bulk solids handling Volume 2, Number 1, March 1982

Bulk Transport of Retorted Oil Shale for Mechanical Backfilling

Vasudevan Rajaram, USA

Summary

Mine backfilling is a desirable method for the disposal of retorted oil shale and is an environmentally acceptable alternative to surface disposal. Hydraulic, mechanical, and pneumatic transport and stowing methods were investigated, and the mechanical transport and stowing method using belt conveyors was selected as the most promising system. A bulk transport system was designed to convey retorted oil shale from the Paraho retorting process at the rate of 2,700 t/h (3000 stph), from the surface to sublevel stopes situated at a depth of about 610 m (2,000 ft). A unique feature of the system is a large-diameter borehole which facilitates gravity flow of the material from the surface to the backfill level. This paper describes the sublevel stope layout, the theory of gravity flow, flow properties of retorted oil shale, the design of the borehole and hopper system, and the underground transport of material. Underground disposal is technically and economically feasible for oil shale operations producing more than 1,270 m³/d.

1. Introduction

The waste material from an above ground gas combustion oil shale retort amounts to approximately 82 % of the retort feed. The importance of developing an environmentally acceptable and economically feasible method for disposing of retorted oil shale is well known to those concerned with the development of oil shale resources, both in private industry and in the appropriate governmental agencies. As a result of this mutual concern, the U.S. Bureau of Mines contracted, in 1976, with The Cleveland-Cliffs Iron Company, Western Division, to develop a viable method for underground disposal of retorted oil shale. Hydraulic, mechanical and pneumatic transport and stowing methods were investigated. Mechanical transport and stowing using belt conveyors was selected as the most promising system based on a ranking analysis which included subjective and objective technical factors, and capital and operating costs [1].

The mine is assumed to be located in the central area of the Piceance Creek Basin in northwestern Colorado. The surface elevation is 1,890 m (6,200 ft) above sea level with typical canyon-plateau topography. Mining and backfilling activities will be at a depth of 610 m (2,000 ft) in the lower saline zone of the Green River Formation. The recorded ambient rock temperature at this depth is in the range of 32—38 °C.

A commercial mining and retorting operation capable of producing shale oil at a rate of 7,950 m³/d (50,000 barrels/d) on a 365 day per year basis is used in this study. Assuming a retort efficiency of 0.95, 106 l/t (28 gallons/ton) of oil shale, 5 % residual moisture, and a retorted shale to raw shale weight ratio of 0.82, the retort facility will produce 61,690 t (68,000 st) of retorted shale per day. The nominal retorted shale flowrate into the mine will be 2,700 t/h (3,000 stph) and the remaining 30 % of the waste material will be disposed of on the surface. Partial surface disposal is necessary because expansion during blasting and crushing is greater than the volumetric loss resulting from oil extraction during retorting.

Nomenclature

u = superficial slip gas velocity (relative to solid)
v = true absolute solid velocity
w = true absolute gas velocity
τ = particle density, pcf
γ = solids bulk density, pcf
γ_s = solids bulk density at a surface, pcf
ν = voids ratio
σ_z = solids pressure in the vertical direction, psf
σ_s = solids pressure below which Eq. 13 does not apply, psf
ϕ = friction angle between the solid and borehole casing, degree
Θ_c = maximum recommended angle (from vertical) of conical hoppers and end walls of transition hoppers for mass flow, degree
A = channel cross-sectional area, ft²
B = diameter of a circular outlet of a mass flow hopper, ft
D = diameter of channel (borehole)
g = acceleration due to gravity
h = effective consolidating head of solid, ft
K = Janssen ratio between the horizontal and vertical solids pressure
P = gas flow rate, psia x ft³/sec
Q = solid flow rate, lb/sec
p = gas pressure, psia
dp/dz = gas pressure gradient

Vasudevan Rajaram, Mining Engineer, Ernest K. Lehmann & Associates, Inc., 1409 Willow Street, Suite 300, Minneapolis, MN 55403, USA

2. Backfilling Plan

Sublevel stoping with backfilling is a large-production, low-cost open stoping method which is well suited to fairly regular ore bodies having both competent ore and host rock. Open stope production utilizes long hole drilling from levels and sublevels and blasting in successive slices. Fig. 1 shows a typical sublevel stope system during the mining and backfilling phases.

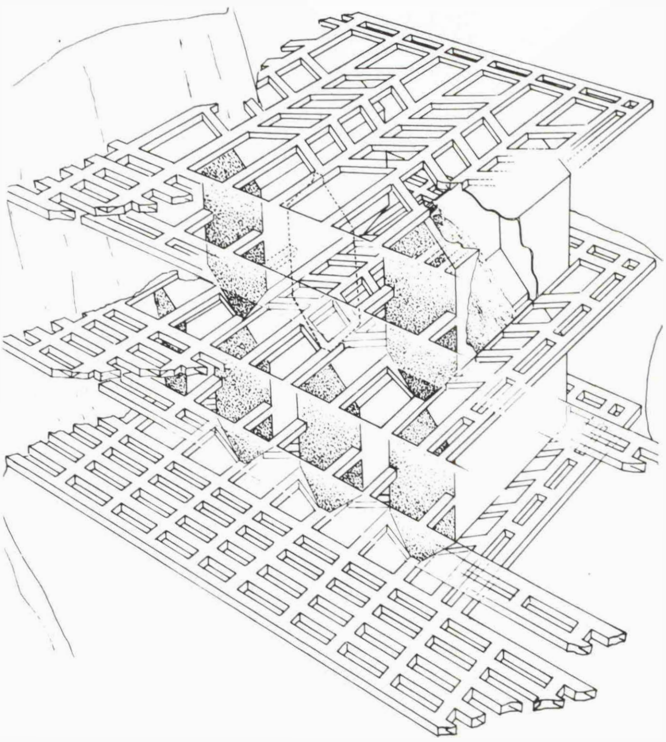


Fig. 1: Typical sublevel stope system during the mining and backfilling phases

The stopes will be mined in an alternating pattern so that backfilling may take place and its supportive effect on adjacent pillars established before the second alternating series of stopes are mined. Thus, the stabilizing effect of backfilling may be exploited during the mining phase which, in turn, will allow relatively thin pillars to remain for support and increase the overall extraction ratio. The backfill also permits the stacking of stopes, eliminating the need for sill pillars between stoping levels. The result is increased resource recovery that is estimated to be as much as 16%. In addition, underground disposal of retorted shale will reduce the amount of surface disturbance.

Since retorted shale leaves the retort at about 205°C it will be necessary to cool the shale prior to transport into the mine. However, retorted shale for surface disposal will not be cooled. Based on water and energy requirements, dust, particle degradation, and costs, an air-swept water tube cooling system was selected. This system uses a rotating drum with four concentric rings of water tubes inside the drum. These tubes carry the counter-current flow cooling water which provides indirect cooling. Air is drawn through the coolers in a counter-current direction and into a cluster of cyclones and baghouses where the dust is removed before being released to the atmosphere. Eight units are needed for cooling the retorted shale that will be returned to the mine. Each unit requires 0.032 m³/s (500 gpm) of water for cooling. Fig. 2 shows the general cooling facility layout.

3. Borehole Transport

A large diameter vertical borehole will be used to transport the retorted shale from surface to the backfilling level. Fig. 3 shows the general borehole configuration. The 2.4 m (8 ft) diameter borehole will be steel lined and will discharge into a

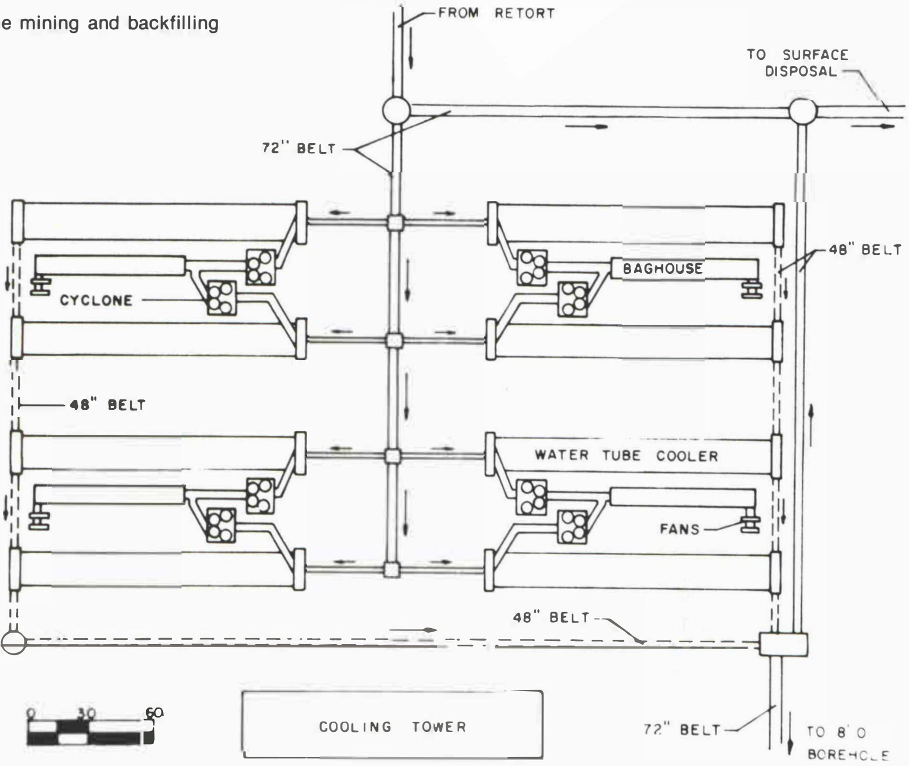


Fig. 2: General cooling facility layout

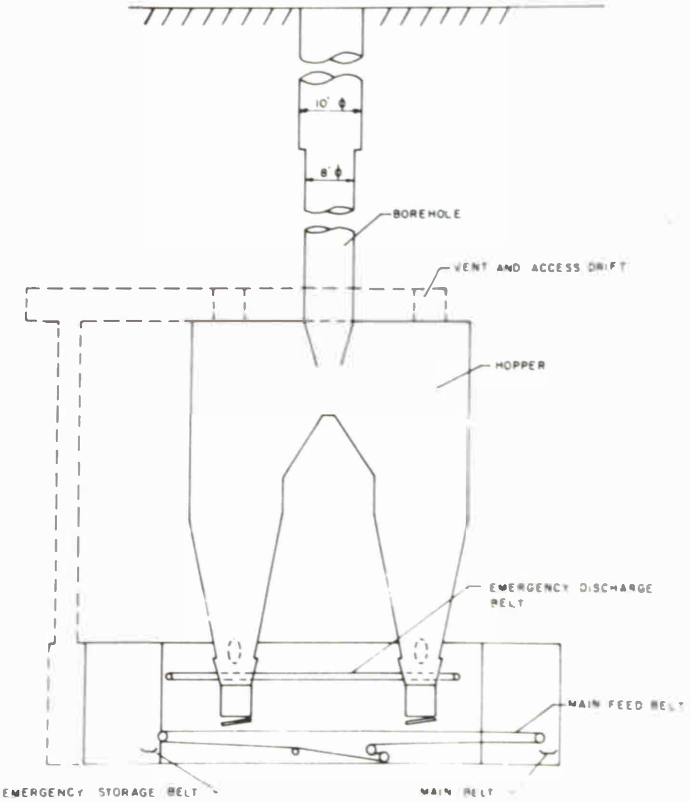


Fig. 3: General borehole configuration

surge chamber above the backfilling level. The borehole-hopper system has been designed for mass flow so that the retorted shale will flow by gravity from the surface discharge conveyor to the main underground feeder conveyor.

Gravity flow of material through a borehole involves two-phase flow of solids and gas. Air is entrained with the retorted shale down the borehole and has a significant effect on the flow of solids. In order to examine this problem, it will be assumed that the flow is one-dimensional. Solid-gas steady-state flow relations and equilibrium equations which govern flow are given below.

Solid-Gas Steady-State Flow Relations. The true slip gas volocity is u/ν, and the true velocities are related by:

$$\nu w = \nu v + u \tag{1}$$

But

$$\nu = \left(\frac{1}{\gamma} - \frac{1}{\tau}\right)\gamma \tag{2}$$

Substituting Eq. 2 in Eq. 1,

$$\nu w = \left(\frac{1}{\gamma} - \frac{1}{\tau}\right)\gamma v + u \tag{3}$$

Darcy's relation for the superficial slip gas velocity is:

$$u = u_0\left(\frac{\gamma}{\gamma_0}\right)^n\left(\frac{1}{\gamma}\ \frac{dp}{dz}\right) \tag{4}$$

Substituting Eq. 4 in Eq. 3,

$$\nu w = \left(\frac{1}{\gamma} - \frac{1}{\tau}\right)\gamma v + u_0\left(\frac{\gamma}{\gamma_0}\right)^n\left(\frac{1}{\gamma}\ \frac{dp}{dz}\right) \tag{5}$$

Eq. 5 applies at any cross-section of a one-dimensional channel. The gas and solid flow rates are given by continuity:

$$P = A P \nu w \text{ (psi a x ft}^3\text{/sec)} \tag{6}$$

$$Q = A \gamma \nu \text{ (lb/sec)} \tag{7}$$

Substituting Eq. 5 in Eq. 6 and using Eq. 7

$$P = \left[\left(\frac{1}{\gamma} - \frac{1}{\tau}\right)Q + A u_0\left(\frac{\gamma}{\gamma_0}\right)^n\left(\frac{1}{\gamma}\ \frac{dp}{dz}\right)\right] p \tag{8}$$

Gravity flow rate of the solid out of a conical hopper is given by:

$$Qg = 1 \cdot 8\ \frac{\pi B^2}{4}\ \gamma\left(\frac{Bg\,(1 - 1/\gamma\ dp/dz)}{4 \tan \Theta_c}\right)^{1/2} \tag{9}$$

Equilibrium Equation: The equation of equilibrium for a vertical channel is [2, 3]:

$$\frac{d\sigma_z}{dz} + \frac{dp}{dz} + \frac{4K \tan \phi'}{D}\,\sigma_z = \gamma \tag{10}$$

The *boundary* at the top surface of the channel is: $z = 0$, $\sigma_z = 0$, $p = p_{\text{ambient}}$. In the limit as $z \to \infty$,

$$\lim_{z \to \infty} \frac{d\sigma_z}{dz} = 0 \text{ and } \lim_{z \to \infty} \frac{dp}{dz} = 0 \tag{11}$$

The effective consolidating head of solid for this limiting condition is:

$$\lim_{z \to \infty} \frac{\sigma_z}{\gamma} = \frac{D}{4K \tan \phi'} \tag{12}$$

The relation between γ and σ_z is:

$$\gamma = \gamma_0\left(\frac{\sigma_z}{\sigma_0}\right)^\beta \text{ for } \sigma_z \geq \sigma_s \tag{13}$$

where σ_0, γ_0 and β are determined from the *compressibility* test.

4. Flow Properties of the Retorted Shale

The particle size of retorted oil shale ranges from approximately 63.5 mm (2.5 inches) maximum to extremely fine silt as shown in Fig. 4. Determination of flow properties consists of two distinct steps:

1. The flow of solid neglecting the gaseous phase: This first step consists of measuring the flow functions and the wall frictional and adhesive properties. Mass flow hopper configurations and minimum outlet sizes for flow without arching are determined from these properties.

Tests of this type have been performed for some 20 years and are carried out on the Flowfactor Tester [2]. The tests run on retorted shale have defined a minimum outlet diameter of 0.4 m (1.3 ft) and maximum hopper wall slope angles of 19° from the vertical for a circular cone, and 30° for a wedge, for a hopper made of carbon steel.

2. The effect of the gaseous phase, in this case air, on the flow of the solid: Air is entrained with the retorted shale down the borehole. As the solid compacts under the increasing solid pressure, the pore size is reduced and air pressure

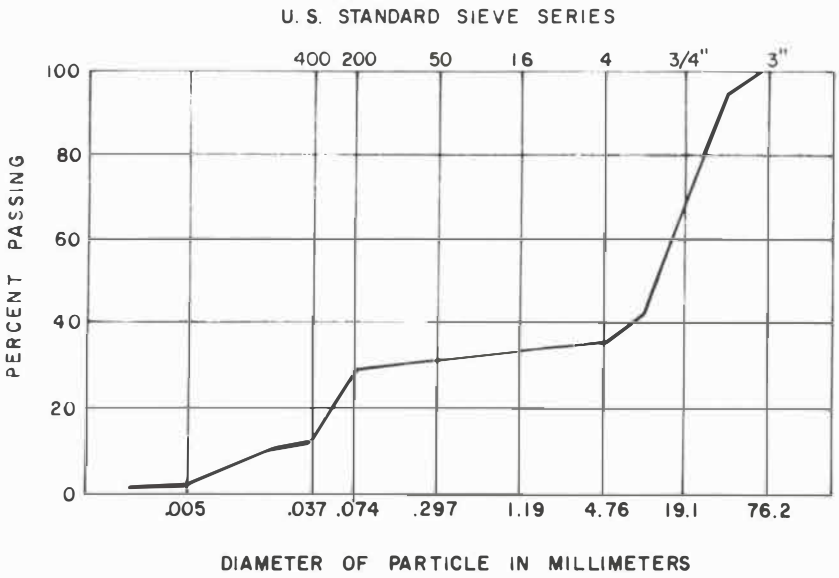


Fig. 4: Particle size of retorted oil shale

increases. At the outlets onto the belt feeder, solids pressure decreases, retorted shale expands, and air pressure drops. The amount of air entrained and the air pressure at the exit depend on the surface density, the compressibility and the permeabiliy of the solid. These properties are determined in the second step.

Compressibility is measured by compressing a sample of solid in a shallow cylinder and determining the bulk density as a function of the effective head of solid.

Permeability is measured by placing a sample of solid in a cylinder and determining the air flow rate for a given air pressure drop as a function of the bulk density of the solid. A combination of the results of these tests with the tests of compressibility yields the following constants:

$\sigma_s = \sigma_o = 0.00547$ kPa (0.114 psf)
$\beta = 0.0289$
$u_o = 0.00133$ m/s (0.00437 ft/sec)
$\gamma_s = \gamma_o = 961.1$ kg/m^3 (60.0 pcf)
$n = -7.88$

Particle density was measured at $\tau = 2{,}643$ kg/m^3 (165 pcf).

5. Design and Operation of Borehole and Hopper System

5.1 Design

Dry retorted oil shale is to flow down a 610 m (2,000 ft) deep borehole and onto a belt feeder at a rate of up to 2,700 t/h (3,000 stph). In order for the flow onto the belt to be uniform and controlled, it is necessary that:

1. The flow of retorted shale in the regions of the hopper above the outlets is steady. This means that the hopper must be mass flow, i.e., all the material must be in motion whenever any of it is withdrawn.

2. The pressure of air in the pores of the retorted shale discharging onto the belt feeder is close to the ambient air pressure. If pore pressure is too high, shale will flush uncontrollably and flood the belt; if pore pressure is too low, flow will be intermittent with arching followed by flushing and flooding of the belt.

3. The area of the outlets is sufficiently large to assure unobstructed flow at the specified rate.

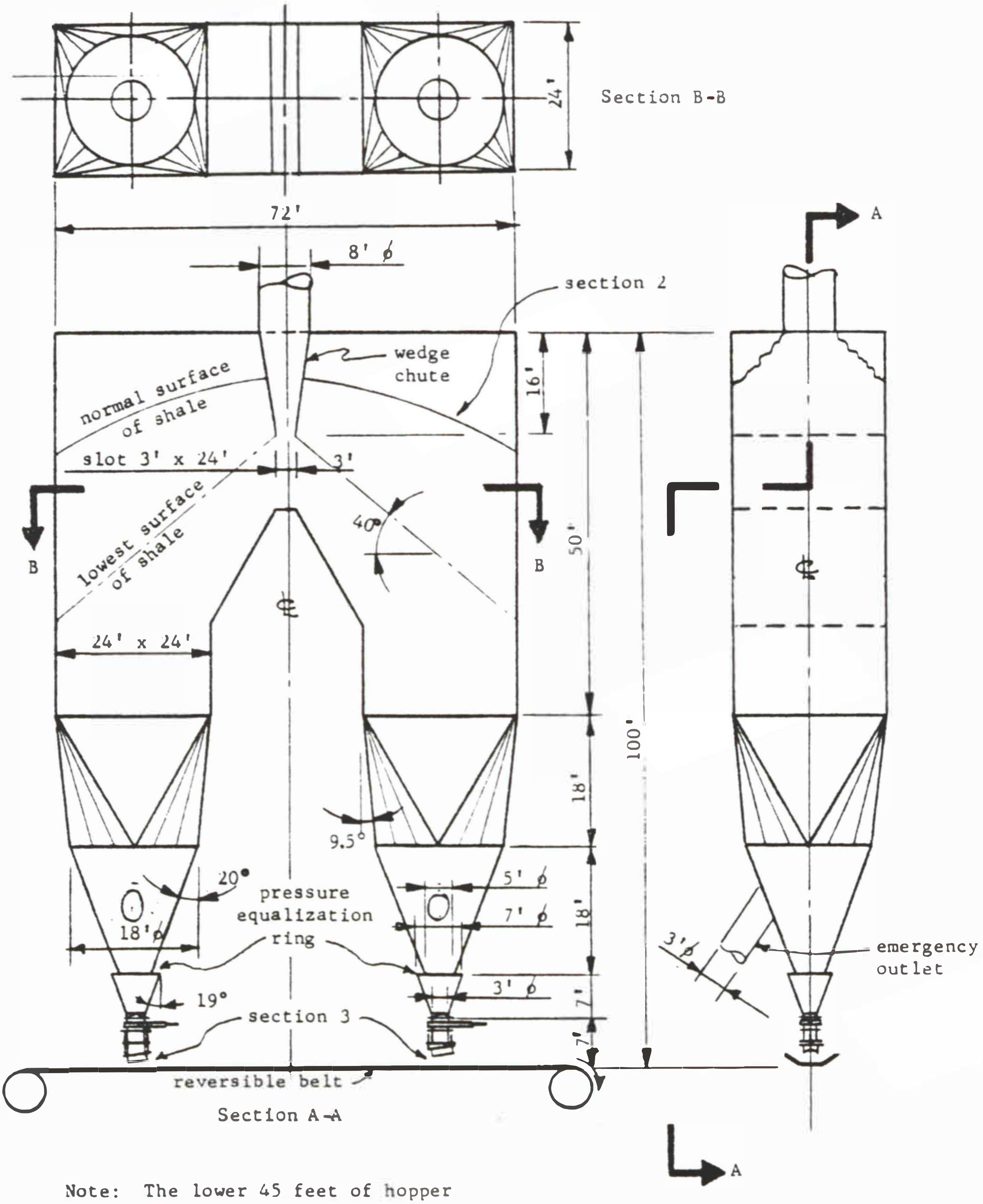
4. The chute and skirt design at the outlet ensure fully live outlets.

In addition to ensuring controlled flow under continuous flow conditions, it is also necessary to provide for start-up during the filling of the borehole and for restarting after a stoppage of flow.

Particulate solids tend to flow in pulsating motion. Coarse (permeable) solids pulsate more, fine (impermeable) solids pulsate less. Pulsation is particularly pronounced in tall vertical channels of constant cross-section, like the borehole under consideration. The magnitude of likely pulsation in the borehole cannot be predicted for the lack of an appropriate theory. It is therefore necessary to provide a disengaging region between the borehole and the hopper outlets so that borehole pulsations do not affect the feed on the belt. Disengagement is obtained by providing a space in the hopper where the solid can form a free fluctuating surface. Through that surface, air can also be introduced or evacuated, as needed, to maintain pore air pressure at the outlets close to ambient air pressure.

The layout of the borehole and hopper is shown in Fig. 3; the hopper is shown in greater detail in Figs. 5 and 6. The top 30.5 m (100 ft) of the borehole is 3.05 m (10 ft) in diameter, the remainder is 2.4 m (8 ft) in diameter. The borehole discharges into a hopper. Retorted shale flows down the mass flow hopper into two 0.91 m (3 ft) diameter outlets which feed onto a 1.83 m (72 in.), 35° trough-angle belt. Since the belt needs to be reversible, the chutes have pivoted skirts to permit each outlet to discharge approximately the same layer of material on the belt, one on top of the other, in either direction.

Calculations indicate that an excess of air is likely to be entrained with the retorted shale in the borehole. The excess will be evacuated at the free surface of the hopper by maintaining an air pressure at the top of the hopper lower than the pressure in the pores of the retorted shale issuing from the borehole. The flow pattern of solids expanding from the borehole into the hopper cannot lead to uniform deaeration. The proposed hopper design aims at the prevention of gross non-uniformities. In addition, hopper ring-expansions are



Note: The lower 45 feet of hopper made of carbon steel

- Dust control closure of belt not shown

Hopper Layout

- Dust control closure of belt not shown

Fig. 5: Borehole and hopper detail

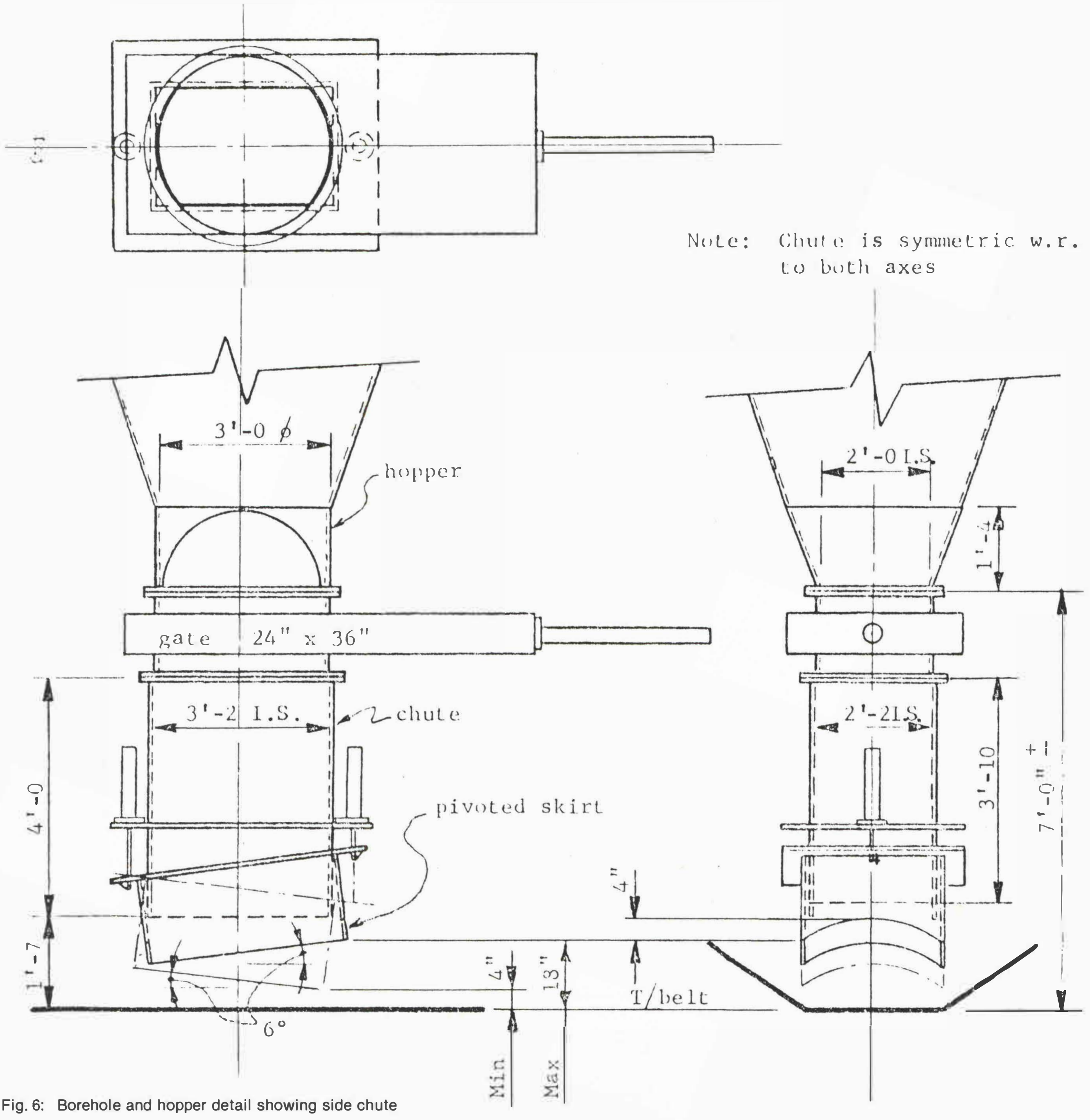


Fig. 6: Borehole and hopper detail showing side chute

indicated. These rings provide a passage through which air pressure equalization can take place across a hopper prior to discharge. This will help prevent flushing of solids through the side of the outlet with an excess of air, while the other side flows sluggishly because of air deficiency.

The gravity flow rate of solids at the hopper outlet, computed from Eq. 9 for $dp/dz = 0$, is 14,105 t/h (15,551 stph). This allows a uniform flow rate by providing an excess of 5.2 times the required rate. The belt speed required to move 2,700 t/h (3000 tph) is 2.1 m/s (423 ft/min.), assuming a surcharge angle of 5°.

5.2 Operation

Initial filling of the borehole will proceed at a low charging rate in order to minimize impact loads on the hopper. After the initial 450 t (500 st) have been dropped, the belt will be started and the gates opened. The withdrawal will proceed through both outlets at approximately one-fourth of the rate of charge into the borehole. The top of the hopper will be vented at the ambient pressure in the mine. When the operating level of solids in the borehole has been reached, all the rates will be increased to normal operating values.

In order to assure smooth start-up, restart after a stoppage and steady-state operation, it will be necessary to monitor and control the following:

1. Level of solids in the borehole: While the borehole will provide a substantial surge capacity, the level of solids will be monitored and the in- and out-flow rates controlled to maintain the retorted shale level within specified high-low limits.

2. Air pressure at the top of the hopper: The amount of air entrained into the borehole depends on the bulk density of

the retorted shale at the surface of the borehole. That density cannot be accurately predicted from a one-dimensional analysis and experiment because, in fact, the problem is two-dimensional with, to date, no available solutions. Similarly, the amount of air expelled through the top surface in the hopper in uncertain because of the lack of a two dimensional solution of the flow from the borehole to the hopper. However, since the rate of air evacuation is directly proportional to the air pressure at the top of the hopper, that pressure can be used effectively to control the uniformity of flow onto the belt. Provision will be made to hold air pressure at any required level between 70 and 80 kPa (10 and 12 psia).

3. Feed rate from hoppers: The height of the chutes above the belt feeder can provide gross feed rate control. Fine adjustment will be best achieved with a variable speed drive. The slide gates at the hopper outlets will not be used for rate control because, in a partly open position, they would prevent mass flow from developing and would lead to non-uniform flow with likely flushing.

In order to provide for emptying the borehole in the event of a breakdown in the main belt feeder, a side chute has been provided (Fig. 6). Retorted shale will be discharged from this chute onto a secondary belt and conveyed to an emergency storage area. If retorted shale is not withdrawn continuously from the borehole during an emergency, air pressure in the borehole will be monitored. If the air pressure drops below 90 kPa (13 psia), air at that pressure will be supplied to the borehole. This will permit rapid return to the normal rate of borehole flow when the emergency ends.

6. Underground Transport

6.1 Transport to the Stopes

All underground conveyor belts, except the main feeder belt, will be supported on wire rope suspended from chain hangers bolted to the mine roof. The main feeder belt which transfers retorted shale from the borehole hopper to the conveyor system will be of conventional rigid frame construction. Fig. 7 shows the typical conveyor layout. All mainline and panel conveyors will use 183 cm (72 inch) wide belts and will be of standardized length once the first panel is reached on either side of the borehole. The flow of retorted shale from the borehole is carried by the main feeder to the mainline conveyors which transport the shale to the active panels. At a point near the stopes being backfilled, short piggyback conveyors extending from the centerline of one stope to the next are used. Retorted shale is transferred from the piggyback conveyors to the extensible backfilling conveyors through three-way splitter chutes. Extensible belts are 91 cm (36 inch) wide.

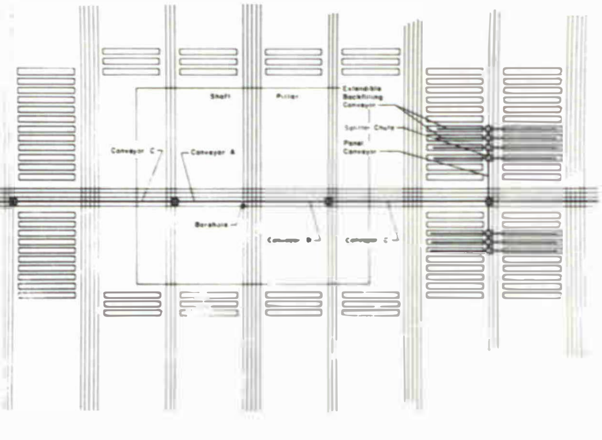


Fig. 7: Typical conveyor layout

A surfactant will be applied to the retorted shale as it leaves the borehole to minimize the dust problem. Dust collection hoods and vortex-type scrubbers will be used at all main transfer points. The slurry from the scrubbers will be placed back on the following conveyor for disposal. Water consumption for dust suppression and control during underground transport will be approximately $3.18 \cdot 10^6$ l/d (840000 gpd). This water will be obtained primarily from mine dewatering activities and from the overlying aquifers as required.

6.2 Backfilling

The stopes are backfilled using extensible conveyors to deposit the material in each stope. A self-propelled head pulley unit is used to advance the conveyor into the stope as backfilling progresses. The backfill material has a final density of 1,200 kg/m³ (75 pcf). Backfilling will progress until the stope has been filled completely to the extensible conveyor level. At that time, the extensible conveyor will begin retreating from the stope and a dozer equipped track loader will push and pack the remaining retorted shale as close to the roof as possible. As backfilling proceeds, all lower level access entries will be bulkheaded and monitored for ground water accumulation. Approximately 70 % of the retorted shale will be returned to the mine.

7. Conclusions and Practical Applications

Underground disposal of retorted oil shale in sublevel stopes is technically feasible and environmentally acceptable. The borehole and hopper system designed for bulk transport of dry retorted oil shale from the surface to a depth of 610 m at a rate of 2,700t/h utilizes the state of the art of one-dimensional gravity flow. This design can be improved if two-dimensional gravity flow, solutions for which have yet to be developed, is analyzed at the borehole-hopper junction.

The proposed bulk transport system can provide an economical method of materials handling in multi-level underground mining. Analysis of the solid and gas flow patterns in a vertical channel permits the design of a system in which bulk flow of material is controlled, resulting in continuous, efficient and cost-effective materials handling.

References

[1] Earnest, H.W., Rajaram, V., Kauppila, T.A., and Hill, J.R.M., "Underground Disposal of Retorted Oil Shale", Proc. of Tenth Oil Shale Symposium, Colorado School of Mines, April 1977, pp. 213—222

[2] Jenike, A.W., "Storage and Flow of Solids", University of Utah Engineering Experiment Station Bulletin No. 123, Nov. 1961

[3] Johanson, J.R., and Jenike, A.W., "Settlement of Powders in Vertical Channels Caused by Gas Escape", ASME Journal of Applied Mechanics, Vol. 39, Series E, No. 4, Dec. 1972, pp. 863—868