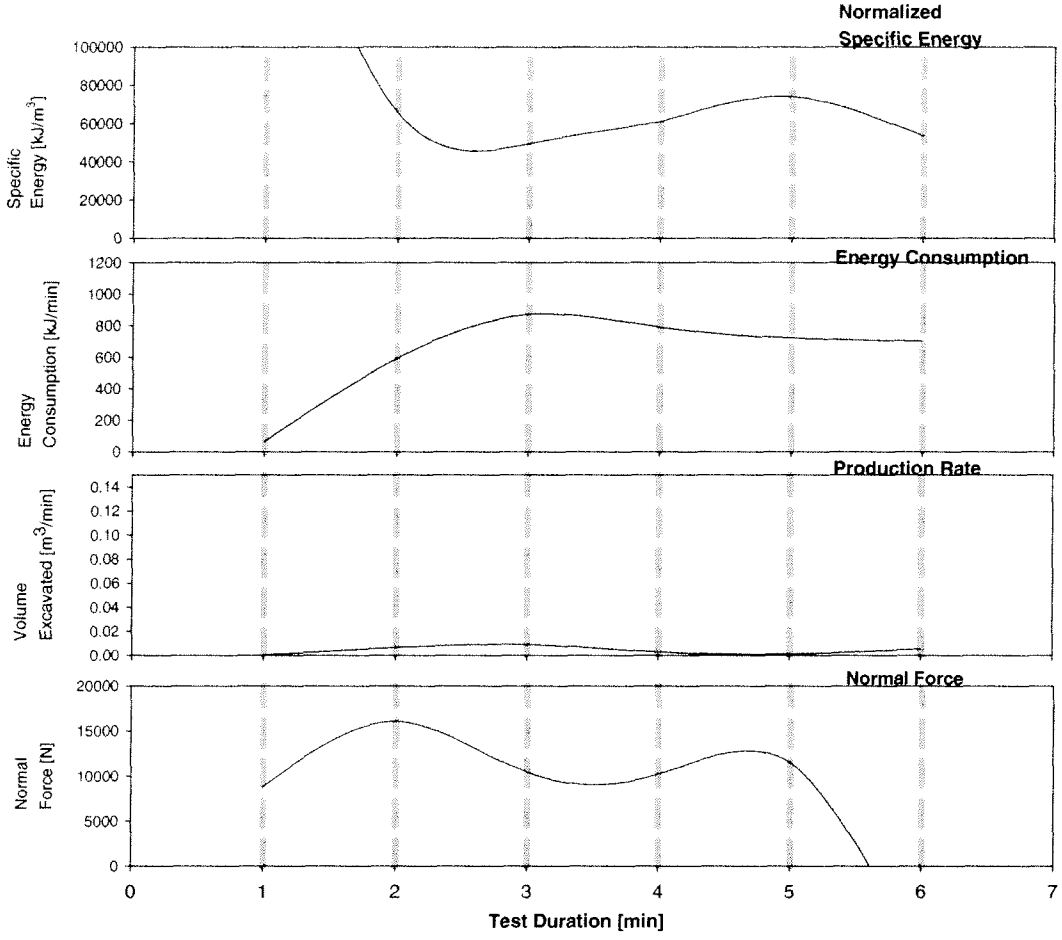

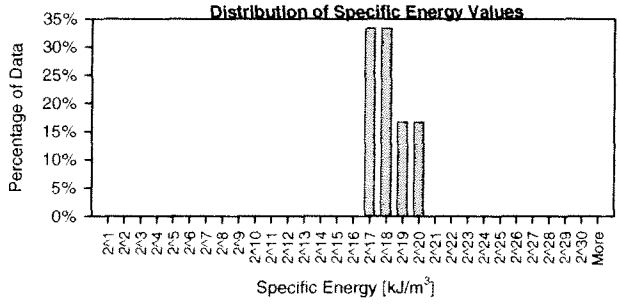

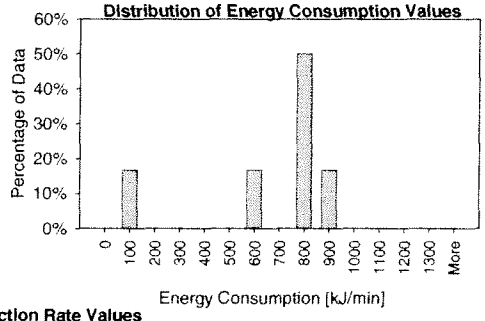

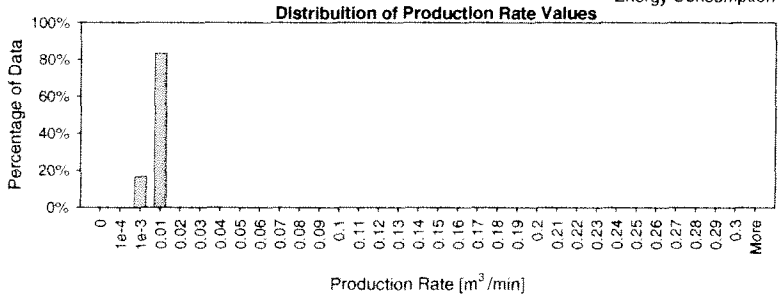

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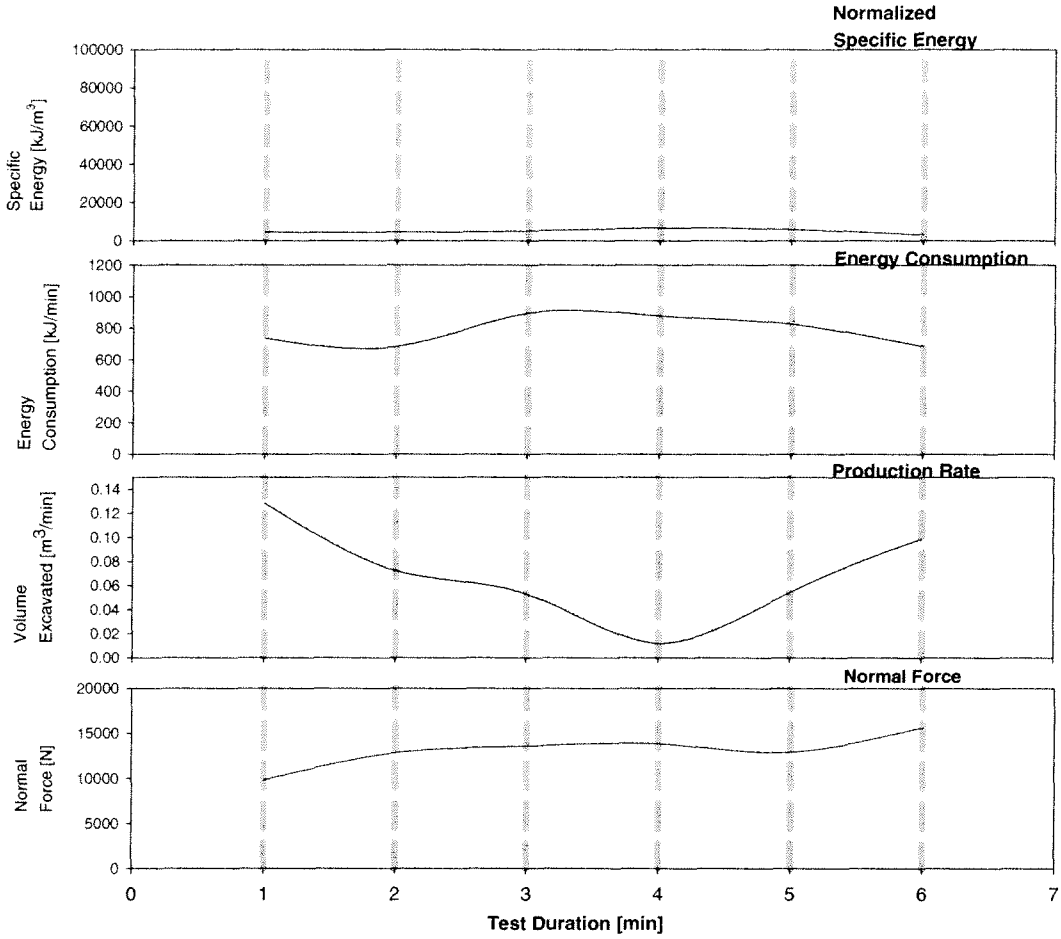

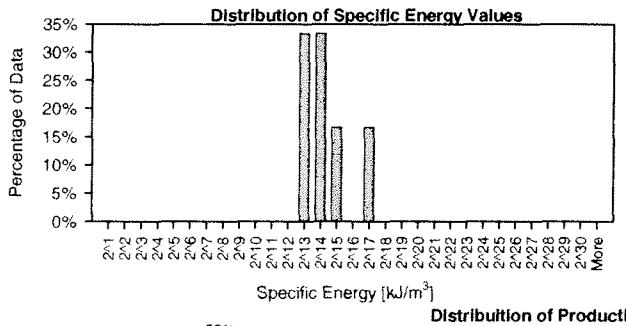

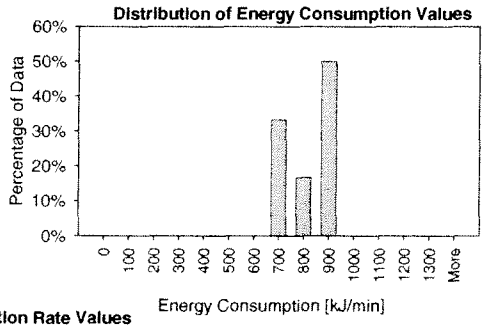

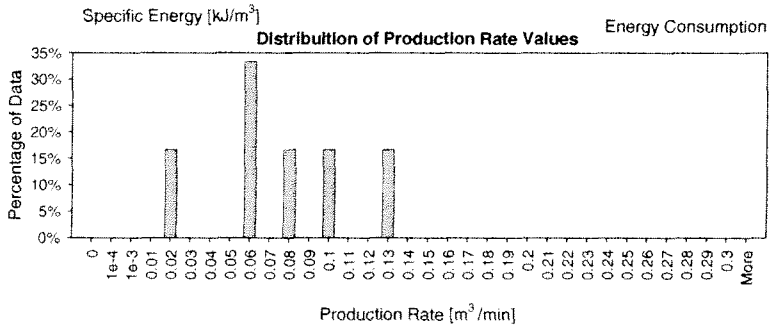

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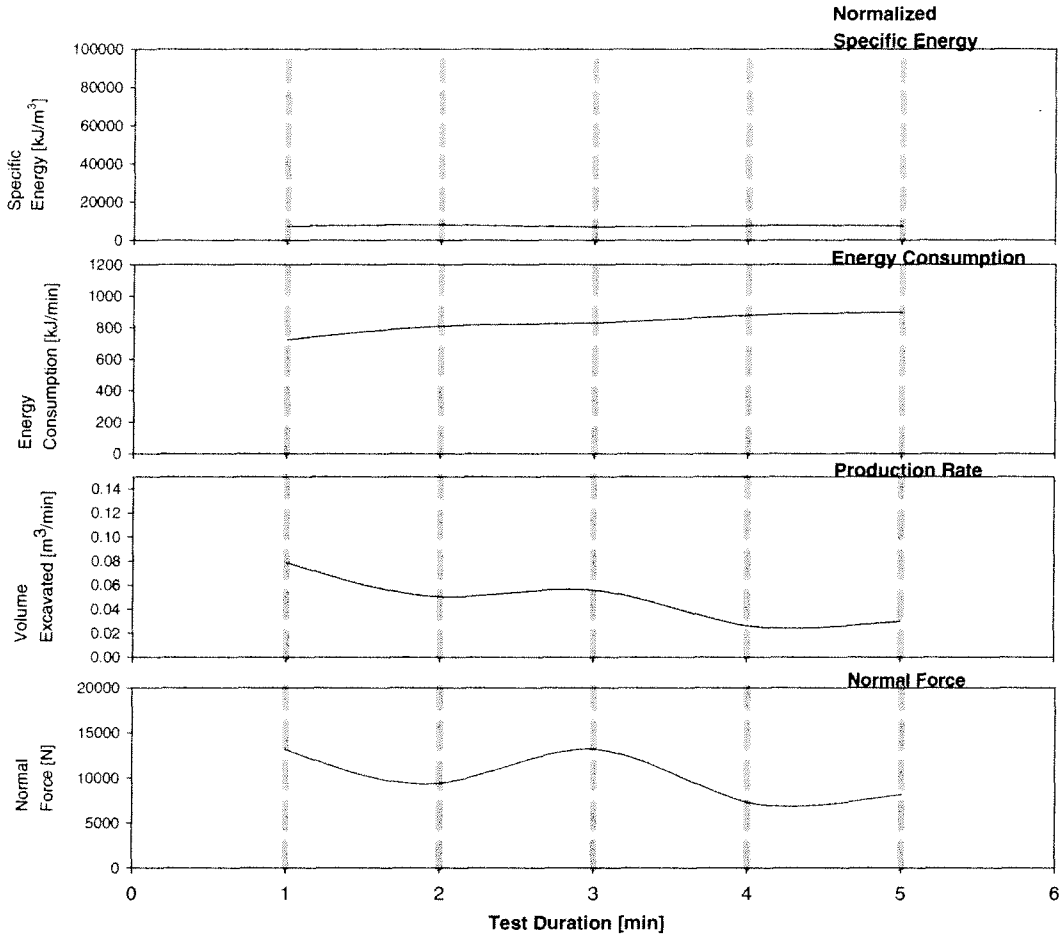
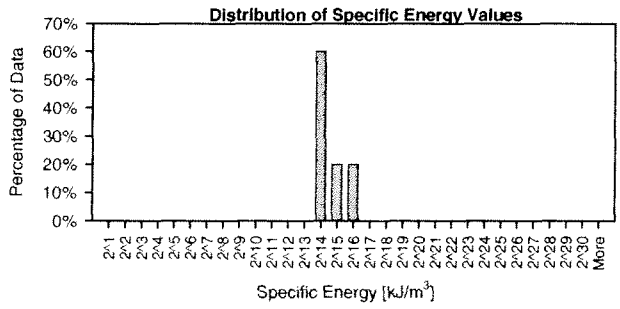
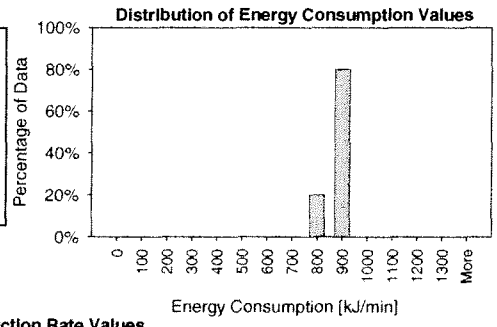
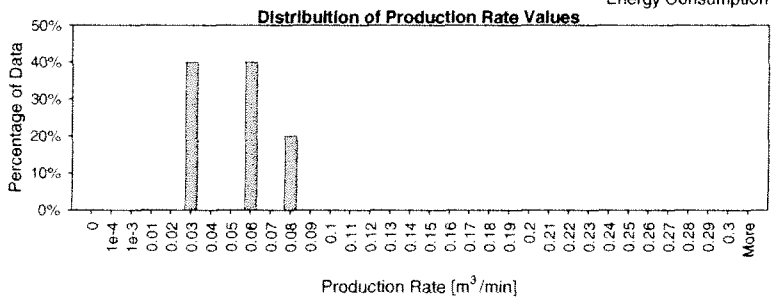
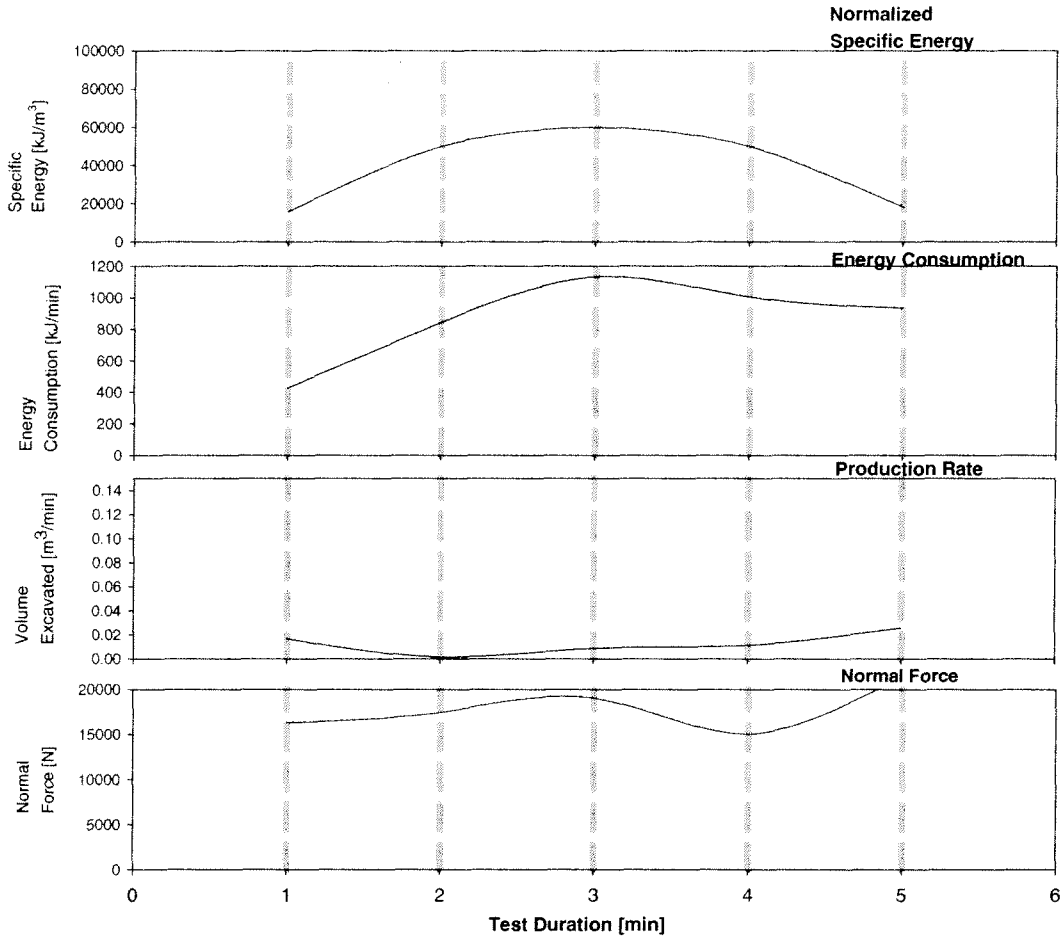


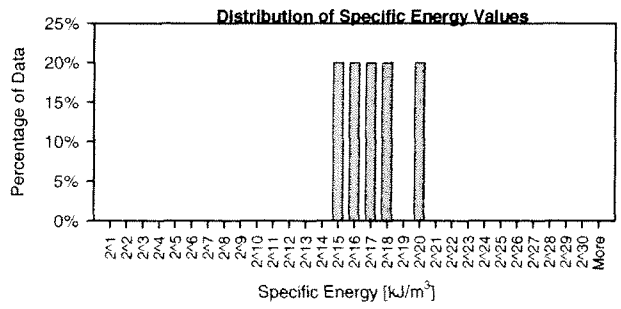


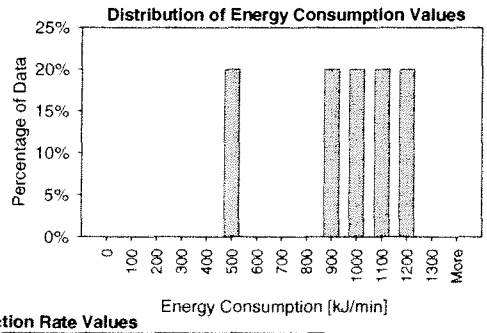


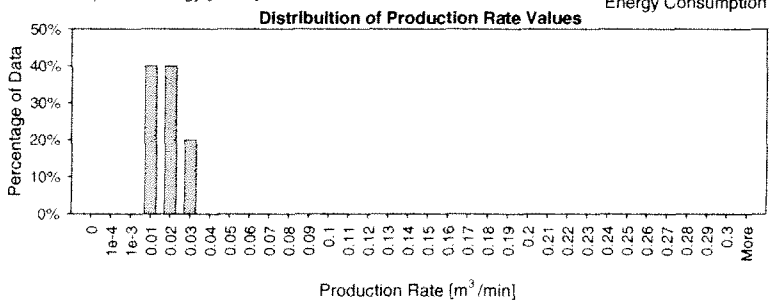


Test 1103.01*0* Data









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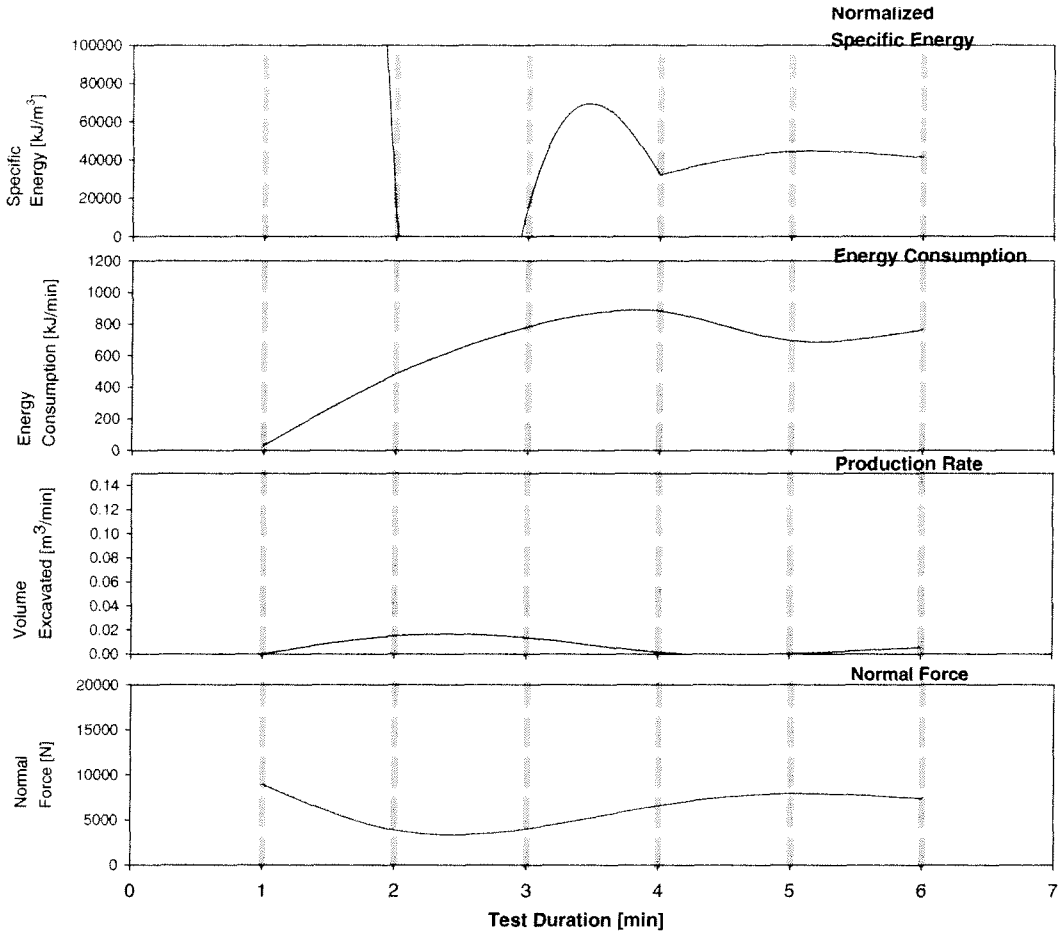

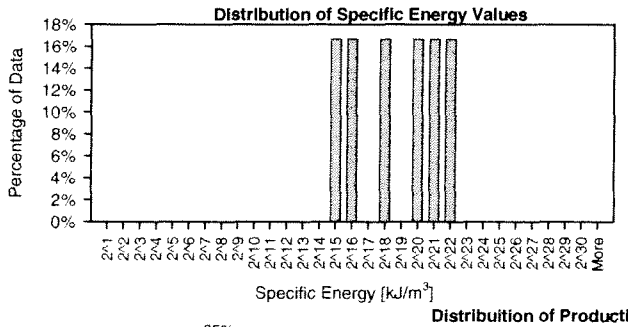

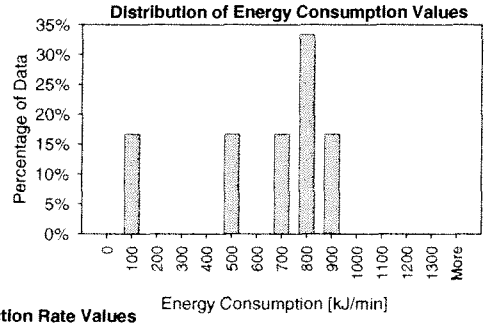

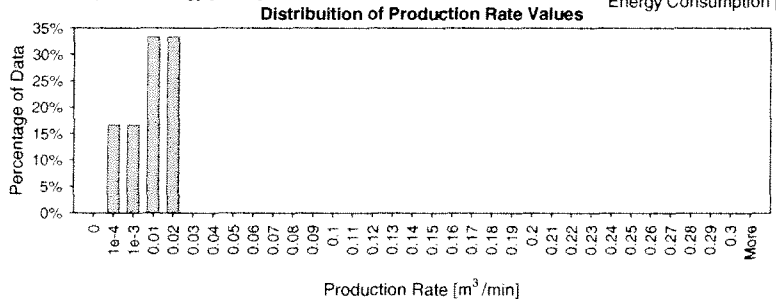

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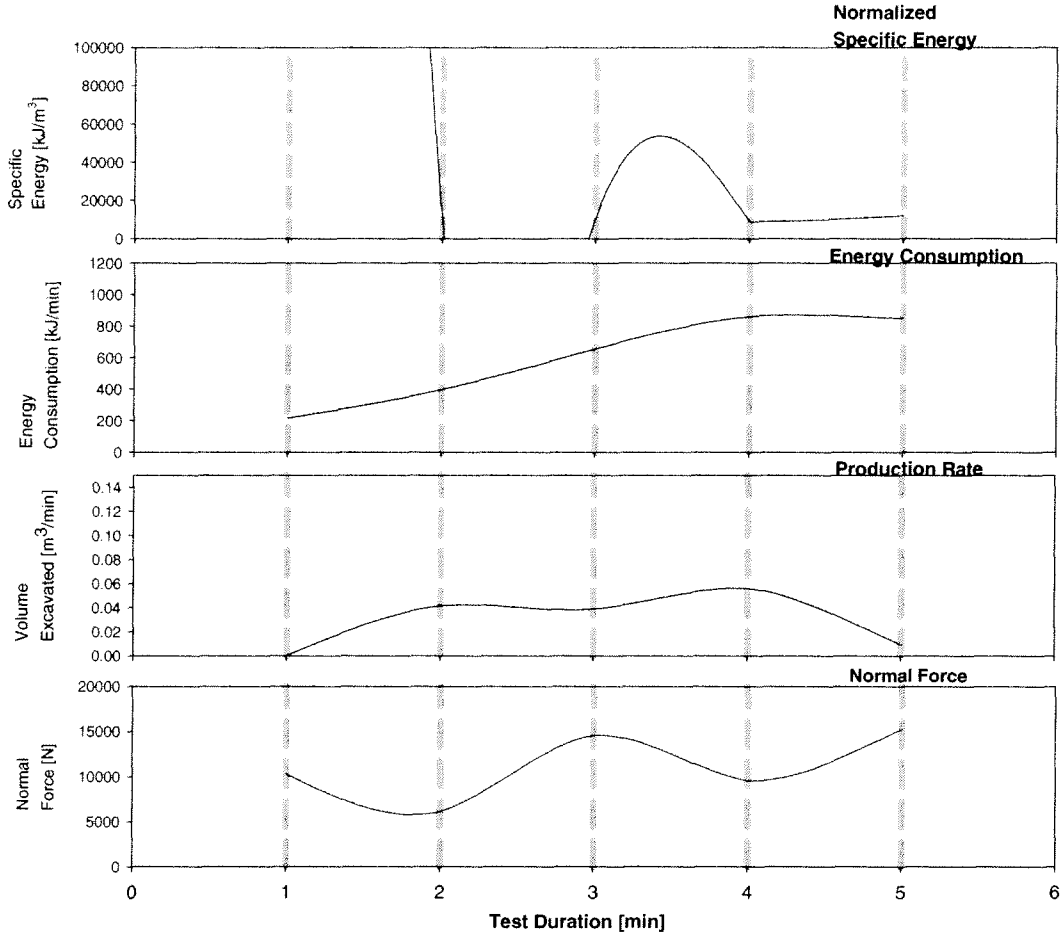

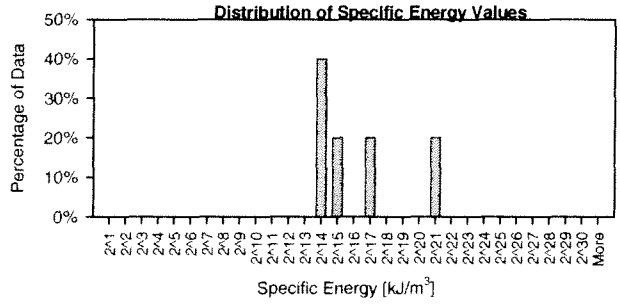

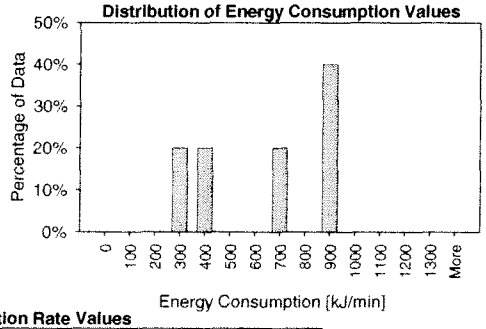

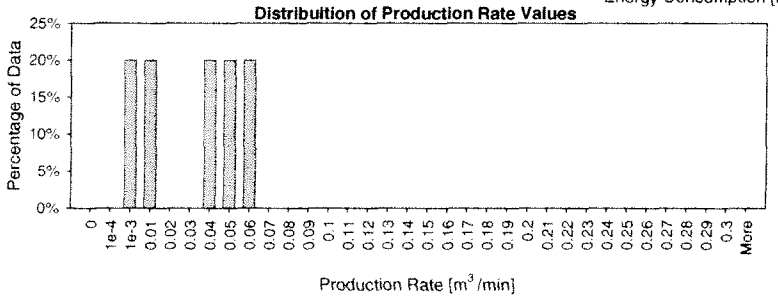

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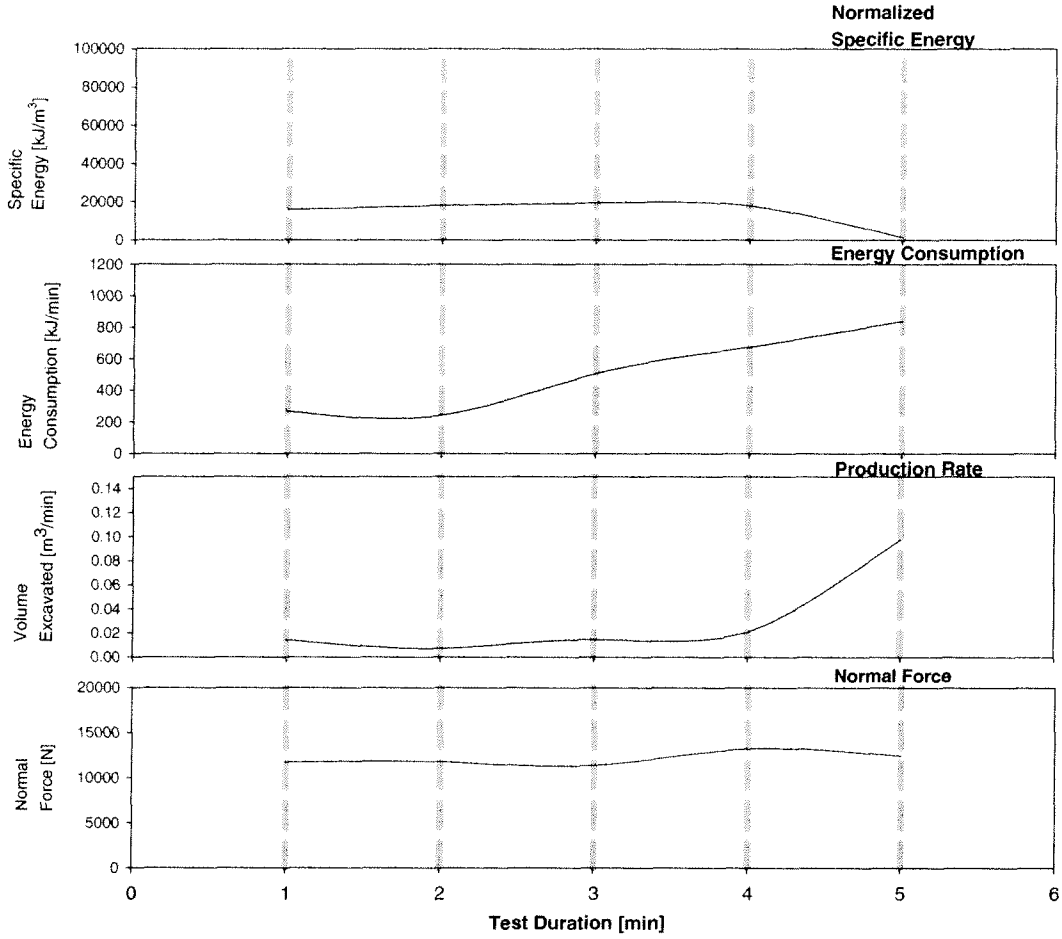

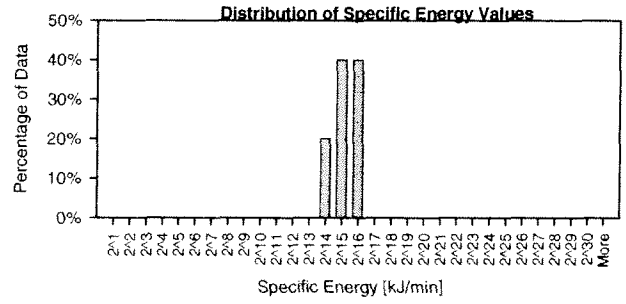

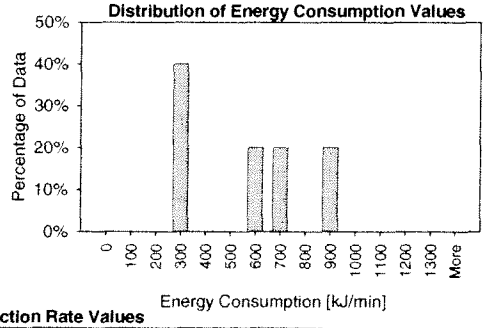

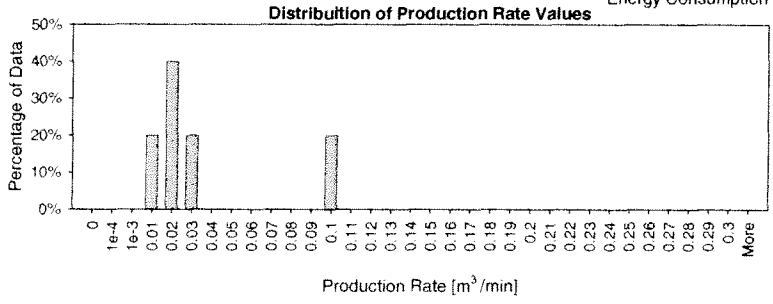

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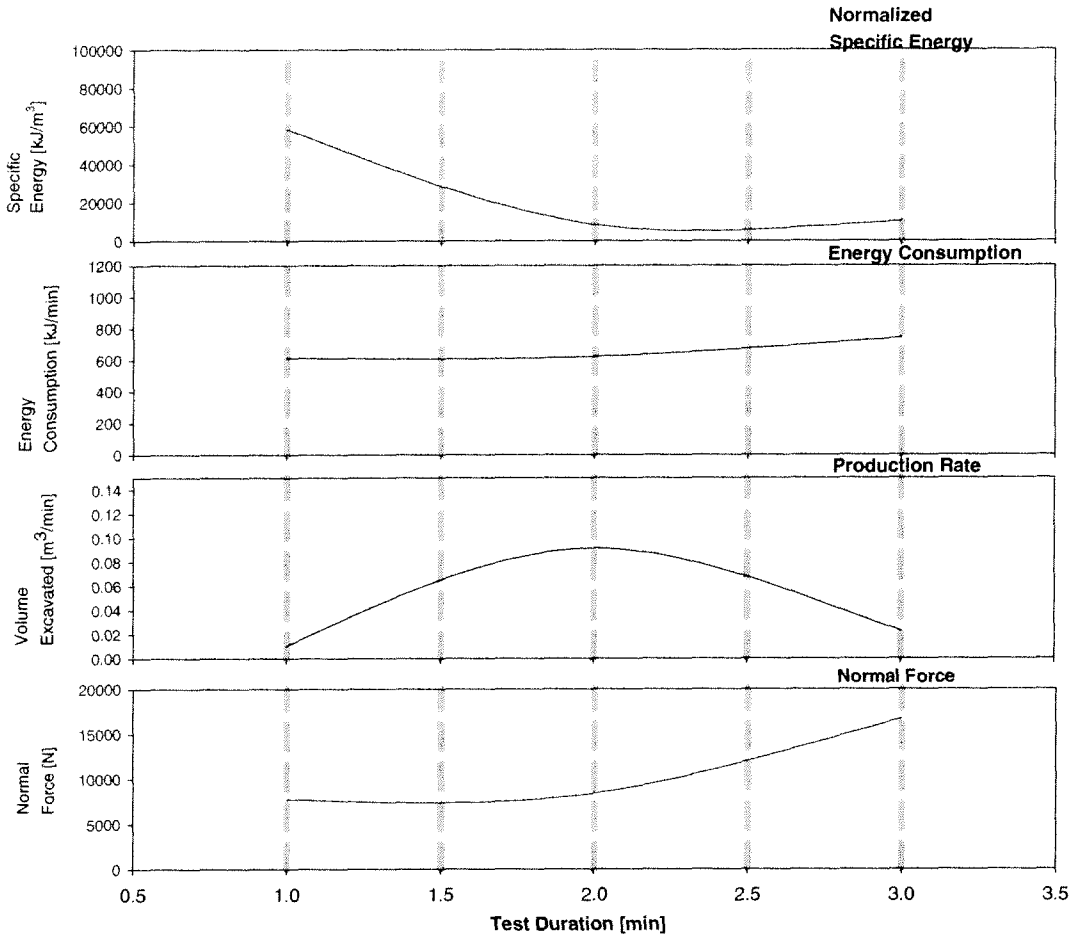
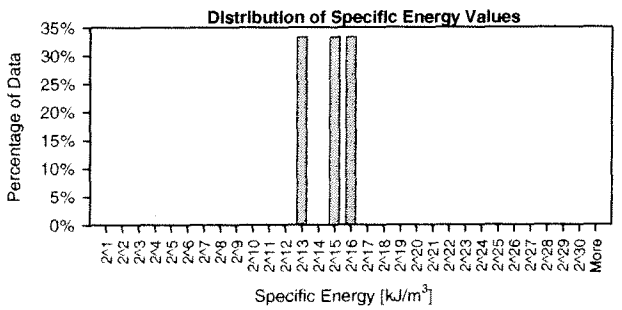
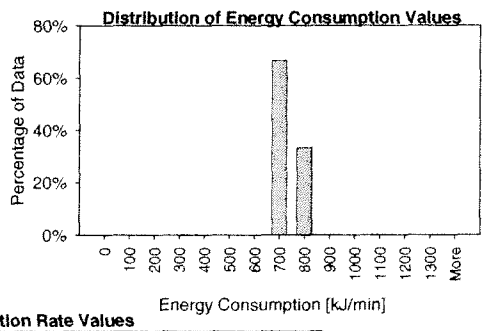
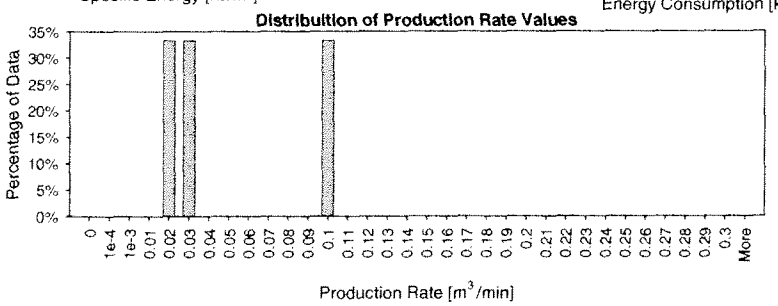
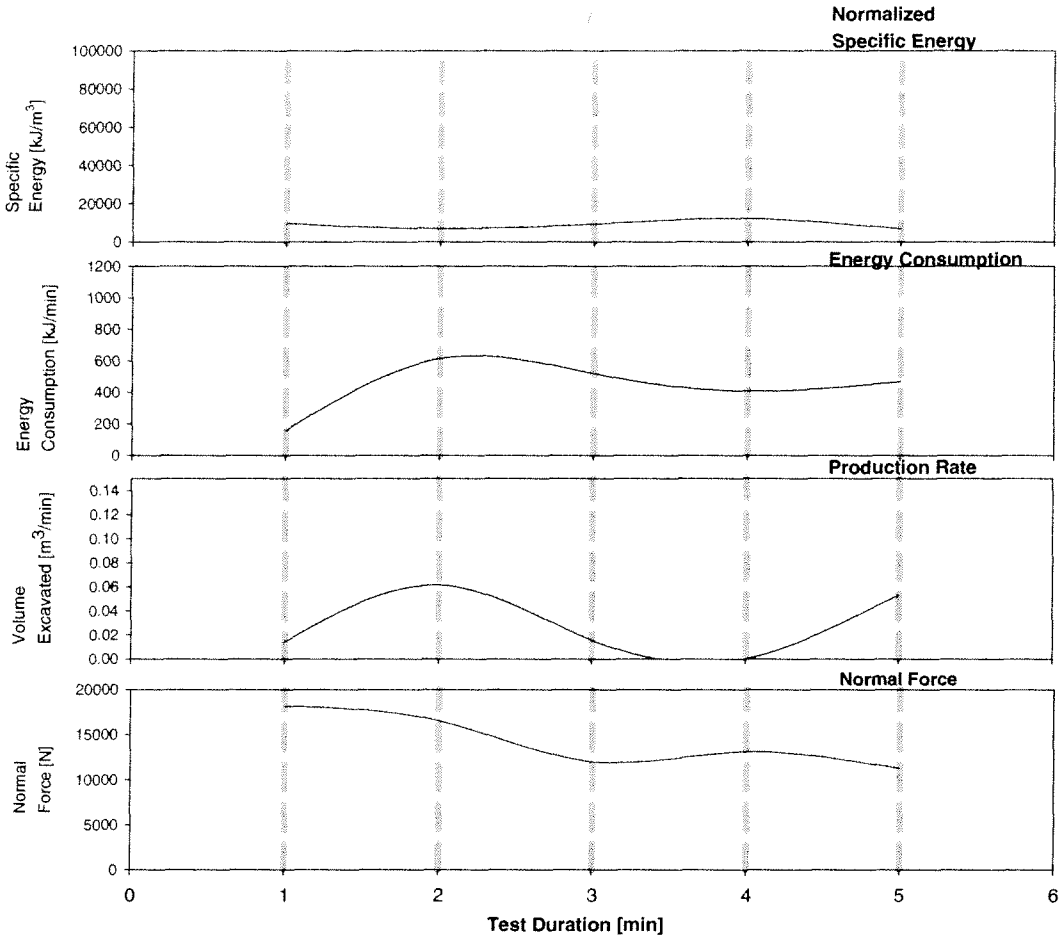


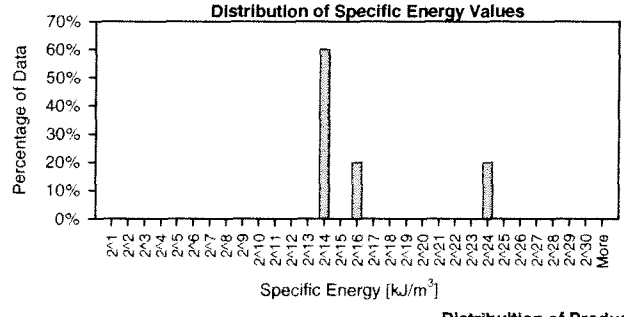


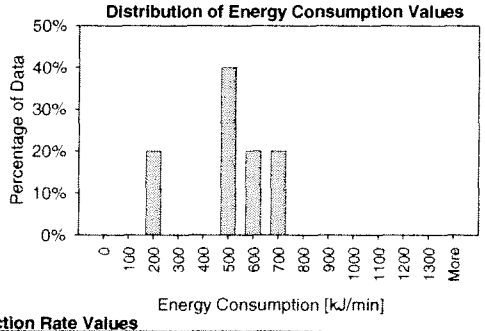


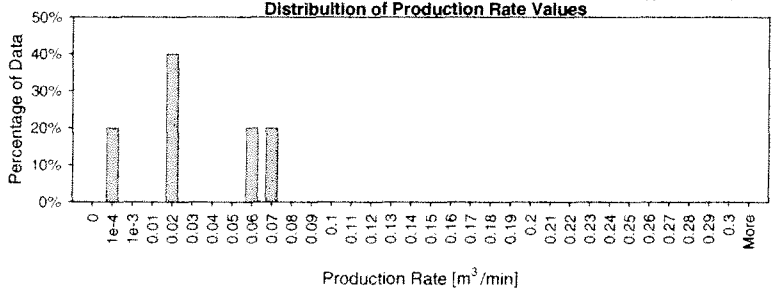


Test 1109.000 Data

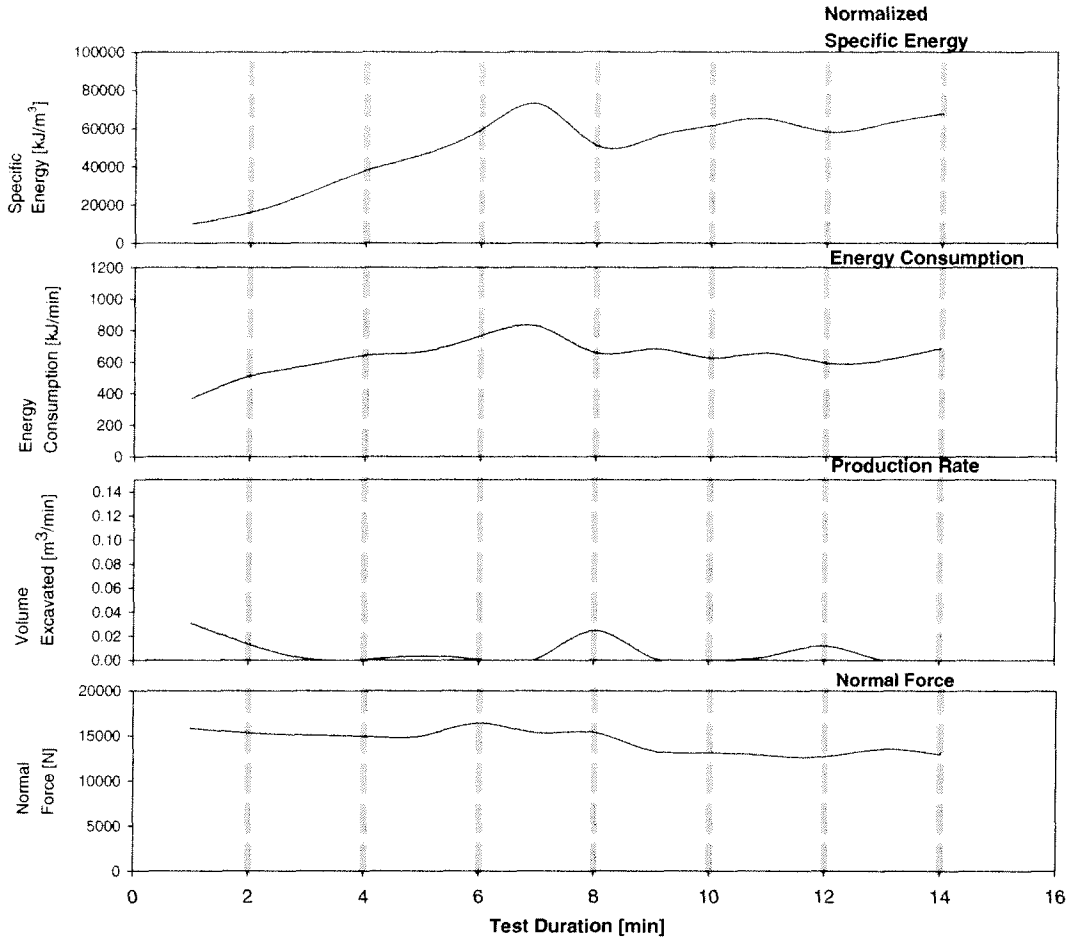


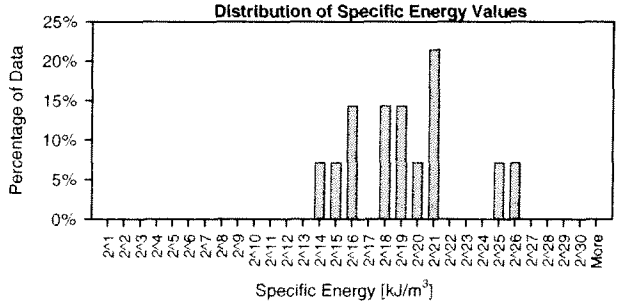


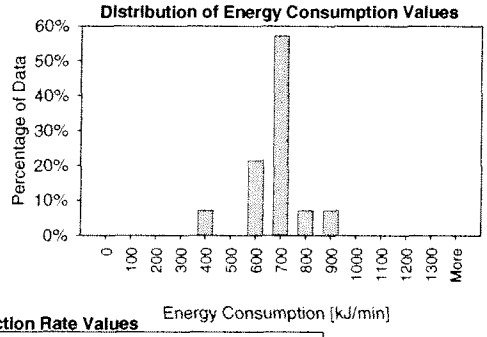


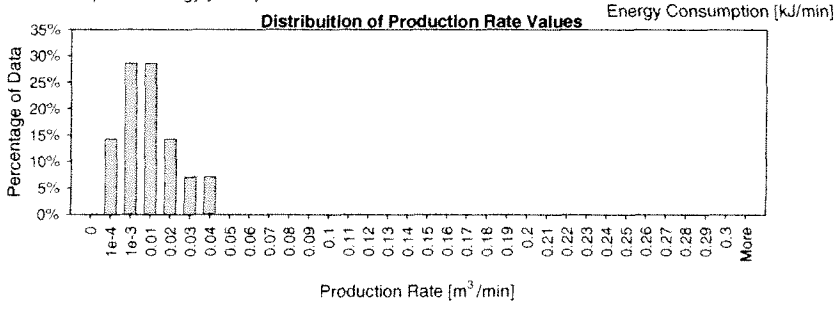


Test 1109.001 Data

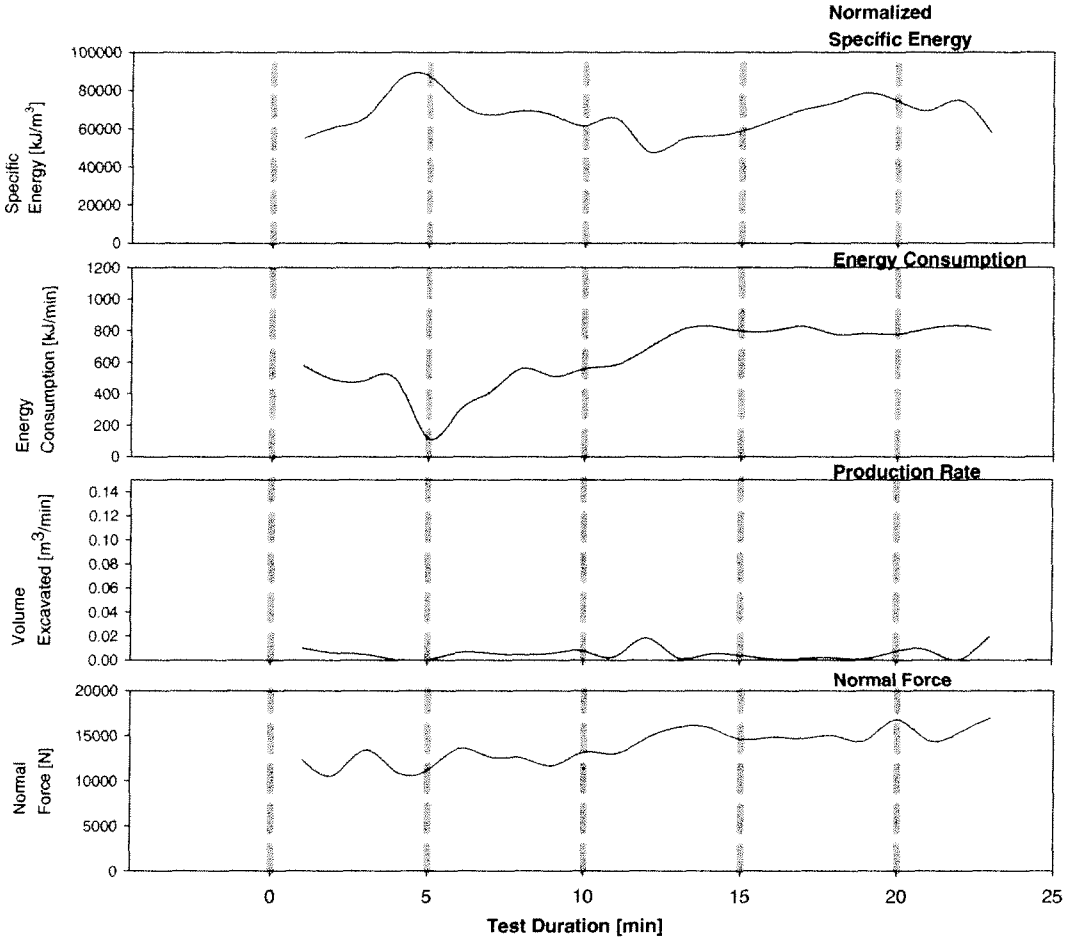


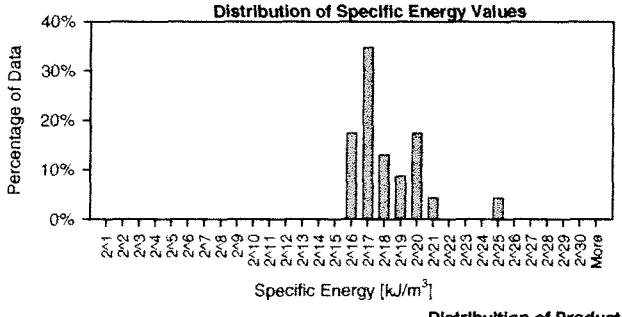


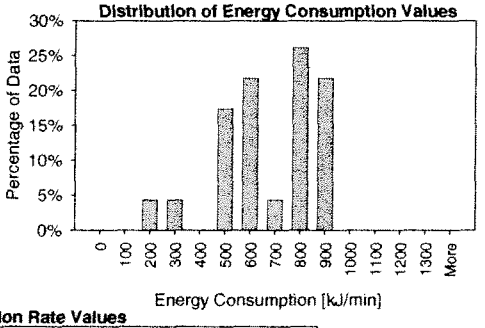


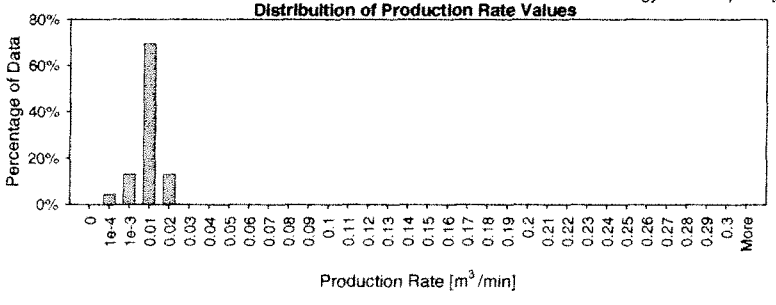


Test 1110.000 Data



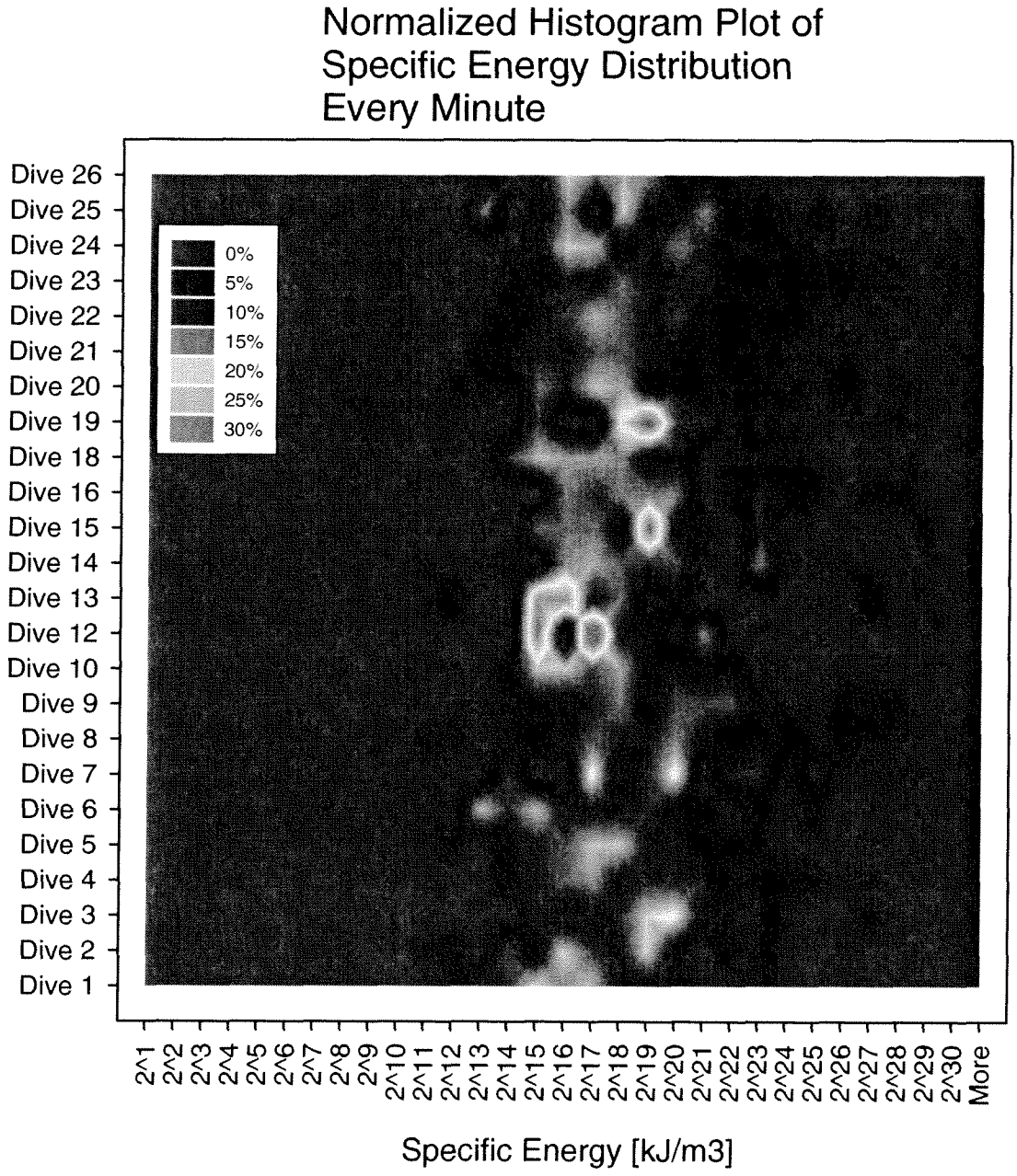




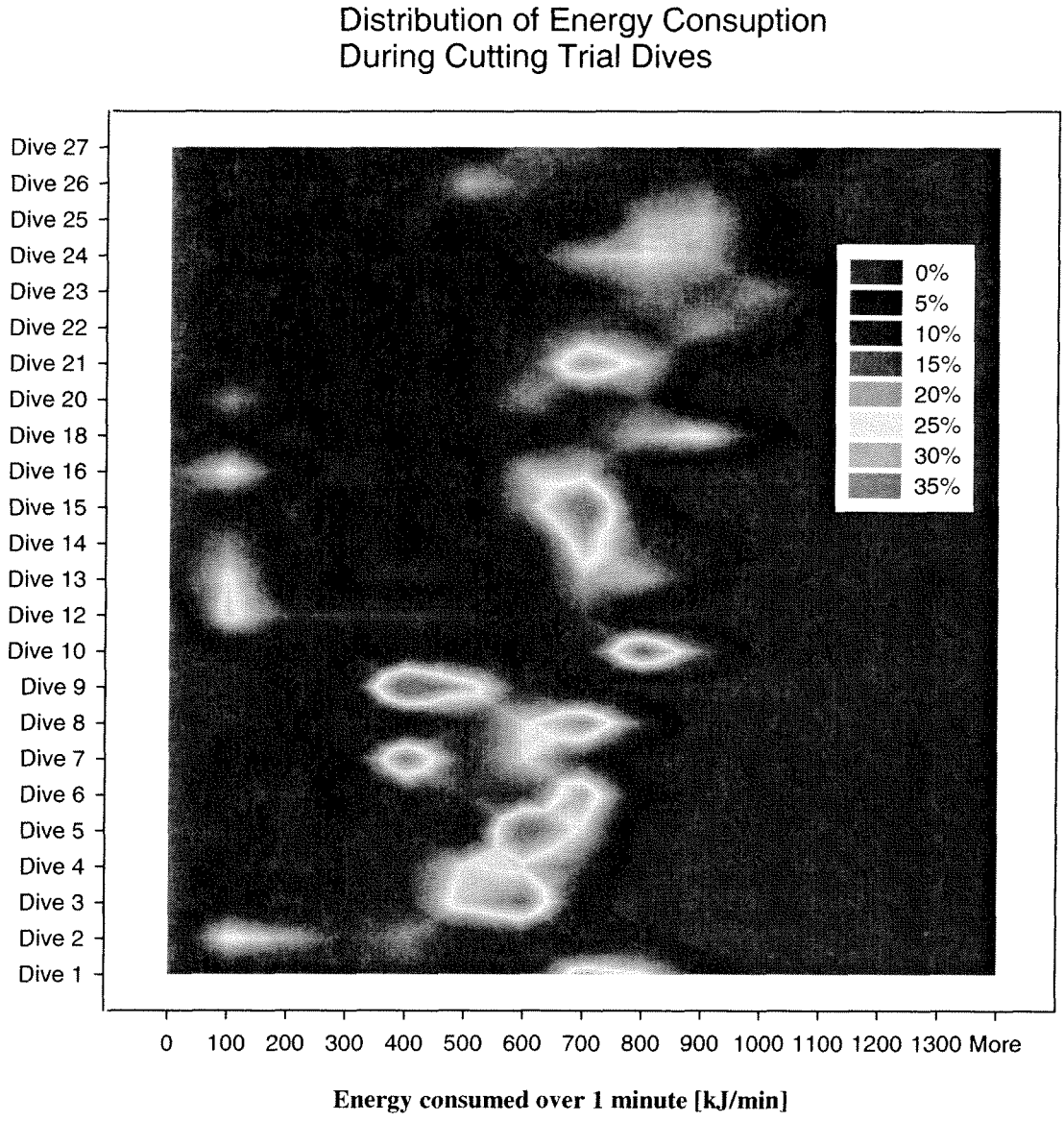


Appendix C: Field Trial Data

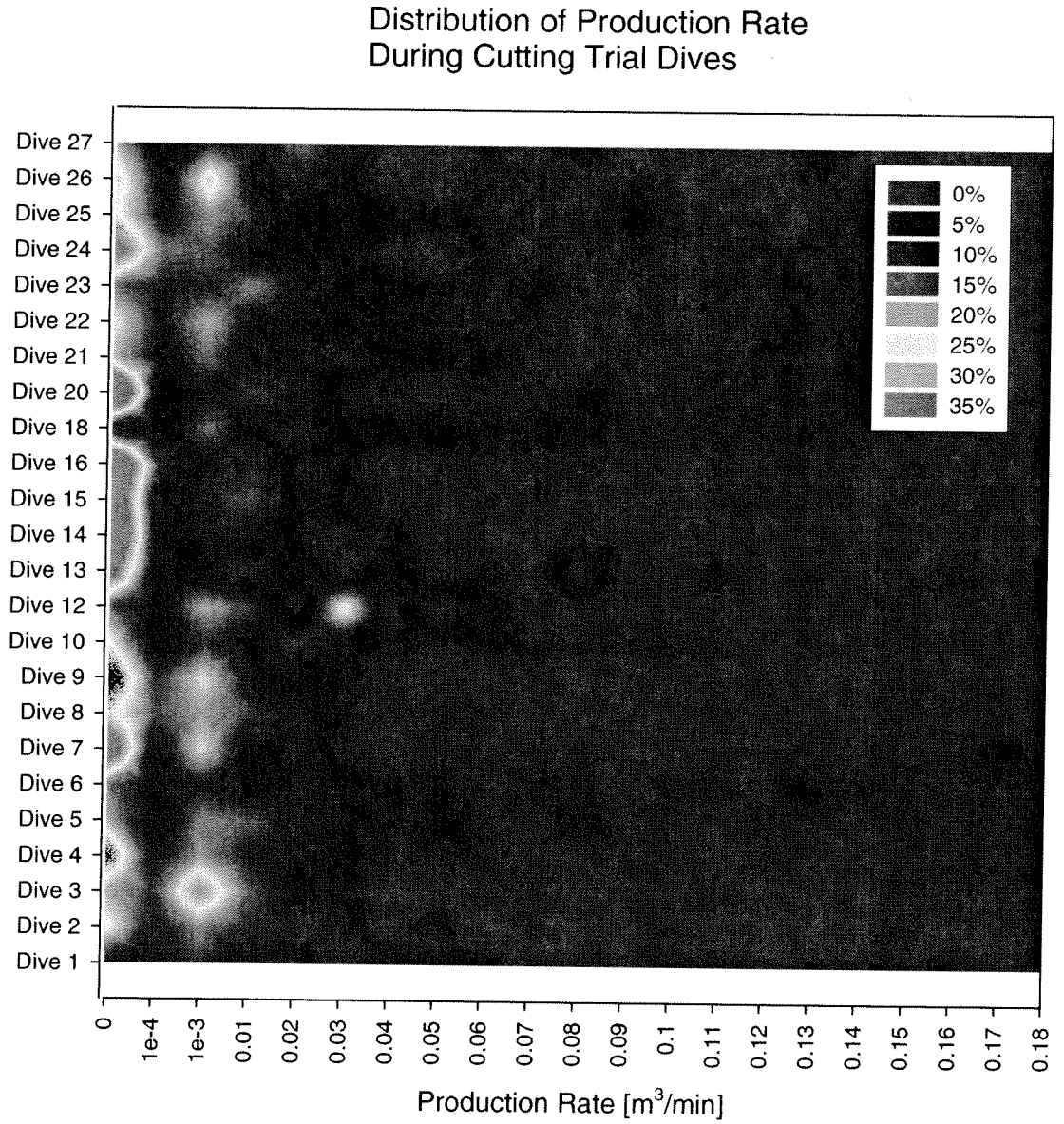
Contour Plot of Specific Energy Distribution During Sea Trials



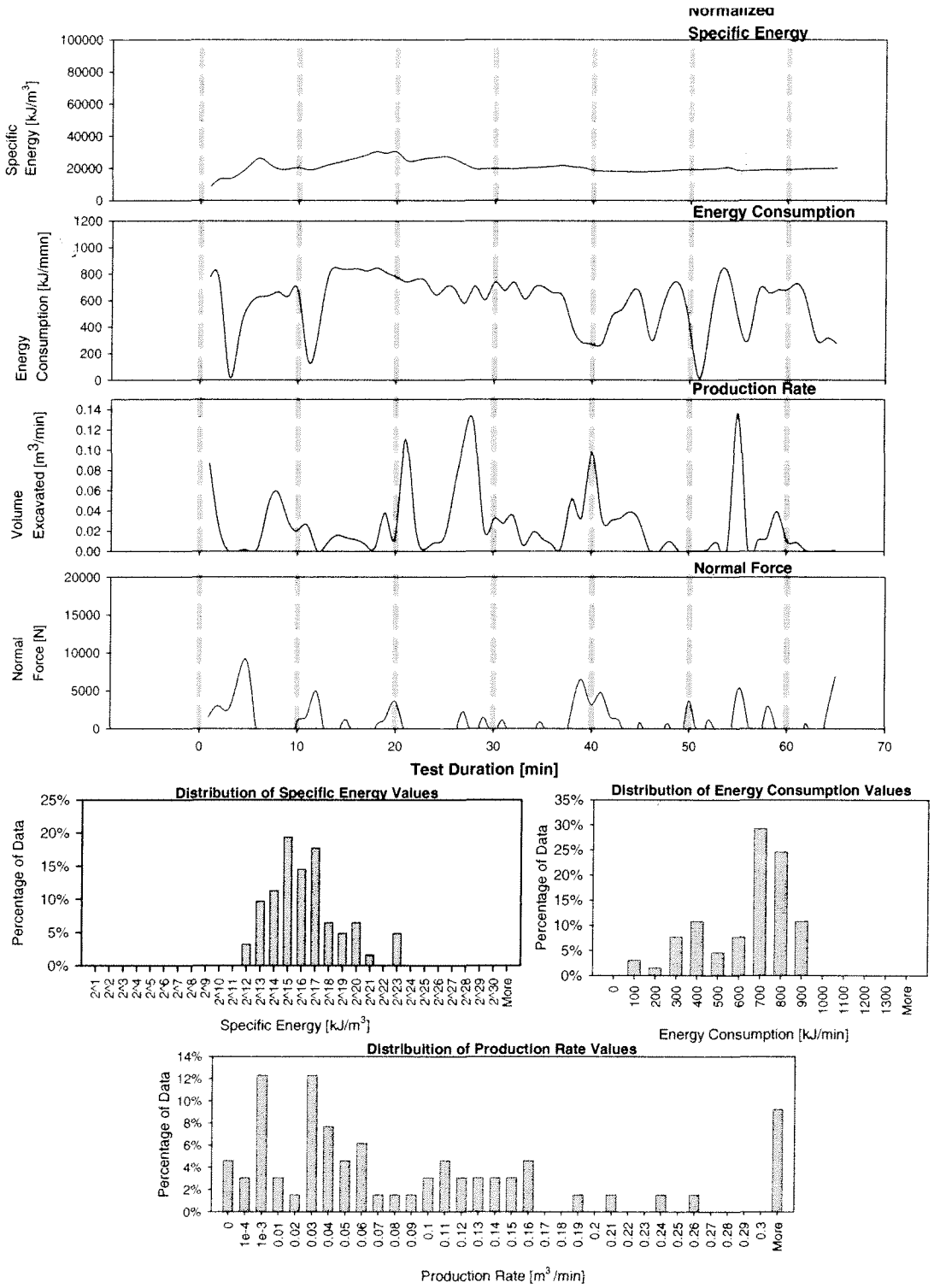
Contour Plot of Energy Consumption Distribution During Sea Trials



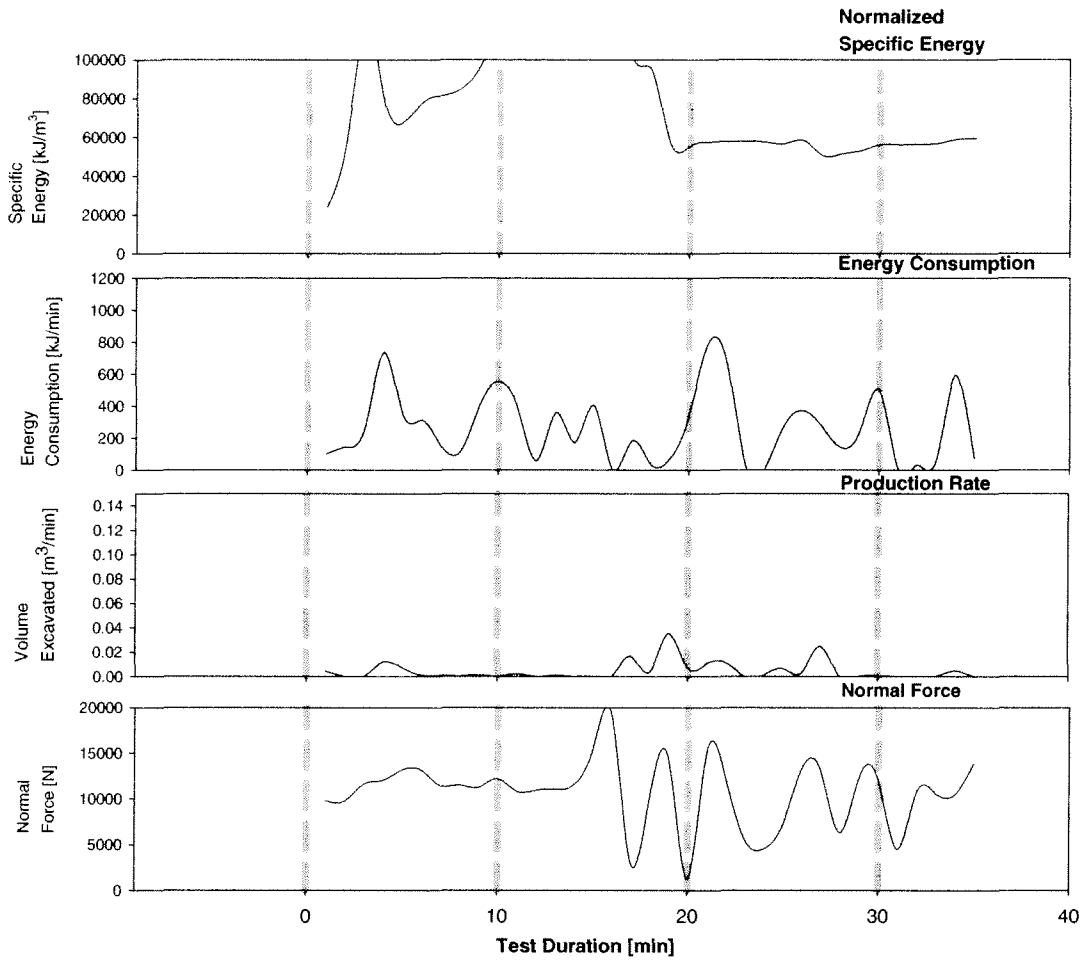
Contour Plot of Production Rate Distribution During Sea Trials

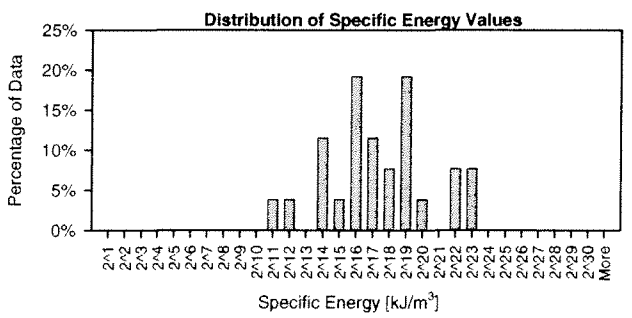


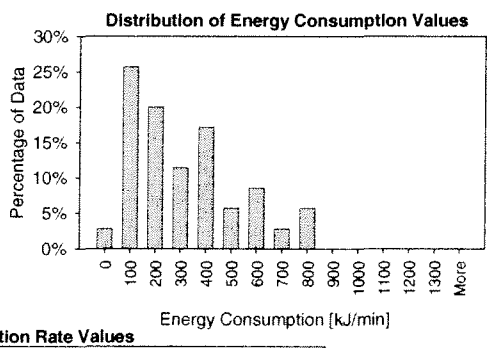
Site 1 Data

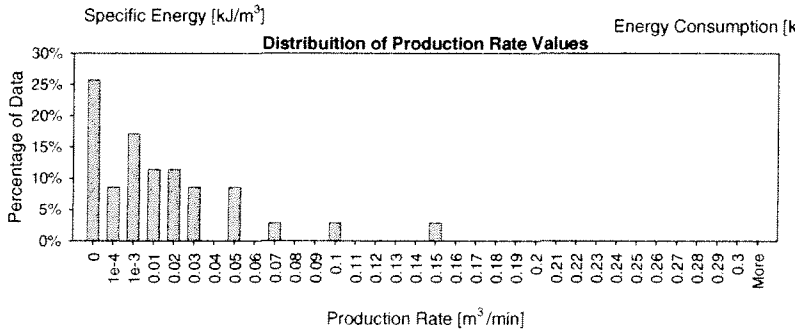

Normalized
Specific Energy
Specific Energy [kJ/m³]
Energy Consumption
Energy Consumption [kJ/mmn]
Production Rate
Volume Excavated [m³/min]
Normal Force
Normal Force [N]
Test Duration [min]
Distribution of Specific Energy Values
Percentage of Data
Specific Energy [kJ/m³]
Distribution of Energy Consumption Values
Energy Consumption [kJ/min]
Distribution of Production Rate Values
Production Rate [m³/min]

Site 2 Data

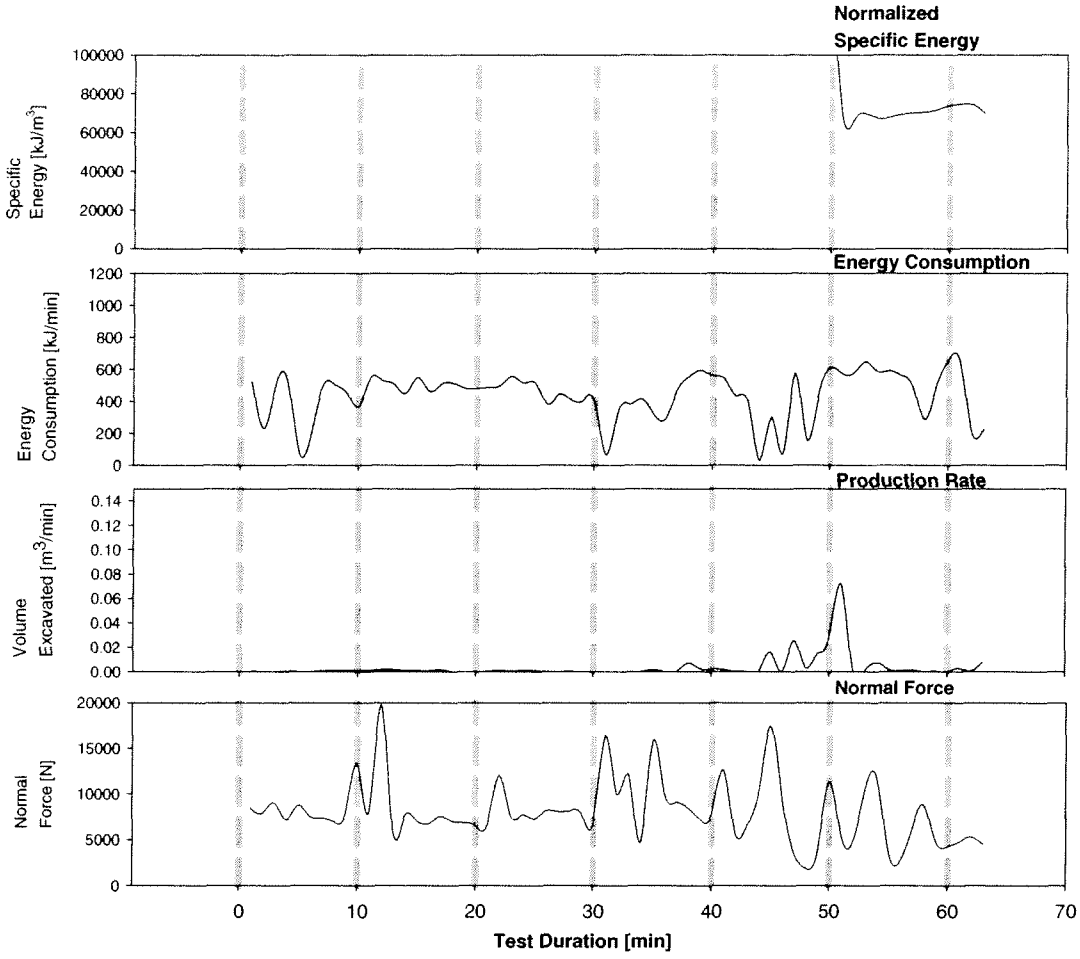

Normalized Specific Energy
Specific Energy [kJ/m3]
Energy Consumption
Energy Consumption [kJ/min]
Production Rate
Volume Excavated [m3/min]
Normal Force
Normal Force [N]
Test Duration [min]

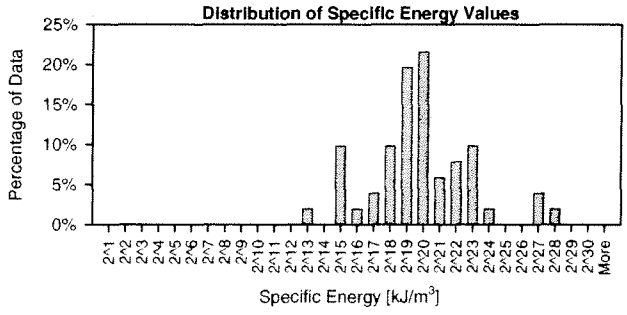

Distribution of Specific Energy Values
Percentage of Data
Specific Energy [kJ/m3]

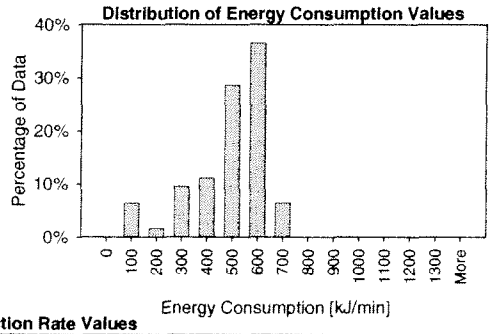

Distribution of Energy Consumption Values
Percentage of Data
Energy Consumption [kJ/min]

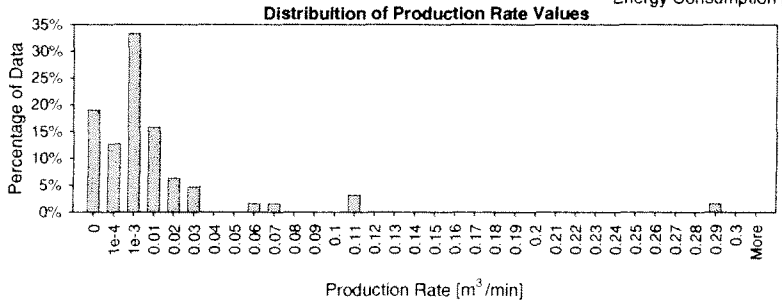

Distribuition of Production Rate Values
Percentage of Data
Production Rate [m3/min]

Site 3 Data

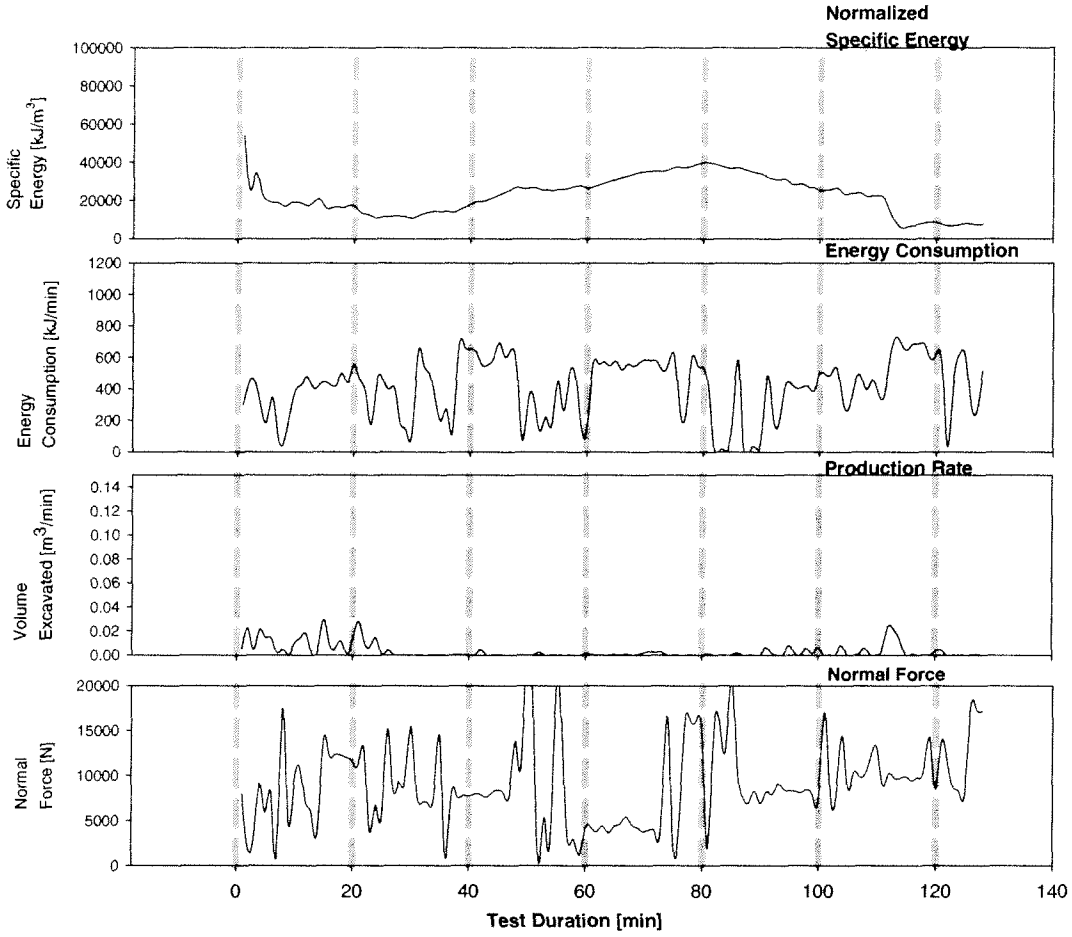

Normalized Specific Energy
Specific Energy [kJ/m³]
Energy Consumption
Energy Consumption [kJ/min]
Production Rate
Volume Excavated [m³/min]
Normal Force
Normal Force [N]
Test Duration [min]

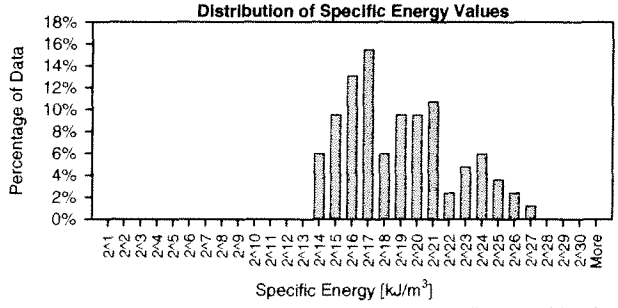

Distribution of Specific Energy Values
Percentage of Data
Specific Energy [kJ/m³]

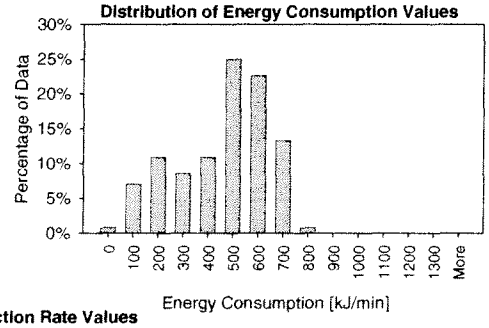

Distribution of Energy Consumption Values
Percentage of Data
Energy Consumption [kJ/min]

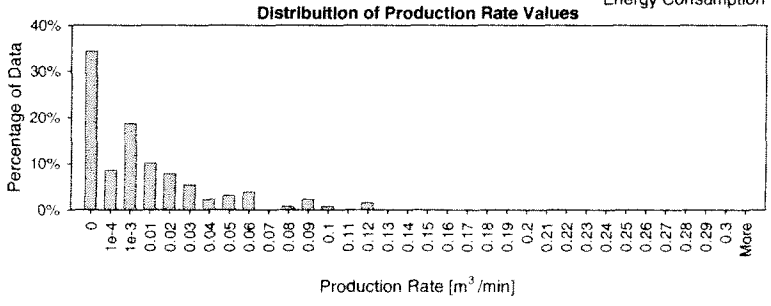

Distribution of Production Rate Values
Percentage of Data
Production Rate [m³/min]

Site 4 Data

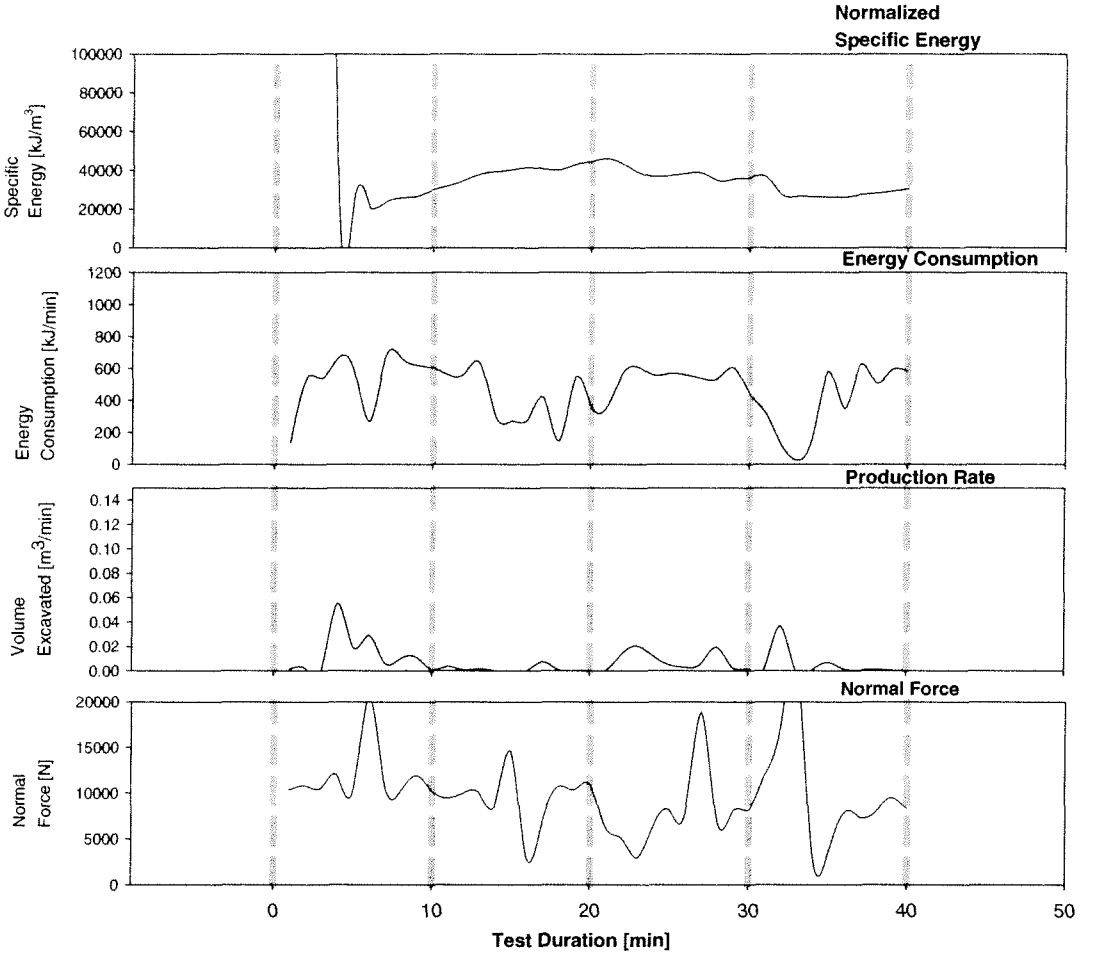

Normalized Specific Energy
Specific Energy [kJ/m3]
Energy Consumption
Energy Consumption [kJ/min]
Production Rate
Volume Excavated [m3/min]
Normal Force
Normal Force [N]
Test Duration [min]

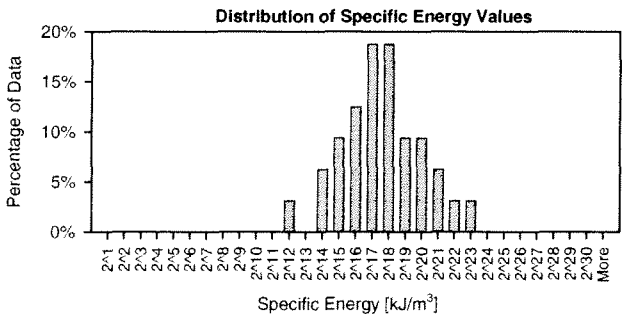

Distribution of Specific Energy Values
Percentage of Data
Specific Energy [kJ/m3]

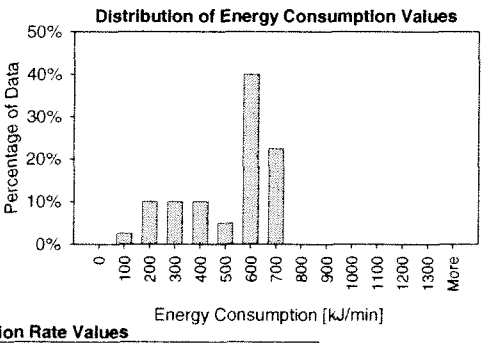

Distribution of Energy Consumption Values
Percentage of Data
Energy Consumption [kJ/min]

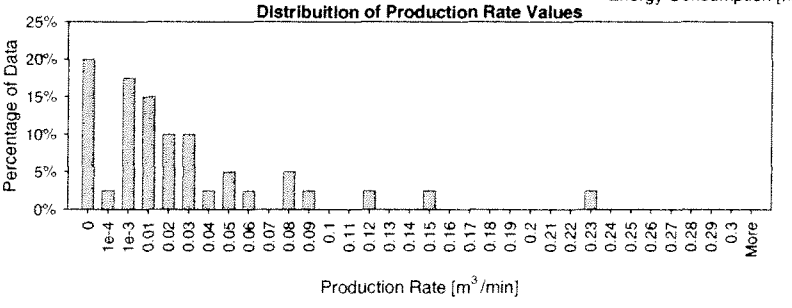

Distribution of Production Rate Values
Percentage of Data
Production Rate [m3/min]

Site 5 Data

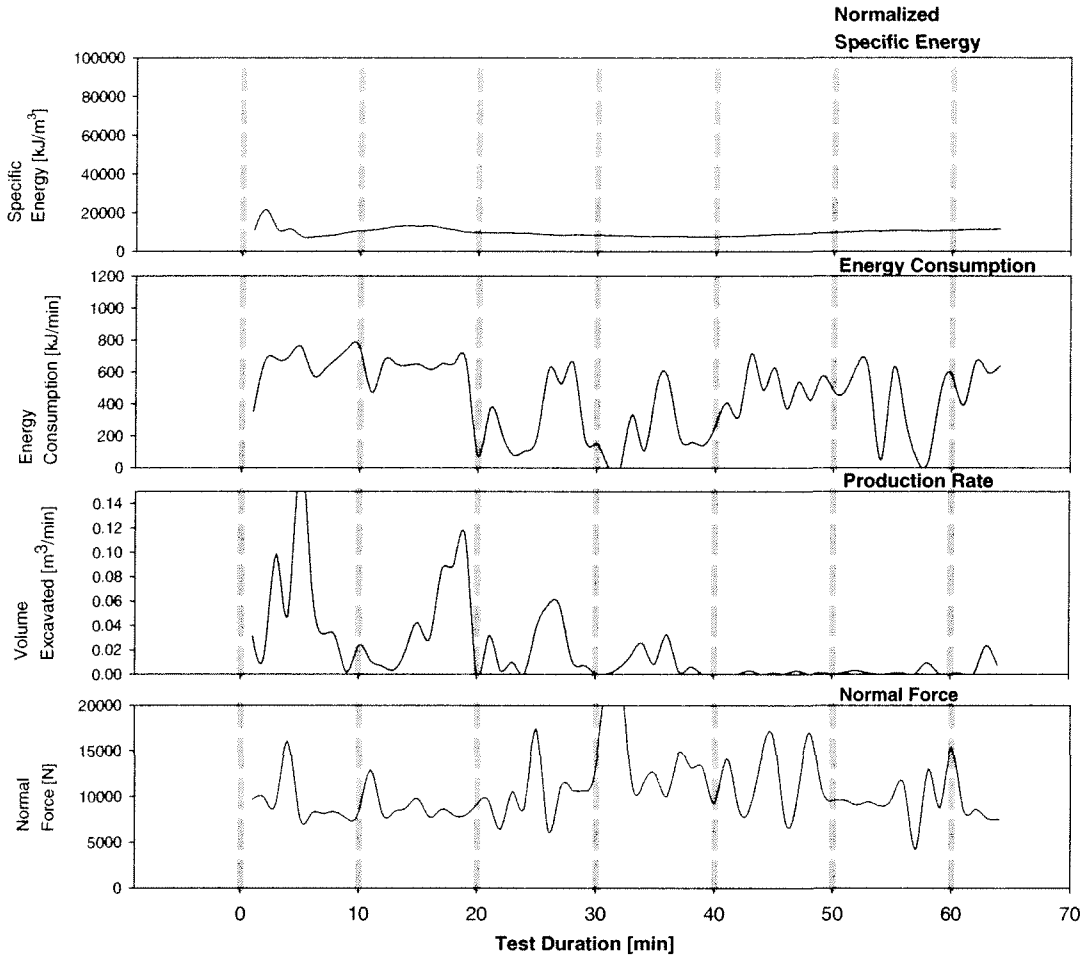

Normalized Specific Energy
Specific Energy [kJ/m3]
Energy Consumption
Energy Consumption [kJ/min]
Production Rate
Volume Excavated [m3/min]
Normal Force
Normal Force [N]
Test Duration [min]

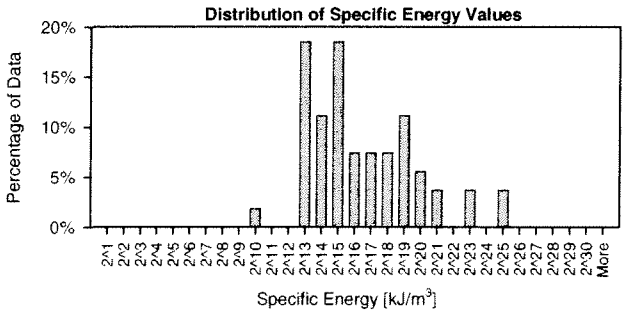

Distribution of Specific Energy Values
Percentage of Data
Specific Energy [kJ/m3]

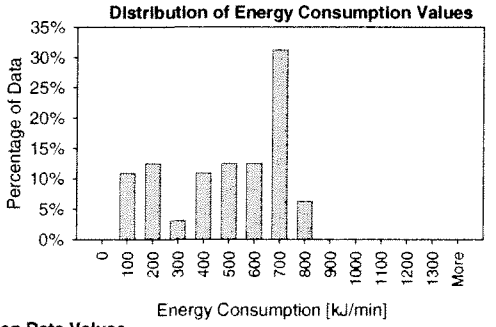

Distribution of Energy Consumption Values
Percentage of Data
Energy Consumption [kJ/min]

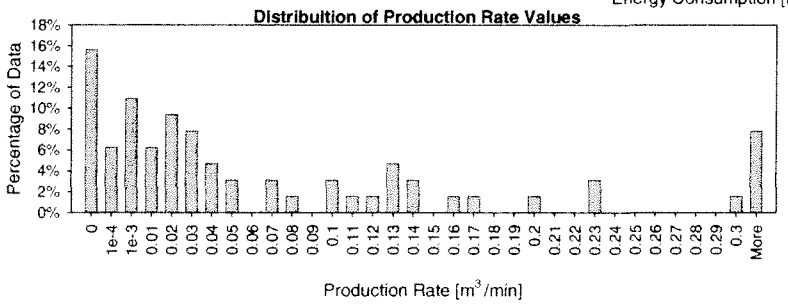

Distribution of Production Rate Values
Percentage of Data
Production Rate [m3/min]

Site 6 Data

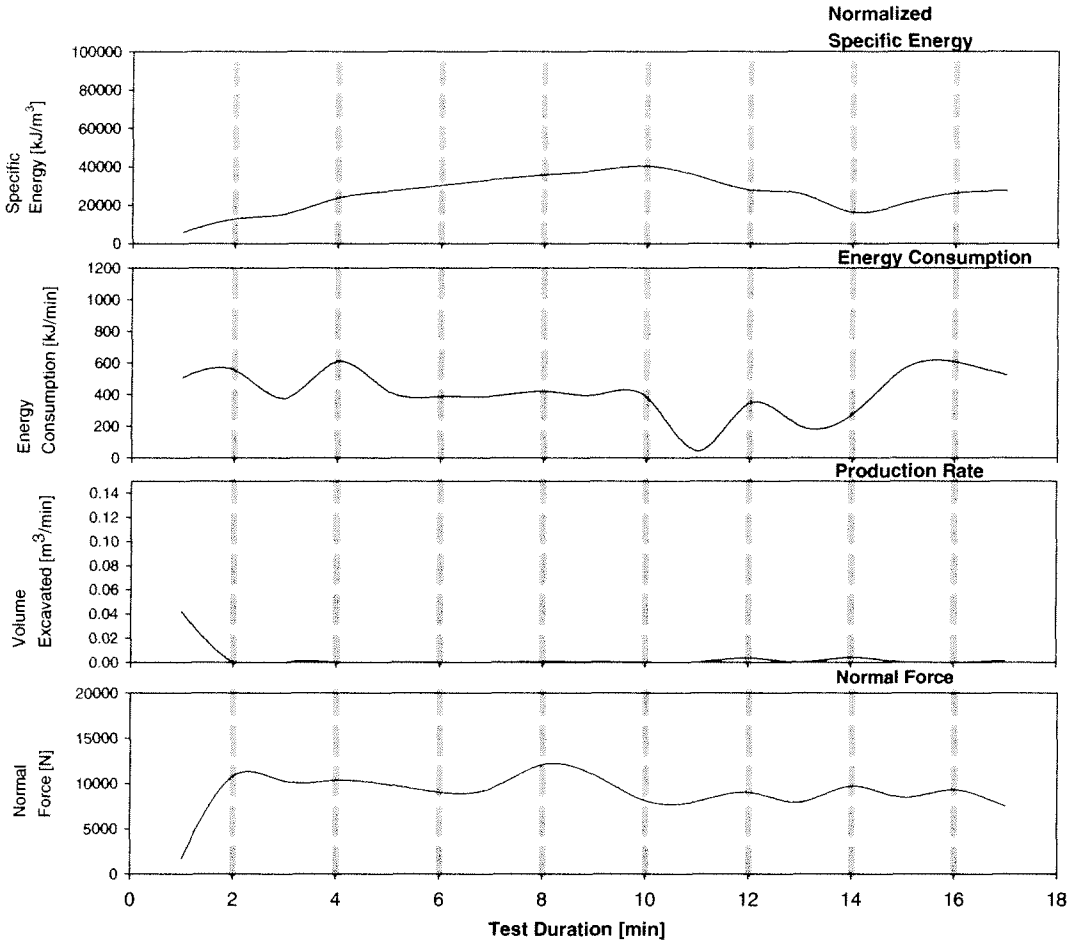

Normalized Specific Energy
Specific Energy [kJ/m3]
Energy Consumption
Energy Consumption [kJ/min]
Production Rate
Volume Excavated [m3/min]
Normal Force
Normal Force [N]
Test Duration [min]

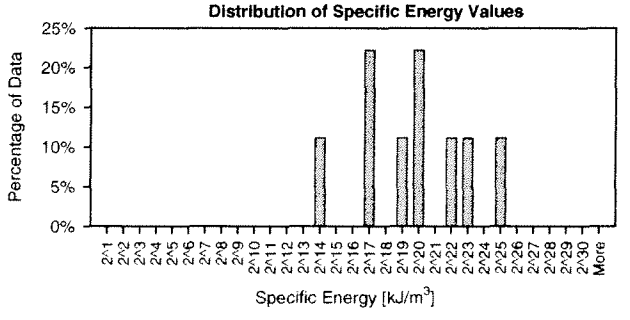

Distribution of Specific Energy Values
Percentage of Data
Specific Energy [kJ/m3]

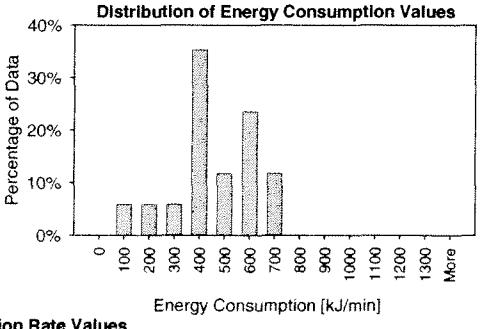

Distribution of Energy Consumption Values
Percentage of Data
Energy Consumption [kJ/min]

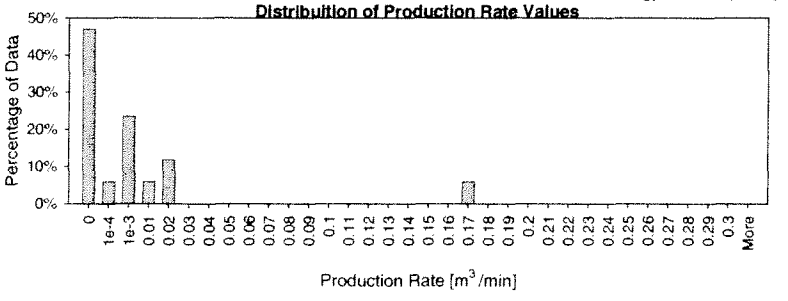

Distribution of Production Rate Values
Percentage of Data
Production Rate [m3/min]

Site 7 Data

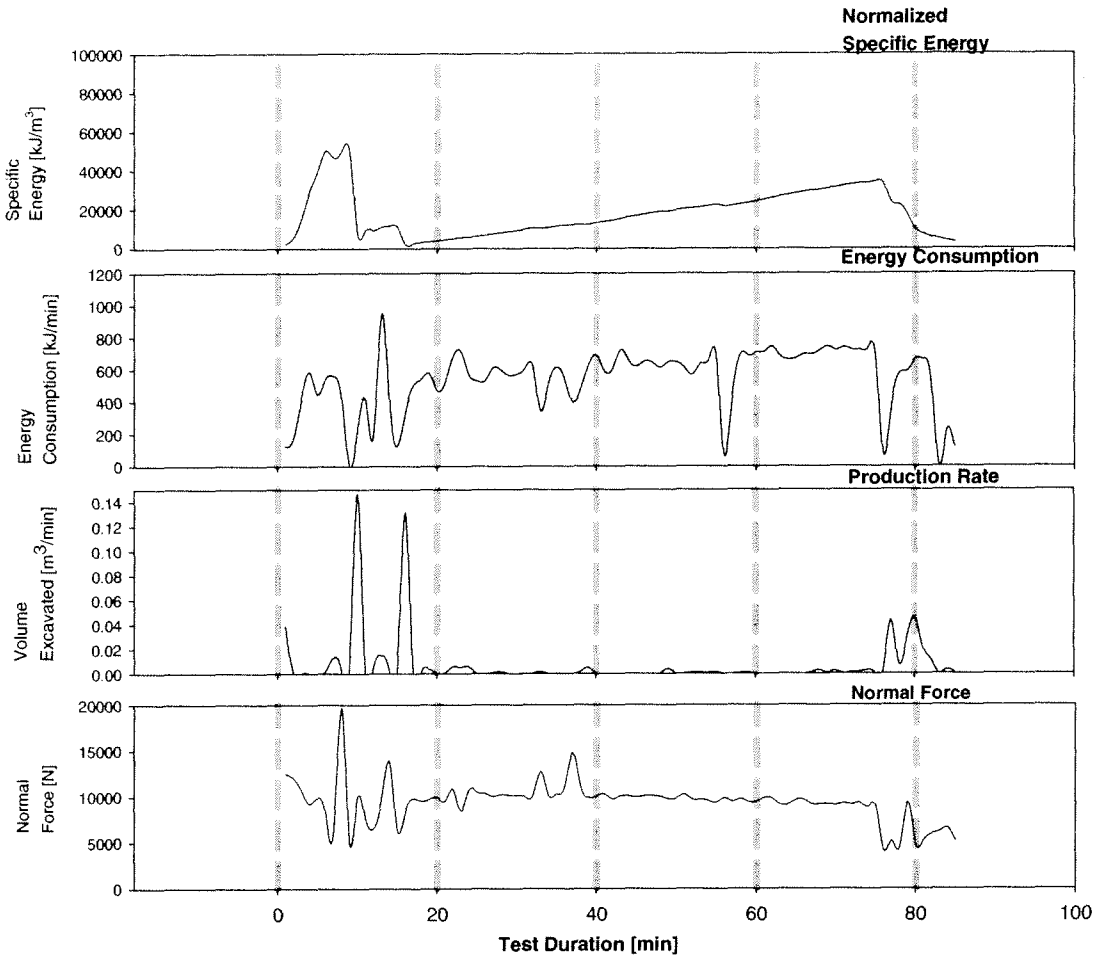

Normalized
Specific Energy
Specific Energy [kJ/m3]
Energy Consumption
Energy Consumption [kJ/min]
Production Rate
Volume Excavated [m3/min]
Normal Force
Normal Force [N]
Test Duration [min]

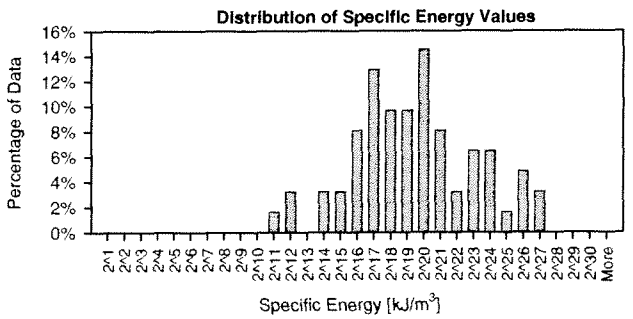

Distribution of Specific Energy Values
Percentage of Data
Specific Energy [kJ/m3]

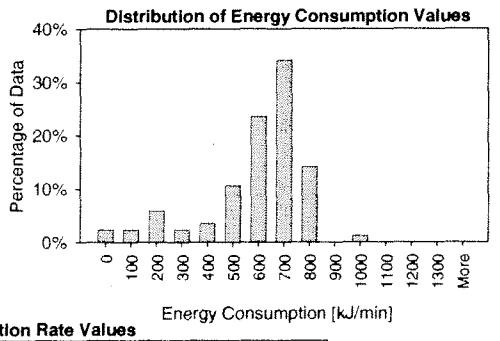

Distribution of Energy Consumption Values
Percentage of Data
Energy Consumption [kJ/min]

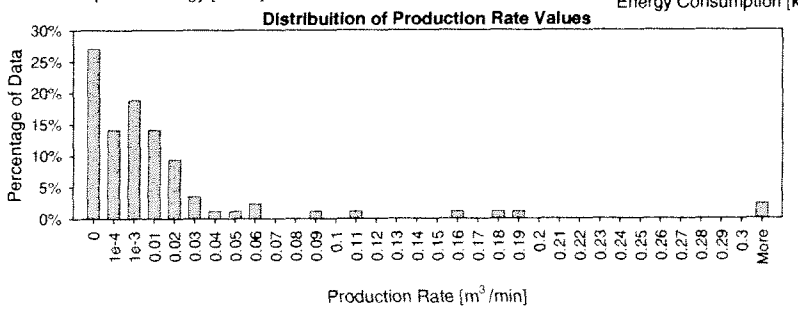

Distribution of Production Rate Values
Percentage of Data
Production Rate [m3/min]

Site 8 Data

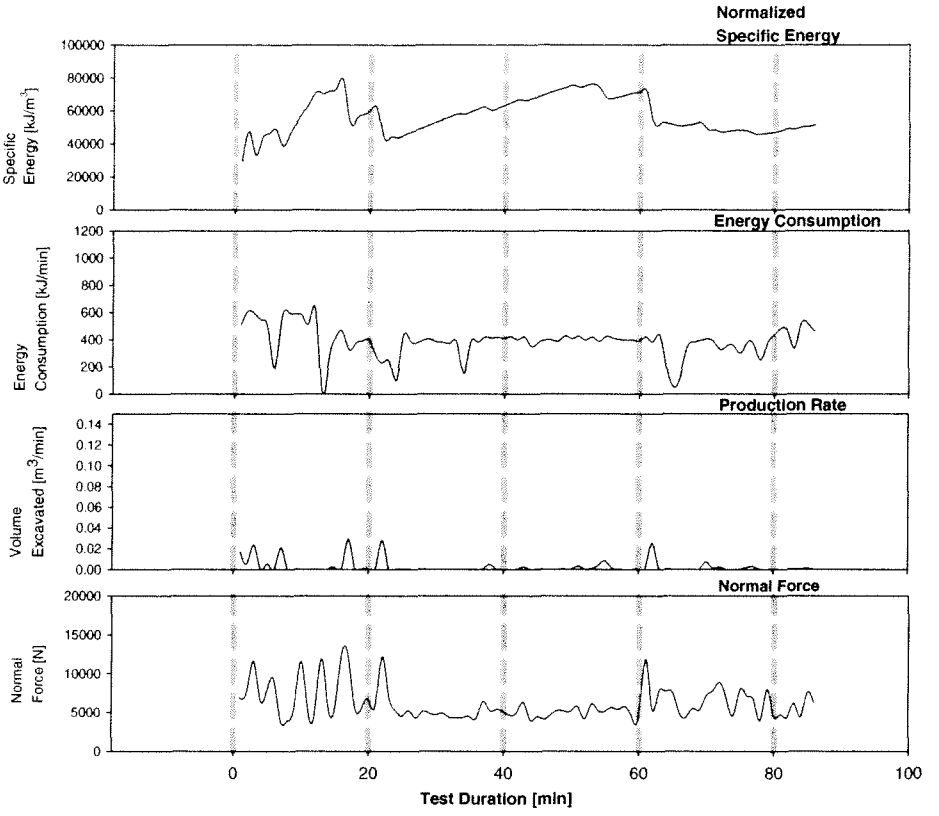

Normalized Specific Energy
Specific Energy [kJ/m3]
Energy Consumption
Energy Consumption [kJ/min]
Production Rate
Volume Excavated [m3/min]
Normal Force
Normal Force [N]
Test Duration [min]

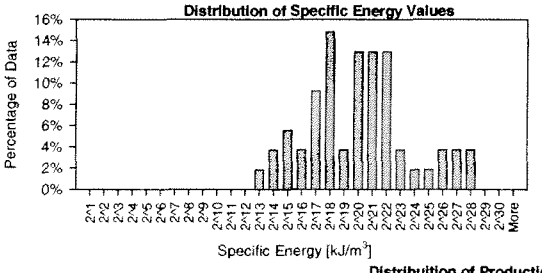

Distribution of Specific Energy Values
Percentage of Data
Specific Energy [kJ/m3]

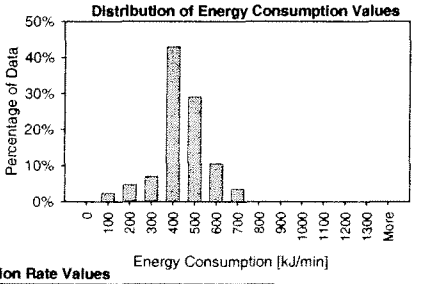

Distribution of Energy Consumption Values
Percentage of Data
Energy Consumption [kJ/min]

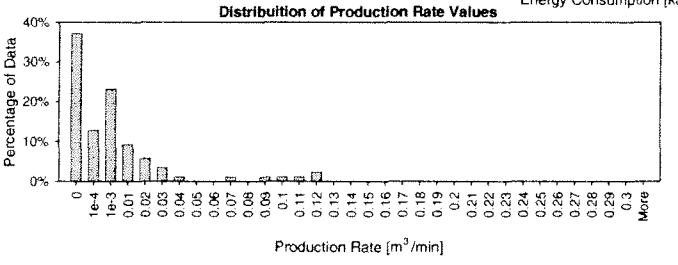

Distribuition of Production Rate Values
Percentage of Data
Production Rate [m3/min]

Site 9 Data

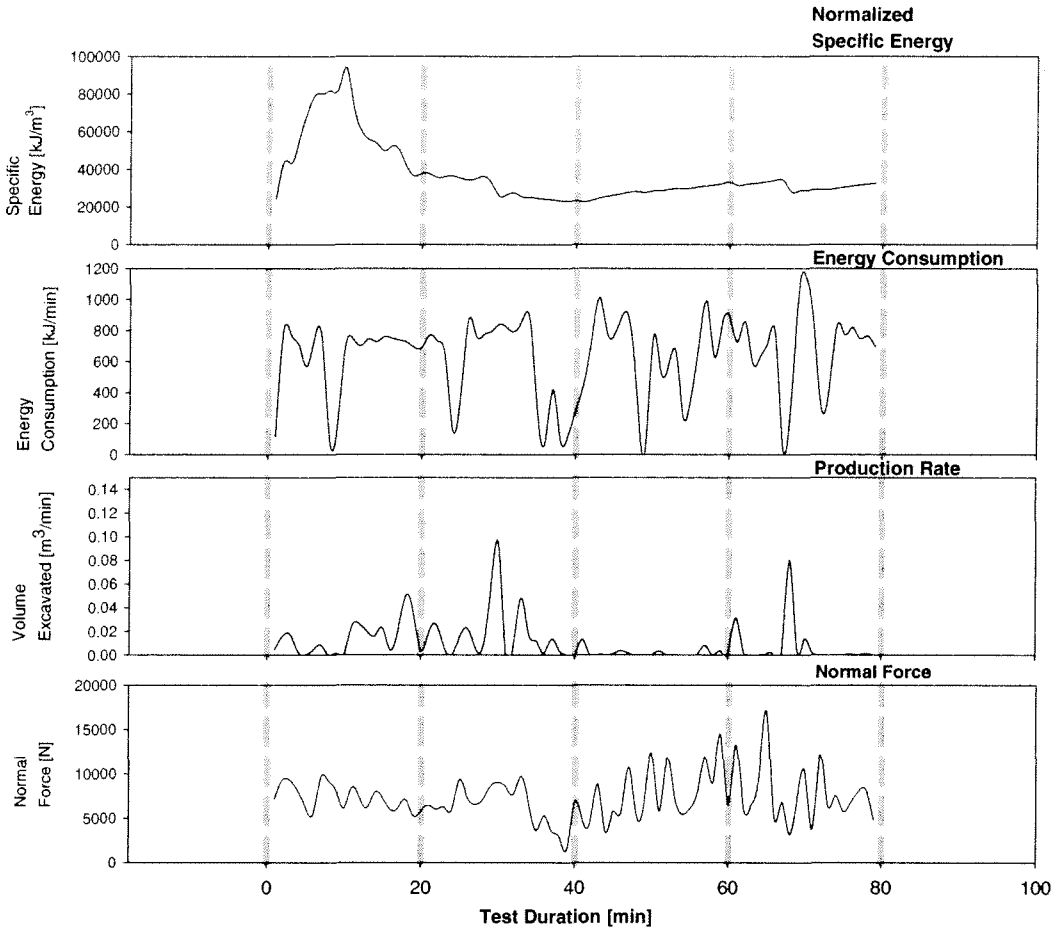

Normalized Specific Energy
Specific Energy [kJ/m³]
Energy Consumption
Energy Consumption [kJ/min]
Production Rate
Volume Excavated [m³/min]
Normal Force
Normal Force [N]
Test Duration [min]

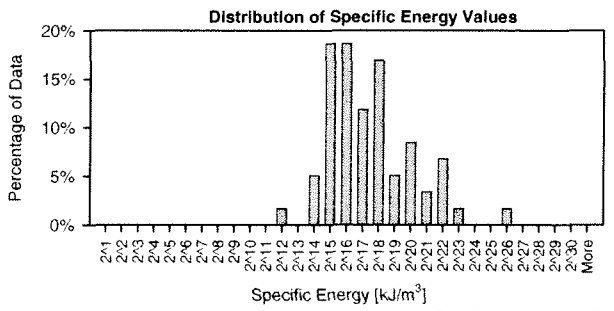

Distribution of Specific Energy Values
Percentage of Data
Specific Energy [kJ/m³]

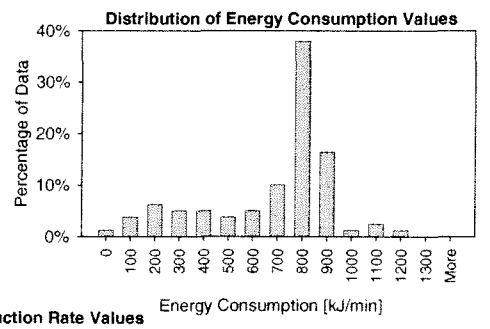

Distribution of Energy Consumption Values
Percentage of Data
Energy Consumption [kJ/min]

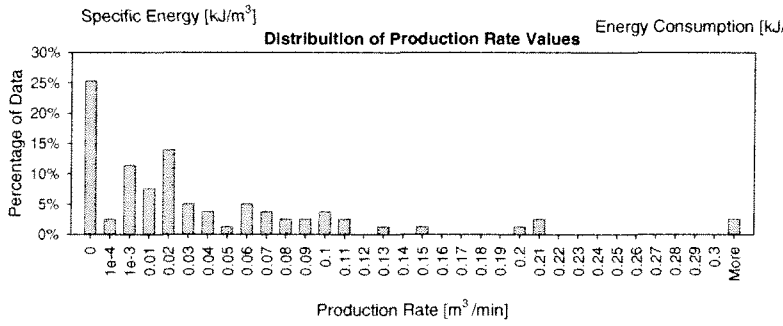

Distribution of Production Rate Values
Percentage of Data
Production Rate [m³/min]

Site 10 Data

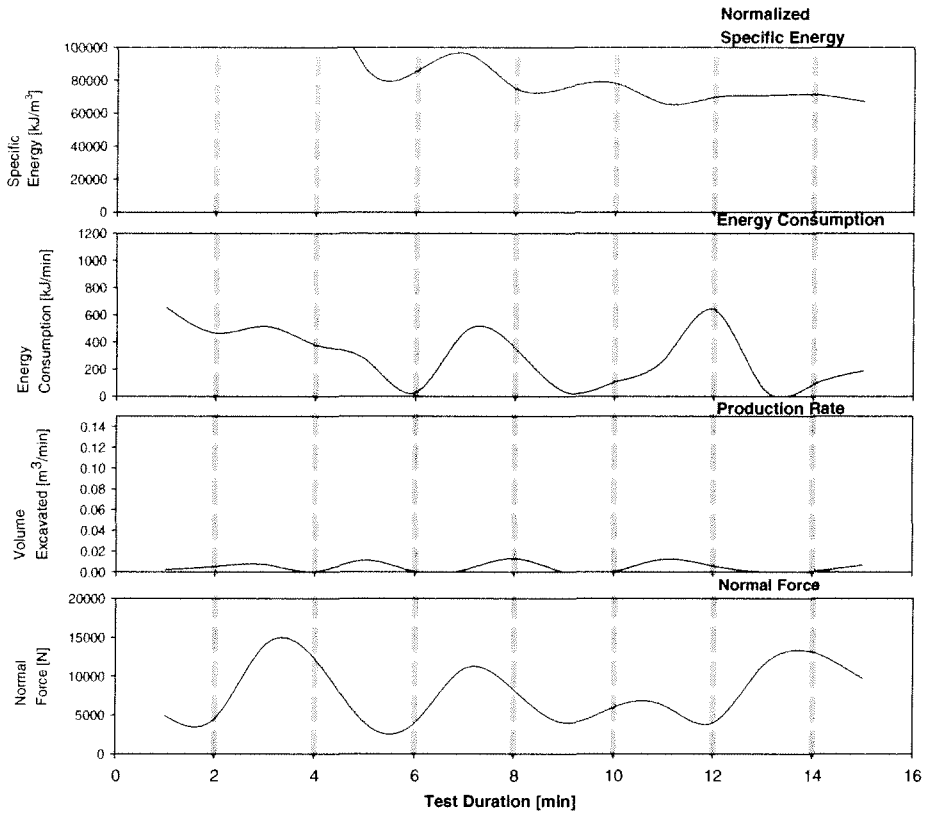

Normalized Specific Energy
Specific Energy [kJ/m³]
Energy Consumption
Energy Consumption [kJ/min]
Production Rate
Volume Excavated [m³/min]
Normal Force
Normal Force [N]
Test Duration [min]

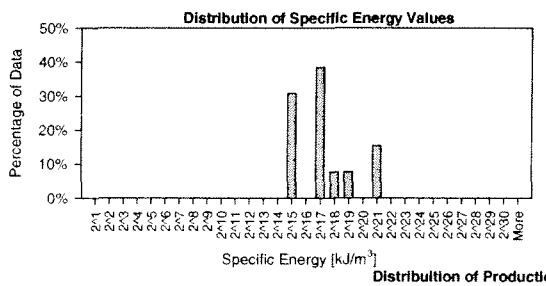

Distribution of Specific Energy Values
Percentage of Data
Specific Energy [kJ/m³]

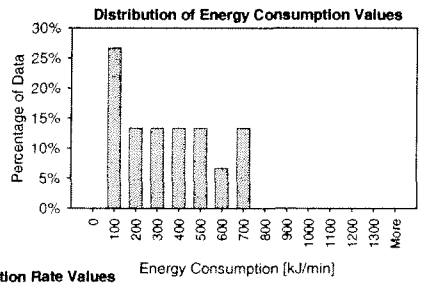

Distribution of Energy Consumption Values
Percentage of Data
Energy Consumption [kJ/min]

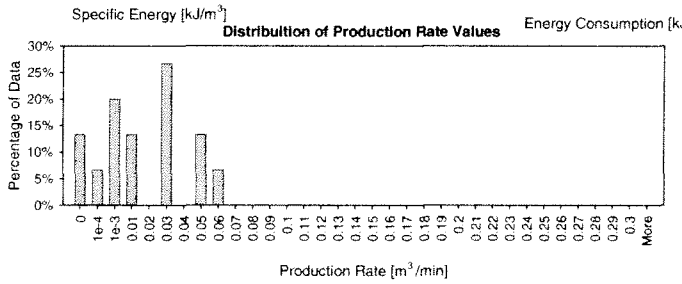

Distribution of Production Rate Values
Percentage of Data
Production Rate [m³/min]

Site 12 Data

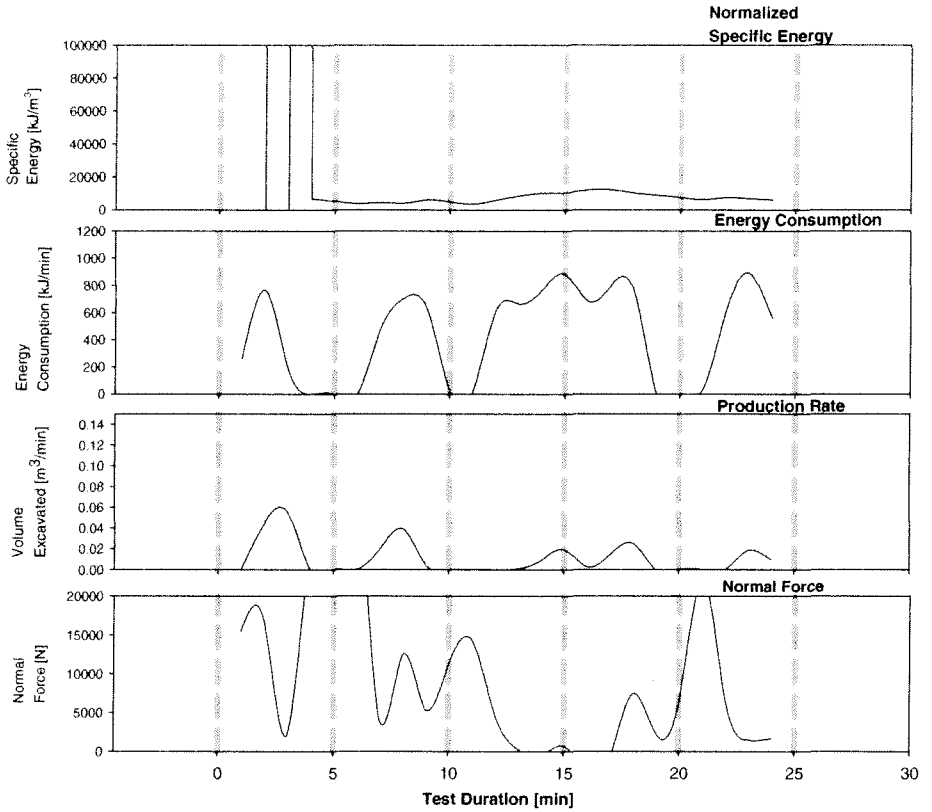

Normalized Specific Energy
Specific Energy [kJ/m³]
Energy Consumption
Energy Consumption [kJ/min]
Production Rate
Volume Excavated [m³/min]
Normal Force
Normal Force [N]
Test Duration [min]

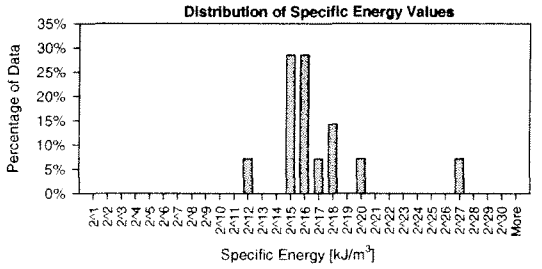

Distribution of Specific Energy Values
Percentage of Data
Specific Energy [kJ/m³]

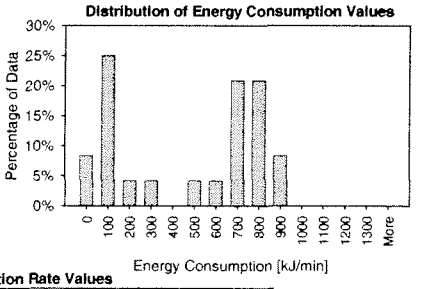

Distribution of Energy Consumption Values
Percentage of Data
Energy Consumption [kJ/min]

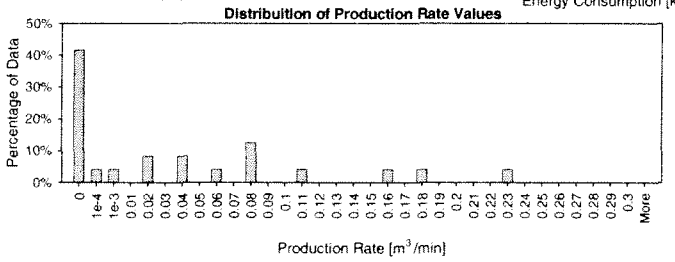

Distribution of Production Rate Values
Percentage of Data
Production Rate [m³/min]

Site 13 Data

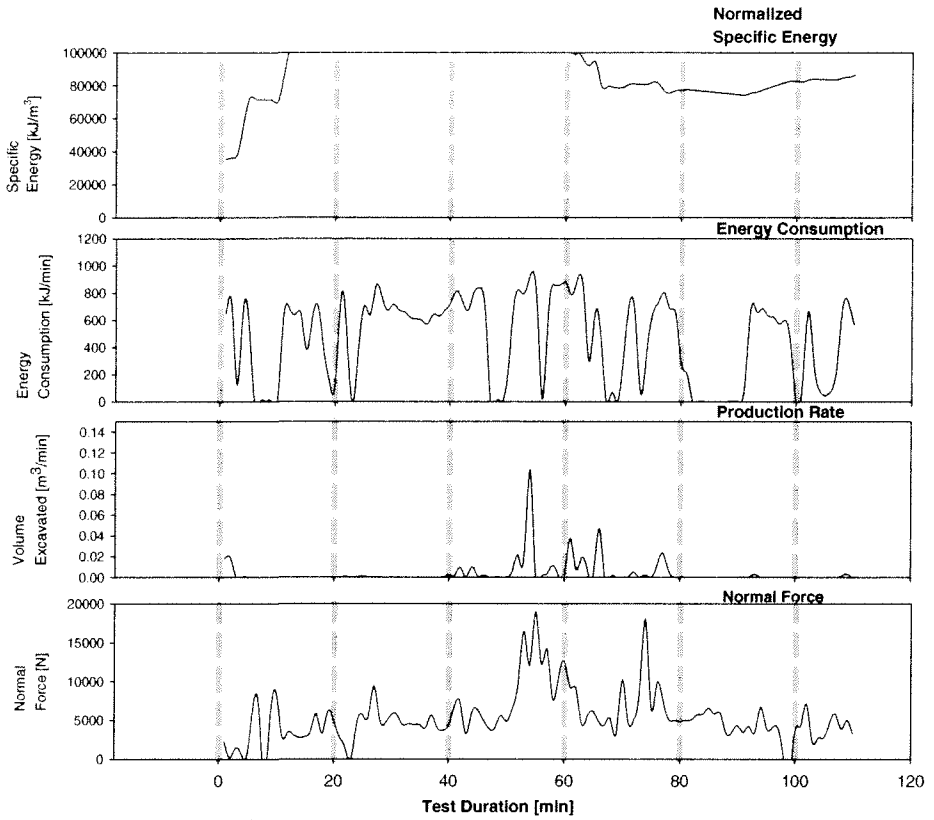

Normalized Specific Energy
Specific Energy [kJ/m³]
Energy Consumption
Energy Consumption [kJ/min]
Production Rate
Volume Excavated [m³/min]
Normal Force
Normal Force [N]
Test Duration [min]

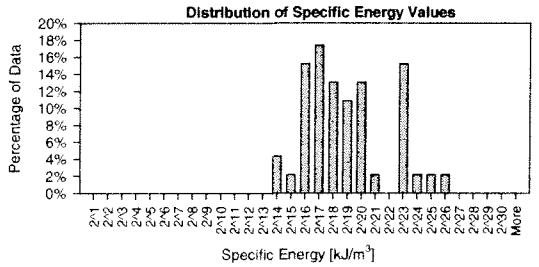

Distribution of Specific Energy Values
Percentage of Data
Specific Energy [kJ/m³]

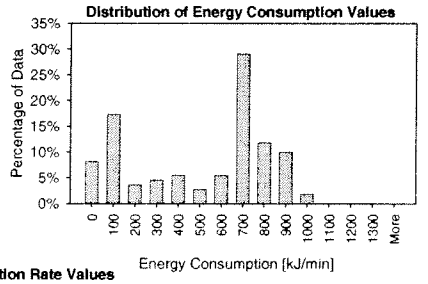

Distribution of Energy Consumption Values
Percentage of Data
Energy Consumption [kJ/min]

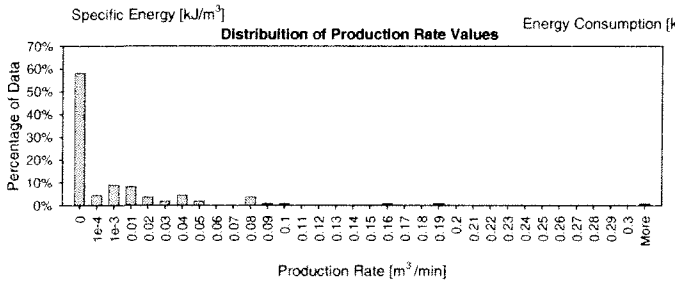

Distribution of Production Rate Values
Percentage of Data
Production Rate [m³/min]

Site 14 Data

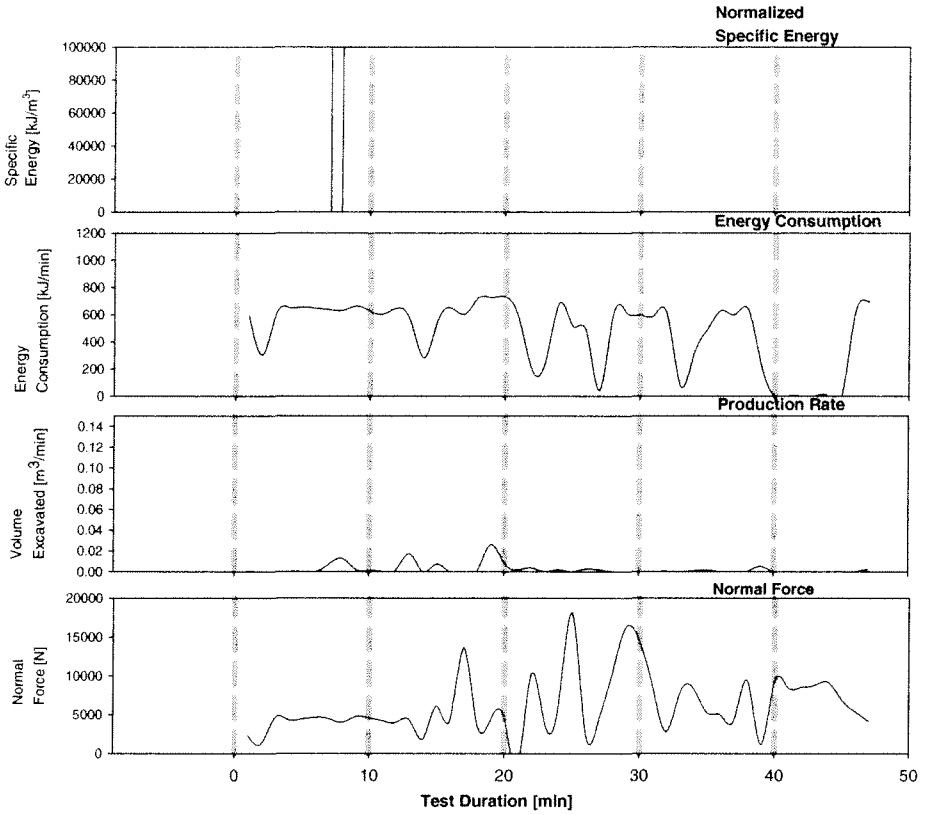

Normalized Specific Energy
Specific Energy [kJ/m³]
Energy Consumption
Energy Consumption [kJ/min]
Production Rate
Volume Excavated [m³/min]
Normal Force
Normal Force [N]
Test Duration [min]

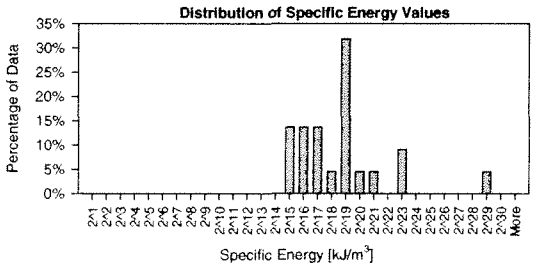

Distribution of Specific Energy Values
Percentage of Data
Specific Energy [kJ/m³]

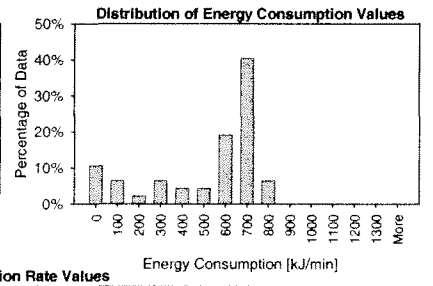

Distribution of Energy Consumption Values
Percentage of Data
Energy Consumption [kJ/min]

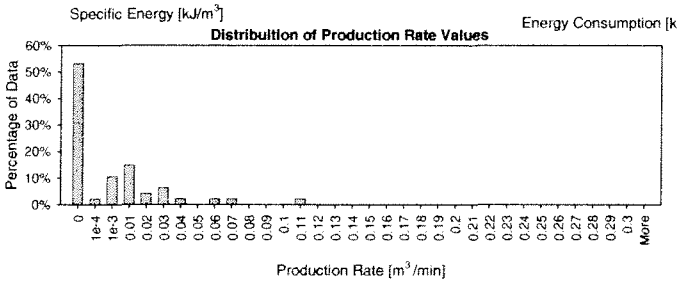

Distribution of Production Rate Values
Percentage of Data
Production Rate [m³/min]

Site 15 Data

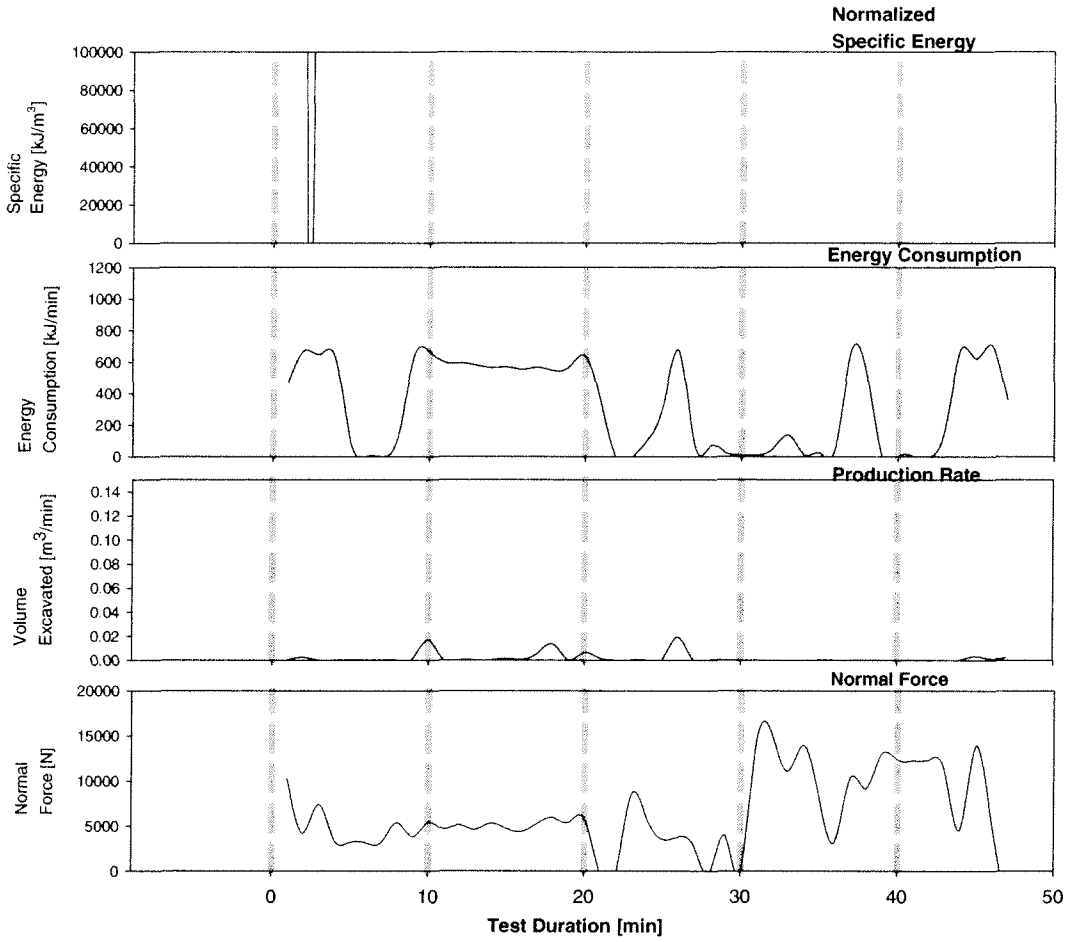

Normalized Specific Energy
Specific Energy [kJ/m³]
Energy Consumption
Energy Consumption [kJ/min]
Production Rate
Volume Excavated [m³/min]
Normal Force
Normal Force [N]
Test Duration [min]

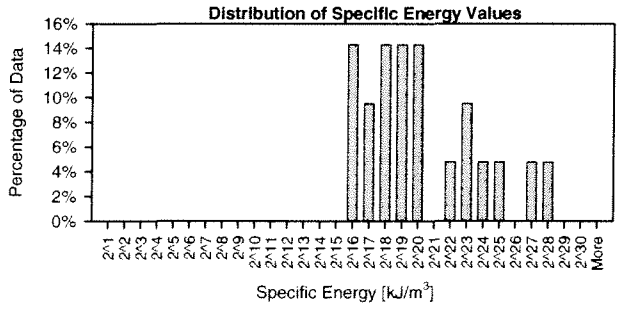

Distribution of Specific Energy Values
Percentage of Data
Specific Energy [kJ/m³]

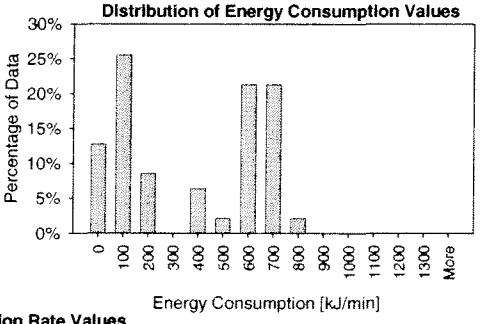

Distribution of Energy Consumption Values
Percentage of Data
Energy Consumption [kJ/min]

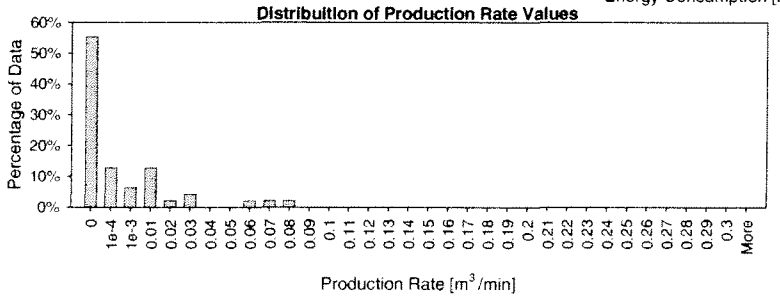

Distribution of Production Rate Values
Percentage of Data
Production Rate [m³/min]

Site 16 Data

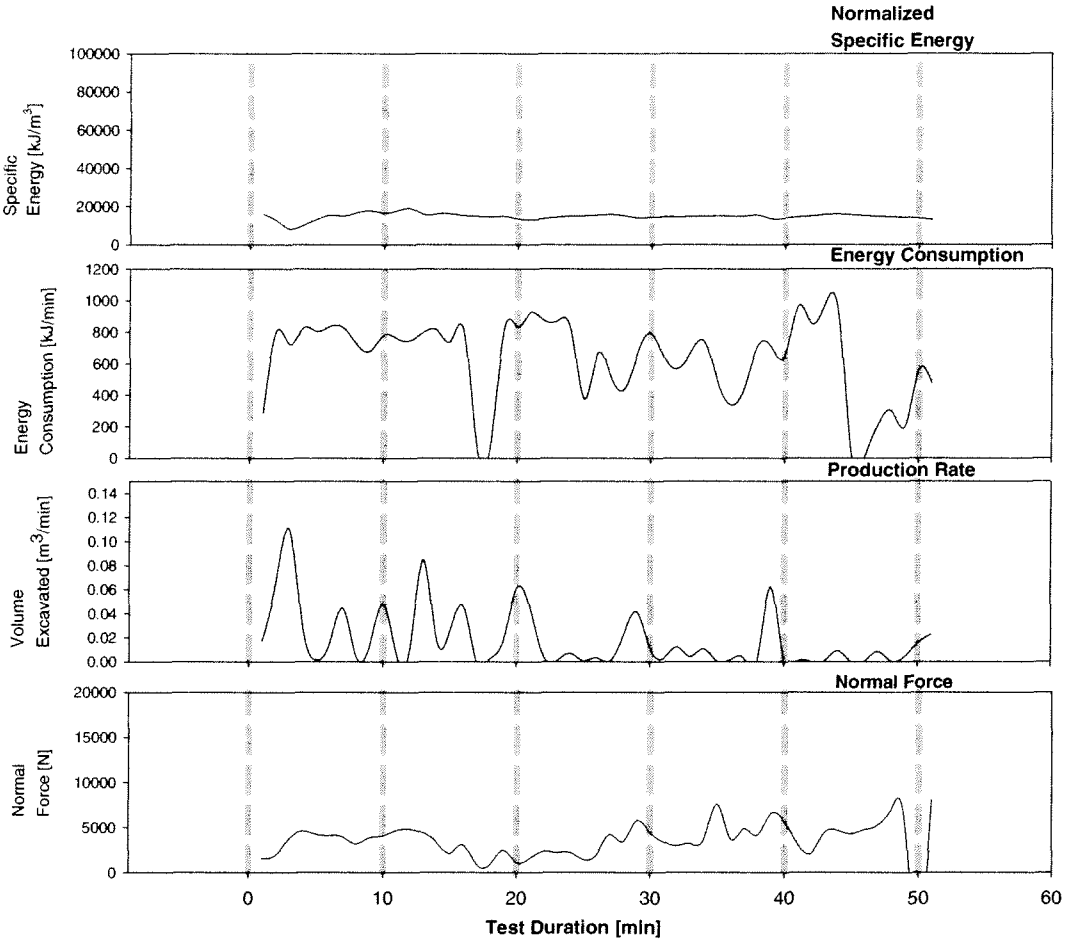

Normalized Specific Energy
Specific Energy [kJ/m³]
Energy Consumption
Energy Consumption [kJ/min]
Production Rate
Volume Excavated [m³/min]
Normal Force
Normal Force [N]
Test Duration [min]

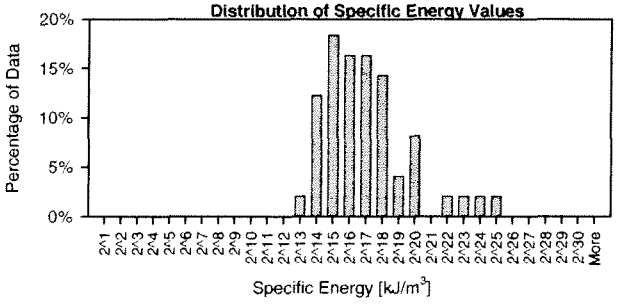

Distribution of Specific Energy Values
Percentage of Data
Specific Energy [kJ/m³]

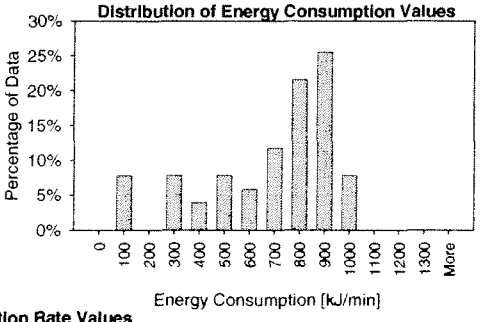

Distribution of Energy Consumption Values
Percentage of Data
Energy Consumption [kJ/min]

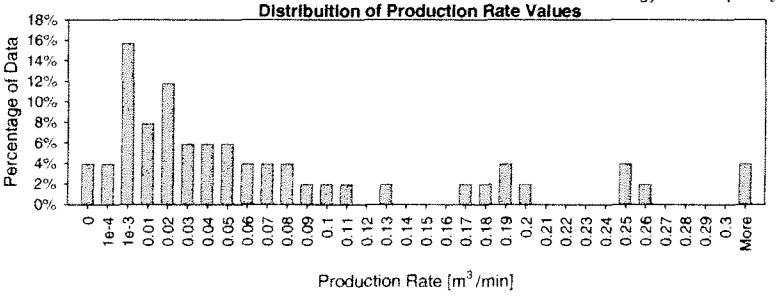

Distribution of Production Rate Values
Percentage of Data
Production Rate [m³/min]

Site 18 Data

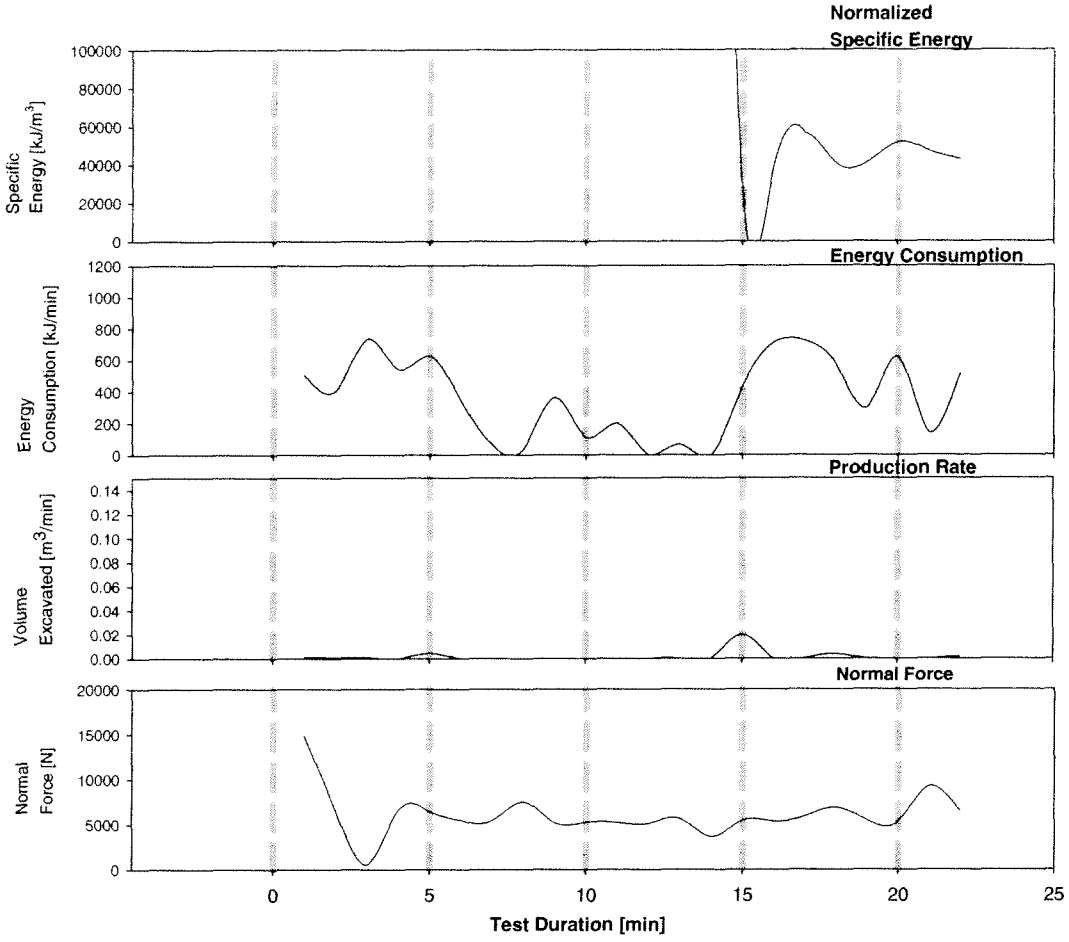

Normalized Specific Energy
Specific Energy [kJ/m³]
Energy Consumption
Energy Consumption [kJ/min]
Production Rate
Volume Excavated [m³/min]
Normal Force
Normal Force [N]
Test Duration [min]

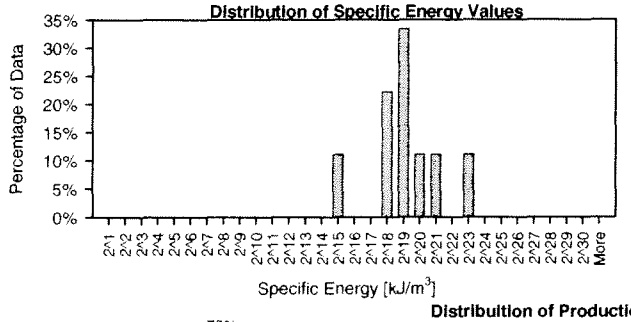

Distribution of Specific Energy Values
Percentage of Data
Specific Energy [kJ/m³]

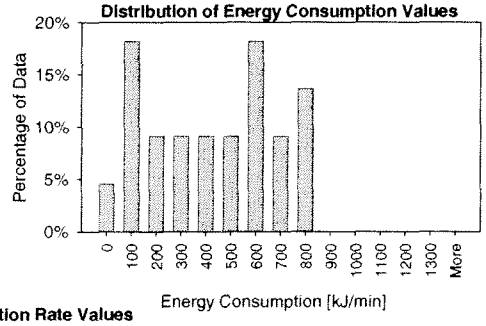

Distribution of Energy Consumption Values
Percentage of Data
Energy Consumption [kJ/min]

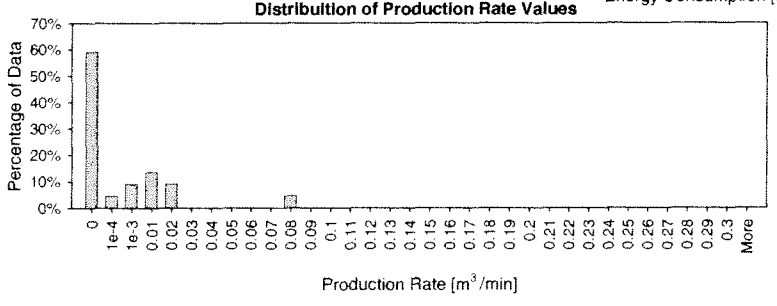

Distribution of Production Rate Values
Percentage of Data
Production Rate [m³/min]

Site 20 Data

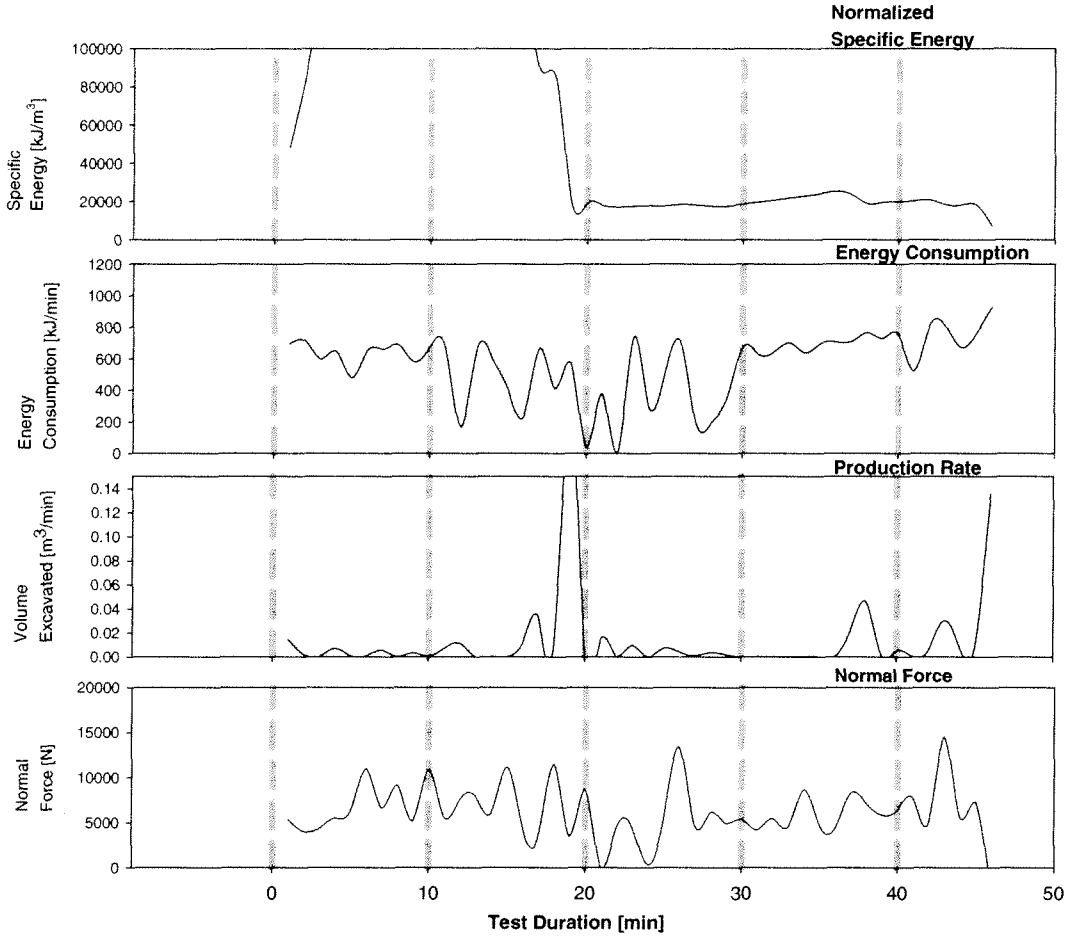

Normalized Specific Energy
Specific Energy [kJ/m3]
Energy Consumption
Energy Consumption [kJ/min]
Production Rate
Volume Excavated [m3/min]
Normal Force
Normal Force [N]
Test Duration [min]

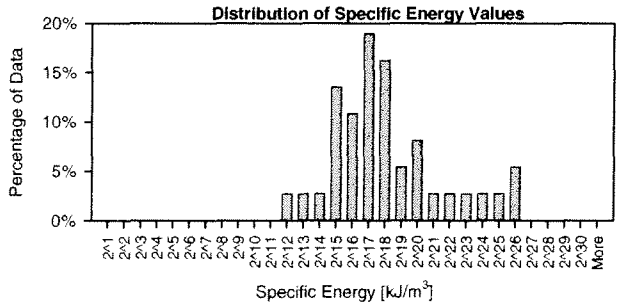

Distribution of Specific Energy Values
Percentage of Data
Specific Energy [kJ/m3]

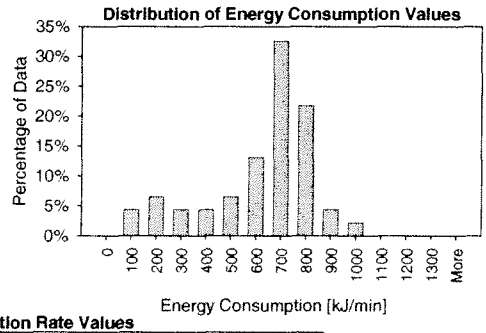

Distribution of Energy Consumption Values
Percentage of Data
Energy Consumption [kJ/min]

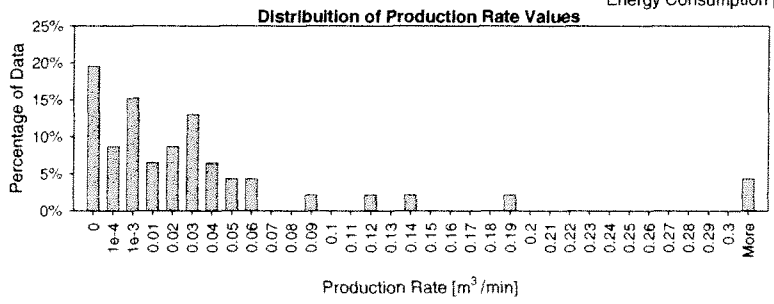

Distribution of Production Rate Values
Percentage of Data
Production Rate [m3/min]

Site 21 Data

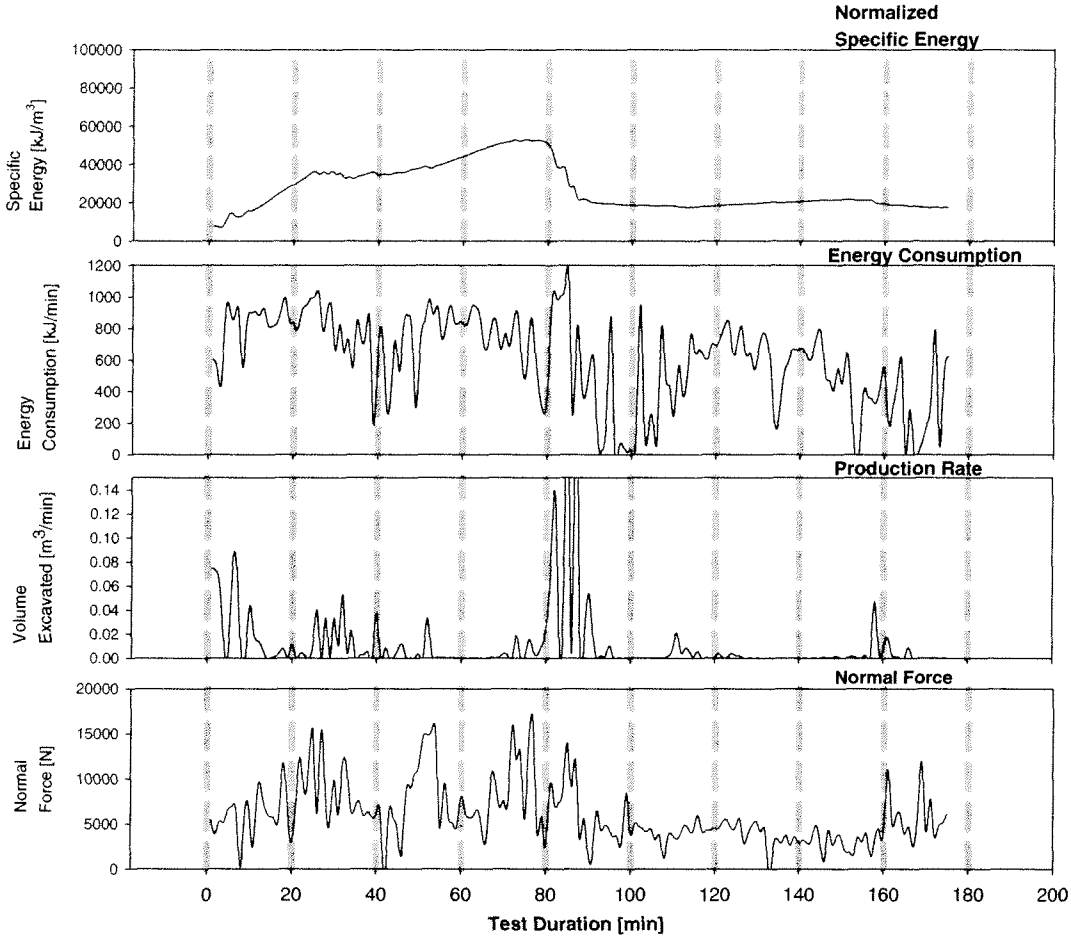

Normalized Specific Energy
Specific Energy [kJ/m³]
Energy Consumption
Energy Consumption [kJ/min]
Production Rate
Volume Excavated [m³/min]
Normal Force
Normal Force [N]
Test Duration [min]

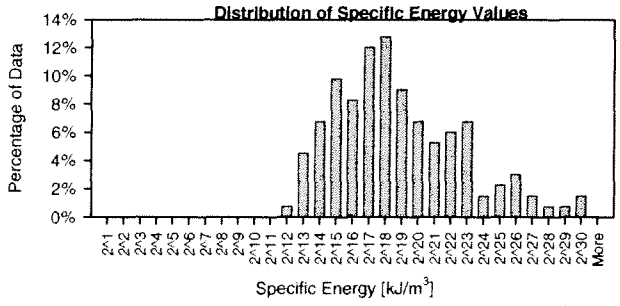

Distribution of Specific Energy Values
Percentage of Data
Specific Energy [kJ/m³]

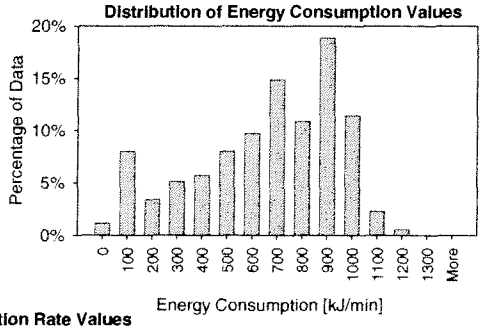

Distribution of Energy Consumption Values
Percentage of Data
Energy Consumption [kJ/min]

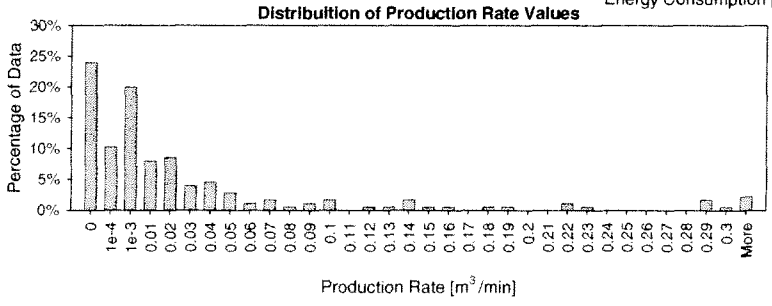

Distribution of Production Rate Values
Percentage of Data
Production Rate [m³/min]

Site 22 Data

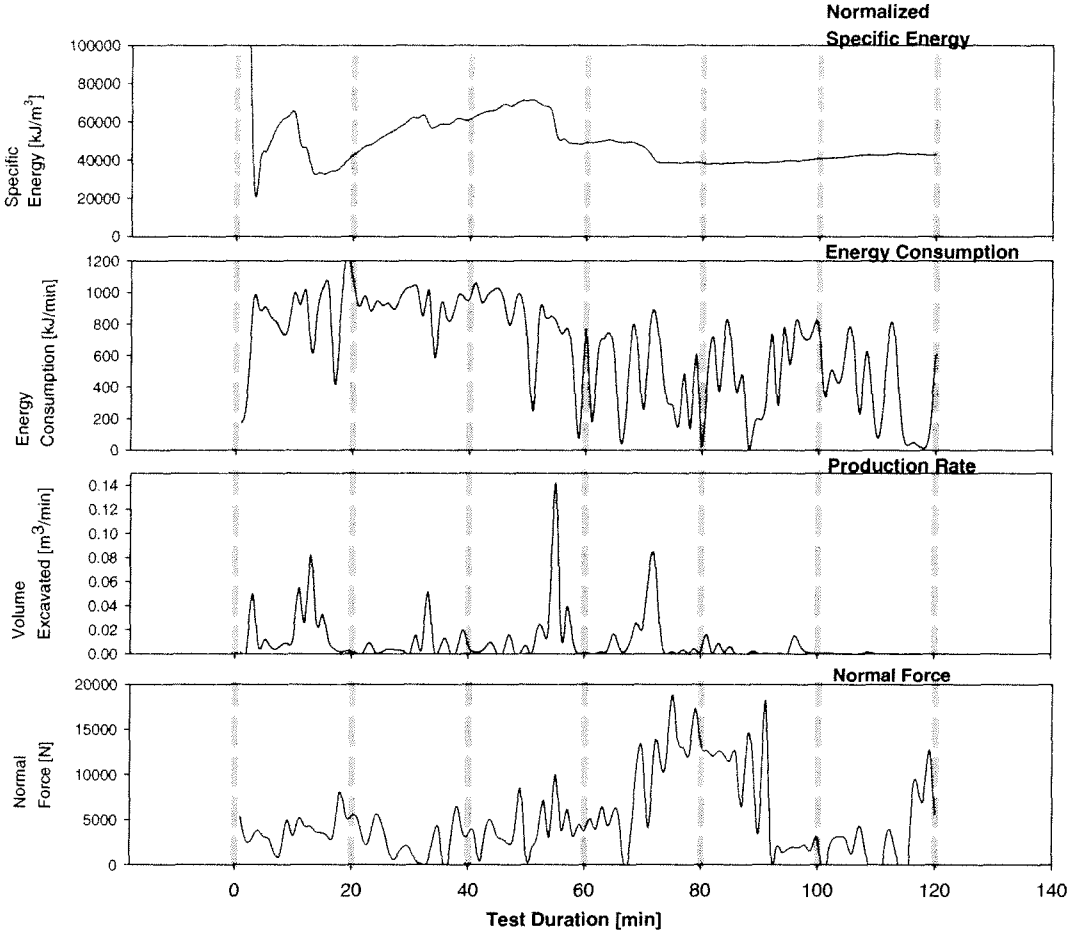

Normalized Specific Energy
Specific Energy [kJ/m3]
Energy Consumption
Energy Consumption [kJ/min]
Production Rate
Volume Excavated [m3/min]
Normal Force
Normal Force [N]
Test Duration [min]

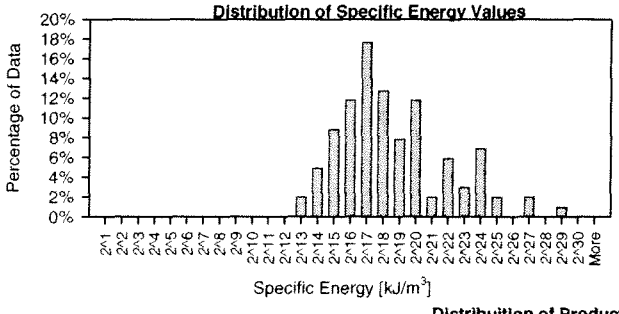

Distribution of Specific Energy Values
Percentage of Data
Specific Energy [kJ/m3]

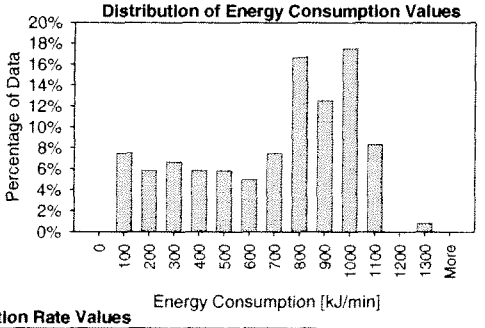

Distribution of Energy Consumption Values
Percentage of Data
Energy Consumption [kJ/min]

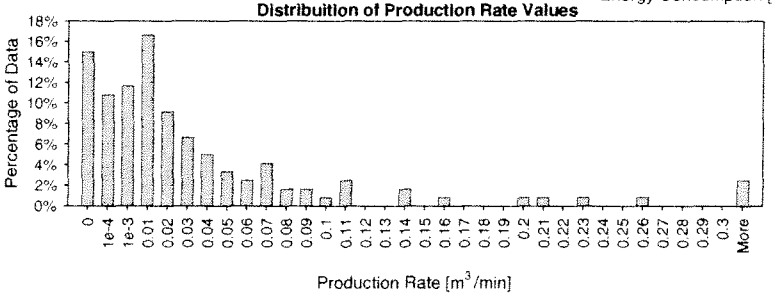

Distribution of Production Rate Values
Percentage of Data
Production Rate [m3/min]

Site 23 Data

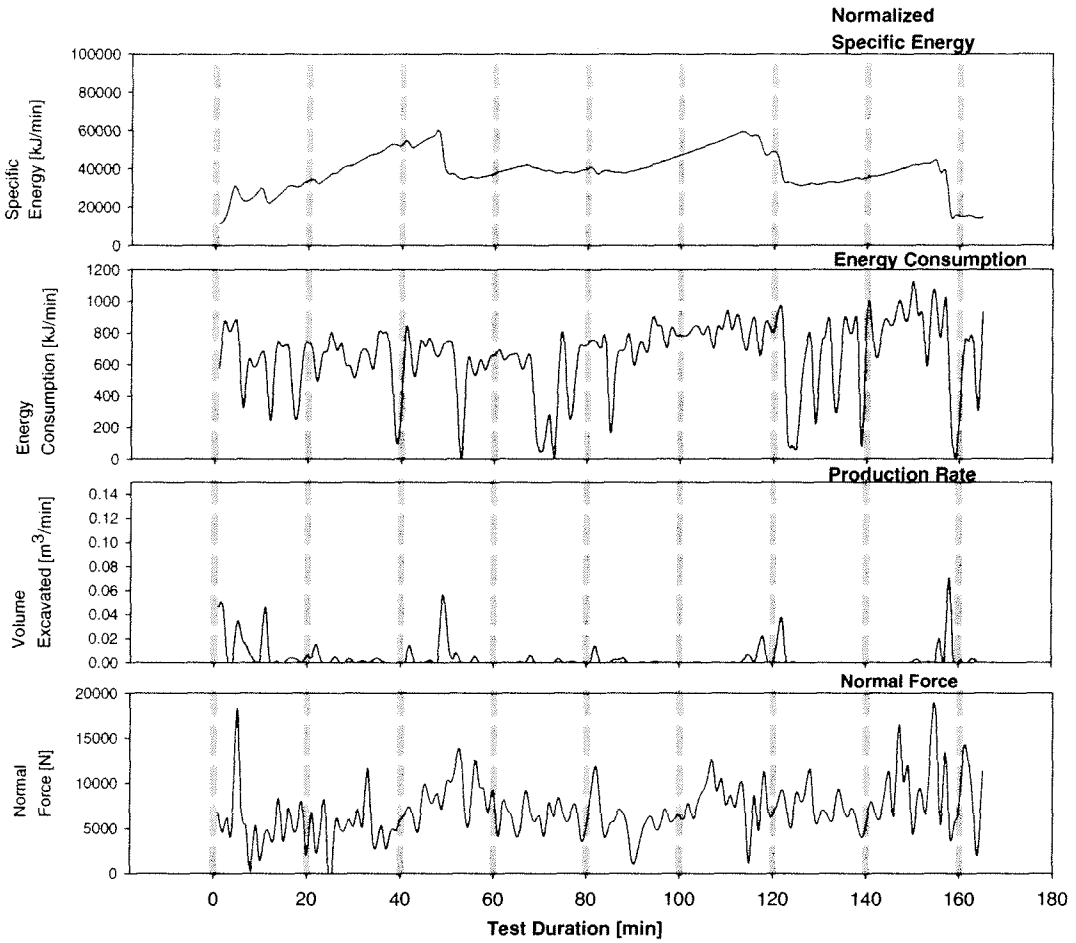

Normalized Specific Energy
Specific Energy [kJ/m3]
Energy Consumption
Energy Consumption [kJ/min]
Production Rate
Volume Excavated [m3/min]
Normal Force
Normal Force [N]
Test Duration [min]

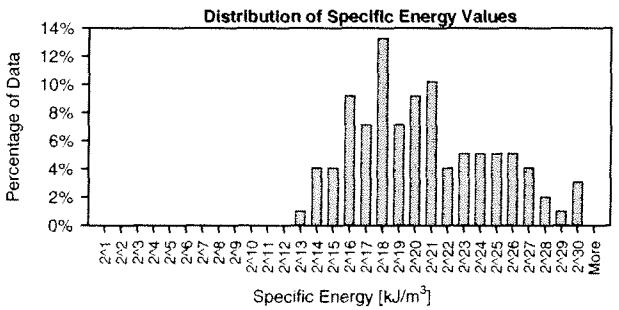

Distribution of Specific Energy Values
Percentage of Data
Specific Energy [kJ/m3]

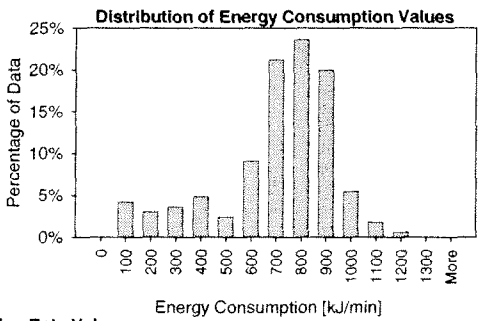

Distribution of Energy Consumption Values
Percentage of Data
Energy Consumption [kJ/min]

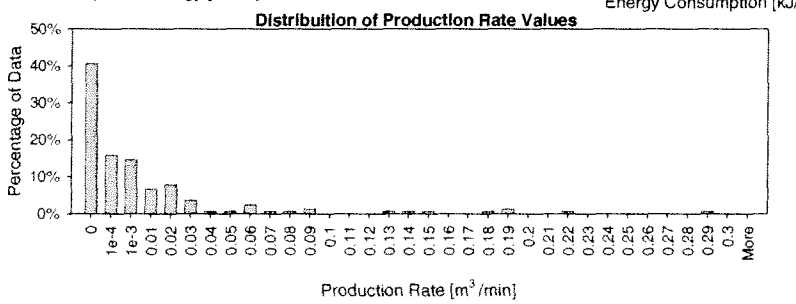

Distribuition of Production Rate Values
Percentage of Data
Production Rate [m3/min]

Site 24 Data

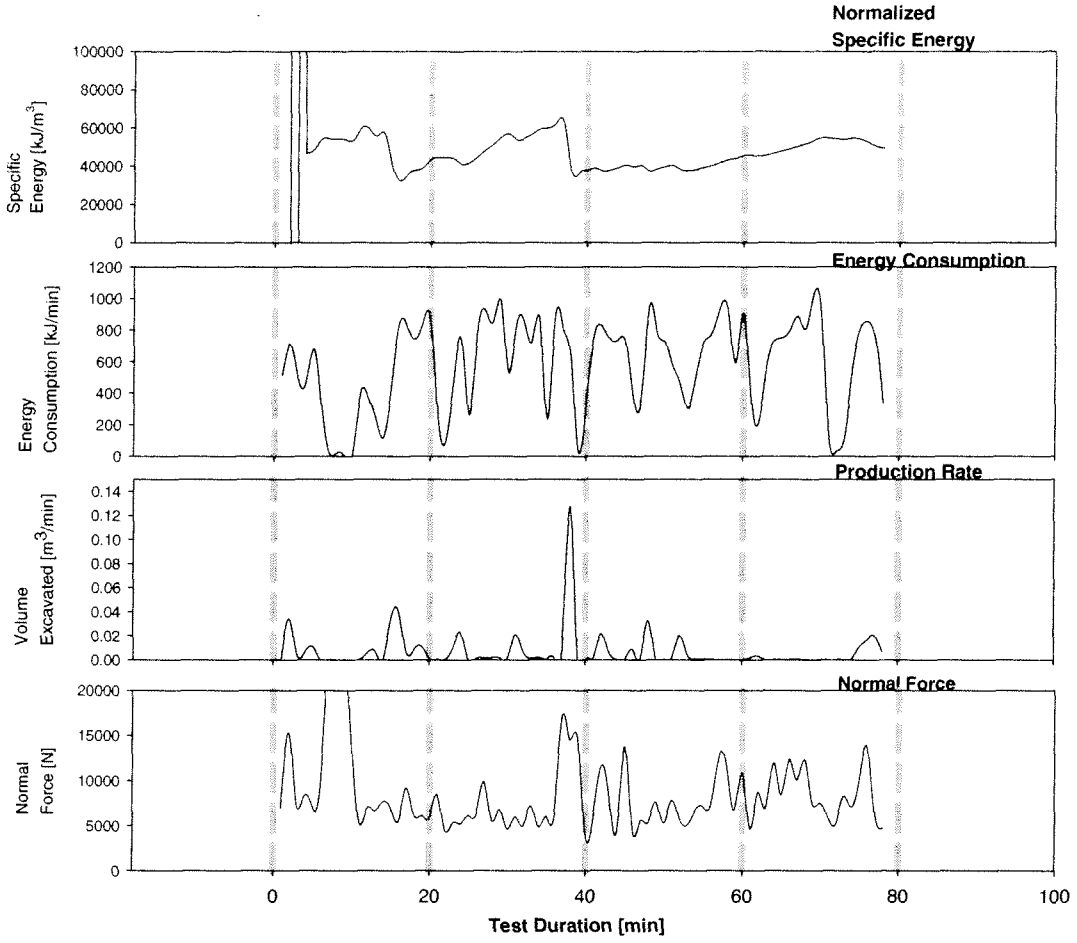

Normalized Specific Energy
Specific Energy [kJ/min]
Energy Consumption
Energy Consumption [kJ/min]
Production Rate
Volume Excavated [m3/min]
Normal Force
Normal Force [N]
Test Duration [min]

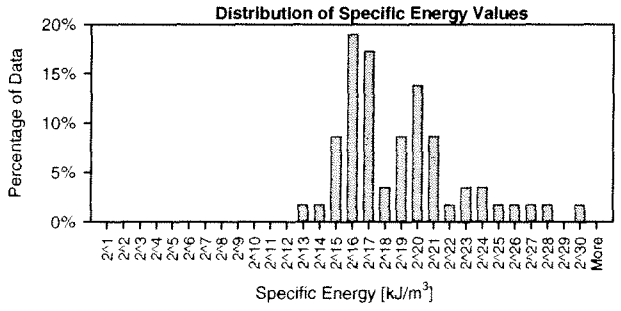

Distribution of Specific Energy Values
Percentage of Data
Specific Energy [kJ/m3]

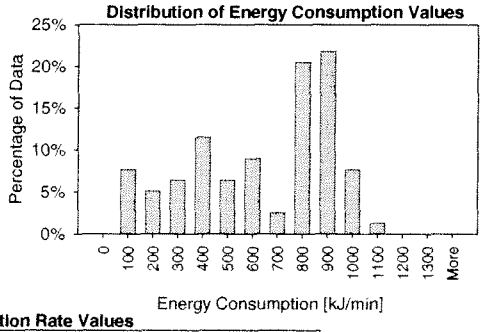

Distribution of Energy Consumption Values
Percentage of Data
Energy Consumption [kJ/min]

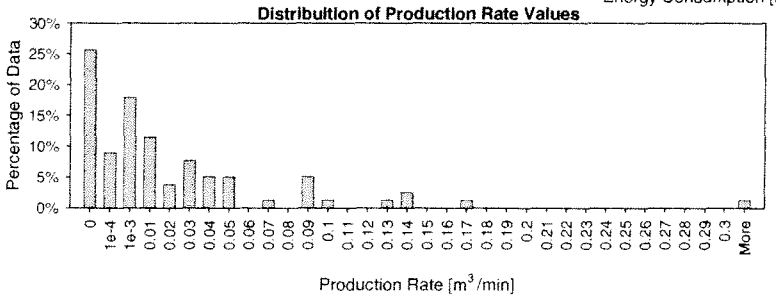

Distribution of Production Rate Values
Percentage of Data
Production Rate [m3/min]

Site 25 Data

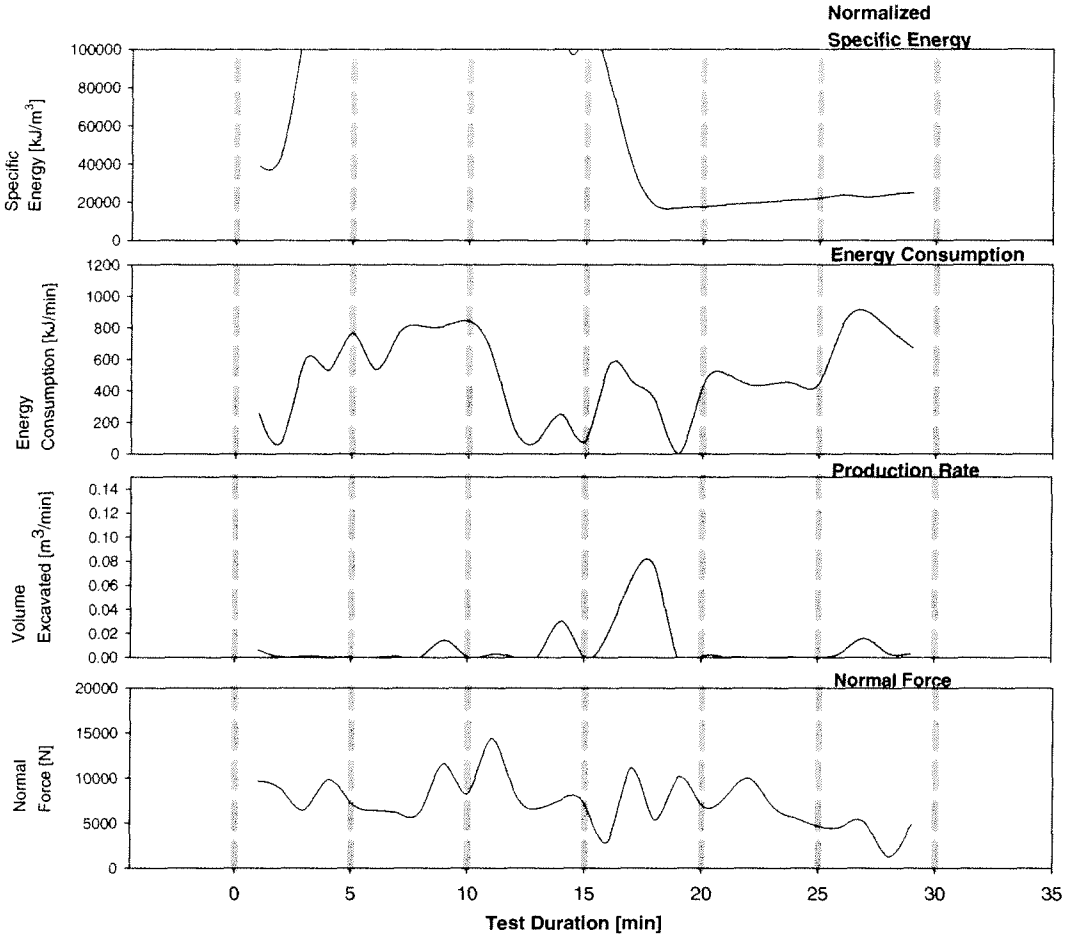

Normalized Specific Energy
Specific Energy [kJ/m³]
Energy Consumption
Energy Consumption [kJ/min]
Production Rate
Volume Excavated [m³/min]
Normal Force
Normal Force [N]
Test Duration [min]

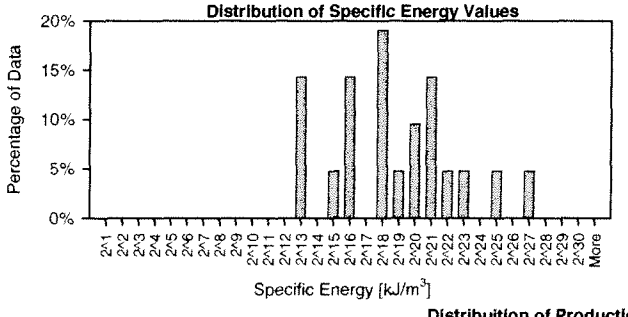

Distribution of Specific Energy Values
Percentage of Data
Specific Energy [kJ/m³]

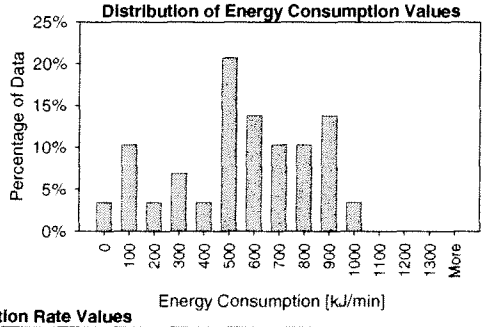

Distribution of Energy Consumption Values
Percentage of Data
Energy Consumption [kJ/min]

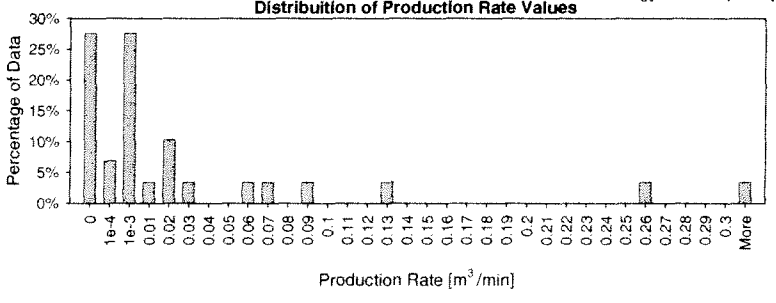

Distribution of Production Rate Values
Percentage of Data
Production Rate [m³/min]

Site 26 Data

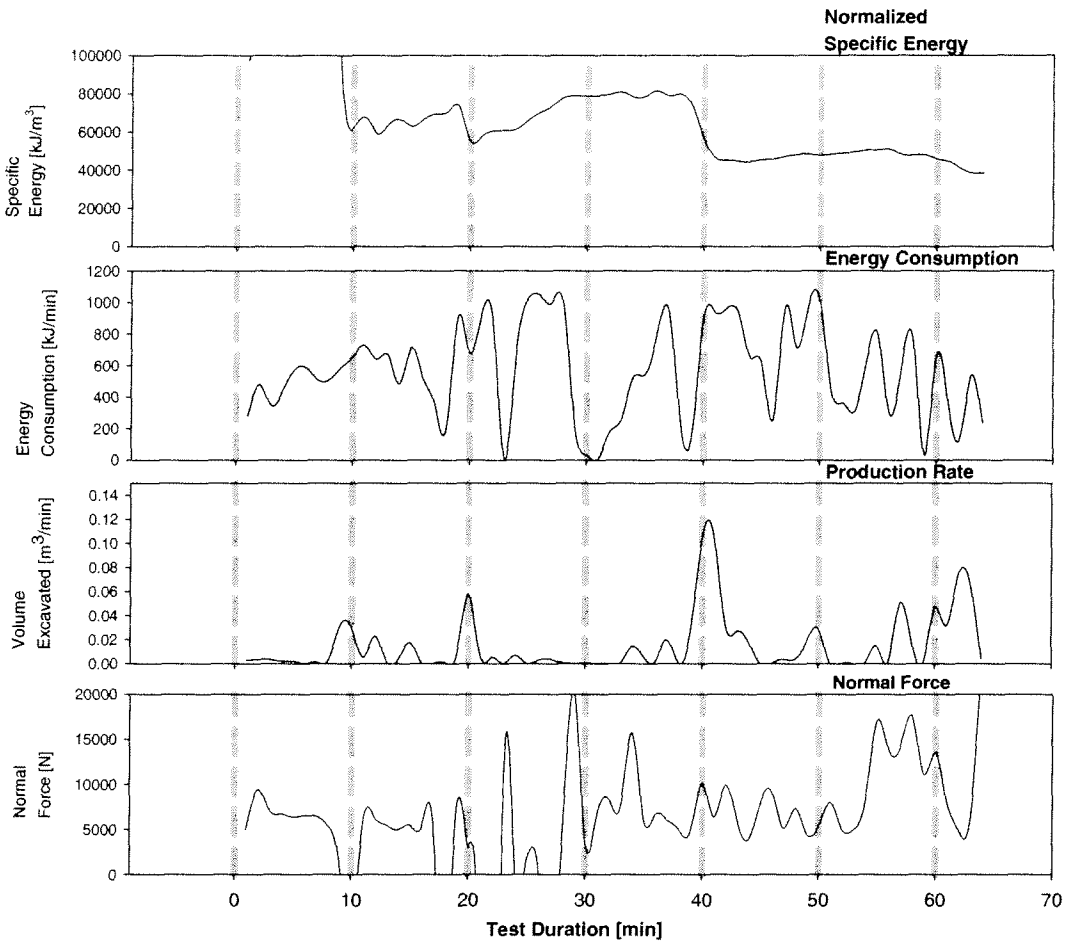

Normalized Specific Energy
Specific Energy [kJ/m3]
Energy Consumption
Energy Consumption [kJ/min]
Production Rate
Volume Excavated [m3/min]
Normal Force
Normal Force [N]
Test Duration [min]

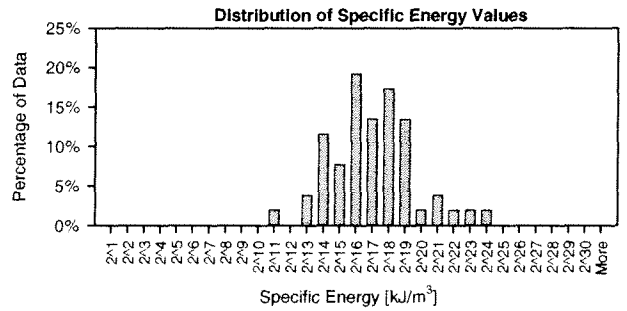

Distribution of Specific Energy Values
Percentage of Data
Specific Energy [kJ/m3]

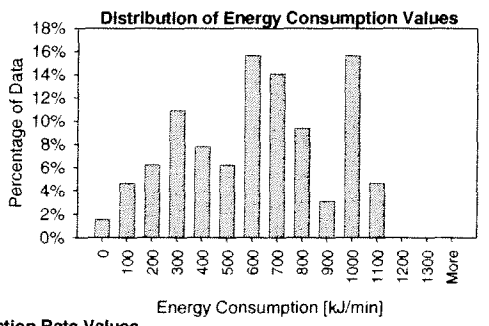

Distribution of Energy Consumption Values
Percentage of Data
Energy Consumption [kJ/min]

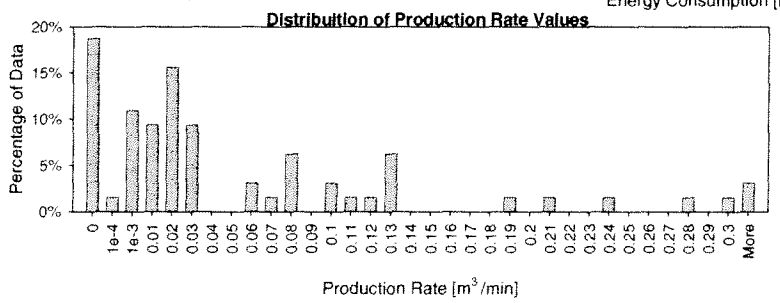

Distribuition of Production Rate Values
Percentage of Data
Production Rate [m3/min]

Site 27 Data


Normalized Specific Energy
Specific Energy [kJ/m3]
Energy Consumption
Energy Consumption [kJ/min]
Production Rate
Volume Excavated [m3/min]
Normal Force
Normal Force [N]
Test Duration [min]


Distribution of Specific Energy Values
Percentage of Data
Specific Energy [kJ/m3]


Distribution of Energy Consumption Values
Percentage of Data
Energy Consumption [kJ/min]


Distribution of Production Rate Values
Percentage of Data
Production Rate [m3/min]