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Blind Pneumatic Stowing in Voids in Abandoned Mines

By P. F. Sands, C. M. K. Boldt, and T. M. Ruff

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cfm	cubic foot per minute	psig	pound per square inch, gauge
ft	foot	m/s	meter per second
ft/s	foot per second	st	short ton
in	inch	st/h	short ton per hour
pct	percent	yd	yard
psi	pound per square inch		

/ .

BLIND PNEUMATIC STOWING IN VOIDS IN ABANDONED MINES

By P. F. Sands,[1] C. M. K. Boldt,[2] and T. M. Ruff[3]

ABSTRACT

This U.S. Bureau of Mines report reviews the state of the art in blind pneumatic stowing of backfill in voids in abandoned coal mines. It contains a short history of the development of pneumatic equipment in mining and four recent case histories of blind pneumatic stowing. Limitations of pneumatic stowing in terms of equipment wear, costs, backfill material, and methodology are discussed, and some new procedures and designs are reviewed. A bibliography covering pneumatics in mining is included also. This report provides background for the preparation of a Bureau test program in which the variables affecting the efficiency of pneumatic backfilling will be studied using a full-scale surface test facility.

[1]Mining engineer.
[2]Civil engineer.
[3]Electrical engineer.
Spokane Research Center, U.S. Bureau of Mines, Spokane, WA.

INTRODUCTION

As part of its environment protection program, the U.S. Bureau of Mines is investigating subsidence control through backfilling underground voids in abandoned mines. However, because these mines have been abandoned, unsafe conditions require that the backfill be placed blind, that is, from a remote location on the surface. This report reviews blind backfilling techniques in which the backfill was transported using pneumatic stowers. The Bureau is using its full-scale test facility at Lake Lynn, PA, to investigate the many variables influencing the efficiency and applicability of pneumatic backfilling. This is an ongoing test program designed not only to define the limitations of existing methods, but to develop new concepts.

BACKGROUND

BACKFILL CONVEYANCES

Backfilling, whether in voids in abandoned mines or in actively mined areas, may involve mechanical (conveyor, truck), manual, hydraulic, and/or pneumatic processes. The conveyance method for the backfill material is usually limited by site conditions, which include the accessibility or inaccessibility of the void, hazards to workers, material availability, or condition of the void itself (inundated, rubbled, or interconnected). Hydraulic backfilling is a relatively inexpensive and well-tried method but has limitations because it requires large quantities of water and because directing and placing the flow of the backfill material is often difficult. There may also be undesirable side effects associated with pumping large quantities of water underground. Inaccessibility of a void precludes most mechanical methods of backfilling. Pneumatic filling has been used where water was not readily available or where hydraulic backfilling was not acceptable.

PNEUMATIC TRANSPORT

Pneumatic transport involves entraining solids in a stream of continually flowing air, either in a vacuum or under pressure. The earliest use of a pneumatic machine was in the early 1900's in England when a vacuum was used to unload ships (*1*).[4] In mining, as in other industries, a vacuum is used mainly for pickup, and pressure is used for stowing or transporting.

A pipeline conveyance system is described as being either dilute (or lean) or dense phase. Dilute-phase transport uses low air pressures at high velocities to accelerate particles through a pipeline. Dense-phase transport moves material in low-velocity "slugs" along the pipeline. Figure 1 illustrates the various phases of flow.

Dilute-phase pneumatic conveyances have been the most popular. However, they are subject to intensive wear. Average velocities are around 30 m/s, which can cause considerable wear on all system components when highly abrasive materials such as crushed gravel are used. Saltation along the bottom of the pipe and particle impact on pipe walls where the pipe bends are principal causes of pipe wear. Feeder wear occurs between feed rotors or blades and the holding capsule. Wear at the bends of pipelines and in feeders has been a major cost factor limiting the use of pneumatic equipment. Wear leads to decreased material velocity and decreased carrying capacity of the pipeline, increases dust at the feeder, and accelerates further wear (*2*). Typical management methods to reduce wear include the use of segmented plates, dirt boxes, high-strength materials, high-density polyethylene, and blind T elbows.

Dense-phase conveyances have been studied since the 1970's (*3-4*). These systems have advantages over dilute-phase conveyances in that lower air-to-material ratios (25:1 versus 100:1) and lower air velocities are required, which increase system efficiency and decrease component wear. Carrying velocities range from 0.5 m/s for sand to 10 m/s

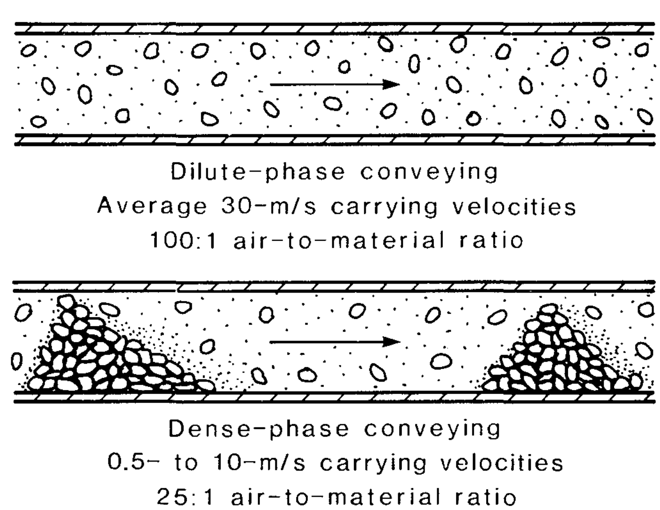

Figure 1.—Dilute- and dense-phase pneumatic transport.

[4]Italic numbers in parentheses refer to items in the list of references preceding the bibliography at the end of this report.

for large coal particles. Because material is moving at a relatively slow rate, large (>1/2 in), dense particles are usually not suitable for this type of conveyance.

PNEUMATICS IN MINE BACKFILLING

In 1942, a pneumatic stowing machine was manufactured in England by Markham and Co., Ltd.,[5] a privately owned engineering shop that made equipment for various plants and collieries. The Markham system consisted of a blower, feeder, conveyor, and pipe, and was used to backfill with mine waste at one of the coal collieries. The pneumatic stower became a major product of the company, which made improvements in the air blower, automatic stowing valve, constant flow control valve, and pipelines with decreased bend radii and replaceable bend inserts. In 1966, the Markham Co. and Rader Pneumatics of Vancouver, BC, jointly developed (under the Radmark trade name) North America's first pneumatic stower for the Cominco, Ltd., Sullivan Mine, Kimberley, BC. In 1980, Radmark ceased operations and company personnel started Beric, Inc., which subsequently became Hanna-Beric, Inc., Pittsburgh, PA. This company has continued to improve the system, particularly the airlock feeder for the infeed system (*5*).

In the mining industry, pneumatic equipment is used to hoist waste rock and ore, transport drill cuttings, transport and place backfill material in mine openings, transport coal, and seal surface mine openings. Examples of these operations have appeared in the literature. Two Bureau reports (*6-7*) documented the operations and costs of sealing abandoned surface mine openings in Pennsylvania and Ohio with pneumatically placed aggregate. Both projects involved a manually operated, single-nozzle discharge hose positioned at the opening and required some preparatory work in the entry prior to sealing. No remote monitoring of the operation took place. These projects are summarized below.

1. Thirteen openings in Pennsylvania were successfully sealed using 1-1/2-in, well-graded limestone aggregate. In some entries, cement, expansive cement, and/or bentonite were added to the aggregate to obtain a water seal (*6*). Low-pressure (13 psi), high-volume pneumatic equipment incorporating the Radmark feeder was used to seal openings up to 90 ft deep. At that time, it was recommended that a 40-ft-long horizontal pipe be installed beyond the discharge elbow to increase particle velocity and subsequent material compaction.

2. During the Ohio project, high-volume, low-pressure blowers were used to stow limestone and gravel up to 2 in. in size into five openings and a shaft (*7*). The greatest compaction was obtained when a long, straight section of pipe was used near the pipe exit. The results indicated that small-diameter pipe could be used with various pressure ranges to transport material at high velocities. This finding was confirmed by other studies (*8*).

Blind pneumatic stowing equipment was used to isolate a coal mine fire in abandoned workings in Colorado in 1982 (*9*). A high-volume, low-pressure blower assisted in blocking passages around the fire. Gravel was blown to an average depth of 110 ft. Because there were no lateral directing elbows (fig. 2), the gravel formed in cones. Sampling of placed material and remote monitoring were not attempted.

A low-volume (1,500 cfm), rotary airlock feeder (RALF) was used with compressed air for small projects in Pennsylvania and West Virginia (*10*). This system was meant for small-tonnage projects of less than 50 st/h and used 4-in-diam pipelines, which made pneumatics a competitive option for backfilling small sites.

In the mid-1980's, the Montana Department of State Lands contracted with the L. C. Hansen Co., Helena, MT, to develop a system that simply dropped <3/4-in materials down boreholes for subsidence suppression (*11-12*). The company incorporated an innovative air-jet technique in which material was fed into a hopper from the surface and compressed air was introduced laterally at the bottom of the borehole to accelerate the fill material in the void. Because there were no elbows or feeders to contend with, the backfilling operation was not hampered by mechanical wear. The laterally directed air "scooted" the dropped

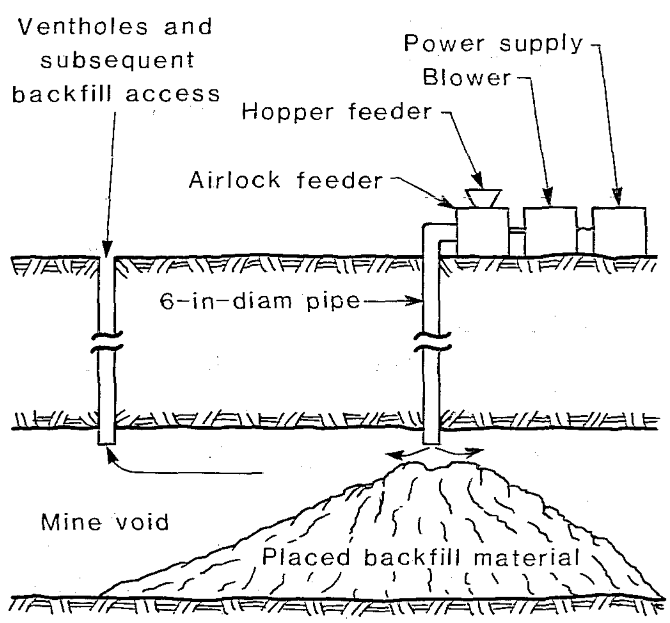

Figure 2.—Nondirected system for pneumatic blind backfilling.

[5]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

material along the surface of the previously placed material, and horizontal distances of 35 ft or better were attained. The steerable air line allowed filling of voids to within 1 ft of the roof, after which pressurized grout was introduced to finish filling. The injection process was monitored remotely with small video cameras; however, no properties testing was done on the emplaced material.

In 1987, the U.S. Office of Surface Mining Reclamation and Enforcement (OSMRE) supported research by Burnett Engineering, Sudbury, MA, in which a simulated mine void was used as a test platform for developing an accelerated air-jet technique for blind stowing (*13*). Material was fed into a hopper from the surface, and compressed air was introduced laterally at the bottom of the borehole. This air was passed through a nozzle that accelerated it to supersonic speeds before catching up solid particles. Sixty short tons of sand and gravel were placed using a variety of nozzle designs, including single, single with baffle, and multiple outlet. The ejected materials reached the full 50-ft length of the opening with a production rate up to 140 st/h. Because the void was simulated in an accessible crawlspace, there was no need for remote monitoring. The emplaced material was not sampled or tested for engineering properties.

BLIND STOWING CONCEPTS

Currently, there are two main concepts being tested for blind pneumatic backfilling. One is the ejector-nozzle system, which feeds material down a borehole or pipe and blows it off a pile with an air jet (fig. 3). The McKenzie Burnett system of Burnett Engineering is a modification of the original ejector-nozzle system. Even though this systems has limitations, it is considered the most cost-effective method at this time.

The second concept, in which a RALF is used, is still the basis for the Hanna-Beric system. This system (fig. 4) uses low-pressure, high-volume air to move the fill material, which is introduced into the airstream with a RALF. Continued development has improved the reliability and wear resistance of RALF's. Wear surfaces are now made from a high-carbon steel heat treated to Rockwell C hardness 62-65. Past attempts at using ceramic or other nonmetallic, wear-resistant materials were unsuccessful because the brittleness of these materials could not withstand the shearing action between stator and rotor.

Standards to evaluate the wear characteristics of fill material have been developed at the Hanna-Beric research facility at Hibbing, MN. On the basis of field and laboratory tests, abrasiveness of the fill materials has been quantified to some degree by assigning an abrasive index number. Typical abrasive index numbers are limestone, 0.2; limestone with some silica, 0.4; Cu-Ni slag, 0.6; silica sand, 1; and river gravel, 1.6. Hanna-Beric believes that its

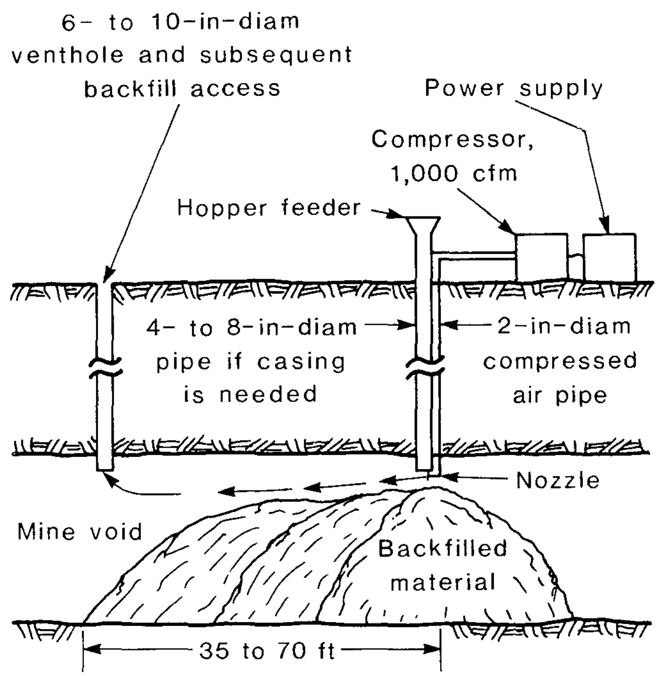

Figure 3.—Ejector-nozzle system for pneumatic blind backfilling.

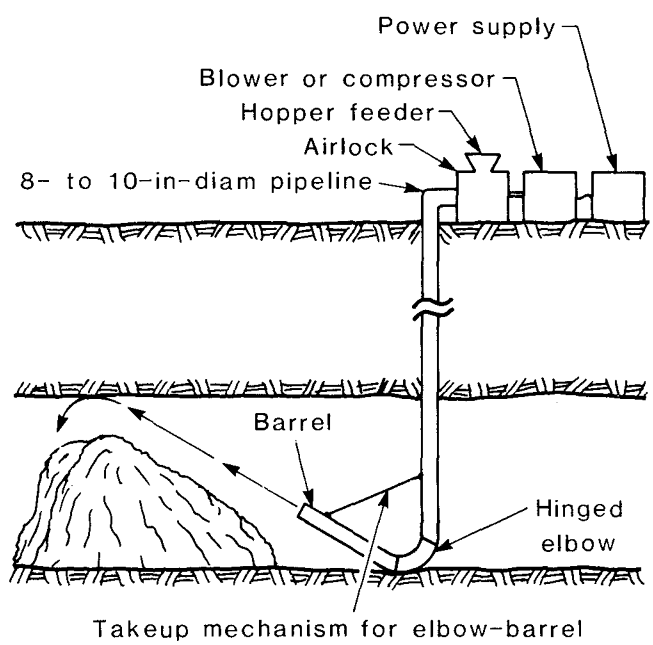

Figure 4.—Airlock feeder system for pneumatic blind backfilling.

RALF is capable of handling 50,000 st of material having an abrasive index of 0.2 before the RALF must be rebuilt. Material with an abrasive index of 0.8 is not recommended because it causes too much wear.

Theoretically, this system (fig. 4) can propel material farther than can the ejector-nozzle system, but it has both a higher initial cost and a higher operating cost. Pneumatic Techniques, Inc., Pittsburgh, PA, and Macawber Engineering, Maryville, TN, both manufacture variations of the airlock feeder system. These variations incorporate dense-phase pneumatics and supposedly wear less than a RALF (*14*). If this is true, dense-phase pneumatic systems could be more competitive than ejector-nozzle systems.

Other variations in both concepts are possible. Many new ideas, some original and some adaptations of existing technology, are needed to address the problems cited in this report.

CASE HISTORIES

Blind pneumatic stowing projects have been undertaken by various companies. Each project revealed new and different problems that either were resolved or remain as potential areas for investigation. Most of the following information was gathered through discussions with the personnel involved with the projects.

CASE 1. L. C. HANSEN CO., HELENA, MT

Numerous backfilling projects in which a blind pneumatic system was used have been completed by L. C. Hansen. All projects employed a method first used in 1981 and originated by the Montana Department of State Lands (*11-12*). A similar design has been used by McKenzie Burnett Co. in Massachusetts (*13*).

The L. C. Hansen ejector-nozzle method was developed to eliminate the RALF because of the feeder's high maintenance cost. Instead of using a RALF to introduce backfill into a high-velocity airstream, this method simply drops the backfill material down a drilled hole and allows it to pile up on the mine floor. About 1,200 cfm of air is blown at 90 psi through a pipe 2 in. in diameter. Sand is carried in the airflow through an orifice 3/4 in. in diameter. At first, the sand accumulates in a large pile, but as filling continues, the sand is blown off the pile out to a distance of about 30 ft. As the sand continues to accumulate, a flat plain or sheet is created until the height of the orifice is reached. Sand must be used for the fill material because larger particles cannot be accelerated enough to reach any appreciable distance.

A venthole is required to allow the large amounts of air introduced into the closed void by the pneumatic system to escape. Without a venthole, air and particle velocities will be greatly reduced. A small, off-the-shelf TV camera suspended down a hole drilled behind the fill hole monitors the fill operation. The direction the camera points can be controlled to within ±3°. A better picture is provided when the fill is wet, but wet fines clog the venthole. While backfilling with the Radmark system costs about \$14/yd, backfilling with hydraulic systems and the ejector-nozzle system costs only \$7/st, not counting assembly and dismantling costs.

CASE 2. MINE X

Mine X has used pneumatic equipment to place several hundred thousand short tons of material from surface installations in an effort to control subsidence. The first system was an experiment that involved a fill pipe and a separate air line. Fill material was allowed to flow in free-fall, much like in the L. C. Hansen system. However, a short elbow and a pipe extension were placed at the bottom of the fill hole to accelerate the fill particles horizontally into the opening. This system was capable of propelling material 70 to 80 ft and provided good compaction. The fill aggregate was <1-in limestone and was fed by a vibrating feeder that simply moved material from a hopper to the fill pipe. The pressure in the fill pipe, created by introducing air at the elbow, was partially contained by the bulk material in the hopper above the fill pipe; however, in the tests, the feed hopper did not contain the pressure properly, and instabilities necessitated shutting down the system periodically to flush the system with water and make any necessary adjustments. Numerous nozzle designs were tested to increase the throw distance and reduce wear, but none were fully successful and the nozzles had to be replaced after 2,000 to 3,000 st of material had been placed. Having to remove the drill string to make repairs was costly. Because of these difficulties, the system was replaced with a conventional Hanna-Beric RALF system.

The Hanna-Beric RALF fed between 25,000 and 50,000 st of <1-in limestone between rebuilds. Material bigger than 1-1/2 in jammed the feeder. Seventy thousand short tons of 3/8-in pea gravel were also placed before the feeder had to be rebuilt. Regrinding the rotor and stator cost \$10,000, but a complete rebuild cost \$30,000, which was about half the cost of a new RALF. The elbow attached to the bottom of the fill pipe handled 20,000 to 40,000 st before having to be replaced and cost only \$800.

The system was still relatively expensive to operate. The RALF system was replaced by a less expensive hydraulic backfilling system when conditions improved and was shipped to another location.

CASE 3. BETHENERGY, WASHINGTON COUNTY, PA

In an attempt to contain a mine fire before it spread, backfilling was tried in an 800-ft-deep coal mine owned by BethEnergy in Washington County, PA. However, the severity of the fire forced personnel to abandon the mine, and a project was initiated to use an airlock feeder system to blind-backfill 23 stoppings.

Ultimately, there were seven rigs drilling at one time. Because the fill material was expected to be blown into the entries for about 75 ft and the entries needed to be plugged between crosscuts (which were spaced at 100-ft intervals), attempts were made to drill into an intersection on line with a rib. However, the holes were surveyed only after they were drilled and about 6 of the 23 holes were so inaccurately located that they had to be redrilled.

The standard nozzle was 45 in long, although a 20-in-long nozzle was also used to move material successfully. The holes were 10 in. in diameter. Different equipment was used at each fill hole, and some performed better than others. In some instances, longer horizontal runs having circuitous routings were needed to reach the drill holes, and this seemed to reduce the throw distance. In other cases, the elbow extension at the end of the pipe was broken off because it either hit the bottom of the entry when the pipe was lowered into the hole or hit the rib as it was raised into position or rotated.

Another difficulty was in not knowing in which direction the pipe was pointing when it reached the bottom. Thirty-nine threaded joints had to be twisted together to add extensions of pipe to reach 800 ft, and so the direction the nozzle pointed after assembly could not be determined. Notching the pipe while it was assembled on the surface and aligning the notches when the pipe was being reinstalled in the hole improved directional control somewhat, but did not always allow full tightening of the joints.

Because they were concerned about a methane explosion, Mine Safety and Health Administration (MSHA) personnel would not allow a TV camera truck to be positioned over the borehole itself, and this complicated setting up the camera suspension system. To help orient the pipe nozzle, a camera was finally lowered down the fill pipe.

Eventually the backfill in the stoppings cut off the oxygen supply to the fire and the fire was extinguished. However, the damage was so extensive that it is questionable whether anyone will ever be allowed back in the mine to examine the effects of backfill placement in more detail.

CASE 4. BURNETT ENGINEERING'S HAGEN PORTAL, YORKVILLE, OH

The Hagen portal in Yorkville, OH, was pneumatically backfilled through boreholes using a new procedure developed by the OSMRE. The goal of the project was to seal a mine entry and to stabilize an overlying roadway, as well as to provide a field demonstration of the procedure itself. Three 10-in-diam boreholes were drilled, and a straight, 6-in-diam polyvinyl chloride pipe with a 2-in-diam air line strapped to it was lowered down each hole with a crane. The air line was used to introduce 2,100 cfm of air at a pressure of 120 psig and a velocity of 1,600 ft/s just below the pipe to accelerate fill material horizontally. Because the fill material was allowed to drop from the surface in free-fall through a vertical, straight pipe, the bottom elbow was eliminated and the particle velocities inherent in systems that accelerate fill with a RALF were reduced, thus reducing wear. If the air-jet nozzle were tilted upward slightly, downward velocity of the particles could be slowed and the particles could then be directed so that they could fill voids nearly 75 ft from the pipe. Problems occurred when moist material clogged the system and coarse material maintained enough momentum so that it fell through the air jet without being redirected. A balance of factors among particle size, filling and air feeding rates, and angle of the air jet was necessary to accelerate the fill material successfully. This system created no back pressure in the feed pipe, eliminating the need for a RALF. The cost of placing material was about $7/st, not including material (fill) costs, drilling costs, and costs of assembling and dismantling the system.

SUMMARY OF PROBLEMS

Through the study of available publications and discussions with personnel involved with pneumatic stowing projects, some common problems became evident.

1. A major difficulty is the inability to view the fill area adequately while backfilling. The lack of light, the light-absorptive character of coal, and airborne dust create a visually flat surface on a TV screen. Using a color TV monitor rather than a black-and-white one would enhance depth of field. An ultrasonic or other waveform coupled with a computer-imaging system may be the solution if one can be developed to provide a profile of the fill where it meets the roof.

2. Costs for pneumatic conveyance systems have been relatively high compared with costs of other systems (*15*), largely because of high wear rates on the pipeline and feeder. Wear is especially excessive at elbows and feeders when highly abrasive backfill aggregates are being transported through dilute-phase systems. Larger, denser particles are attractive backfill materials because they help compact the fill material when they impact. However, this type of material is nearly impossible to transport with the less wear-intensive, dense-phase system. Higher velocities must be maintained to keep particles suspended and to avoid plugging the lines. Because wear is proportional to velocity cubed (*2*), increased velocity increases wear of system components. Feeder failure was noted after 2,000 st of mine waste material had been moved (as little as 350 st for overhauled units) (*16*). The ejector nozzle and the domed airlock chamber designed by Macawber Engineering show promise in reducing wear costs. The Hanna-Beric feeder has also been improved, and wear has been reduced.

3. Drilling access boreholes is a major component of project costs, making the capability to space boreholes farther apart appealing. Higher velocities are needed to propel particles over greater throwing distances if fewer boreholes are drilled. However, a minimum number of boreholes is necessary to explore void layout, to vent and direct the injected air, and to provide video camera accessways (*11-12*).

4. A system for surveying the drill hole during drilling must be used to properly locate the point where the drill hole enters the void.

5. Another high-cost factor is the energy that a pneumatic system requires. Large blowers are needed to generate the volumes of air necessary to keep particles in suspension. Compressed air is regaining popularity as an air supplier, even though the quantities needed are large and special care is needed to reduce noise levels, particularly at the pipe outlet.

6. For those systems using gravity free-fall and high-pressure, low-volume air to accelerate particles, a method is needed to move material for longer distances. Accelerating fill material without its being contained in a pipe (i.e., from the top of a pile as is done in the ejector-nozzle method) allows air to dissipate energy a short distance from the nozzle. This limits the accelerating force and the size of particles that can be used. In most cases, the farther the fill material can be blown, the fewer the holes that must be drilled and the less the equipment must be moved.

7. The backfilling method should be capable of handling material coarser than sand. Even though fine materials can be accelerated in a shorter distance than can larger particles, and fine particles are easier to entrain in an airstream, large particles can be thrown farther once they are entrained. Also, the velocity of small particles is countered more by any reverse air currents that may occur at the face than is the velocity of large particles. Larger particles also aid in the compaction of emplaced material, which improves the final structural strength.

8. An indirect cost associated with pneumatically transported material is the material's inability to flow around large obstructions. Uneven roof lines, rubble, pillars, and trajectory limitations all interfere with the ability to fill a void completely. In some cases, the resulting gap is left unfilled; in others, it is filled with some sort of pressurized grout.

9. The system must be capable of filling 180° in both directions in a drift. A 6-ft-high drift only allows, at most, a 5-ft-long section to be rotated up into position.

10. When an extendable nozzle is lowered, both the pipe and the nozzle must be clear of the floor and ribs during filling. If the nozzle strikes rock, it could be damaged, which requires that the pipe be removed from the borehole and the nozzle replaced. Not only is this process expensive, but time is wasted. Methods are needed to identify (1) the proximity of the bottom of the pipe to the bottom of the entry as the pipe is being installed and (2) the azimuth of the bottom of the pipe with the entry.

11. The design of the elbow requires not only that it be extendable over as great a distance as possible, but also that it be retractable. How long a distance the elbow can be extended horizontally has a great influence on how large the largest particle to be propelled can be. The extension must be long enough either to completely entrain the fill material in the high-velocity air or to generate a spiral movement of the material along the inside walls of the extension so that the material exits from the top of the pipe. If the material does not exit from the top, the particles will not have air beneath them to carry them forward.

12. To attain high particle velocities at the nozzle exit, the air must expand within a confined cross section. To design this expansion chamber and determine the proper position for the jets that introduce air at the elbow requires trade studies and a test program. If new designs could provide higher air and particle velocities, the length of the barrel could be reduced.

13. More durable materials are needed for the barrel. They should be inexpensive and dispensable because even small errors in positioning and manipulating can break them. Elbows must be made of a lightweight, but rigid, material if they are to support a horizontal extension, and they should also have enough wear resistance to handle the tonnage needed to fill all the space within reach of the system. New designs incorporating wear-resistant elbows are needed for situations in which particles are accelerated with air introduced into the pipe at the surface.

Conventional wear-resistant elbows have such a large radius of curvature that they cannot be installed in a reasonably sized borehole.

14. For systems requiring a RALF, new construction concepts and materials may reduce wear costs. Rebuilding the RALF to replace worn parts increases backfilling costs significantly. Currently, a RALF handling fill materials with abrasiveness indices over 0.2 is expected to introduce about 50,000 st of backfill into voids between rebuilds. Tailoring the fill material to reduce wear and increase the service life of the RALF also reduces costs.

15. Methods of improving compaction are needed as well as methods for measuring in situ compaction. The principal variables are grain-size gradation and top particle size, the distance the aggregate is propelled, and the moisture content of the aggregate.

DESIGN CALCULATIONS

To address the need to propel fill material farther to reduce costs, an attempt was made to calculate particle trajectories and distances traveled under different conditions. The results do not define a design, but illustrate the principles that govern the capabilities of a pneumatic backfill system. The results also show that simple calculations are not adequate because they do not take into account the varying conditions found underground. What are needed are the empirical and proprietary relationships derived by manufacturers, as well as laboratory test data.

The main design feature was to allow the free-fall of the material down a pipe, after which the particles within an extended horizontal barrel were accelerated with air introduced into a long elbow. This eliminated high particle velocity at the lower elbow where wear is normally excessive and allowed air to be introduced in a manner that encouraged entrainment of larger particles. However, introducing air at the elbow pressurized the system, necessitating the introduction of free-falling backfill material into a fill pipe with a RALF or some other pressure-locking system.

To illustrate the effects of extending the barrel and using high-velocity air to propel the material, the distance was calculated as shown below.

The drag force imposed upon a smooth sphere in an air current is defined by

$$D_T = \frac{C_D \rho U^2 A}{2},$$

where D_T = drag force,

C_D = drag coefficient,

ρ = air density,

U = air velocity,

and A = frontal or cross-sectional area when looking in the direction of U.

For a sphere, the drag coefficient is found by calculating the Reynolds number and then referring to the drag coefficient-Reynolds number relationship shown in figure 5. Reynolds number is defined by

$$Re = \frac{Ud}{\nu},$$

where Re = Reynolds number,

U = air velocity,

d = diameter of sphere,

and ν = kinematic viscosity of air.

From a free-body diagram,

$$F = ma,$$

where F = force,

m = mass,

and a = acceleration.

If W = weight of particle, a barrel angle 30° from the horizontal results in the equation

$$a = \frac{D_T - W \sin 30^\circ}{m}.$$

The propelling distance is found from $U^2 = 2as$, where s = propelling distance assuming no air friction.

The acceleration and propelling distance for different conditions are shown in table 1. *The propelling distance is given as 0.5 s because this represents the distance to the highest part of the trajectory.* This is most important because, in theory, it is only at the highest point of the trajectory that the space directly under the roof can be filled. However, there is empirical evidence that if the air can escape ahead of the fill, fill material will scoot along a surface and can be deposited some distance beyond the high point of the trajectory.

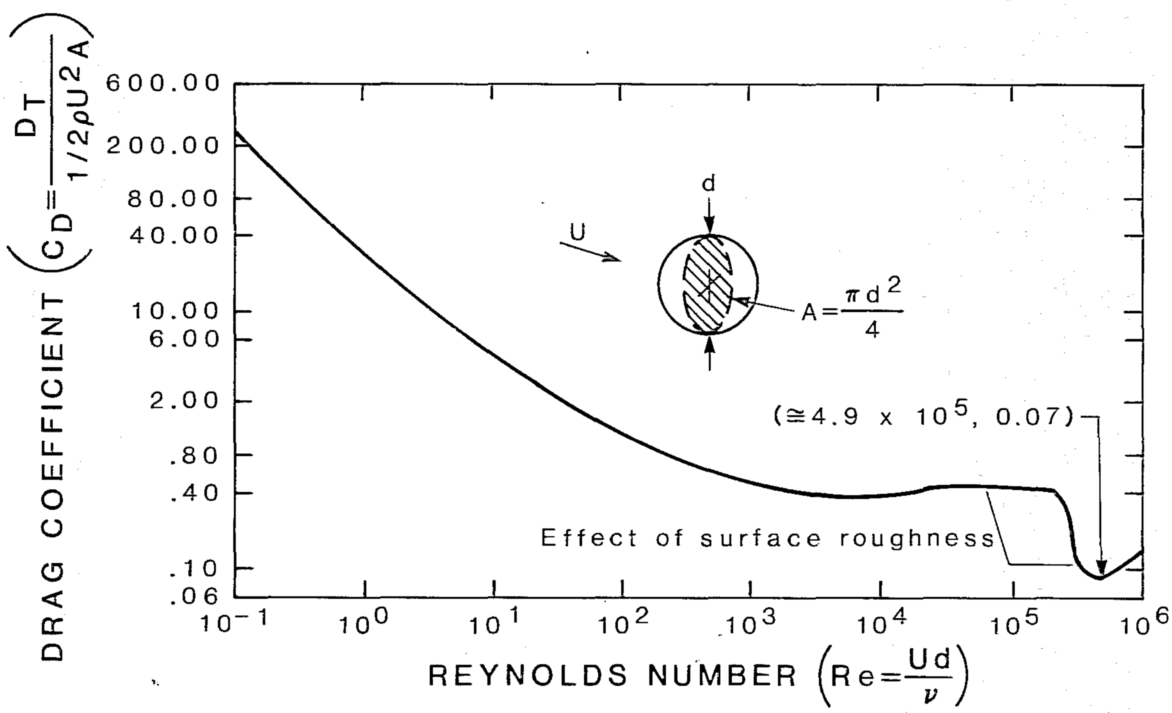

Figure 5.—Drag coefficient versus Reynolds number.

Table 1.—Theoretical distances of particle propulsion

Barrel diameter, in	Barrel length, ft	Air velocity, ft/s	1/2 distance,[1] ft
PARTICLE DIAMETER, 1 in			
7.2	3	1,000	35.9
	6	1,000	71.6
	9	1,000	107
4	3	3,200	153
	6	3,200	306
	9	3,200	460
PARTICLE DIAMETER, 0.5 in			
7.2	3	1,000	112
	6	1,000	225
	9	1,000	391

[1]To highest part of trajectory.

These calculations do not account for many factors. For instance, a rough-surfaced particle will require less drag force to accelerate it than will a smooth sphere. Air friction against the particle after it leaves the barrel will slow the particle. In these calculations, the angle of the barrel was kept constant at 60° and no consideration was given to the height of a seam. Neither were the effects of forcing high volumes of air through these small-diameter pipes considered.

The results show that propelling distance can be increased significantly by lengthening the barrel, which increases the time available for the particle to accelerate and therefore attain greater exit speed. Fine material is accelerated more easily than large particles unless there are reverse air currents within the mine opening. Larger particles can be made to reach higher velocities by increasing power and reducing the nozzle opening.

REMOTE MONITORING OF BLIND BACKFILLING

To determine the extent to which backfilling has filled a void, the operation is usually monitored. The size and shape of the void is determined through a preinjection survey, the tonnage of injected material is measured, and sounding lines are used to detect the height of the emplaced fill. Preinjection surveys can include the use of borehole cameras or sonic calipers in conjunction with accurate mine maps. Microgravity instruments that measure changes in the density (weight) of the fill can help in determining the location and amount of material that has been injected. However, these sensors must be installed before filling begins (*17*).

TV cameras can show the configuration of the void before backfilling, help in the proper placement of the fill material, and show when the void is filled. Previous backfilling projects have used a separate borehole behind and near the fill nozzle for lowering and rotating a TV camera. A high-resolution, waterproof camera 1-19/32 in. in diameter and 11-5/6 in long has been developed by Rees Instruments of England for inspecting the interior walls of nuclear reactors. This camera can be lowered 1,200 ft and will operate under low light conditions and at temperatures from -13° to 140° F. The camera has had numerous applications, including the exploration of Egyptian tombs. A subsystem may be required to keep the lens clear of dust, and a special lighting system is needed to see long distances.

The OSMRE in Pittsburgh used a Westinghouse ETV-1252 closed-circuit TV at the Lekvold-Shaw and Jennison Mine backfill projects to monitor backfilling. Another camera, modified by L. C. Hansen, has azimuth control capabilities and has been used in the field.

Circon Corp., Santa Barbara, CA, has developed many small, durable, color TV cameras. The small size is obtained by splitting the electronic components between a camera and a console, but there have been difficulties in coordinating timing when using long umbilical lengths. The specifications for Circon's MV9393 color, charge-coupled device camera are as follows:

1. Cylindrically shaped, 3.25 in. in diameter and 5.8 in long.
2. Operates with up to a 200-ft umbilical, farther with a line booster.
3. Operating temperature range of 23° to 104° F in up to 75-pct humidity.
4. Sturdily built to withstand vibration and shock up to 80 g.
5. Designed for operation under low light conditions.
6. Interchangeable lenses.

MEASUREMENT AND CONTROL OF PNEUMATIC TRANSPORT SYSTEMS

Monitoring and controlling the flow of solids when using a pneumatic transport system help optimize the process of feeding materials into the system. One method to measure the flow of pneumatically conveyed solids incorporates two axially spaced, nonintrusive capacitance transducers built into the wall of a pipeline. Flow signals from each transducer are compared in a cross-correlator that calculates the time taken for a particle to travel between the transducers. The signals are then fed to a microcomputer. The computer calculates flow velocity and instantaneous mass flow rate and displays the information. The computer can be designed to sense when flow rate is low or blockage might occur, provide audio or visual warning, and control the backfill feed rate automatically (*18*). The Granucor Measuring Line is a new instrument that uses the principles described above (*19*).

To the authors' knowledge, none of these flow-measuring systems has been used in the field during blind pneumatic stowing.

RECOMMENDATIONS

Test plans for pneumatic stowing should include methods of monitoring an underground opening. Approaches that might improve the ability to monitor backfilling operations include a range of techniques from video enhancement to application of totally different remote-sensing technology. While various pieces of off-the-shelf equipment are available, some would require modifications. The coupling of two or more systems might result in a single superior system (*17*).

The first and most reasonable approach would be to improve lighting and use a video enhancement unit. Such devices produce higher quality pictures in low-light areas without decreasing signal-to-noise performance.

An alternative technology might be ultrasonic ranging systems. Such systems commercially available now are capable of measuring distances up to 200 ft. These systems, coupled with a microcomputer and appropriate software, could produce solid body contours of the readings. They can be made immune to dusty, steamy, and turbulent environments.

Other remote-sensing technologies that can be used to position equipment are based on microwave (radar) and infrared systems. The Bureau's Twin Cities Research Center has studied this technology for a number of years in situations where back-up obstruction warnings for large mobile equipment and positioning equipment for underground mines are needed (*20*).

For those systems requiring controlled material injection, such as a RALF, the use of capacitance sensors and microcomputers to monitor mass flow and control feed rate would increase productivity and increase the life of the system components.

New designs and materials are needed for systems using air pressure within a feeder pipe. Different methods of introducing air at the bottom of a pipe and within pipe extensions should be studied, as well as different nozzle designs and air supply systems that will allow better acceleration of fill material. Fill material must also be investigated, particularly the effects of different sizes and various moisture contents; such variables should be tested with each design to evaluate performance and lower costs.

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