THE DEVELOPMENT OF A TUNABLE CLAY WINNING JET

BİR AYARLANABİLİR KİL ÇIKARMA JETİNİN GELİŞTİRİLMESİ

T.W.DAVIES*

Keywords : Hydraulic Mining, Water Jets, China Qay.

ÖZET

Bu çalışmada China kili hidrolik madenciliği üzerine yapılan deneysel ön çalışmamızın ve geniş boyutlu su jetinin iki fazlı tabiatı üzerine yapılan deneysel çalışmamızın sonuçlan birlikte incelendi. Hem jet oluşturulması heni de malzeme çıkarılması için aşın seki şartlanna ilişkin optimum jet etkisi özelliklerinin aralığını tahmin etmek için sonuçların exrapilasyonunu mümkün kılan basit modeller geliştirildi. Bir bakir sekide madencilik için tahmin edilen nozzle şartlan aralıkları şunlardır

$$0 < \frac{x}{d_0} < 100$$

$$500 < P_0 < 1000kPa$$

$$0.023 < d_0 < 0.043m$$

Bu aralıklar ocaktaki ve çalışma şartlanndaki sık değişmelerin üstesinden gelmek için bir değişken çaplı nozzle'a sahip olan uzaktan kumandalı ve hareket kabiliyetli bir su topu'nun gerekliliğini destekler.

ABSTRACT

Experimental results from a preliminary study of the hydraulic mining of china clay and of the two-phase nature of large scale water jets are combined. Simple models of both jet development and material removal are formulated, enabling exrapolation of the results to estimate the range of optimum jet impact characteristics corresponding to extremes of stope conditions. The estimated range of optimum nozzle conditions for the mining of virgin stope is:

$$0 < \frac{x}{d_0} < 100$$

$$500 < P_0 < 1000kPa$$

$$0.023 < d_0 < 0.043m$$

This range advocates the requirement for a remotely controlled mobile monitor equipped with a variable diameter nozzle to meet frequent changes in pit and operating conditions.

* **School of Engineering, Exeter University, Exeter, UK**

1. INTRODUCTION

1.1 Objectives

Large scale water jets are used to mine china clay from the St. Austell area of Cornwall. Monitors (water canons) are used to produce and direct the water jets which remove, disaggregate and subsequently slurry stope material. The slurry is then pumped downstream, where separation, chemical treatment and dewatering operations take place. Fig. 1 indicates the hardware and production parameters defining the existing mining system for a single monitor Table 1 indicates the parameter range in which current operations are conducted.

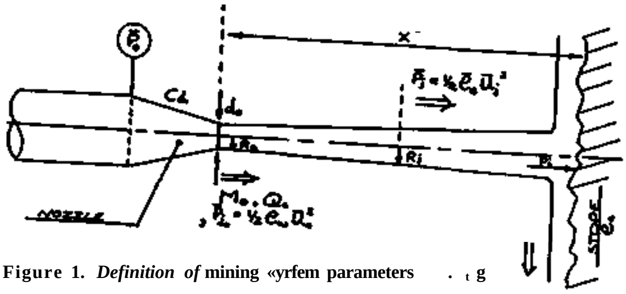

Figure 1. *Definition of* **mining «yrfem parameters** . ι g

TABLE I OPERATIONAL PARAMETER RANGES

Parameter	Range
Standoff distance, x	10 27 m
Nozzle pressure, P_0	690 2400 kPa
Nozzle flow rate, Q_0 (C_d=0 96)	0 018 - 0 34 $m^3 s^{-1}$
Nozzle diameter, d_0	0 0254 0 0588 m
Dimensionless standoff distance x/d_0	320 800

The optimum combination of values of hydraulic mining parameters is that which yields a maximum mining efficiency, characterised by a minimum specific energy of mining, *E*,, defined as the amount of energy required to remove a unit mass of stope material. In general this requires a move towards a minimum primary hydraulic power requirement and a maximum 'wash density', (i.e. mass of stope material slurried per unit volume of slurry returning from the stope).

Additional downstream efficiency credits are realised by increasing wash density since the volume of slurry processed per tonne of product clay is reduced. In this paper, however, attention is confined to the primary mining process.

1.2 Stope material

Naturally occurring or 'virgin' stope material consists of a matrix of St. Austell granite 'frozen' at various stages of kaolinisation. Depending upon the degree of kaolinisation the nature of the matrix deposit varies from soft, friable and thoroughly rotted to hard and unaltered. Larger fragments (0.05 - 2.0 m) of the harder consolidated rock form what is known locally as 'stent'. Stent consists of non granitic rocks, non and partially kaolinised granite. The term stent is a relative one and varies from stope to stope in both nature and quantity. Partially kaolinised material which constitutes stent in a soft pit may form the bulk of the matrix in a hard pit.

Non stent material is known collectively as the 'china clay matrix' and from a soil mechanical definition consists of material ranging from fine clay to medium gravel.

Fig. 2 indicates the particle size distributions of the matrix material for Treviscoe and Rocks pits - examples of hard and soft pits respectively. For the purposes of this study the boundary between china clay matrix material and stent is taken to be the approximate lOOdefining the efficiency of the primary hydraulic mining process, stent removal is assumed to require a negligible hydraulic power input.

Matrix properties vary considerably according to the degree of initial mechanical disaggregation resulting from the mining method and both pit and site location. Even at any one site inhomogeneity of stope matrix results in local spatial and temporal variations in matrix properties. Previous work (METCALFE, 1982) on the classification of stope material lends support to a subjective classification, according to relative hardness, adopted by English Clays Lovering Pochin Ltd. Fig. 3 indicates the correlation between moisture content and shear strength for a number of pits. The boundaries of the subjective classification are illustrated.

1.3 Mining technique

The objective of the mining technique is to remove systematically the china clay matrix from the stope, disaggregate and separate the matrix material from the stent and subsequently transport' the matrix material out of the pit.

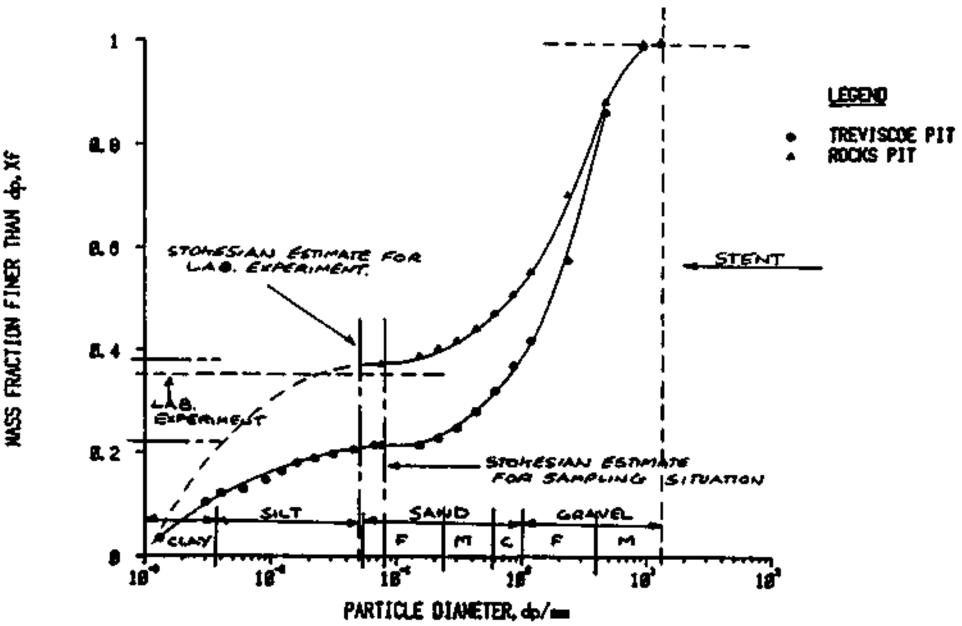

Figure 2. *Material particle size distribution*

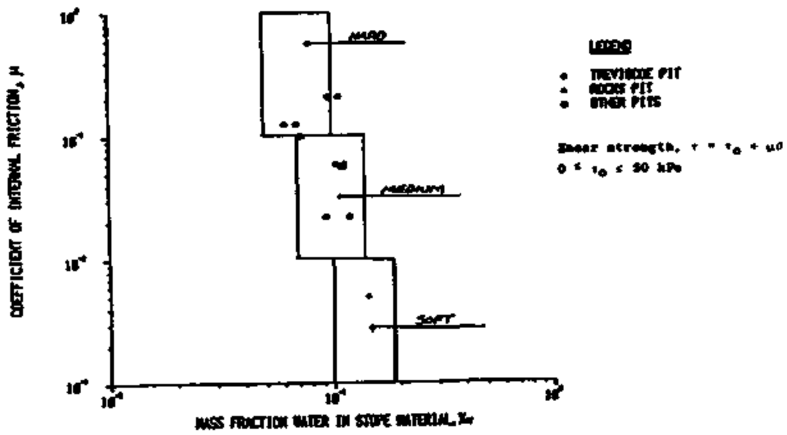

Figure 3. *Definition of material relative hardness*

Mining technique varies with relative hardness of stope material and relative pit size. Specification of product clay properties requires that slurry streams from pits of various hardness and size be blended.

In latter years, in order to increase dry clay production rates, the fraction of time that virgin stope is washed relative to 'blasted' or 'dozed' stopes, has been reduced. In this paper the mining of virgin, stope is taken to be the case where the removal of matrix from the stope is by hydraulic means only.

When mining virgin stope the monitor operator Uses the jet to erode and break out large pieces of matrix, thus causing rockfall. Weak areas, i.e. cracks or fissures of softer material, are sought out and exploited. Disaggregation of large pieces of matrix and washing of stope material to separate matrix from stent are performed at the foot of the stope. Stent removal plant (SRO), available 30% of the day and during daylight hours only, consists of a front end loader (FEL) and a team of dump trucks (DTs). SRP works in conjunction with the monitor. As stent accumulates at the foot of the stope progressive washings remove less matrix material and the wash density

as indicated by the opacity of the resultant slurry stream, falls to an unacceptably low level, e.g. **1005 *kg*** *m*~^{3} for a hard pit and 1015 *kg* m~^{3} for a soft pit. At this point the operator moves **the** jet to a new location, the FEL takes a 'bite' of stent and loads a DT, which transports the **stent** from the pit. Ideally the operator now returns the jet to the original location and washes out matrix exposed by stent removal. The concept of applied traversing rate has little meaning, except perhaps when mining uniform soft stopes. When mining virgin stope at Treviscoe (hard pit) wash densities of between 1005 and 1016 *kg m*~^{3} were obtained. Relatively high densities, 1030 - 1040 *kg m*~^{3}, were obtained for a short time if the stope was allowed to 'age' or 'weather'. At Rocks **(soft** pit) wash densities of between 1030 and 1080 *kg* m~^{3} were obtained.

Where stope material is so hard that over dilution of the slurry stream would occur or where **large** tonnages are required, blasting and/or ripping and dozing are employed. In such cases the **jet** is mainly employed to disaggregate, separate and transport matrix material.

At Treviscoe the stope is blasted once or twice weekly to produce rockfall and the monitor is used to wash the resultant pile of matrix and stent at the foot of the stope. The FEL, in addition **to** removing stent, may also assist by dozing blasted material into the path of the jet. This is taken as an example of mining blasted stopes. Wash densities of between 1005 and 1025 *kg* m~^{3} were witnessed.

At Rocks stope is ripped and then dozed to form piles of material which yield wash densities of up to 1200 *kg* m~^{3}. Blasting is resorted to only occasionally to remove massive intrusions of hard rock. This is taken as an example of mining dozed stopes. Dozed stopes are washed in conjunction with SRP as previously described. Dozed stopes are continually reconstructed by the FEL until 'blinding' by stent or gravel reduces the wash density to an unacceptably low level (1015 - 1020 *kg m*~^{3}), when washing ceases and stent and gravel are removed. Hence stent contents of between 0 and 60% are common as progressively more material is washed out.

Regardless of stope relative hardness, nozzle pressure and diameter are set in general to yield a given flow rate. Pressure and nozzle changes are made with regard to volume of 'coming' water (e.g. rainfall runoff) and dry clay production rate rather than with regard to wash density or power consumption. Standoff distance is determined by the minimum safe working distance from nozzle to stope and varies according to stope height, availability of appropriate supply piping lengths and monitor operation; hence the range indicated in Table 1.

1.4 Optimisation

The range of stope material properties encountered together within the range of operations that the monitor is required to perform during mining makes a general optimisation of mining parameters impossible.

The need for in situ optimisation establishes the requirement for a 'tunable clay winning jet'.

Previous work (JACKSON, 1981) indicates the potential gains that may be derived from a reduction in standoff distance. These arise due to the jet dynamic pressure decay characteristics of large scale water jets. Safe and efficient operation at reduced standoff distance (< lOOrfo) advocates the requirement for a remotely controlled mobile monitor. Such a monitor equipped with a variable area nozzle, permitting changes in nozzle flow-head characteristics, provides the mechanical facility to 'tune' the jet.

To permit nozzle design, the desired range of operating conditions must be estimated. These correspond to an estimate of optimum jet impact characteristics resulting from a range of stope conditions.

In this paper, experimental results from a preliminary study of the hydraulic mining of china clay from Treviscoe and Rocks pits and of the two phase nature of large scale water jets are combined. In view of the nature of preliminary data obtained optimbation b confined to mining of virgin stope.

From the results simple models of both jet development and material removal are formulated. The models enable extrapolation of the results to estimate the optimum jet impact characteristics corresponding to the extremes of stope conditions.

2. EXPERIMENTAL

2.1 Water jet characteristics

The jet was projected onto a perspex target plate held normal to the flow. Water was recirculated via a 12 m tank, above which the target plate, enclosed by a surrounding canopy, was situated. The pumps used to pressurise the water drew suction from the tank and discharged to the monitor via flexible hosing. Standoff distance was varied by moving the bogie on which the monitor was mounted along a railway track extending some 25 m from the tank in a direction normal to the target plate.

Jet dynamic pressure distributions were measured by means of a total pressure pitot tube designed according to B.S. 1042 Pt 2A and incorporating a 3 mm diameter piezo-electric pressure transducer.

The central traverse plane with respect to the vertical axis was accurately determined by initially noting that the output signal at a particular jet radius was a maximum and subsequently performing traverses in the central position and above and below. Radial traverses were accomplished in increments of 3 mm and 30 seconds of transducer output signal were recorded on an FM tape recorder at each station.

Jet impact pressure measurements were performed using an array of 20 pressure transducers flush mounted in the perspex target plate.

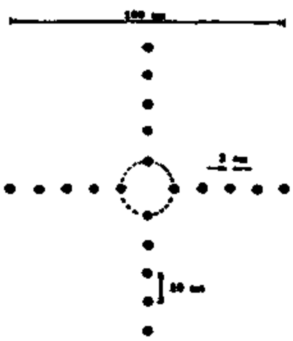

Figure *4. Impact pressure transducer array*

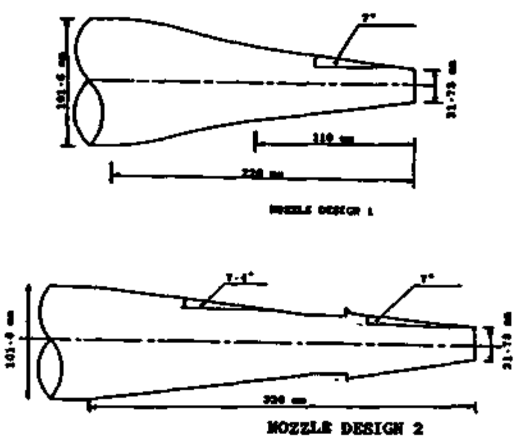

Figure 5. *The two nozzle designs*

The jet was centred on the array by moving the monitor barrel by means of hydraulic rams and noting that the signal levels from the 4 transducers on each spatial contour were equal. Thirty seconds of signal from each of the 5 spatial contours were recorded on a 4 channel FM tape recorder. All signals were subsequently replayed to a PDP 12 computer for analysis.

Nozzle pressure was measured using the same Bourdon gauge against which the transducers were calibrated. Nozzle designs used are illustrated in Fig. 5.

2.2 Material removal

Pit trials were conducted using nozzle designs similar to those of design 2. The range of mining conditions encountered during the trials is indicated in Table 2 Nozzle pressure was measured using a Bourdon gauge mounted on the monitor barrel. Pressure was varied by switching on or off second stage series mounted pumps and/or by passing flow to and from other monitors operating in the pit. Standoff distance was estimated from photographs used to augment a log which recorded stope condition, operator technique and SRP operations.

TABLE 2 PARAMETER RANGE DURING PIT TRIALS

Stope	$Po(kPa)$	$d_0(m)$	$x(m)$	x/d_0
Blasted	690 - 1310	0.041 - 0.045	10-20	220 - 490
Dozed	860 - 2000	0.038 - 0.045	10- 14	220 - 370
Virgin	690 - 2000	0.038 - 0.045	10- 18	220-480

Measurement of wash density was accomplished by dipping a bucket into the wash stream and pouring a sample into a container, shaking the container and then inserting a hydrometer. The specific gravity 15 seconds after termination of shaking was recorded. Precise timing of measurements was required at Treviscoe especially, since a rapid decay in density with time occurred. Laboratory sedimentation tests were performed in order to determine the mode of the settling process, and hence to estimate the fraction of stope material sedimented prior to wash density measurement. Stope material from Rocks pit, to which the particle size distribution of Fig. 2 refers, was used. Experiments were conducted for a range of slurry density (1008 - 1080 $kg\ m^{-3}$). Pitwash sampling frequency varied from between once per 30 seconds and once per 5 minutes and was most commonly once per minute. Rapid sampling was required due to fluctuations in wash density resulting from stope inhomogeneity and monitor operation. Sampling was performed as close to the stope as possible. Distance varied from 15 m to 75 m.

3. ANALYSIS OF RESULTS AND DISCUSSION

3.1 Water jet characteristics

Detailed analysis of pressure signals from both pitot and impact transducers has been undertaken, allowing complete quantitative description of the two-phase nature of large scale water jets. In this paper, however, only time average pressure distributions are presented.

Fig. 6 represents a typical time average jet dynamic radial pressure distribution. The data were obtained using nozzle design 2 at a standoff of 315 d and nozzle pressures of between 559 and 572 kPa. Various formulae, LEACH ,1966), SHAVLOVSKY (1977), VANAIDA (1980) have been used to fit such distributions including that of SCHLICRTING (1968):-

$$\frac{P_j}{P_{j_{max}}} = f(\eta) = (1 - \eta^{1.5})^2 \qquad where \qquad \eta = \frac{R_j}{R_{j_{max}}} \tag{1}$$

The above formula was selected for simplicity. In Fig. 6 jet dynamic pressure is non-dimensionalised with respect to nozzle pressure, P_0 . The best fit curve corresponding to Pj_{mai}/Po — 0.3 and Rj_{maz}/Ro = 6.3 is indicated by the solid line. Reproducibility, governed by ambient operating conditions and determination of the central traverse plane, is about ±6% *(±14kPa).*

Fig 7 indicates time average jet impact radial pressure distributions obtained experimentally and curve fitted using Eqn. 1. Eqn. 1 adequately represents both jet dynamic and jet impact[1] pressure distributions.

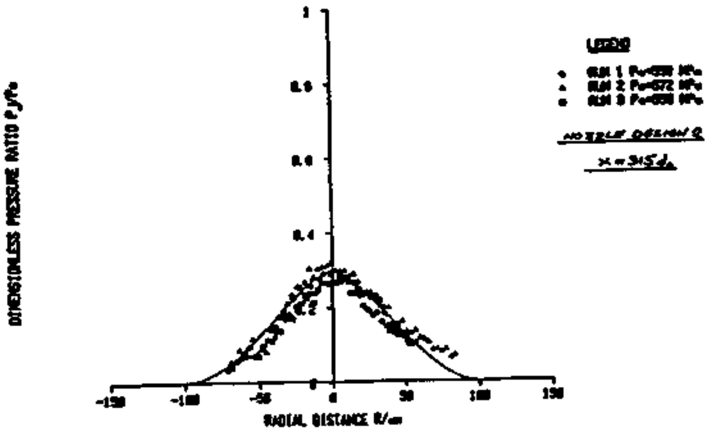

Figure 6. *Time averaged jet dynamic pressure distribution*

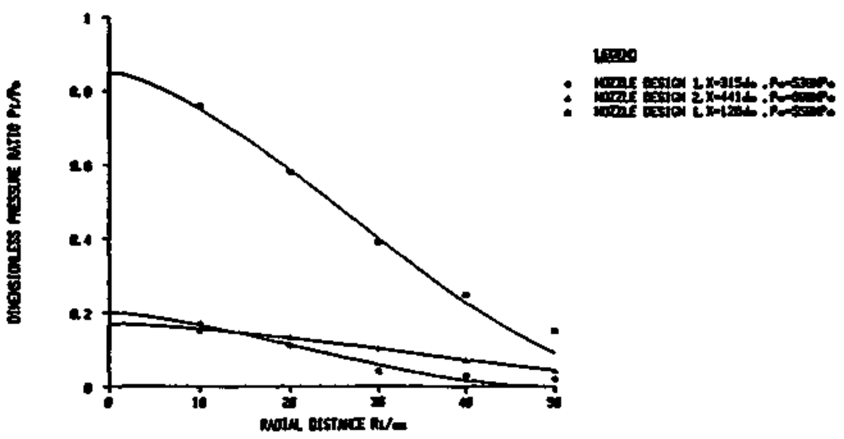

Figure 7. *Time averaged jet impact pressure distributions*

Fig. 8 suggests a simple model of axial jet dynamic pressure decay, namely that minimal pressure decay occurs within the initial 100 do , followed by a power law decay thereafter. Maximum or centre-line pressure decay is non-dimensionalised with respect to nozzle pressure and plotted against non- dimensionalised standoff on log-log coordinates. Differences between nozzle designs 1 and 2 appear to have little effect on pressure decay and for the purposes of correlating material excavation rates the data are combined. The equation describing pressure decay is given by:- :

$$\frac{P_{j\,max}}{P_0} = 1, \qquad \frac{x}{d_0} \le 100, \qquad \frac{P_{j\,max}}{P_0} = C\frac{x^k}{d_0}, \qquad \frac{x}{d_0} \ge 100 \tag{2}$$

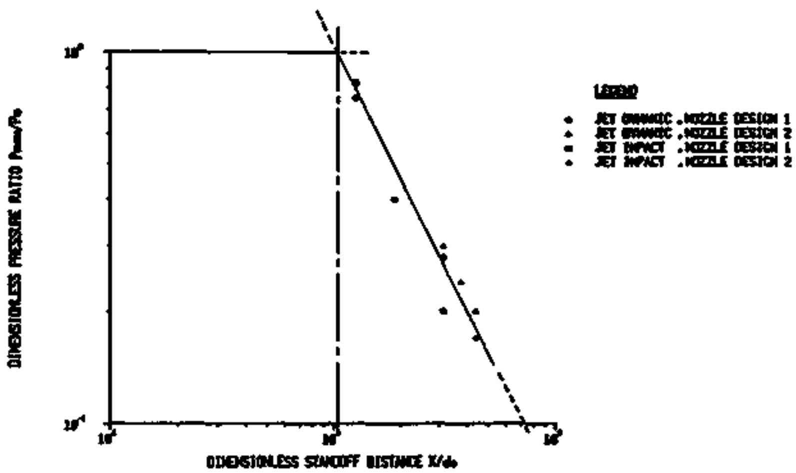

Figure 8. *Axial jet dynamic pressure decay*

A least squares fit gives C = 240, k = - 1.19. Jet dynamic pressure is given by:-

$$P_j = 0.5\rho U_j^2 \tag{3}$$

Jet dynamic pressure decay occurs as a result of the combined effects of aerodynamic drag and jet breakup. These manifest themselves as air entrainment, or a reduction in the effective homogeneous density of the jet fluid, and velocity decay. The point at which pressure decay commences corresponds to the limit of the potential core in which no velocity decay or air entrainment occurs. Integration of Eqn. 1 gives the ratio of radial mean pressure to maximum pressure Pm/Pj_{max} = 0.257, valid for x/d_0 > 100. Hence the equation governing radial mean pressure decay is given by:-

$$\frac{P_m}{P_0} = 61.7\frac{x}{d_0}^{-1\,19}, \qquad \frac{x}{d_0} \ge 100 \tag{4}$$

3.2 Material removal

Figs 9 and 10 show some results from pit trials at Treviscoe and Rocks pits respectively. Dry matrix material removal rates, Af$_o$ are plotted against radial mean jet dynamic pressure, P_m. M_c is calculated from experimental measurements of pit wash density,/),, using the following equation derived from a material balance:-

$$M_c = \frac{\frac{\rho_c}{\rho_w}\left\{\frac{\rho_s-\rho_w}{\rho_c-\rho_w}\right\} M_0}{x_f\left[1-\frac{\rho_c}{\rho_w}\left\{\frac{\rho_s-\rho_w}{\rho_c-\rho_w}\right\}\left\{\frac{x_w \times x_f}{1-x_f}\right\}\right]} \tag{5}$$

where: $M_0 = 8.94 \times 10^2 . C_d . d_0^2 . \rho_w (P_0/\rho_w)^{0.5}$ tonnes per hour.

Required are z, , the mass fraction of matrix material removed **that is sampled and x the' mass** fraction of water present in matrix mat*-;»] «™pl ea, **ana** x«, , the

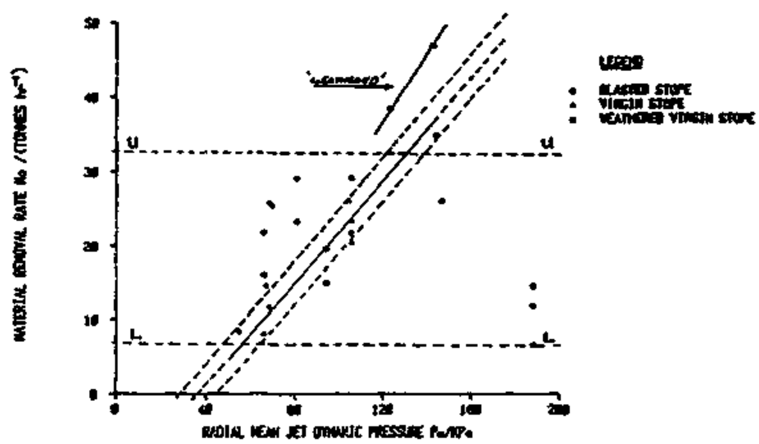

Figure 9. *Material removal rate versus radtal mean jet dynamic pressure (Trevtscoe ptt)*

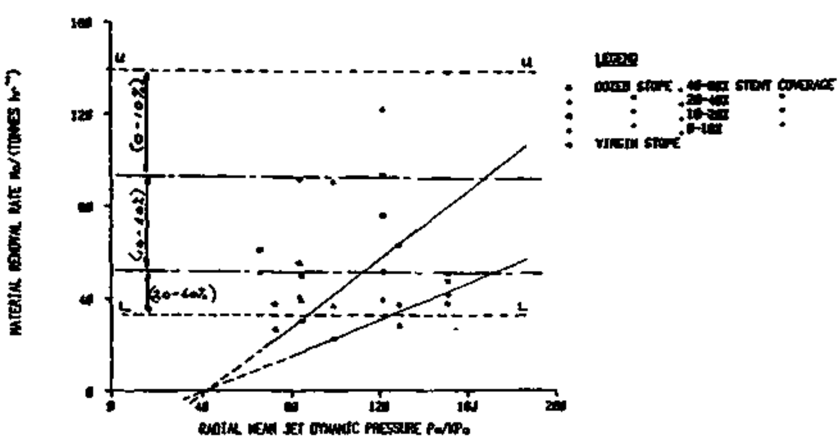

Figure 10. *Material removal rate versus radial mean jet dynamic pressure (Rocks pit)*

From sedimentation experiments it was determined **that all material of particle size greater^** than that remaining in suspension during density **measurement sedimented in the free or Stokesian** mode. Via the particle size distribution **of Fie. 2 laboratory sedimentation results are shown to** agree well with Stokesian theory. Calculating the particle size which would have settled in 15 seconds during pit measurements, *Xj* may be estimated from Fig. 2. In practice a large percentage of the medium and fine gravel would rapidly fall out of suspension and not be slurried or subsequently sampled, *xj* is calculated as 0.22 and 0.38 for Treviscoe and Rocks pits respectively. From Fig. 3 x_w is taken to be 0.06 and 0.14 for Treviscoe and Rocks pits respectively.

From Figs 9 and 10 the effects of stope type, stope relative hardness and stent removal operations may be inferred. For virgin stope material removal rates are linearly dependent upon impact pressure and may be simply modelled according to:-

$$M_c = K_r(P_m - P_t) \quad tonnes \quad hr^{-1} \tag{6}$$

This equation implies that a given threshold pressure P_t has to be exceeded before material removal occurs. For both pits P_t lies between 35.6± 9 kPa. K_T varies between 0.35 - 0.47 tonnes $hr^{-1}kPa^{-1}$ at Treviscoe and between 0.40 - 0.74 tonne* $hr^{-1}kPa^{-1}$ at Rocks.

For blasted and dozed stopes material removal rates are generally independent of impact pressure and are strongly dependent upon monitor operation, availability of stent removal plant and, at Rocks, on the degree of stent coverage. In Fig. 9 the upper limit, U, corresponds to the washing of a recently exposed blasted stope with the aid of SRP, whilst the lower limit, L, corresponds to the washing of stent or gravel in the absence of SRP. In Fig. 10 similar limits define band widths of material removal rate corresponding to degrees of stent coverage of between 0 and 60%. The greater the degree of stent coverage, the lower are material removal rates.

P_t is of the same order of magnitude as values of cohesion, defined by the Coulomb failure equation (7). Material removal rates show qualitative dependence on coefficient of internal friction,/», represented in Fig. 2.

$$\tau = \tau_0 + \mu\sigma \tag{7}$$

It therefore appears likely that material removal rates are a function of shear strength r, although further work is required to verify this dependence.

4. OPTIMISATION

In order to determine the range of optimum mining conditions it is required to calculate the specific energy of mining *E,* for a range of nozzle pressure *Po* , dimensionless standoff distance x/d_a and relative stope hardness characterised by K_T . The specific energy of mining *E,* is given by:-

$$E_s = \frac{1}{\eta}\frac{P_0}{\rho_w}\frac{M_0}{M_c} \quad (MJ \quad tonnes^{-1}) \tag{8}$$

M_c is calculated from Eqn. 6 and P_m from Eqn. 4. *P,* is taken to be 40 kPa. Values of K_r are taken to be 0.35 and 0.75 *tonnes* $hr^{-1}kPa^{-1}$ for hard and soft pits respectively.!; is taken to be 0.70 and assumes that available gravitational head is equivalent to frictional head losses between pump and monitor.

Fig 11 illustrates the effect of both standoff distance and nozzle diameter on specific energy at a given nozzle pressure. Specific energy increases exponentially with both increase in standoff distance and decrease in nozzle diameter. A move from current operational standoff range to within 100 *do* results in a five to tenfold reduction in specific energy.

Figs. 12 and 13 indicate the effect of nozzle pressure on specific energy, at a given dimensionless standoff distance for hard and soft pits respectively. The pressure at which the minimum in specitic energy displayed by all curves occurs, increases with increasing standoff. Above the minimum pressure specific energy is a weakly increasing function of nozzle pressure; however, below the minimum pressure specific energy increases exponentially with decreasing nozzle pressure. Specific energies for the mining of virgin stope are typically 20 $M\ J\quad tonne$ for hard pits and 10 $M\ J\ tonne^{-1}$ for soft pits under present operating conditions.

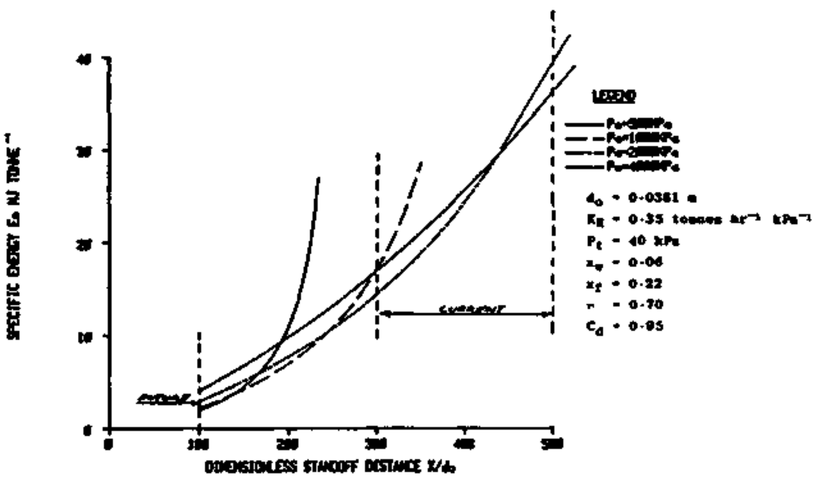

Figure 11. *Effect of standoff distance and nozzle diameter on specific energy consumption*

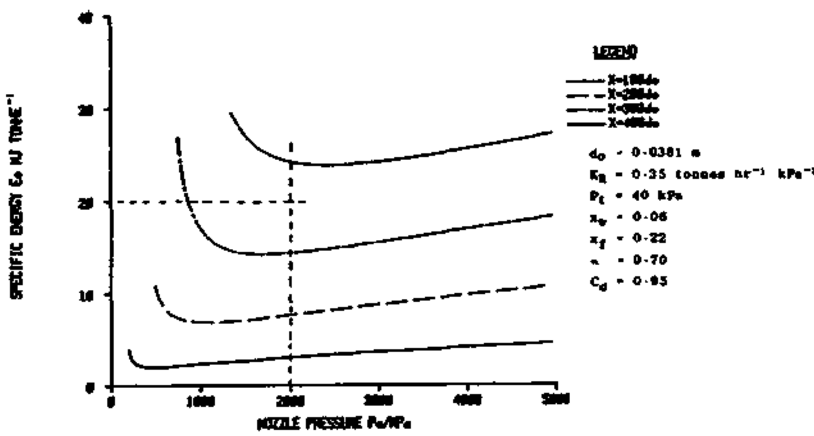

Figure 12. *Effect of nozzle pressure on specific energy consumption (hard pit)*

Figs. 14 and 15 indicate the associated variation in pit wash density with nozzle pressure at a given standoff distance. In spite of the minima in Figs. 12 and 13 pitwash density exhibits no maxima with respect to nozzle pressure and is an increasing function of nozzle pressure. Upper

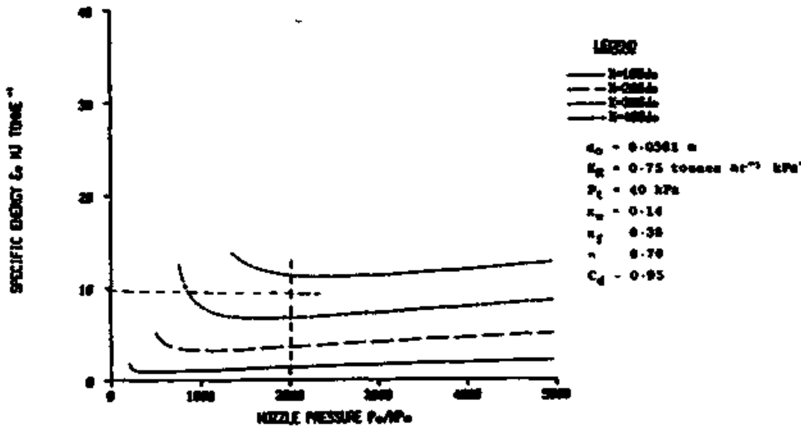

Figure 13. *Effect of nozzle pressure on specific energy consumption (soft ptt)*

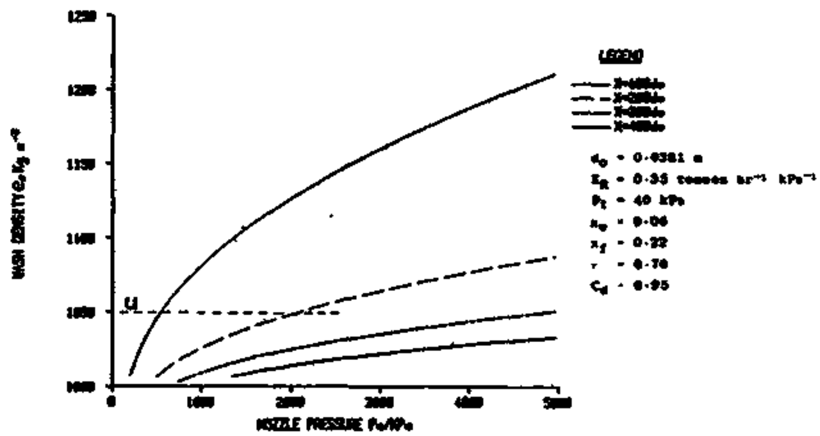

Figure 14. **Uffeci o/ nozz/e** *pressure on wash density (hard pit)*

limits of pit wash density corresponding to the upper limits of material removal rate shown in Pigs. 9 and 10 are indicated. It can be seen that densities equivalent to those presently achieved may be obtained by mining virgin stope at reduced standoff distance and nozzle pressure, and hence

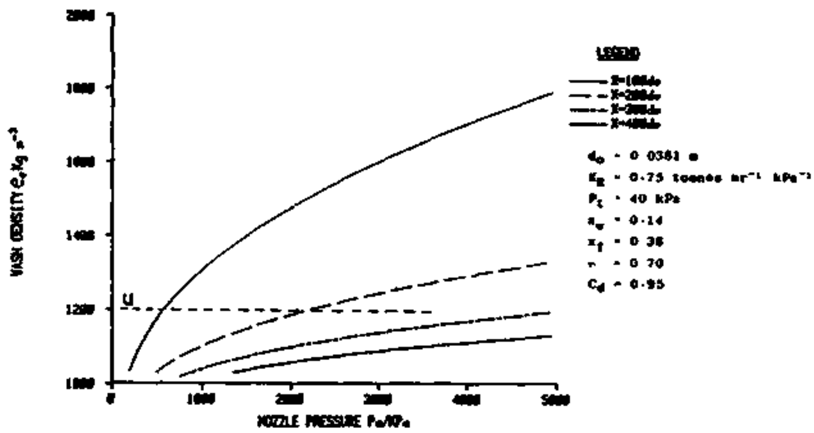

Figure 15. *Effect of nozzle pressure on wash density (soft pit)*

reduced specific energy.

Optimum operating policy when mining virgin stope is to operate at $x/d_0 < 100$ and a nozzle pressure which is close to, but above that which corresponds to a minimum specific energy, i.e. $500 < P_o < 1000 kPa$. This enables nozzle diameter to be the maximum that required dry clay production rates permit. The lower limit of nozzle diameter is set by the minimum production rate required from a soft pit at maximum nozzle pressure, whilst the upper limit is set by the maximum production rate required from a hard pit at minimum nozzle pressure.

Present production rates per monitor at Treviscoe and Rocks pits advocate $0.023 < d_o < 0.043$.

5. CONCLUSIONS

• E.L.C.P.'s operating experience has shown that (i) higher rates of material removal may be obtained by mining dozed or blasted stopes than by mining virgin stope; (ii) material removal rates are primarily dependent on SRP and monitor operations and relative stope hardness when mining both dozed and blasted stopes; (iii) in addition, when mining dozed stopes, material removal rates are dependent on stent coverage; (iv) material removal rates are dependent on standoff distance as well as relative stope hardness, SRP and monitor operations when mining virgin stope.

The above were confirmed by observations made in this study. In addition it may be concluded that material removal rates are primarily dependent on impact pressure levels when mining virgin stope.

•From an extrapolation of results considered in this paper, the range of optimum operating conditions for a single monitor mining virgin stope is:-

$$0 \leq x/d_0 \leq 100$$

$$500 \leq P_0 \leq 1000 \quad kPa$$

where $0.023 < d_o < 0.043$ m and is dependent on dry clay production rate.

do should be a maximum advocating a 'stop-go' production policy rather than continuous operation. The above operating conditions result in a five to tenfold reduction in specific energy of mining to 1 - 4 MJ per tonne.

• Since the cost of ripping and dozing equipment limits application in smaller pits and wash densities decay more rapidly in the absence of SRP when mining dozed and blasted stopes, optimisation of the mining of virgin stope provides a valuable contribution to overall system efficiency.

• Optimisation must be extended to dozed and blasted stopes and for systems incorporating more than one monitor. In practice overall system optimisation must include the effects of pit wash density on downstream operations.

• Optimum mining of all stope types advocates the requirement for a remotely controlled mobile monitor equipped with a variable area nozzle enabling in situ 'tuning' of the jet to a variety of pit and production requirements.

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