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# Inflatable Devices for Use in Combating Mine Fires

UNITED STATES DEPARTMENT OF THE INTERIOR

UNITED STATES BUREAU OF MINES

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***Cover: Mine rescue team members in the positive pressure inflatable walk-through escape device. (Photo by Ronald S. Conti, Pittsburgh Research Center, U.S. Bureau of Mines)***

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By E. S. Weiss, R. S. Conti, E. M. Bazala, and R. W. Pro

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## ILLUSTRATIONS

## UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

### Metric Units

| | | | |
|---|---|---|---|
| cm | centimeter | $m^3$/min | cubic meter per minute |
| kg | kilogram | $m^3$/s | cubic meter per second |
| kL | kiloliter | ML | megaliter |
| kPa | kilopascal | mm | millimeter |
| L | liter | m/min | meter per minute |
| L/s | liter per second | min | minute |
| m | meter | MPa | megapascal |
| $m^2$ | square meter | Pa | Pascal |
| $m^3$ | cubic meter | | |

### U.S. Customary Units

| | | | |
|---|---|---|---|
| cfm | cubic foot per minute | min | minute |
| fpm | foot per minute | pct | percent |
| gal | gallon | psig | pound per square inch gauge |
| h | hour | °C | degree Celsius |
| in | inch | | |

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# INFLATABLE DEVICES FOR USE IN COMBATING MINE FIRES

By E. S. Weiss,[1] R. S. Conti,[2] E. M. Bazala,[3] and R. W. Pro[1]

## ABSTRACT

The U.S. Bureau of Mines is conducting full-scale laboratory studies on the development of lightweight inflatable devices that can be used for rapidly isolating mine fire areas to allow for fire suppression and/or personnel escape.

These inflatable devices were able to stop airflows of over 1,100 $m^3$/min within several minutes. The remotely installed bag was designed to rapidly isolate the fire zone and to then serve, if necessary, as a containment form for the remote injection of low-density organic or inorganic foams.

Other inflatable bag concepts that were tested include an inflatable feed-tube seal for high-expansion foam generators and a positive pressure inflatable walk-through escape device. Laboratory studies indicated that a high-expansion foam plug will travel 183 m through an entry with a 4.5 pct rise in elevation before foam leakage from around the inflatable feed-tube seal. Additionally, the positive-pressure, inflatable walk-through escape device with its "pass-through" feature may allow extra time for personnel evacuation. All of these inflatable devices have shown merit during laboratory studies in providing a rapid method for isolation of a mine fire prior to suppressant foam injection or personnel escape.

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# INTRODUCTION

Fires are an unfortunate, but all too common occurrence during underground coal mining operations. During the period of 1984 through 1994, the Mine Safety and Health Administration (MSHA)[4] investigated 115 reportable underground mine fire incidents, or an average of 10 fires per year. These fires resulted in 28 fatalities and 30 injuries. Mine fires have resulted in loss of life and production losses totaling hundreds of millions of dollars. When a fire is detected in its early stages, a small window of opportunity exists for the fire fighters to directly combat the fire. When coal mine fires can no longer be fought directly, the standard fire-fighting procedure is to construct airtight seals in mine passages leading to the fire zone so that the oxygen supply to the fire can be cut off. The more rapidly the seals are constructed, the more successfully they contain the fire. Conventional methods of sealing passageways surrounding the fire zone are not only time-consuming but also dangerous because of the presence of potentially toxic combustion products and explosive gases. Sometimes mine crews have the opportunity to construct explosion-resistant ventilation seals along accessways to the fire zone. However, the final sealing has to be completed at a safe location.

One of the primary missions of the U.S. Bureau of Mines (USBM) is to protect the health and safety of mining industry personnel particularly against fires and explosions. The USBM has conducted explosion and hydrostatic tests on concrete block bulkheads and other types of ventilation seal designs to evaluate the ability of these seals to function as explosion-resistant and/or water seals (*1-3*).[5] Many of these ventilation seals have withstood explosion pressures up to 0.32 MPa (46 psig), thus providing a fair degree of explosion isolation for abandoned mine areas and fire zones. Often, however, these seals require considerable time to erect and are not conducive to fighting fires in the early stages of the fire when suppression is significantly easier to accomplish. Therefore, there is a compelling need for a rapid sealing system that can be deployed relatively close to the fire zone for the early isolation of underground mine fires. By necessity, these rapid sealing techniques and/or devices must be able to stop or redirect the air supply (oxygen) away from the fire zone and withstand methane ($CH_4$) and/or coal dust explosions that may occur prior to the extinguishment of the fire or the installation of the final permanent seals. The expertise and unique testing facilities of the USBM provide an ideal combination for the development and implementation of inflatable devices that can rapidly and, if necessary, remotely isolate underground fire zones.

This report summarizes the USBM research in developing inflatable devices for isolating and combating underground mine fires. It describes the development of the remotely installed inflatable device and its capabilities. Also discussed are the in-mine inflatable devices for use in isolating mine entries for controlling ventilation airflows, injecting suppressant foam to the fire zone, and aiding personnel to evacuate the mine.

# INFLATABLE FLOW RESTRICTOR

## PRESENT REMOTE MINE SEALING TECHNOLOGIES

At present, the construction of fire seals by workers in the mine is a very hazardous operation. With an active fire in a coal mine, the possibility of explosion is high. Because of this, considerable effort has been directed toward developing systems that can remotely seal off a mine passage from the surface (*4-5*). Remote sealing methods for underground mine entries have been investigated and, in some instances, developed for industry use.

One type of remote sealing method involves pumping any one of a number of materials through a borehole into a mine passage. A particular method that shows promise for providing a remotely installed mine seal is the pneumatic stowing technology, which is being developed by the USBM for ground subsidence abatement (*6*). Several past experiences in remotely sealing mine entries with phenolic or polymer expanding foaming agents have resulted in failure or excessive expense due to the geometries of the entries, rapid setting time, and the presence of ground water. If the mine entry slopes, the seal material being pumped into the mine entry through a borehole has the tendency to spread down the slope and result in incomplete sealing and/or the use of excessive materials. The presence of mine water, both in the borehole and on the entry floor, has resulted in the removal of the sealing material from the immediate vicinity near the bottom of the borehole. This also results in incomplete sealing and/or the use of excessive materials.

[4]The mine fire statistics were obtained from MSHA mine investigation reports maintained at MSHA's Pittsburgh Safety and Health Technology Center, Bruceton Research Center, Pittsburgh, PA 15236.

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

There have been successful sealing operations conducted remotely from the surface. In one such operation (*7*), three boreholes were drilled into the appropriate entries near the fire zone. Concrete and graded products were injected into the two end boreholes to form two stoppings to provide a more rigid, final seal. These materials also acted as a form for the two-part high-expanding resin material that was then injected through the center borehole to create a more airtight seal. However, many of the remote sealing applications discussed above are usually very expensive, labor intensive, time-consuming, and require excessive amounts of sealing material. Quite often, these efforts still do not result in a successful seal. For these reasons, the USBM began to explore the development of alternative sealing methods that are relatively inexpensive, yet provide a rapid means to isolate a fire zone. Efforts also focused on deploying these seals either remotely from the surface or from within the mine.

## DEVELOPMENT OF THE INFLATABLE FLOW RESTRICTOR (IFR)

The current remotely deployable inflatable device was developed and redesigned, based, in part, on previous USBM work with inflatable stoppings for noncoal mines (*8-9*). An in-mine deployment version is also available. These former inflatable stopping designs were installed from within the mine and utilized a single-layer neoprene-coated nylon material that was typically inflated (a one-time inflation period) to internal pressures up to 6.5 kPa (26 in $H_2O$). Upon reaching that pressure, the inflation system was shut off. These stoppings were designed for long-term duration for ventilation control during underground production operations in noncoal mines. The previous USBM work also examined the use of 3.7-m-diam inflatable spheres as emergency stoppings in mine fire rescue and recovery operations (*9*). These spheres were difficult to inflate in rectangular entries having high airflows, and the inflated spheres did not form a good air seal. However, it was perceived that these inflatable spheres might serve as short-term temporary seals during the installation of permanent seals.

Japanese and German researchers have also developed inflatable seal applications that were designed to be installed from within the mine. The Japanese erected a series of three or four inflatable seals per location and inflated the nylon/canvas bags with air to about 3.7 kPa (15 in $H_2O$) (*10*). Explosion tests with coal dust were conducted in their experimental gallery. The results showed that these inflatable seals, when installed in series, were capable of withstanding low-level explosion forces generated from pressures up to 0.09 MPa. The Germans have patented an in-mine inflatable sealing system that was designed to be first inflated with air to 5 kPa (20 in $H_2O$) and then filled with a material that would quickly harden to provide a solid barrier extending across the mine gallery (*11*). The Germans have also included a crawl tube extending horizontally through the bag to provide access to the fire side of the bag. In another recent patented version, an expandable bag was used as a barricade for isolating open areas from spreading fire or smoke, and also providing access for personnel to pass from one side of the barrier to the other (*12*).

The USBM also developed a system that used an array of inflatable barrier bags to suppress full-scale explosions in a mine passageway (*13*). Upon activation (initiated by the explosion pressure pulse), the barrier bags become inflated with a suppressing agent, thereby blocking the cross-sectional area of the mine entry. The inflated bags then vaporize due to the heat of the propagating fire ball, thus releasing the suppressing agent and extinguishing the explosion.

The USBM is advancing the above-mentioned inflatable sealing technologies one step further. Work has begun on the design of an inflatable container system capable of being remotely deployed from the ground surface through a vertical borehole into an entry nearby the fire zone. This system is called the inflatable flow restrictor (IFR).

Development of the IFR started with small-scale simulations in a clear plastic rectangular duct representing a mine entry. Many of the characteristics of the final IFR design were based on the results obtained during these small-scale simulations. Present in-mine inflatable containers are generally spherical or oval and have limited contact area with the mine entry surface. As a consequence, the inflatable containers are usually constructed from heavy materials able to withstand the internal pressures required to hold the seal in place against the mine walls. The IFR was designed to be oversized for the mine entry in which it will be deployed. When the oversized container is inflated, it provides a large surface contact area with the mine walls. This large contact area enhanced the frictional resistance between the container and the mine entry, thereby reducing the internal pressure required for the inflated container to withstand the ventilation flow while still maintaining a relatively airtight restriction.

The first fabric container design for the IFR was rectangular to match the mine entry geometries and was expected to provide an airtight fit when inflated. However, considerable difficulty was encountered in obtaining the desired orientation of the container during the deployment and inflation period, resulting in a less than ideal fit. Proper orientation of the rectangular container is critical for an airtight seal. Because an actual remote deployment of the IFR into a mine entry may be through a borehole several hundred meters deep, it would be very difficult to maintain any kind of container orientation during lowering. For these reasons, an oversized, cylindrical container design was chosen, because its final configuration after inflation would always remain the same regardless of how it was deployed through the borehole. The small-scale tests in the clear plastic duct supported these conclusions.

In order to be remotely deployed from the ground surface, the IFR had to be fabricated from lightweight material so that the entire package could be lowered through typically sized boreholes with diameters ranging from 15 to 20 cm. To make the IFR resistant to low-level explosion forces, quick-setting materials could be pumped through the borehole from the surface into the inflated bag. To accommodate the injection of these liquid reactant materials and prevent the incursion of mine water into the bag (or the filler material out of the bag), the IFR had to be fabricated with waterproof material.

To perfect a procedure for filling an inflated bag with a fast-setting material, several bench-scale tests were conducted. A vendor demonstrated the use of binary reactants to generate polyurethane foam. After equal volumes of reactants were thoroughly mixed, setting occurred very rapidly. Structural rigidity was achieved within about 5 min. In a small-scale test, an oversized, cylindrical fabric bag was inflated with air inside the clear plastic rectangular duct. The premixed reactants were injected into the inflated bag. The foam rapidly expanded to fill the duct. The foam generated an expansion force that ruptured the box, suggesting that a thick polymer seal erected in a similar fashion in a mine entry would not be easily dislodged by a weak explosion.

Based on the positive small-scale bench tests, several larger-scale demonstrations were conducted to evaluate the IFR concept. A 1.2-m-high by 3-m-diam fabric bag was remotely deployed through a simulated borehole (15-cm-diam by 2.1-m-long pipe) and then inflated inside an 2.4-m-wide by 0.9-m-high by 3.7-m-long plywood frame (approximately quarter-scale of a typical coal mine entry). A portable air compressor was used during the inflation process. In less than 2 min, the inflated bag totally filled the simulated entry. Because the bag, when inflated, was much larger than the simulated entry, the bag filled the rectangular corners of the entry's cross-section very well. Effective blockages of the entry were accomplished with the inflated bag when the bag was deployed through a simulated borehole under two different scenarios. In the first scenario, the simulated borehole penetrated the roof in the center of the simulated entry. In the second case, the borehole penetrated the roof of the simulated entry 0.3 m from the simulated rib.

To obtain a rigid seal, a specially formulated polyurethane expanding foam was introduced into the preinflated bag. To inject the liquid foaming agents, the two binary reactants were drawn from their respective containers, blended together in-line, and pumped through the simulated borehole and into the inflated bag. The expansion of the blended reactants began in approximately 5 min. Due to the use of a small pump, a total of 47 min was required to pump the material (454 kg) into the bag. Thermocouples were positioned to measure the heat release of the polyurethane during its reaction period. A maximum temperature of 47 °C was measured in the center of the bag. The expanding polyurethane completely filled the bag thus generating an outward pressure on the plywood entry with sufficient outward force to bow the simulated roof and floor to a maximum of about 5 cm.

After a 24-h curing period, the entry was disassembled for further evaluation of the seal. It was observed that the surface contact area on the entry walls ranged from 6 m (side walls) to 2.4 m (roof and floor). However, gaps in the upper corners were evident; this was due to an insufficient initial volume of the polyurethane reactants and the low rate of injection. Nevertheless, the test results were very encouraging.

A second test was conducted in the quarter-scale simulated entry using the inflated bag and polyurethane. However, in this test, the polyurethane reactants were premixed and rapidly injected, in less than 2 min, into the inflated bag. The manufacturer slowed the reaction time of the materials to allow for the complete transfer of material into the inflated bag prior to any expansion. The polyurethane then expanded from the entry floor to completely fill the entry (and corners). The temperature in the center of the polyurethane-filled bag reached a maximum of 144 °C, 40 min after the initial injection of the reactants. A thermocouple located between the entry floor and the bag indicated a maximum temperature of 44 °C. At least 2.4 m of full contact was achieved on each of the four sides. Subsequent examination showed the seal to be uniform in texture throughout. There was no evidence of layering as was experienced during the first test wherein the reactants were slowly injected into the bag and the foam expanded early in the injection process, thus resulting in a nonuniform and layered product.

A third test was then conducted that was similar to the second test except that the bag was not preinflated with air. In this test, the force of the expanding polyurethane was sufficient to unfurl the bag and fill the entry. For all three of these tests, the bag served as a containment vessel for the expanding polyurethane and successfully limited the amount of material required to fill the entire cross-section of the entry.

The reaction time between initial blending of the reactants and the expansion of the foam can be varied by the manufacturer during the production process to range from seconds to minutes. From the preliminary quarter-scale data, a slowed reaction time provided for a better overall seal in terms of complete entry coverage and uniform seal density. To recommend an optimal reaction time, additional studies would be required using various entry sealing volumes.

## FULL-SCALE TESTING OF THE IFR

Based on the encouraging results from the small- and quarter-scale tests with the IFR, full-scale tests were then conducted in the entries of the USBM's Lake Lynn and Bruceton Experimental Mines to evaluate the ability of the IFR to serve as a rapid and remote deployment method for ventilation control to and from a fire zone. The experimental mine entry dimensions ranged from 1.8 to 2.4 m high by 5.5 to 7 m wide, typical of modern U.S. coal mine geometries.

The primary emphasis of this effort was to develop a mine seal capable of remote deployment from the ground surface to isolate mine fires. In mining applications, the IFR's would be deployed several hundred meters away from the fire location so that heat from the fire would dissipate and not adversely affect the devices (see figure 1). By placing the IFR's at strategic locations around the fire zone, the combustion products from the fire could be rapidly isolated within the fire area. At the same time, if necessary, inert gases or other materials could be injected into the zone to limit the oxygen supply to the fire.

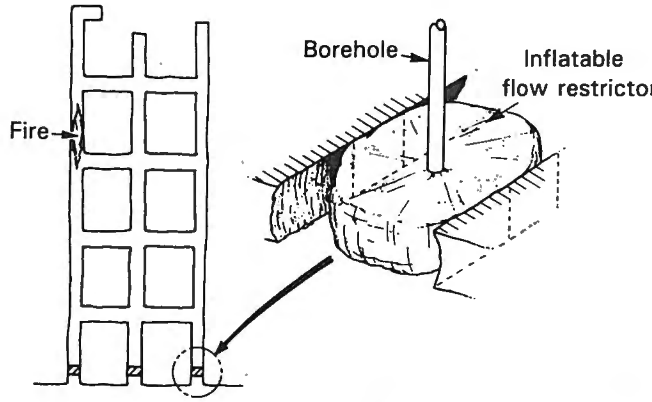
The first phase of the research with the small- and quarter-scale tests showed that this type of remote isolation and sealing application using inflatable bags was feasible. The research then was directed toward validating these findings in full-scale applications. Two types of deployment methods for the IFR have been considered, in-mine and remote.

### In-Mine Deployment Methods

Experiments with the inflatable devices were conducted in the USBM's Lake Lynn Laboratory Experimental Mine (LLEM) (*14-15*). This former limestone mine now serves as one of the world's foremost multipurpose mining research laboratories for conducting large-scale health and safety and environmental research; particularly fire and explosion prevention research. The entry dimensions of the underground mine range from 1.8 to 2.4 m high and from 5.3 to 6.7 m wide. The average cross-sectional area is 12 m². Figure 2 is a plan view of the LLEM showing the entry configurations.

The first full-scale tests were conducted with the in-mine deployment design of the IFR. A 2.4-m-high by 6.7-m-diam bag was fabricated using a lightweight, waterproof, rip-stop nylon fabric. This fabric was chosen for its puncture and tear resistance and waterproof characteristics and also to facilitate the remote deployment experiments. Other fabrics can be substituted during actual in-mine applications for increased fire resistance and durability. However, these fabrics are usually much heavier because of greater material thickness and, therefore, cannot be utilized during the remote deployment experiments due to the restrictive size of a typical 15 to 20-cm-diam borehole.

*Figure 1*

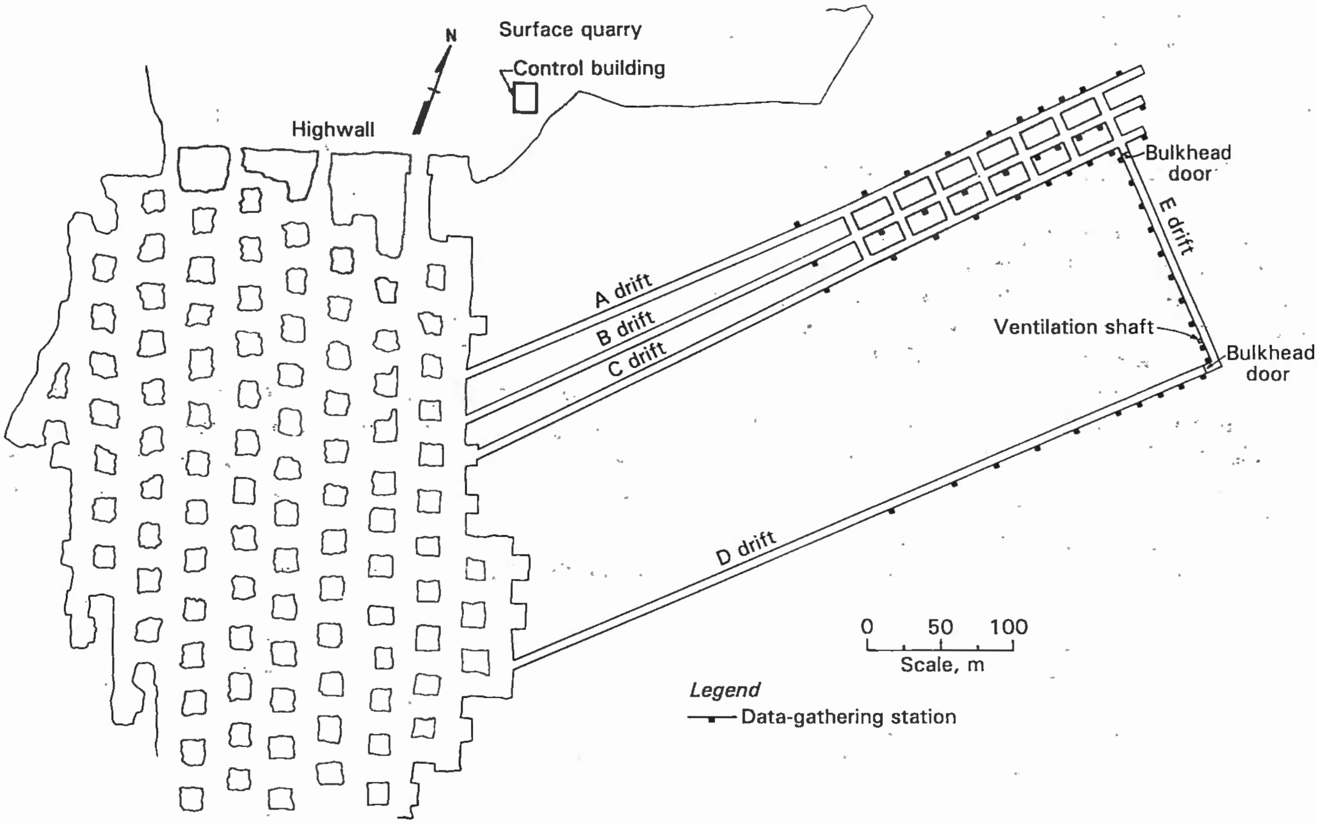



***Conceptual drawing showing an inflatable flow restrictor (IFR) as it would appear in the mine entry following remote deployment through a borehole. A series of IFR's could be positioned in the entries nearby a fire to isolate the zone.***

The in-mine bag was designed with an air injection port on the curved cylindrical surface near the base. The bag was easily inflated in about 12 min by using an electric blower. The bag just barely filled the 6.4-m-wide and 2.1-m-high entry, at the test location in E-drift. To determine the bag's effectiveness in controlling ventilation, a portion of the airflow from a 1,840 m³/min fan was directed against the bag. The seal easily withstood a pressure differential of 50 Pa (0.2 in $H_2O$).

Additional tests were conducted with the IFR in C-drift of the LLEM at a location between the first and second outby crosscuts. A concrete block seal was installed in the first outby crosscut. The entry at the location of the inflation trials was 2.4 m high by 6.7 m wide. The bag used in this test was 3 m high and 9.1 m in diameter. To rapidly inflate the bag, a 40-cm-diam axial fan with an explosion-proof motor housing and a delivery of 74 m³/min was used in place of the electric blower. The time for full inflation of the IFR was 3 min. At the start of the inflation of the bag, C-drift was being ventilated at a rate of 910 m³/min (32,000 cfm), which provided an air velocity of 76 m/min (250 fpm). Even before the bag had been totally inflated, the ventilation flow in C-drift was reduced

*Figure 2*




***Plan view of the Lake Lynn Experimental Mine.***

to zero, thereby forcing all of the airflow through D-drift. It took less than 1.5 min of inflation time to effectively isolate C-drift from the ventilation airflow. Figure 3 shows the IFR fully inflated and the axial fan used for inflation.

A stability problem was encountered when inflating the IFR in ventilation flows greater than 910 $m^3/min$ (32,000 cfm). During the initial inflation period, the high ventilation flow in the entry resulted in the downstream movement of the bag-fan assembly. When the bag was inflated to the point of contact with the mine walls, this downstream movement was halted because the ventilation flow could not overcome the resistant, frictional forces of the partially inflated bag against the ribs. To prevent this initial movement, a 6-m-wide by 9.1-m-long section of nylon net was secured to roof bolt plates across the entry roof 6 m downstream of the deflated bag-fan assembly. The length of netting was then extended along the entry floor and under the bag-fan assembly. This prevented movement of the bag-fan assembly during the inflation process in ventilation flows as high as 1,130 $m^3/min$.

*Figure 3*

***A fully inflated IFR during an in mine deployment using an axial fan at the LLEM.***

In some cases, the use of such quick-to-erect IFR's may control ventilation to and from the fire zone so effectively that the fire may be combated without having to erect permanent seals. Furthermore, this type of ventilation device would appear to have application in rescue operations. Because the bag-fan assembly is relatively lightweight, it could be easily transported to a suitable location near a power source, i.e., air, water, or electricity. In a matter of minutes, the IFR could be erected in the entry. By appropriately deploying such quick-to-erect IFR's strategically around a fire zone, it is conceivable that contamination of the air in escapeways could be effectively reduced. Likewise, a combination of IFR's can be used in a leapfrog fashion to create a rapid airlock system for recovery of the mine following a fire.

Experiments have also been conducted wherein the portable fan with the explosion-proof motor housing was interfaced with a smoke sensor to automatically deploy (inflate) the IFR from a preinstalled location. This type of installation has application to smoke containment, especially in the escape airways. The preinstalled IFR's can also be automatically or manually inflated (as the escaping mine personnel pass by) using permissible fans powered by air, water, or electricity. The IFR's could also be connected to the mine's air compressor supply lines or air tanks.

Deployment of IFR's as described in all the cases above would alter the existing mine ventilation. Care must be exercised that this does not create a greater hazard (*16*), for example, by reducing ventilation in other parts of the mine and/or creating conditions in which toxic or flammable gases behind ventilation seals could be forced into the active workings due to a lowering of the pressures in the active workings relative to that in the sealed areas behind the ventilation seals.

### Remote Deployment Methods

To perfect the procedure for remotely deploying the IFR within various mine entry configurations, six full-scale experiments were conducted at the USBM's Safety Research Coal Mine located at the Pittsburgh Research Center (PRC). In each of these tests, a 3-m-high by 9.1-m-diam bag was remotely deployed from the ground surface through a 30-m-deep by 20-cm-diam, PVC-lined borehole into a 1.8-m-high by 7-m-wide entry. One end of a 2.5-cm-diam air hose was secured to the inside of the deflated bag; the other end was attached to an air compressor on the surface. To aid in monitoring the inflation pressure, a length of 0.6-cm-diam plastic tubing was secured alongside the air hose with one end near the bottom, inside of the bag. To keep the collapsed bag closely packed for lowering down the borehole, straps were placed about every 0.6 m along the bag-hose assembly. As the 9.1-m-long packed bag and hose assembly were lowered down the borehole, the constraining straps were removed.

The bag was initially lowered down the borehole until 3.7 m of the bag extended into the entry (lowering distances were premarked on the air hose), leaving the remainder of the bag-hose assembly in the borehole. The bag was then partially inflated until a pressure gauge, that was attached to the surface end of the plastic tubing, indicated a pressure rise within the bag. The air delivery was then temporarily turned off, which resulted in a pressure drop within the bag. An additional 2.4 m of hose was then lowered into the entry and the air inflation was resumed until the internal pressure of the bag once again began to increase. This inflation and lowering process was repeated until all 9.1 m of the packed bag was inside of the entry. An interval of less than 30 min was required to deploy the bag down the borehole and fully inflate it within the entry. Figure 4 is a series of photographs showing this process.

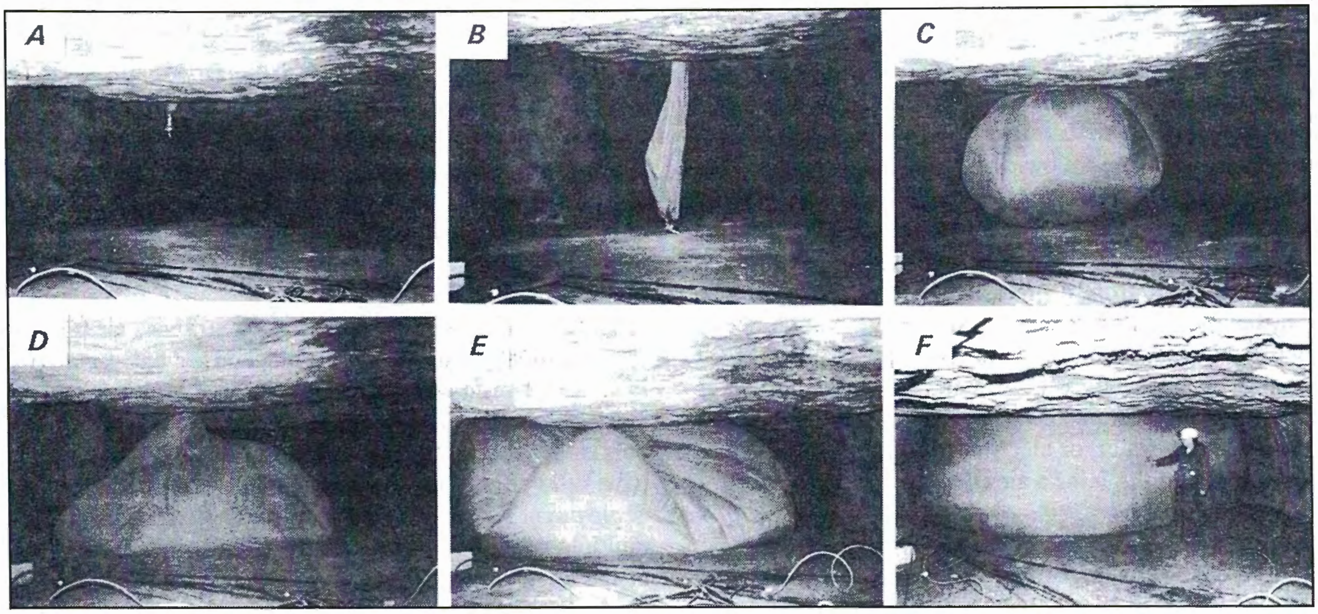
In the deployment of the IFR in a straight, clear entry, the fully inflated bag effectively blocked the entry, resulting in 4.6 to 9.1-m-long contact zones between the bag and the entry surfaces. Obstructions within the mine, such as timbers and cribbing for roof support, track, etc., appear to have little effect on the deployment of the IFR. Remote deployment tests also were conducted with the IFR where multiple roof support cribs were installed along one side of the mine entry (0.6-m spacings between crib supports). Evaluation of the fully inflated bag showed that the bag inflated between the cribs and effectively blocked the entry.

The key to the success of the IFR was the use of the lightweight, oversized bag. This bag enabled the IFR to be remotely deployed through a borehole and allowed it to inflate in and around obstacles within the mine. Additional remote deployment tests with the IFR were conducted from the surface through a 60-m-deep borehole into a 2-m-high by 5.8-m-wide mine entry at the LLEM. A diesel-powered winch with wire rope was used to lower the bag and air hose assembly down the deeper borehole. These tests were equally successful in that the entry was completely blocked in less than 30 min.

Although the remotely deployed IFR, when filled with air, offers a means of controlling ventilation to and from a fire, it would be unable to withstand the pressures generated from a $CH_4$ and/or coal dust explosion within the fire zone area. However, if the air in the IFR were replaced by a relatively quick-setting material, it might be possible to obtain a seal capable of withstanding these explosion overpressures. The quarter-scale tests, in which the IFR was filled with polyurethane, showed that there was merit in future investigations with full-scale IFR tests filled with a rigid material.

For an IFR filled with a rigid material to be considered a mine seal, it first must meet the requirements as defined in the Code of Federal Regulations. These regulations for underground coal mines state that ventilation seals must be capable of isolating the sealed areas (abandoned workings, fire zones, areas susceptible to spontaneous combustion, etc.) from the active workings. To effectively isolate these areas, a seal must control the gas-air exchanges between the sealed and active areas so as to

*Figure 4*




*Installation process of the IFR as it was remotely deployed from the surface through a borehole into the mine entry.*

prevent toxic and/or flammable gases from entering these active workings. A seal must also be capable of preventing an explosion initiated on one side, from propagating to the other side of the seal. In addition, a seal must continue its intended function as a ventilation seal for up to 1 h when subjected to a standardized fire test. The intended use of the IFR filled with a rigid material was that it would serve as a rapidly deployed temporary seal until the fire was extinguished or permanent seals could be installed at a safer outby location.

Future research plans involve the remote deployment of the IFR from the surface through a borehole into the LLEM. Once installed in the mine, the IFR will be filled with a rigid material and evaluated as to its ability to withstand the pressure forces generated from $CH_4$ and/or coal dust explosions. Several materials are being considered for use in the IFR: polyurethane expanding foams and low-density cementitious expanding and nonexpanding slurries. The advantages of the cementitious materials over those of the organic resin foams are that they are incombustible and exhibit higher strength characteristics.

## PARTITIONS FOR USE WITH HIGH-EXPANSION FOAM (HEF) GENERATORS

### UTILIZING HEF DURING MINE FIRES

When an underground mine fire cannot be directly attacked due to heat, smoke, or hazardous roof conditions, HEF can be used to remotely quench the fire. The firefighting personnel and HEF equipment can be located away from the immediate vicinity of the fire in a less hazardous underground location. High-expansion foam is a convenient means of conveying water to a fire (*17*). It quenches or extinguishes a fire by diluting the oxygen concentration through the production of steam, blocking the air currents to the fire, and blocking the radiant energy from the fuel (*18*).

High-expansion foam cannot control a fire unless the foam plug reaches the fire (*19*). Attempts have been made to push foam plugs into the burning entry downwind of the fire. However, the tremendous heat and gases on the downwind side of the fire tend to break down the foam. As the heated foam breaks down, it converts into steam that is carried down the entry, away from the fire. Additionally, practical experience has shown that HEF generators may not produce quality foam (bubbles may not form) if the intake air is contaminated with smoke.[6] Foam pushed into the fire on the upwind side of the fire stands a much greater chance of reaching and cooling the fire.

[6]Private communication with Will Jamison, Jamison Engineering, Aug. 1993.

In two instances, foam was successful in controlling mine fires at least temporarily. In a fire that occurred in a Colorado coal mine (*20*), miners started fighting the fire with an 11.3 $m^3/s$ diesel-powered foam generator and a supply of fifteen 208-L drums of foam concentrate. Additional foam concentrate was obtained from several other mines and a local vendor. Unfortunately, sufficient quantities of foam to quench the fire were unavailable and, when the foam was depleted, the fire became uncontrollable. At the Montour No. 4 Mine fire in Pennsylvania (*21*), firefighters generated foam for nearly 3 days. Over 1.1 kL (4,000 gal) of foam concentrate and 1 ML (270,000 gal) of water were depleted during that period. It was stated that "the foam took over successfully at a critical time and reduced one of the largest mine fires on record to a safe sealing operation." (*21*).

To effectively use the foam method for remotely fighting fires in underground mine entries, it is often necessary to construct a partition or stopping in fresh air, at some distance from the fire site, to separate the foam generator and its operators from the smoke and toxic fire products. If this is not done, the HEF could flow back over the foam generator, rendering the fire attack futile. This problem is especially acute when the fire is located uphill on a sloping entry. Concrete block, wood, plastic sheeting, brattice or similar materials have been used for such partitions (figure 5). Often, mine entries have irregular dimensions to which the partition must conform to avoid leakage around the periphery. Construction of such partitions can be a time-consuming process.

After the partition is constructed, a hole must be cut through it to allow passage of the HEF from the foam generator to the fire site. Cutting a hole in the partition can be labor-intensive, time-consuming, and could be a dangerous process depending on fire conditions (such as the accumulation of flammable gases on the other side of the partition). This through-hole in an improperly sealed partition often can result in substantial leakage around the HEF feed tube due to the backpressure of the advancing foam plug.

It must be realized that the installation of any partition reduces the ventilation airflow and can cause the fire to burn fuel-rich. This can be hazardous if the unburned volatiles are ignited. Due to this potential explosion hazard, advance planning, training, and preassemblage of correct materials (foam generator and concentrate, water supply, partition, etc.) are essential. To minimize the explosion hazard, the use of the foam generator should occur immediately following the installation of the partition.

Earlier tests conducted by the USBM (*18*) using foam to control and extinguish experimental underground coal, wood, and oil fires indicated that a foam plug could travel 488 m in a level entry (2-m-high by 2.9-m-wide). Several limitations of using the foam plug method included time required to assemble the equipment at the fire location; the limited distance foam can be transported, including upward and downward sloping passageways; the requirement of electrical power (fan motor used to produce foam) near the fire area; and the effect of the foam plug on ventilation. Despite these limitations, the underground mine experiments indicated that foam was effective in controlling or extinguishing fires.

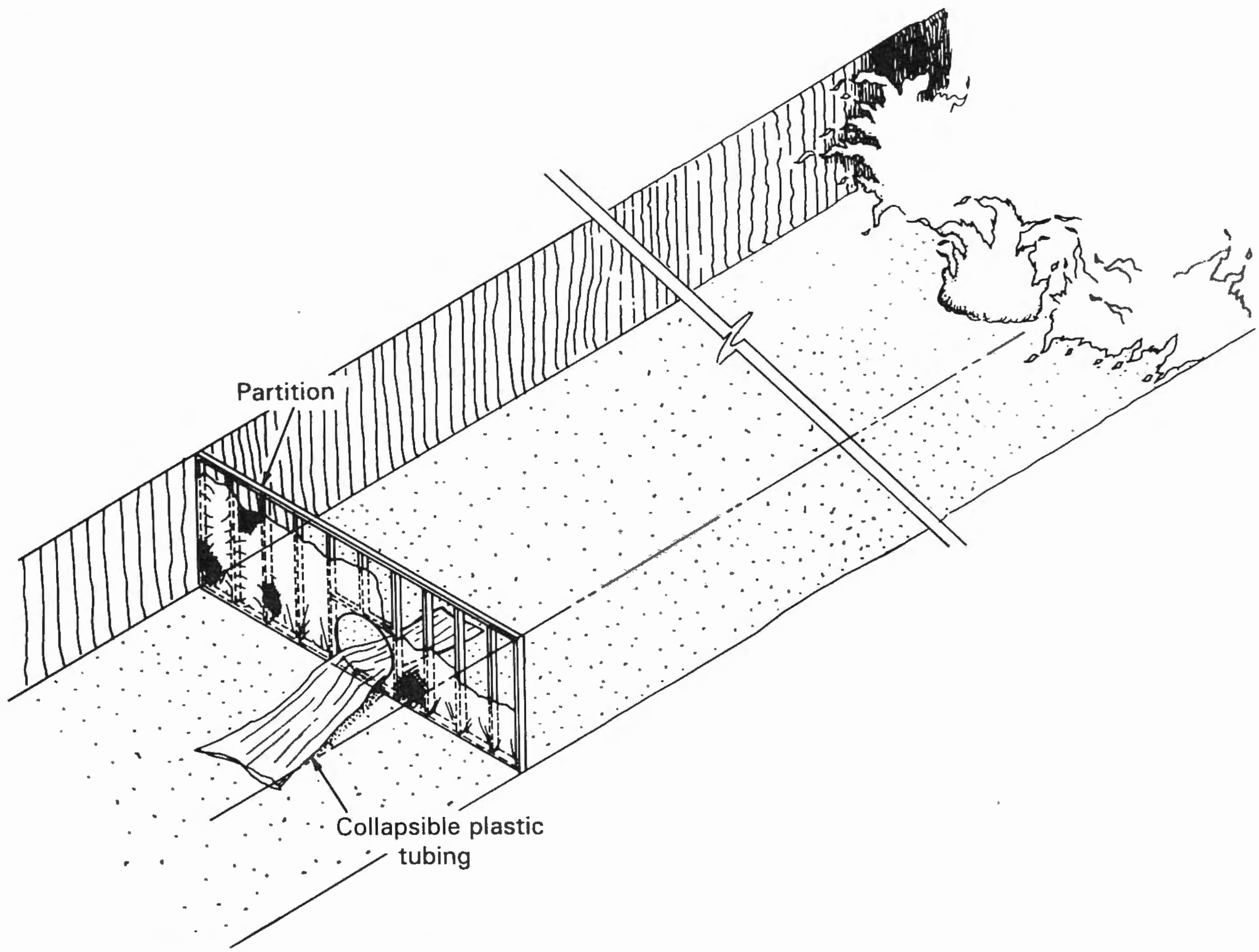
## INFLATABLE FEED-TUBE SEAL (IFTS)

To address the drawbacks of constructing a partition, the inflatable feed-tube seal (IFTS) was developed (*22-23*). The IFTS is a lightweight, portable, rectangular, inflatable bag that is used in conjunction with HEF generators. The device can rapidly block large openings, such as those in underground mines (figure 6) and simultaneously provide a feed tube for HEF.

The portable IFTS can be easily transported to a mine passageway leading to a fire area and then be inflated by an air blower or other source of compressed gas. The IFTS, similar to the IFR, is fabricated from a water- and heat-resistant, lightweight fabric (0.076-mm-thick, chemically treated, rip-stop nylon). The IFTS could also be fabricated from a material such as mylar or fire-resistant materials such as kevlar. The shape and size of the IFTS depend on the passageway dimensions in which it may be used. For example, for a mine entry 2.1-m-high by 5.8-m-wide, the IFTS would take the shape of a slightly oversized rectangular bag approximately 2.6-m-high by 6.1-m-wide and 3.1-m-long, weighing 8.2 kg. Traversing the IFTS is an aperture comprised of a collapsible cylindrical passage lined with the fabric of the bag. A collapsible plastic feed tube is passed through the aperture and conveys HEF from a foam generator on one side of the IFTS to the other side. This allows the foam generator to fill the passageway leading to the fire area with foam. The pressure of the foam in the tube exceeds the pressure of air in the IFTS, and thereby keeps the aperture open. When the foam generator is deenergized, the aperture collapses and no longer affords passage of the foam through the IFTS.

Figure 7 depicts the IFTS being deployed in a mine entry containing a fire. The IFTS is inflated (to about 0.14 kPa) by a fan attached to the IFTS with an air tube. When inflated, the IFTS blocks off the entry, as depicted in figure 8. A collapsible plastic feed-tube extends through the aperture (approximately 3.1 m long). At this stage, the aperture is collapsed, thereby closing the aperture and the feed tube. Air pressure in the IFTS is maintained by the fan through the air tube. One end of the collapsible plastic feed tube is connected to the HEF generator (figure 9). Operation of the foam generator results in an expansion of the feed tube due to the pressure of the generator's fan.

*Figure 5*




*A partition for high expansion foam generators.*

This allows the HEF to freely flow through the IFTS and down the entry to the fire site.

## Experimental Section

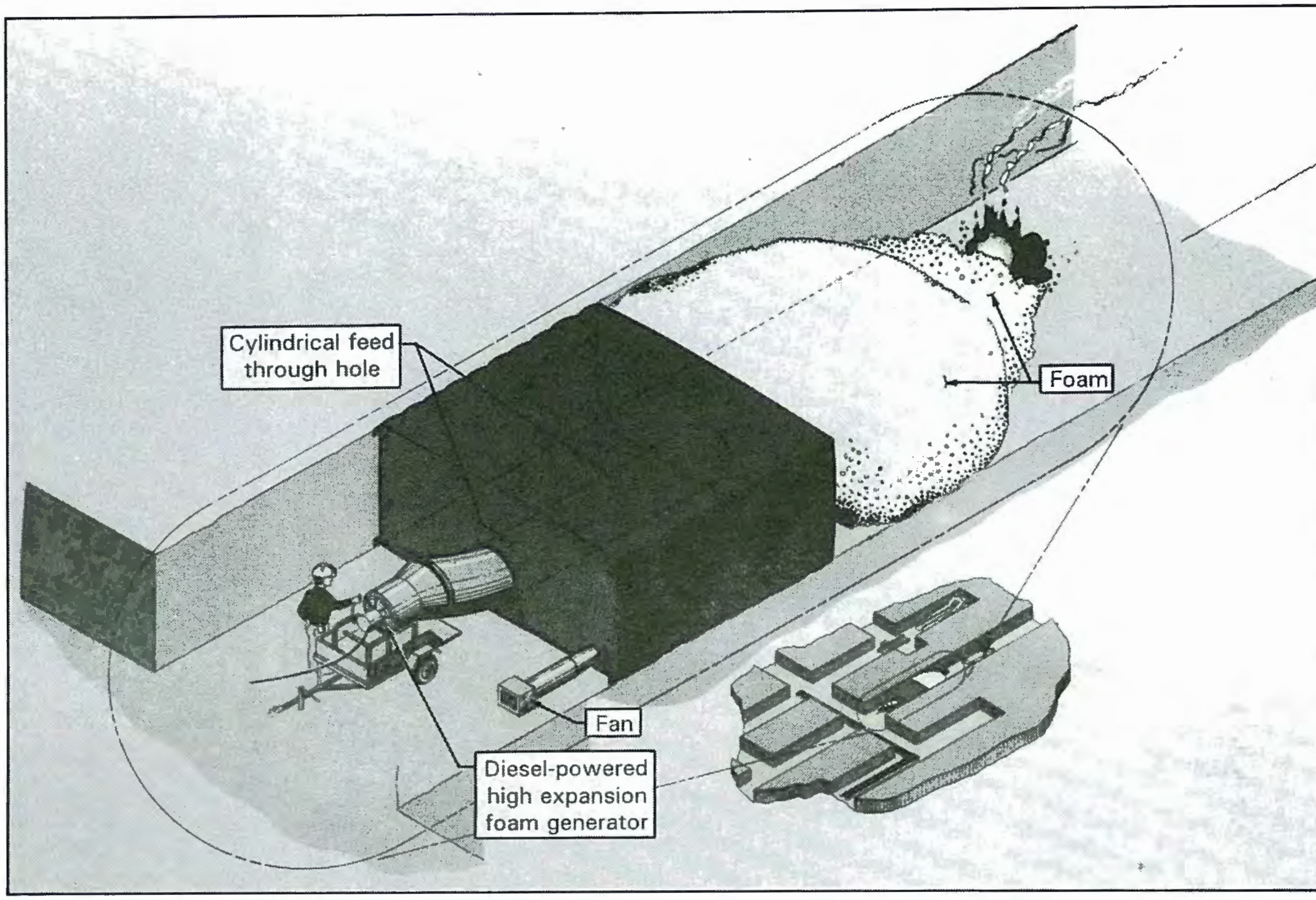
### HEF Tests

Foam tests were conducted in the LLEM to determine the quantity of foam concentrate required to produce sufficient HEF to fill a mine entry. For a 2.8 $m^3/s$ diesel-powered HEF generator, the expansion ratio is 850:1, using a 2 pct HEF concentrate solution. Operating parameters were set at 3.15 L/s of water and 0.551 MPa water pressure at the eductor. Eductors, the most common form of proportioning equipment, use the Venturi principle to introduce the proper percentage of foam concentrate into the water stream. In 1 h, 11,600 L of water and 227 L of foam concentrate were used with this foam generator. It required 2.2 min to fill 30.5 m of a 5.8-m-wide by 2.1-m-high entry (372 $m^3$).

Tests in the LLEM also showed that a HEF plug readily traveled up and completely filled an entry with a 4.5 pct rise in elevation, including a crosscut with the above dimensions. The foam plug also moved forward around corners and obstacles, such as wood cribs. With a plywood partition to separate the foam generator from the foam plug, the foam spread 207 m before the partition failed (the failure criterion was foam leakage from the foam feed-tube hole or around the partition, that rolled back over the foam generator). The advance rate of the foam for the first 30 m was 11.7 m/min, gradually decreasing to 1.74 m/min when the foam reached 207 m from the partition. The amount of foam concentrate used in the test was 182 L.

Additional tests indicated that the advance rate of the foam plug over the first 30 m was 12 pct slower in a dry

*Figure 6*




*Inflatable partition for high expansion foam generators.*

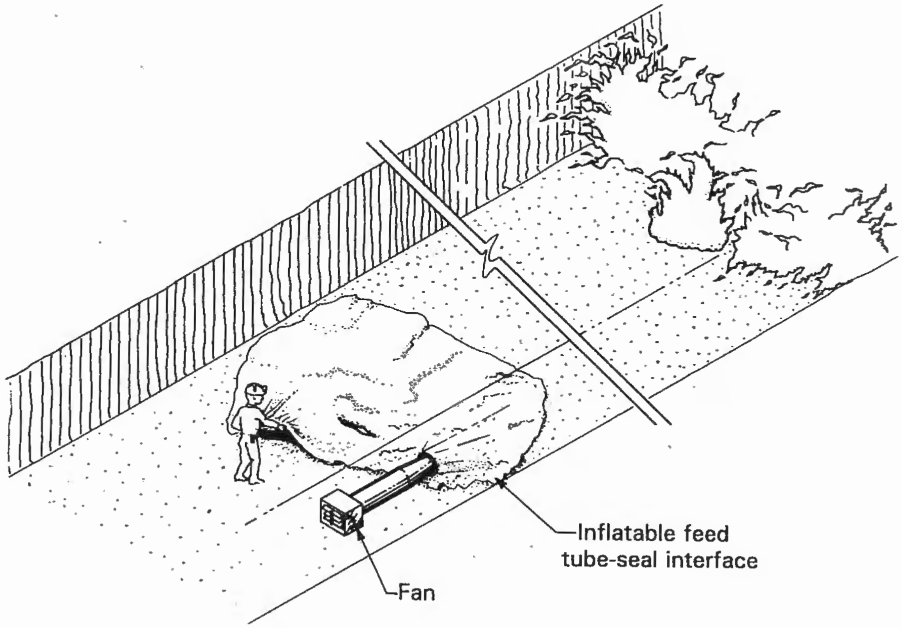
entry than in an entry wetted with a water hose prior to the test. It also required 38 pct more foam concentrate to completely fill 30 m of the entry under dry conditions with HEF foam as compared to a wet entry. The foam initially shrunk 0.31 m from the roof over the first 24 h, and continued to shrink an additional 0.46 m over the next 96-h period. Figure 10 shows the height of the foam plug in the entry with time.

### Tests With IFTS: First Prototype

The IFTS was tested in the LLEM (figure 11), with entry dimensions of 2.1 m high by 5.8 m wide. An IFTS of appropriate size (2.6 m high by 6.1 m wide and 3.1 m long) was inflated in the entry. The diesel-powered HEF generator was turned on and produced foam that propagated up the entry 91.5 m (4.5 pct rise), including the filling of a crosscut. After the experiment, the foam generator was deenergized and the feed-through tube self-sealed.

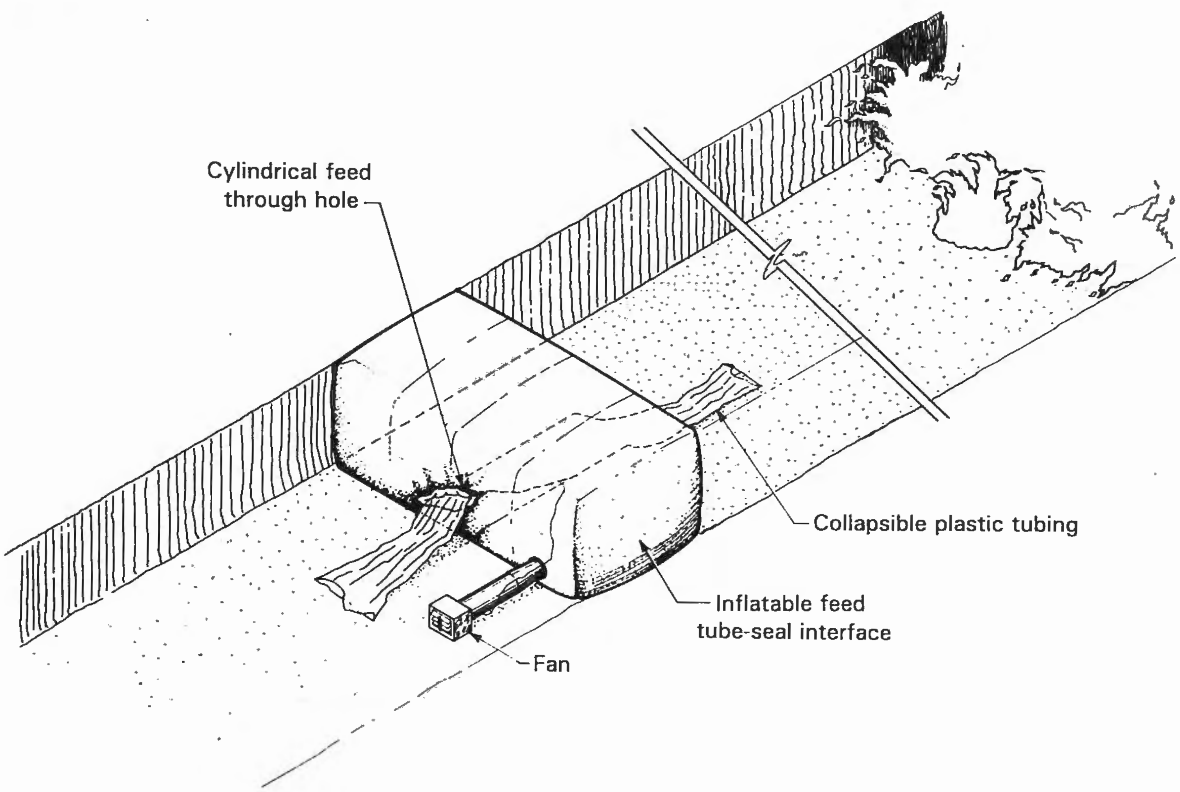
Another experiment was conducted with the IFTS in an entry 2.1 m high by 5.9 m wide to determine the rate of advance of a HEF plug and the distance the foam plug would travel in dry entry conditions before IFTS failure. The failure criterion was foam leakage that rolled back over the foam generator. The advance rate of the foam for the first 30 m was 7.2 m/min, decreasing to 6 m/min when the foam reached 92 m. The advance rate was significantly slower than the 11.7 m/min advance rate of the tests performed with the plywood partition. The slower advance rate can be attributed to the restriction offered by the diameter of the aperture through which the feed tube is passed. The test was terminated when the foam plug traveled 92 m because the IFTS started leaking foam around both ribs. It is possible that such leakage could be mitigated by increasing the size of the IFTS with respect to the entry dimensions. Additional tests, which included inserting a 117-cm-diam rigid tube through the feed-tube hole, increased the advance rate to 10.2 m/min for the first 30 m. The initial experiments of the first prototype

*Figure 7*



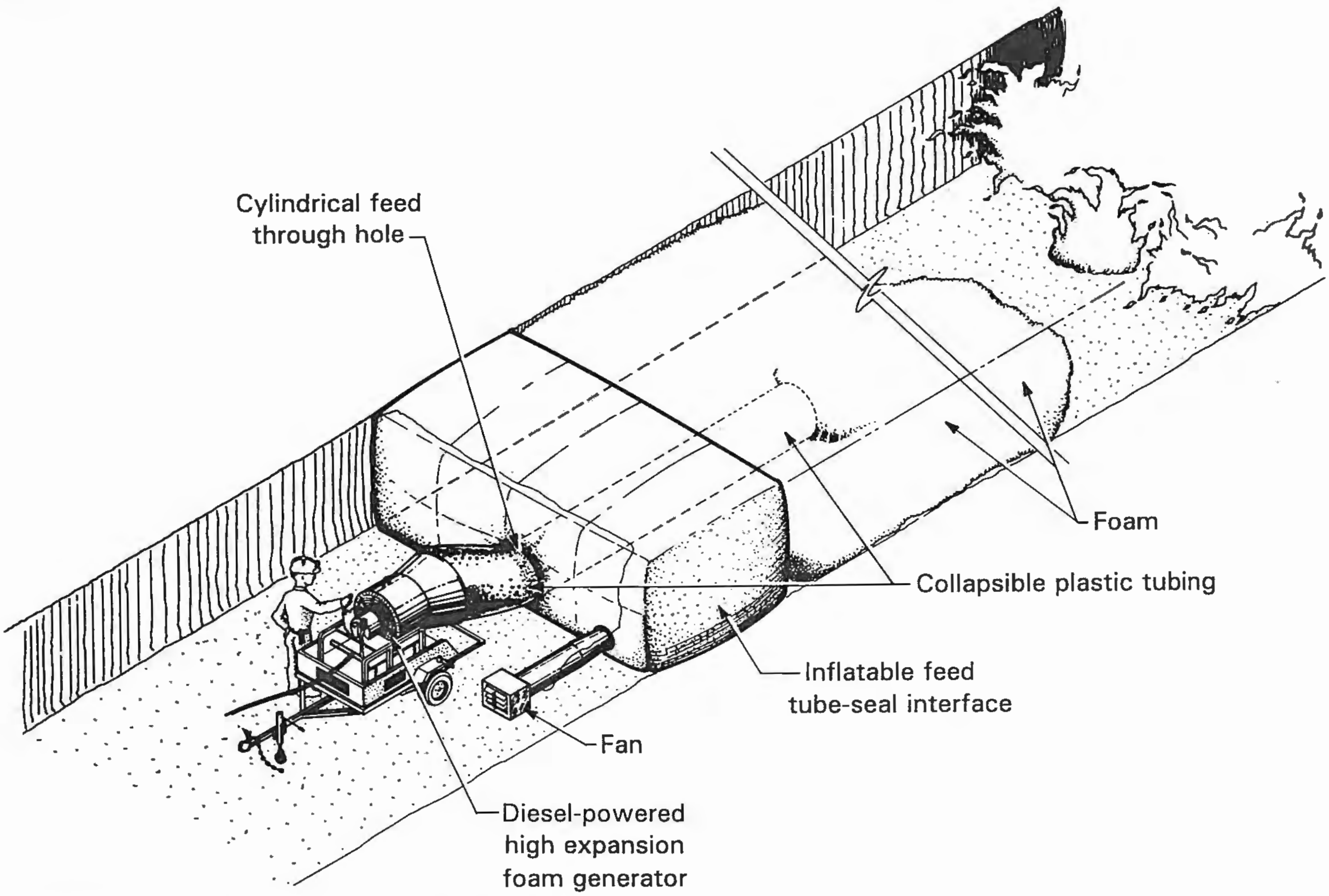

*Inflating the feed-tube seal with fan.*

*Figure 8*



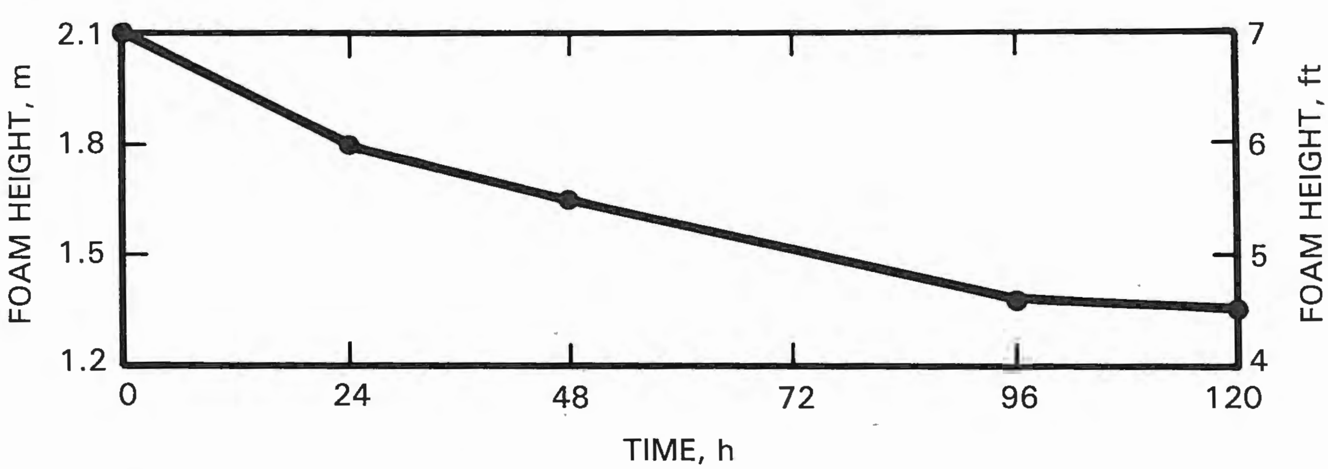

*Inflated feed-tube seal.*

*Figure 9*



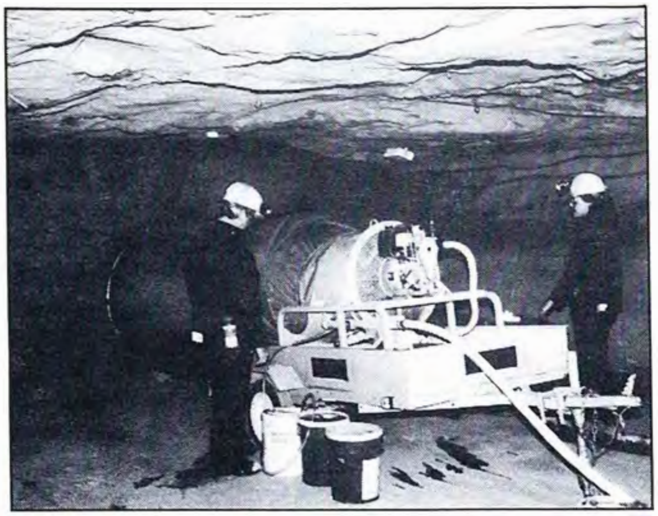

*Inflated feed-tube seal coupled to foam generator.*

*Figure 10*




*Shrinkage rate of a foam plug.*

*Figure 11*



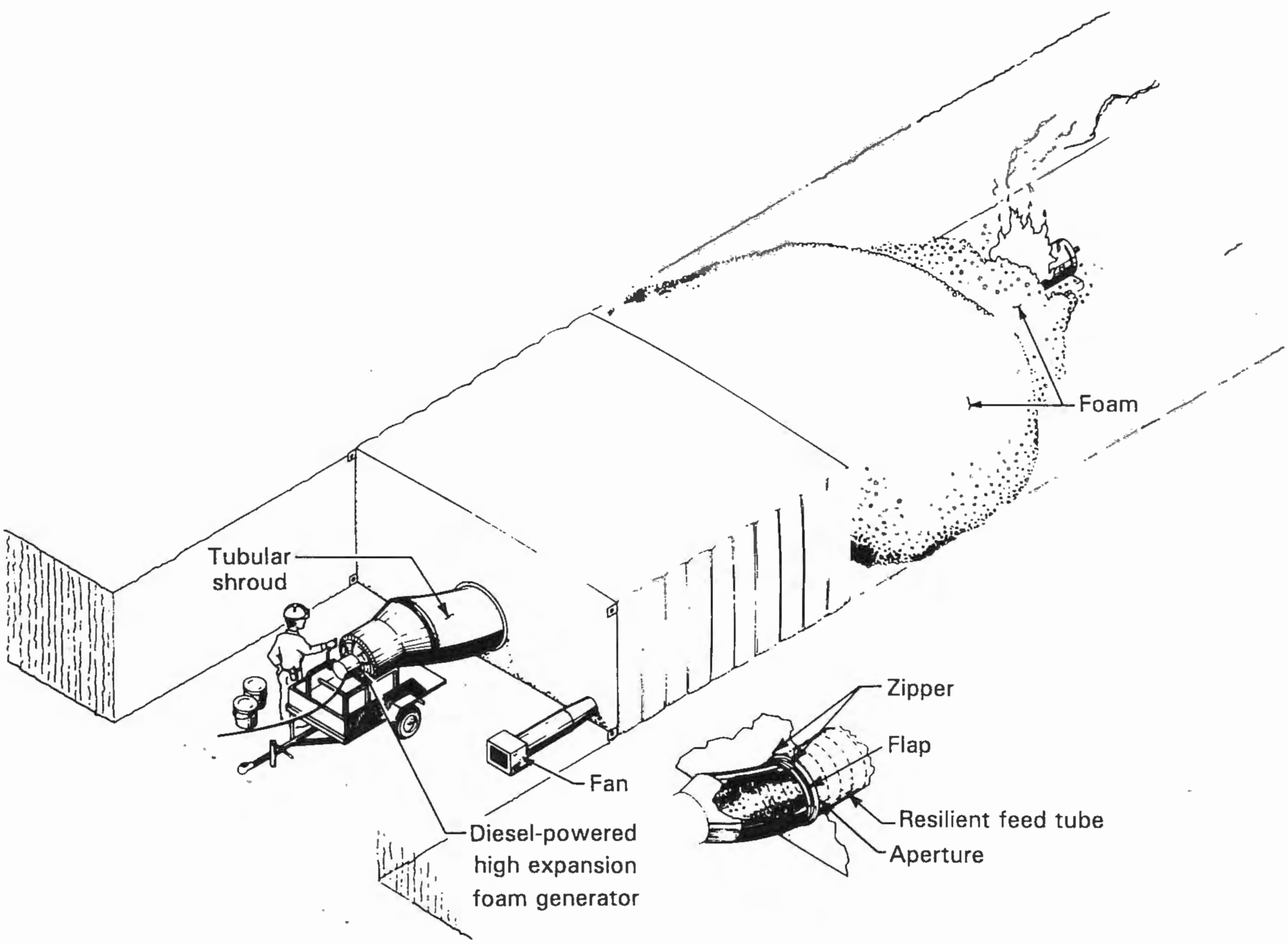
*Inflatable feed-tube seal in LLEM.*

showed that the IFTS concept had merit, and additional experimentation was warranted.

### Tests With IFTS: Second Prototype

In another version of the IFTS (figure 12), a tubular shroud was used to convey HEF from the foam generator to a resilient feed tube. The overall dimensions of the IFTS were also increased so that it could be rapidly deployed in larger or irregularly shaped entries. This increased size of the IFTS also enhanced the distance a foam plug can travel before the device fails. A larger resilient feed tube, 137-cm in diameter, incorporated a helical metal wire that extended the length of the aperture. The wire stay prevented the aperture from collapsing due to the air pressure in the IFTS, thus maintaining the unrestricted propagation of the foam from the generator through the partition. A tubular shroud was attached to the front side of the IFTS by a zipper and velcro. The

*Figure 12*




*Second prototype inflatable feed-tube seal, depicting resilient feed-tube.*

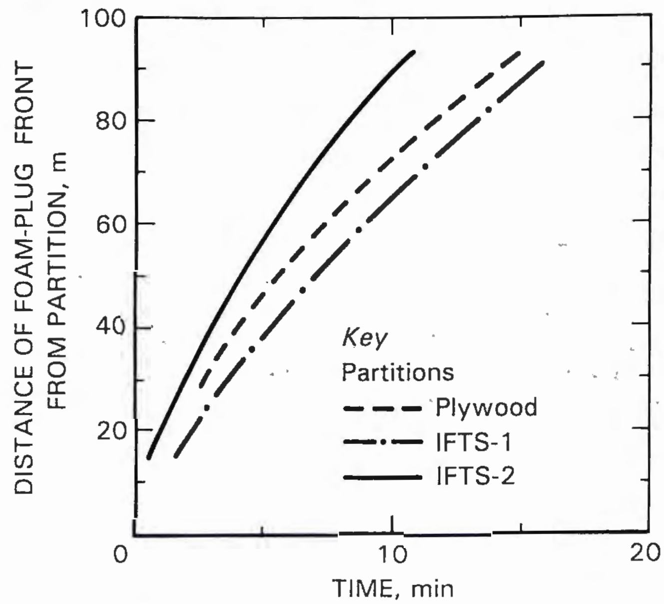
shroud replaced the collapsible plastic feed tube used in the previous IFTS. The shroud was designed to collapse when the foam generator was deenergized, thus preventing flow of HEF back toward the foam generator. The total weight of the IFTS, excluding the blower assembly, was 39 kg.

Experiments with the second prototype IFTS were conducted in the LLEM. The amount of foam concentrate used in the test was 90 L. The average advance rate of the foam plug for the first 30 m was 14.4 m/min, decreasing to 9 m/min when the foam reached 92 m. At 183 m, the test was terminated because the IFTS started to leak foam near the corner of the roof. Such leakage can probably be mitigated by anchoring the four corners of the foam exit side of the IFTS to the ribs.

The distance-time relationships for transport of the foam plug over 90 m for all three partitions are shown in figure 13. The data for all partitions indicate that the advance rate decreases with distance traveled. This is due to the resistance of the foam plug (as the foam plug moves further away from the foam generator) and to the constant driving force of the foam generator. The driving force was constant for this particular foam generator, but can vary depending on the type of foam generator. In addition, and more importantly, the second IFTS prototype (IFTS-2) showed a significant increase in the advance rate of the foam plug, as compared to both the earlier version of the IFTS and the plywood partition. Even though the distance that the foam plug had traveled was less with the IFTS-2 as compared to the plywood partition at partition failure, the foam-producing efficiency was increased. This improved efficiency (the distance the foam-plug front traveled from the partition with respect to time) was mainly due to the enlarged diameter of the resilient feed tube.

Additional experiments are planned to verify the maximum distance a foam plug can extend into an entry

*Figure 13*




***Rate of travel with respect to time of foam plug fronts for three partitions.***

before the IFTS fails, by anchoring the four corners of the foam exit side of the IFTS to the ribs. In addition, an evaluation of foam generators with larger driving forces interfaced to the IFTS will be made to determine the advance rate of the foam plug. Fabricating the IFTS from other materials, such as mylar, is also being considered. The use of other nonporous materials may eliminate the need for a continuous air supply after the bag is inflated. Finally, tests to evaluate the ability of the foam to extinguish experimental mine fires will be conducted.

## POSITIVE PRESSURE INFLATABLE WALK-THROUGH ESCAPE DEVICE

Another conceptual use of the inflatable devices is as a rapidly deployed escape stopping, as shown in figure 14. This escape stopping would be strategically placed in a mine entry, and then either manually or remotely deployed during a mine fire. This device would temporarily isolate the smoke-filled entry from fresh air. Mine personnel escaping from the mine fire would enter the bag from the smoke-filled entry side and exit into the fresh air side. Because the bag is under positive pressure, it would be impervious to outside contaminants (such as smoke and gaseous products) and, therefore, would have the capability of being used as a temporary shelter only if the air intake remains in fresh air.

A positive-pressure, inflatable walk-through escape device was fabricated and tested in the LLEM. During one deployment trial, the rectangular inflatable bag that was mounted at the roof using slide rods and rings (attached every 30 cm on both sides of the top portion of the device) was inflated by an air blower. The device was suspended onto the support rods with the rings and secured into the corner of the roof and rib with strapping material. During the inflation process, the device unfurled and slid across the cross-section of the entry. Mine personnel entered the bag from the "smoke-filled" side by unzipping the doorway or flap, proceeded through the device (figure 15), unzipped the exit doorway or flap into the fresh air side (figure 16) and exited. Both passageways should be re-closed when traveling through the device.

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