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The Road to Zero: The 50-Year Effort to Eliminate Roof Fall Fatalities from US Underground Coal Mines

Christopher Mark[1]

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Abstract
Six decades ago, the most dangerous job in the USA was mining coal underground. Roof falls were responsible for half of the deaths, killing about 100 miners every year. Fast forward to 2016 and zero roof fall fatalities. Just three miners were killed by roof falls during the following 6 years. How did the mining community achieve this historic goal? This paper starts by analyzing the roof fall fatalities in 1968, categorizing them by their fundamental cause. Then, it shows how each type of roof fall was reduced over time, using snapshots of the fatalities occurring in subsequent decades. Along the way, it evaluates the influence of the regulatory environment, changing mining methods, and better ground control technology. The study found that in 1968 more than half of roof fall fatalities at large mines were attributable to an inadequate safety culture. The immediate effect of the 1969 Coal Mine Health and Safety Act was to reduce the riskiest activities, like needlessly going under unsupported roof. Other hazards, like large roof falls, required technological developments before they were brought under control. Roof Control Plans, which the US Bureau of Mines had been advocating since the 1920s, played a significant role throughout the process.

Keywords Ground control · Roof falls · Coal mining history · Mine safety regulation

1 Introduction

The year 2016 was the first ever in which no miners were killed by roof falls in US bituminous coal mines. This feat was repeated in 2018 and 2019, and then again in 2020.[1] It seems fair to say that roof falls are no longer a major source of fatalities underground.

Observers from the not-so-distant past would have been astonished by this. Roof falls were once considered an inevitable, unpredictable hazard of the "inherently dangerous" underground environment. During the last century roof falls claimed more than 50,000 coal miners' lives, half of all deaths underground. Coal mining was known as the most dangerous industry in the US, and roof falls were a big part of the reason why.

How dangerous was coal mining? The year of 1968 provides a useful illustration. During that year, at the peak of the Vietnam War, 16,592 US servicemen were killed in action. The combat fatality rate for the 3.55 million US active-duty military personnel was therefore 4.7 per thousand [1, 2]. That same year, 267 of the 73,000 US underground coal miners perished on the job, at a rate of 3.7 per thousand. In other words, being a coal miner was almost as dangerous as being in uniform at the height of the Vietnam War. Coal miners faced similar odds year after year, for the duration of their careers.

Not only was coal mining dangerous, but safety had hardly improved in decades. Between 1948 and 1968 a coal miner's chances of being killed on the job had decreased by just 9%. The roof fall fatality rate, shown in Fig. 1, was also essentially flat during the 20 years prior to 1968.[2]

During the same period, the fatality rate for all US industry had decreased by 36%, and some industries had fared better, as shown by the 49% reduction in the steel industry [3].

✉ Christopher Mark
Mark.christopher@dol.gov

1 US Department of Labor, Mine Safety and Health Administration, Pittsburgh, PA, USA

[1] Unfortunately, during the same 5-year period 2016–2020, there were seven fatalities due to falls of the face or rib, and one roof fall fatality in an anthracite mine.

[2] The number of roof fall fatalities fell from about 400 to 100 per year during these two decades, but since this reduction was accompanied by a similar decrease in the number of underground coal miners, the net result was that a working miner's chances of being killed in a roof fall (the roof fall *rate*) remained almost constant.

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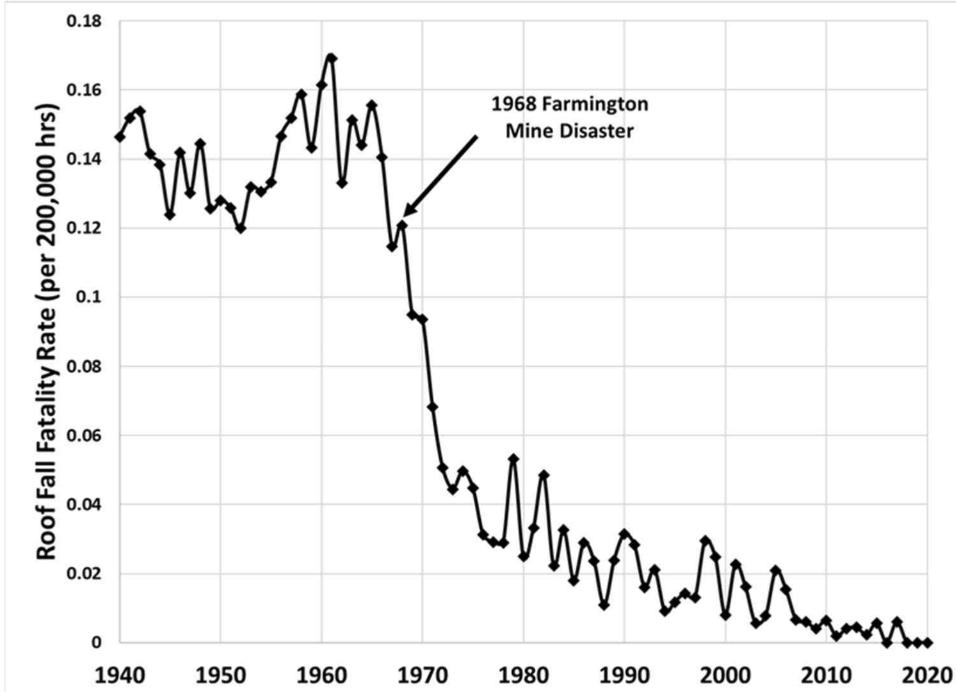


Fig. 1 Roof fall fatality rates in underground coal mining, all mines, 1940–2020

The coal industry was aware that the problem was not purely technical but was caused in large part by an inadequate safety culture. As the leading industry journal, Coal Age, noted in 1960:

> Few are the mines that cannot cut accidents from falls of roof, face, and ribs more than 50% by the intensive, continuous application of well-known basic principles. All that is necessary is to do it. [4]

By the mid-1960s, the ongoing carnage in the coal mines had become a national concern. In 1966, Congress asked the US Bureau of Mines (USBM), then the Federal agency responsible for mine safety, to "conduct a special study to determine the sufficiency of the present safety requirements of the 1952 Federal Coal Mine Safety Act, with particular emphasis upon the requirements relative to roof support, ventilation, and electrical equipment" [5]. Two years later, the House Committee responsible for the 1969 Act wrote that "The death and injury rate from roof falls is shocking. The industry and the Bureau of Mines have been remiss in attempting to solve this problem" [6].

Then, on November 20, 1968, Consolidation Coal's Farmington Mine was destroyed in a massive gas and dust explosion, killing 78 miners. The nation watched in horror as the rescue effort went on for 10 days, until further huge explosions rocked the mine and it had to be sealed with the miners' bodies still inside.

The Federal Coal Mine Health and Safety Act of 1969, passed in the wake of the Farmington disaster, transformed the regulatory environment for coal mining. The following decade witnessed a precipitous 75% drop in the roof fall fatality rate (Fig. 1). Another 40 years of slow but steady progress was then required to reach zero. While Fig. 1 tells the overall story, it does not fully explain how the changes came about. The purpose of this paper is to explore the actual processes that were at work during those 50 years. It evaluates the specific new technologies that came into wide use during each era, as well as the role of the changing regulatory environment.

The first step is to determine what factors were behind the high death rate in the pre-Act era. To accomplish, this the paper analyzes the USBM roof fall fatality reports from 1968. These reports are available at the National Mine Health and Safety Academy Library in Beaver, WV, and on the Library's website.

2 Roof Fall Fatalities in 1968

In 1968 a total of 89 bituminous coal miners were killed in 82 separate roof falls.[3] This analysis focuses on larger mines with more than 15 employees.[4] The 55 fatal roof falls

[3] There were also 10 fatal rib falls, and one fatal ground fall in an anthracite mine.

[4] There were still nearly 3000 small mines in the US in 1968, 1200 of which relied entirely on hand loading. Those small mines accounted for just 10% of the hours worked underground, but 31% of the roof fall fatalities. Almost all the 28 fatal roof falls at small mines occurred while the miners were unprotected by roof support. The number of small mines was already diminishing, however, and that trend would rapidly accelerate after the 1969 Act went into effect.

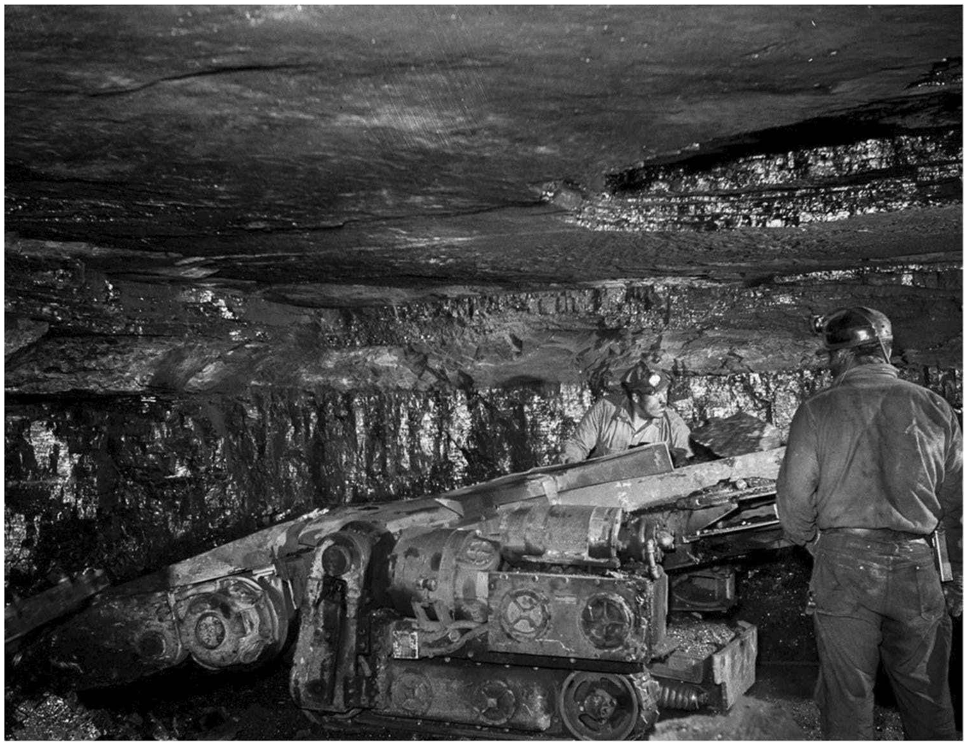


Fig. 2 Two miners loading coal beneath unsupported roof prior to the Mine Act. Note where a portion of the roof has already fallen out. Such photographs were quite common in that era, further indicating that the practice of working beneath unsupported roof was widespread (source: US Bureau of Mines)

in large mines, with 61 fatalities, can be divided into two main categories:

- Those involving "blatant" violations of "well-known basic principles" of roof control, which are indicative of an *inadequate safety culture*.
- Those where the failure could be attributed to *inadequate safety technology*, including the roof support system, the mining equipment, and/or the support plan.

The "basic principles" of roof control had been spelled out years before, most prominently in the voluntary Federal Mine Safety Code [7]:

- "Adequate minimum standards for roof support suitable to the roof conditions and mining system of each mine shall be adopted and followed."
- "The roof in all underground working places, unless self-supporting, shall be secured sufficiently to protect employees from falls of roof, face, or rib."
- "Persons shall not advance beyond artificially supported roof, except those who are assigned to install supports."

Almost three-fifths of the fatal roof falls in the larger mines (32 or 58%) were in the inadequate safety culture group, and almost all of those involved victims who were not under roof support when they were killed. Some examples include the following:

- John Brenza, assistant mine foreman at a Rochester and Pittsburgh mine in PA, was killed when he went beyond (inby) supports to the site where a stopping (a ventilation wall) was to be built.
- Section foreman Joseph Cruze was killed when he went 18 feet past the last row of bolts to set surveying spads at the Ziegler No. 4 Mine in IL.
- Ralph Wallen was killed while operating a continuous mining machine 15 feet beyond roof supports at the Consol No. 34 Mine in WV.
- Joe Lopez, a miner with 40 years of mining experience, was killed installing roof bolts with a hand-held compressed air-powered stoper drill without temporary support at the Castle Gate No. 4 Mine in UT.

That so many of these victims were experienced miners and supervisors, working for some of the largest coal companies, suggests that the practice of going beyond support must have been widespread (Fig. 2). A number of the reports noted that temporary supports should have been in place but were not. Other basic principles that were violated in blatant cases included roof bolts that were spaced too far apart, roof spans that were cut too wide, and areas that were completely unsupported. In

Fig. 3 A large roof fall in ground that had been supported by roof bolts and wood posts. McCormick (1969) estimated that 500 large roof falls occurred for each one that caused a fatality (source: US Bureau of Mines)

fact, six of the miners were killed where the roof was considered “self-supporting,” so no supports had been installed.

The other 23 fatal roof falls can be attributed to failures of the available technology.[5] These may be further divided into four sub-categories, each of which would ultimately require a different solution:

- Work processes that required miners to go inby the roof supports
- Failures of the roof support system that resulted in large roof collapses (Fig. 3)
- Loose rock falling from between supports
- Special projects, including underground construction and rehabilitation of roof falls

There were several reasons why the then-existing technology might require miners to venture inby support. The most common was to set temporary safety posts, which resulted in one fatality in 1968. Three other miners were killed while scaling loose roof, performing gas checks with a flame safety lamp, and shoveling coal with an auger miner.

Large roof collapses accounted for 12, or 22%, of all the fatal roof falls at large mines. These incidents included all three where several miners died in a single event, so they killed a total of 18 miners. All but one of these failures involved roof bolts that were too short, too weak, or too few to control the ground, as illustrated by these examples:

- An intersection of two mine tunnels (entries) collapsed and killed 47-year-old Russel Lamp while he was operating a continuous mining machine. Investigators determined that the roof bolts had not anchored properly in the soft shale roof.
- Three miners were killed while recovering a pillar near the outcrop at the Amherst No. 3 Mine, leaving three widows and seven dependent children. No standing supports had been installed, and investigators concluded that the miners had “placed too much confidence in the roof bolt installations.” Three of the other fatal large roof falls in 1968 occurred during pillar recovery, including another multiple fatality incident.
- Emlyn Davis was operating a mainline locomotive at the Arkwright Mine when he saw rock falling from the roof ahead. He tried to stop the train but was killed in a 40-foot-long collapse of roof supported by bolts, straps, and posts.

[5] A contemporary study of roof fall accidents that occurred between 1966 and 1970 confirms that the 1968 data are broadly representative of the era. That study found that, industry wide, just 27% of roof fall victims were “in compliance with federal rules” when they were killed. Nearly all of those “in compliance” incidents occurred in the larger mines with more than 15 employees [8]. This paper’s “failures of available technology” category, with 28% of all fatal incidents in 1968, is roughly equivalent to the older study’s “in compliance” category.

- At the US Steel Somerset Mine in CO, a continuous miner operator and three company officials were killed when a large intersection collapsed. The place had been mined 41 feet wide to create an angled intersection, was supported with 5-foot-long bolts, and had intersected a geologic fault.

The five miners killed by loose rock that fell from between supports in 1968 included a mine foreman helping to build a stopping, a trackman operating a locomotive, a loading machine operator, and a roof bolter. All three miners killed during special projects were under unsupported roof while cleaning or re-supporting roof falls. The extra height in a roof fall cavity makes the roof much more difficult to support.

3 Farmington and the Mine Act (1968–1976)

The November 1968 Farmington Disaster made mine safety a national priority. Before the year was out a nationwide emergency industry-wide conference on mine safety was held in Washington DC. At that meeting, Secretary of the Interior Stewart Udall announced that the Bureau would conduct five times as many spot inspections in 1969 as it had in 1968 [9]. Throughout 1969 Coal Age and other industry publications published numerous articles discussing the initiatives being taken by individual mining companies, as well as the progress in Congress towards the new mine safety legislation.

President Nixon signed the Mine Act into law on January 2, 1970. For the first time, the Bureau was required to regularly inspect the mines, and Bureau inspectors were given authority to enforce the Act. It took some time before the Bureau[6] could fully implement the Act, however. An Office of the Inspector General (OIG) investigation of two Bureau Districts found that during 1970 they were only able to conduct about a quarter of the required inspections [10]. The Bureau would complain for years about the difficulties of hiring and training enough inspectors.

While enforcement was finding its feet, mine operators acted on their own to improve safety. One very tangible effect was a significant intensification in the use of existing roof support technology. Statistics show that, industry wide, the density of roof bolting increased by at least 40% in the 5 years after Farmington. In 1968, the Bureau reported that mines that produced 69% of the underground coal installed 55 million roof bolts, or 0.23 bolts per ton of coal mined under bolts, while the other 31% of production was split between mines that used wood posts and those where the roof was considered "self-supporting" [11]. By 1973 roof bolt usage had increased to 90 million units, which works out to 0.32 bolts per ton even assuming that 100% of production was now beneath bolts [12].[7] The impact was noted at the time, as when the Superintendent of Mines at the Alabama By-Products Corporation stated that his supply costs rose by 25% after the Mine Act because of the increased number and length of the roof bolts he installed [13].

4 Roof Control Plans

The Mine Act was the Bureau's opportunity to implement the "well-known basic principles" it had been preaching for years. The Act's language included a number of Interim Mandatory Safety Standards that went into immediate effect. One required each mine to adopt and follow "a roof-control plan, suitable to the roof conditions and mining system of the mine." Each plan had to be approved by the Bureau, and their requirements were enforced by the Bureau's inspectors [14].

Roof Control Plans had been at the center of the Bureau's ground control efforts since at least the late 1920s. By then the Bureau had concluded that "a condition responsible for many fatalities from falls of roof is the absence of any policy on the part of management with respect to systematic methods of roof inspection and support" [15] (see also discussion in Mark [16]). Systematic timbering plans were incorporated into the "Federal Mine Safety Code" which was promulgated when President Truman temporarily took possession of the mines during the 1946 coal strike [17]. While the Code was only mandatory for a short time, the Bureau employed it on a voluntary basis from then on, and it was incorporated into the United Mineworkers of America (UMWA) contract. The Bureau carefully tracked how many mines had adopted systematic roof support plans—and how few actually followed them [18] (see also subsequent USBM reports on "Administration of the Coal Mine Health and Safety Act").

In their response to Congress's 1966 request, the Bureau's first recommendation was to require that each mine adopt "a roof-control plan suitable to its roof conditions and mining system, showing the type and spacing of supports, and approved by the Bureau of Mines" [5]. The Congressional Committee

[6] In 1973, the Bureau's enforcement personnel and responsibilities were transferred to a new agency, the Mining Enforcement and Safety Administration (MESA). Four years later, with the passage of Mine Safety and Health Act of 1977, MESA was moved to the Department of Labor and renamed the Mine Safety and Health Administration (MSHA). The USBM continued to conduct mine safety research until 1995, when that function was moved to the National Institute of Occupational Safety and Health (NIOSH).

[7] Underground production was 342 million tons in 1968, and 285 million tons in 1973.

Fig. 4 An early retrofitted canopy installed on a shuttle car (source: US Bureau of Mines)

that wrote the Act 2 years later implemented this recommendation, writing that they expected mandatory roof control plans would "form the basis for systematic upgrading of all roof control practices in this industry" [6]. This expectation was fulfilled over the next 50 years. In fact, roof control plans are today the foundation for ground control practice in coal mines throughout the world (see, for example, Thomas [19]).

5 Cabs and Canopies

Cabs and canopies were another major development in roof control after Farmington (Fig. 4).[8] A canopy is an overhead protective device that is installed on mobile mining equipment, and a cab is a canopy with side protecting members [20]. Cabs and canopies were not mentioned in the Mine Act, but they were required by a regulation issued by the Bureau in 1972.

The concept dated back to the 1950s when US Steel first used cabs to protect miners from rib hazards in thick Utah coal seams [21]. Other US Steel operations were enthusiastic about them, and one mine superintendent called them "one of the most important single steps for physical protection of face men since mechanization" [22]. The Bureau's own analysis of fatal accident reports indicated that cabs and canopies could have saved 221 lives between 1966 and 1972, or 38% of all the miners killed by roof or rib falls during that period [23]. Cabs might also have prevented many other fatalities by protecting equipment operators from collisions with the rib or roof [20]. This paper's analysis of the 1968 fatalities indicates that canopies could have saved 15 miner's lives out of the 61 roof fall fatalities at the large mines that year. Nearly half of those potential saves were miners blatantly inby support, while most of the rest were killed by large falls of supported roof.

The Bureau's canopy regulations required all face equipment operating in mining heights greater than six feet to be equipped with canopies by 1974. The height limit was expected to reduce by six inches every 6 months thereafter, until by 1977 essentially all face equipment would be protected regardless of mining height.

These deadlines proved to be optimistic, and the regulations were initially met with hostility from both operators and miners. Most mining equipment had not been designed with ergonomics in mind, and retrofitted canopies only added to discomfort. A 1971 survey found that miners had four main objections to canopies: (1) they impeded operator visibility; (2) they made ingress and egress tiring and difficult; (3) they were impractical in low coal; and (4) they gave the operator a claustrophobic feeling of being trapped in an emergency [8]. Initially, shuttle cars caused the most problems, in part due to the greater likelihood of the canopy colliding with the roof [24].

[8] The discussion in this section focusses on cabs and canopies for face equipment other than roof bolting machines. Roof bolting machines will be discussed separately.

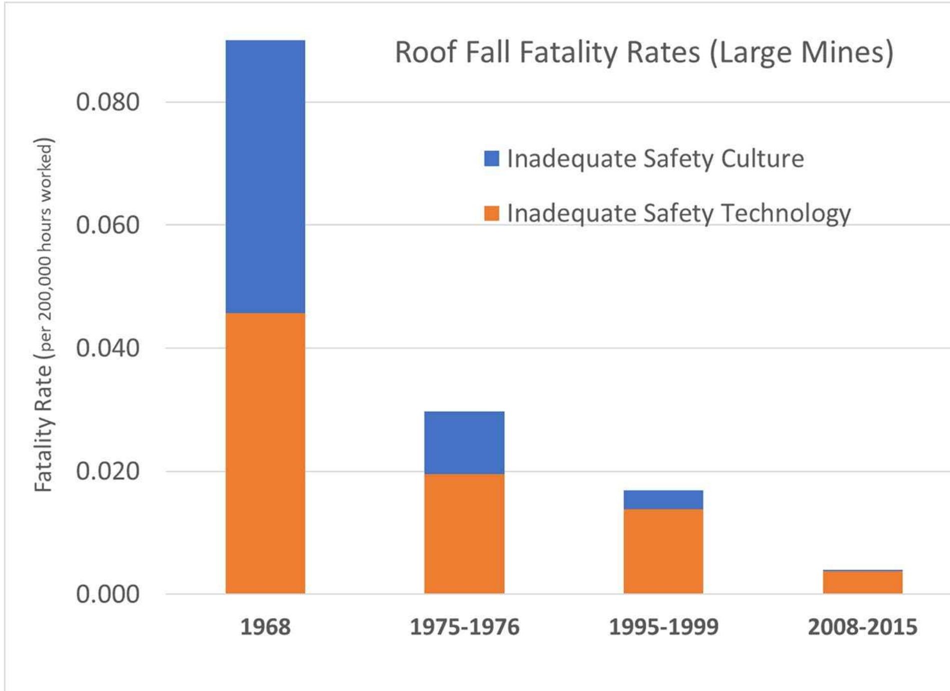


Fig. 5 Roof fall fatality rates for large underground coal mines, by fundamental cause

By the end of 1974, only 50% of the machines required to have canopies were so equipped [25]. Canopies soon became relatively non-controversial in the thicker seams, particularly as new equipment designed with canopies replaced the early retrofits. Joy Manufacturing alone shipped 5000 canopies to their customers in the 10 years following 1971 [26]. The deadlines for low coal were pushed back three times, and ultimately canopies were not required where the mining height was less than 42 inches [27].

6 Roof Fall Fatalities in 1975–1976

Comparing the fatalities that occurred during 1975 and 1976 to those in 1968 allows us to quantify the initial impact of the 1969 Act. During those two later years a total of 77 miners were killed in 70 separate roof falls, compared with 89 during the single year 1968. But while the annual number of roof fall fatalities fell by more than half between 1968 and 1975–1976, the underground work force expanded by almost 50%. Overall, a coal miner in the later period was a third as likely to be killed by a roof fall as his counterpart 8 years earlier.

Of the 54 fatal roof falls at the larger mines (with 61 fatalities),[9] just 35% resulted from blatant violations of the "well-known, basic principles" that were now codified in the new mining regulations. This number is significantly reduced from the 58% in 1968 (Fig. 5). Most of the blatant violations continued to involve miners who were inby support. However, almost half (14 of 31) of the miners killed inby support had a legitimate reason to be there. Nine were setting temporary supports prior to roof bolting, while others were setting posts for pillar recovery or auger mining.

The large number of deaths while setting temporary supports, compared to just one in 1968, indicates that many more temporary supports were now being set. It also shows that this basic safety practice was itself hazardous, because "setting a temporary jack requires the man to be exposed under unsupported roof for at least 15 s" [28]. In fact, the reports indicate that 31% all the fatal roof falls at large mines might have been prevented if Automated Temporary Roof Support (ATRS) systems had been in use. While ATRS technology was already developing, it would not be required by regulation until the next decade.

Large falls of supported roof were the next largest cause of fatalities, with 14 incidents accounting for 31% of the fatalities at the larger mines. Six of the incidents involved intersections, and six involved pillar recovery (some were both). The intersection collapses included one at the Bethlehem Mine No. 106 in northern West Virginia, in which three miners were killed. It had been supported with 4-foot-long bolts, but the fall was 5 feet high. In two other instances, the supports that failed were temporary ones.

Canopies would have prevented five of the fatalities from large roof falls in 1975, but none in 1976, indicating

[9] Small mines that employed less than 15 miners accounted for less than 4% of all hours worked underground during 1975–1976, yet they still accounted for 16 deaths from roof falls (21% of the total). As in the earlier period, nearly all of these involved miners that were blatantly inby support.

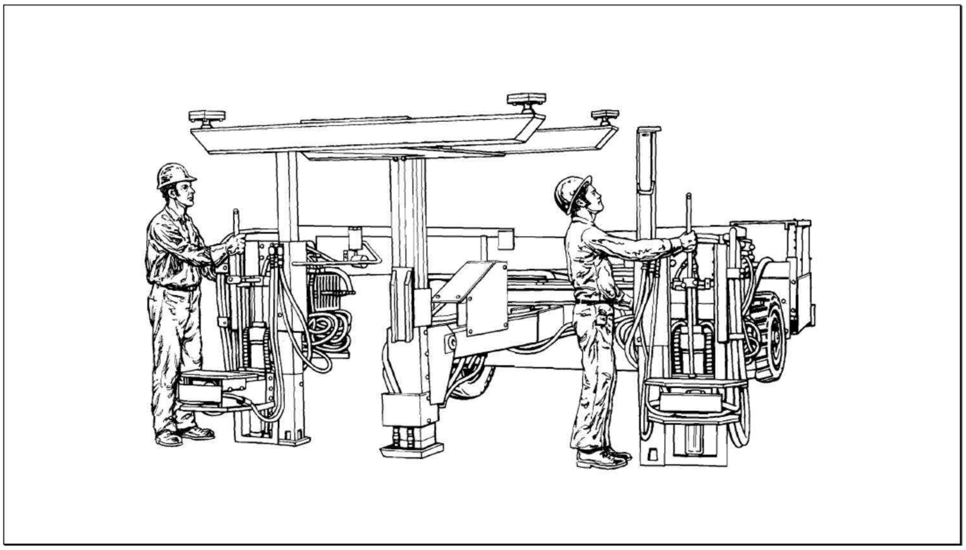


Fig. 6 Drawing showing ATRS attached to a dual-boom roof bolting machine (source: US Bureau of Mines)

that by then they were having a noticeable effect. However, two miners were killed when their canopies proved to be inadequate.

Some miners continued to pay for the roof support sins of the past. Ronnie Hall, a 26-year-old trainee with just 6 days of mining experience, was assigned to shovel loose coal onto the conveyor belt in an old, outby area of the Imperial Colliery in southern WV. The area had been mined in the 1950s without systematic support, only spot bolts and timbers had been installed. He was killed by a piece of rock that measured 8 feet by 4 feet by 6 inches thick. Loose rock killed six other miners beneath supported roof over the 2-year period, and five died in "other" accidents involving roof fall re-support, portal development, or underground construction.

Overall, the big story of the Mine Act's first decade is the reduction in the rate of fatalities caused by blatant disregard of basic safety rules, such as going inby support. A miner's odds of being killed while engaged in a blatant violation were about one-fifth of what they had been before the Act. On the other hand, the odds of being killed while following the rules fell only by a factor of two during the same period. So while the coal industry's safety culture would continue to improve, technological advances now began to make substantial contributions on the road to zero.

7 Resin Grouted Bolts

The development of fast-setting resin anchorage was the next major development in roof bolting technology. Earlier generations of roof bolts, which relied on mechanical shells for anchorage, could be quite effective in ground where they can maintain a solid grip. However, some rock is too soft or moisture sensitive to provide good initial anchorage for mechanical bolts or to maintain acceptable anchorage over time [29].

The earliest resin bolts were developed in Europe, using glass capsules to hold the resin. Other than a handful of special projects, these bolts were not used in the US because of their high cost and long resin set times [30]. In 1971, however, Du Pont collaborated with US Steel to trial a new fast-setting resin [31]. The resin came in two-compartment tubes made of heat-sealed Mylar polyester film. After one of these tubes was placed in a drillhole, it was easily penetrated by the rotating roof bolt, mixing the resin. Another important innovation was a technique for drilling smaller, 1-inch-diameter holes without clogging the drill bits [12].

After the success of the early trials, resin bolt use rapidly increased, from 2.5 million fixtures in 50 coal mines in 1974 to 13 million in 300 mines by 1976 [32]. By 1991, two-thirds of all roof bolts sold in the US used resin, and that number increased to more than 90% by the end of the century [33]. The improved holding capacity of resin bolts surely reduced the number of large roof falls reported to MSHA (the vast majority of which do not result in injuries or deaths).

8 Automated Temporary Roof Support (ATRS)

ATRS are devices that are attached to roof bolting machines and are operable from a location where the equipment operator is protected from roof falls, usually by the canopy (Fig. 6). They eliminate the need to manually set temporary supports [34]. The first ATRS was developed in 1971 through a collaboration between

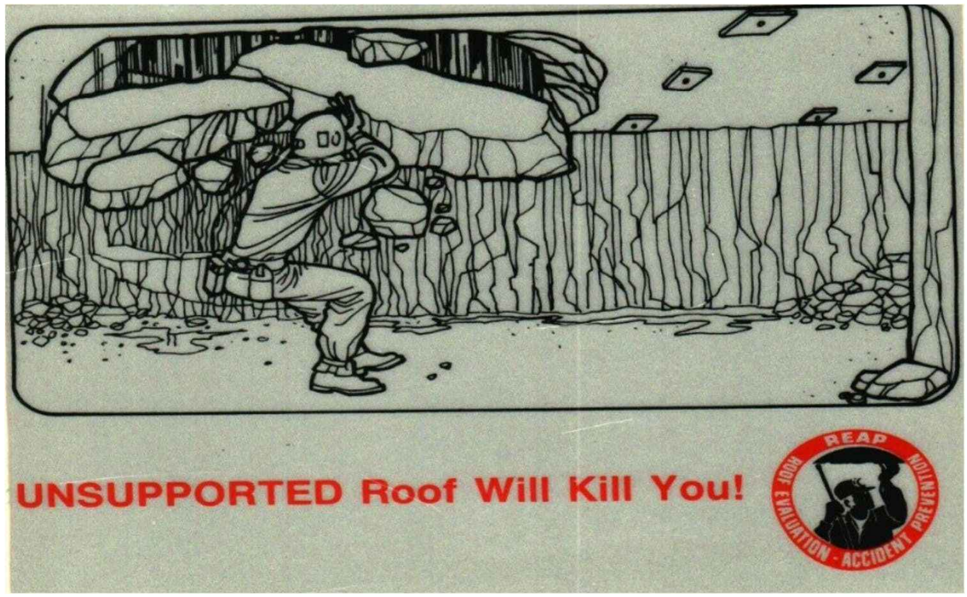


Fig. 7 Hardhat sticker from the 1980s REAP campaign (source: MSHA)

Peabody Coal and Lee Norse, a roof bolter manufacturer. It consisted of a "safety arm" mounted on one of the drill booms [35]. At about the same time the J. H. Fletcher company developed an ATRS for their dual boom roof bolting machines [36].

By the end of the 1970s about 1500 machines were fitted with ATRS nationwide [37], approximately one-third of the roof bolters in service. Despite the expense, many mine operators welcomed ATRS for economic and safety reasons. Setting temporary jacks or posts could consume as much as 20% of a roof bolter's working time [36].

West Virginia was the first state to require ATRS with a regulation promulgated in 1981. A survey conducted at that time found that 95% of the state's 275 dual boom bolters (those with two drilling stations) were already equipped with ATRS, compared to just 15% of its 698 single boom bolters. Single boom machines had been built by nine different manufacturers for a wide range of mining conditions, so designing and installing ATRS for all of them was not a trivial task [38]. Nonetheless, few reservations were expressed about the rule, and apparently, nearly all the state's roof bolting machines were fitted with ATRS by the final deadline of March 1984.

Similar rules were put in place in Kentucky and Virginia during the mid-1980s. The federal rule did not come into force until 1988, by which time 60% of the nation's roof bolters had been purchased new with ATRS, and another 15% had been retrofitted [39]. Two years later, essentially every roof bolting machine in the country was outfitted with ATRS, even in mines where the mining heights were as low as 30 inches.

It is also noteworthy that the 1988 ATRS rule was the last nationwide regulation to address roof control. Since then roof control plans have been the primary mechanism for "upgrading roof control practices" on a mine-by-mine basis.

9 Inby Is Out

While ATRS promised to eliminate routine exposures to unsupported roof, many victims of roof falls continued to be inby support without good reason. Following a rash of such incidents in early 1984, Assistant Secretary Dave Zegeer made unsupported roof MSHA's top priority. He said "whether it was miner inattention or management's push for increased production, defiance of this most fundamental of safety measures was costing lives throughout the coalfields" [40].

One prong of MSHA's attack renewed the traditional educational approach. The REAP (Roof Evaluation and Accident Prevention) program became ubiquitous in the mines, with hardhat stickers (Fig. 7), posters, and training materials all aimed at discouraging miners from going inby support [40]. The REAP program also popularized the idea of using reflective streamers to mark the last row of supports [41].

Enhanced enforcement was Zegeer's second prong. He ordered an inspection blitz, directing inspectors to shut down any mine where they found evidence of workers travelling beyond roof support. Thirteen mines were closed within 5 weeks, and their operators were forced to appear before their MSHA District Managers to outline what actions they would take to correct the problem [40].

In focusing on mine management, Zegeer was following the key conclusion of a prestigious 1982 National Research Council (NRC) report on mine safety. The NRC Committee (of which Zegeer had been a member[10]) found that "there

[10] Prior to his appointment to the top job at MSHA, Zegeer had spent more than 30 years as Division Superintendent in eastern Kentucky for both Consolidation Coal Company and Bethlehem Steel, and he was well known in the industry for his promotion of mine safety.

are persistent and large differences between the injury rates of coal companies which cannot be explained by physical, technological, or geographical conditions, but are due to factors internal to the companies." The most important of these factors was "management's commitment to improving safety." The NRC Committee used the example of unsupported roof to illustrate what it meant: "Every miner knows the danger of going under an unsupported roof, but this is where accidents from roof falls typically occur. Management must be willing to discipline foremen who fail to discipline miners for violating safety rules" [42]. In other words, the key to improving a mine's safety culture was a genuine commitment on the part of its management.

The advent of remotely controlled continuous miners in the late 1970s created new challenges. The technology spread rapidly, because it improved productivity by allowing "extended cuts" that could be twice as deep as the standard 20-foot cuts. Miners who operated radio-controlled machines were no longer confined to protective cabs but were free to move about the worksite while observing the cutting head, monitoring the haulage vehicles, and watching the machine's alignment [43]. These miners could also inadvertently place themselves inby the last row of roof bolts. Initially, mines that practiced extended cuts did seem to have higher rates of inby roof fall fatalities [44]. By the late 1990s, however, the safety record of extended cuts was no different from traditional ones. By then, many roof control plans required miners to keep two rows of roof bolts between themselves and the unsupported roof [45].

The data show that 2001 was the last year in which multiple miners were killed beneath unsupported roof. Perhaps an older generation of miners needed to leave the scene and be replaced by one that was thoroughly imbued with the need to remain under support at all times. The specter of unsupported roof may never be entirely put to rest, however. In an incident more reminiscent of 1971 than 2021, the first fatal roof fall in more than 3 years occurred when a remote-control continuous miner operator placed himself four feet beyond the last row of bolts while extracting an unapproved 60-foot deep cut [46].

10 Longwall Mining

The phenomenal growth of longwall mining during this era also had an effect on roof fall fatalities. Between 1979 and 1999 longwall mines increased their share of underground production from 8 to 50%, and they continued to produce about half the coal until their share increased again in the mid-2010s.

As a group, longwall mines are significantly larger and more productive than room and pillar mines. A large percentage longwall miners work in outby support functions, away from the most dangerous face areas where coal is produced [47]. Even those miners working on the longwall face are better protected, because steel roof canopies provide virtually full coverage. For all these reasons, longwall mines were safer, accounting for just 20% of ground fall fatalities between 1995 and 2015, while employing about 40% of the underground workforce.

11 Roof Fall Fatalities in 1995–1999

During the second half of the 1990s, there were 36 fatal roof falls at large mines that killed 38 miners. Figure 5 shows that the roof fall fatality rate had fallen by about 80% when compared with 1968. Between the mid-1970s and the late 1990s the underground coal mining workforce fell by more than half, while production actually increased by 50%, so the number of fatal roof falls was substantially reduced.

Figure 5 also shows that the safety culture continued to improve, with just 20% of the fatalities attributable to blatant violations. The effects of ATRS and other technologies can be seen in the greatly reduced rate of fatalities due to work practices that required miners to work inby. On the other hand, failures of roof support systems that resulted in large falls continued to occur at approximately the same rate as 20 years earlier, and now accounted for about half of the fatalities (Fig. 8). Reducing this type of failure would be the focus of the next two technologies discussed below.

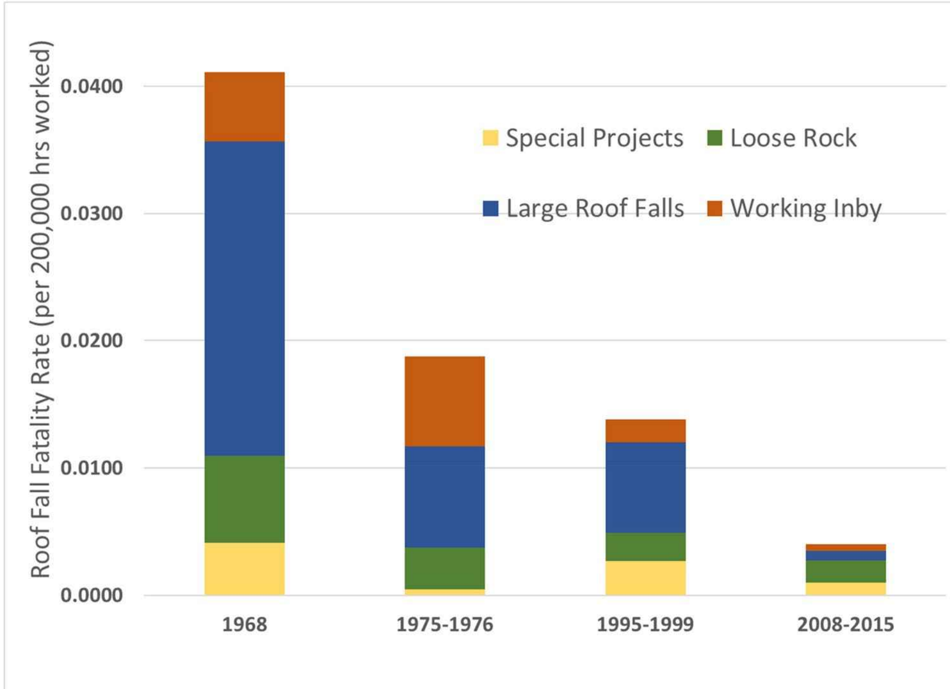
12 Pillar Recovery

Many room-and-pillar mines, particularly in Central Appalachia, conduct "retreat mining" by recovering some of the coal pillars that they previously left to support the overburden (Fig. 9). When pillars are recovered the roof above the worked-out area caves and the overburden subsides. Premature caving can cause hazardous roof falls, and pillar recovery has long been considered a more hazardous method of mining coal [48, 49]. During the 1990s, a miner engaged in pillar recovery was still at least three times more likely to be killed by a roof fall than other coal miners [50].

Studies showed that most of these miners could have been protected by three key precautions: (1) installing more and longer roof bolts, particularly in intersections, (2) not extracting the entire pillar, but leaving an engineered final stump for roof support instead, and (3) using remotely controlled Mobile Roof Supports instead of installing wood timbers by hand [51]. These concepts were being widely incorporated into Roof Control Plans by the mid-2000s.

The 2007 Crandall Canyon Mine disasters focused even more attention on pillar recovery. At Crandall Canyon, six miners were killed when hundreds of support

Fig. 8 Roof fall fatality rates in large underground coal mines attributable different types of inadequate safety technology



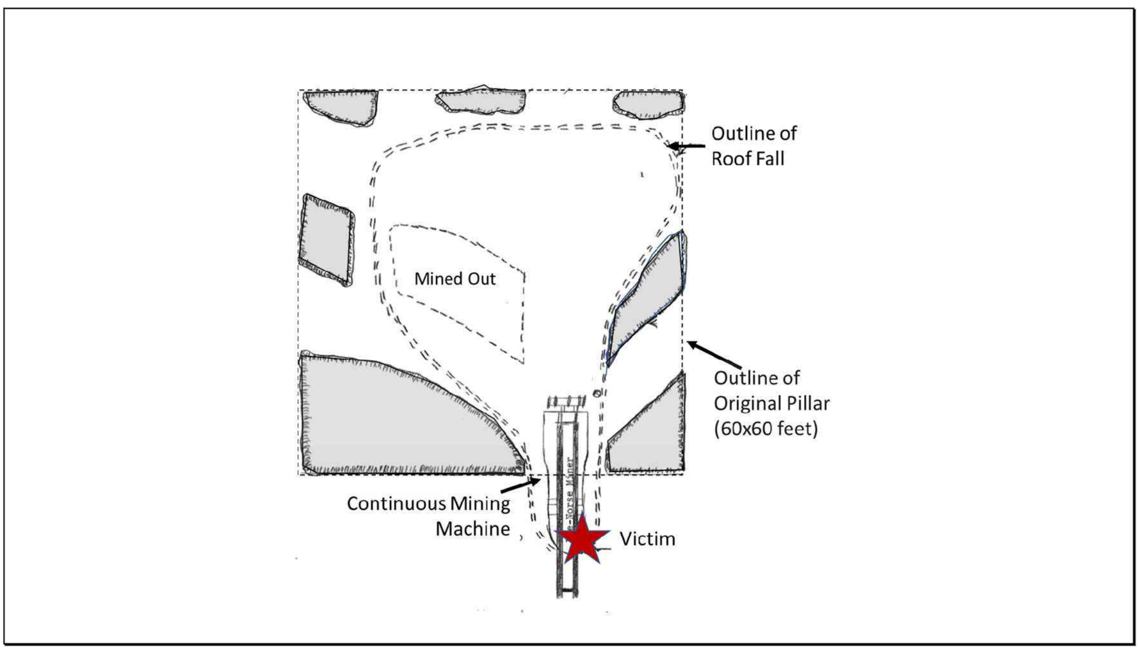


Fig. 9 Sketch map showing where a fatal roof fall occurred during retreat mining. The original coal pillar measured 60 feet square by six feet high, and all but a few "stumps" had been mined out when the roof fall occurred (source: US Bureau of Mines)

pillars suddenly collapsed, and 10 days later three rescuers were killed by a coal burst. MSHA's investigation showed that an inadequate and flawed pillar design caused these disasters, not roof falls, but they did occur while retreat mining was taking place. In the ensuing months, many more pillar recovery mines included the key precautions in their Plans. Since 2007, only one miner has been killed by a roof fall during pillar recovery, compared with an average of two per year throughout the preceding 15 years [52].

Fig. 10 Cable bolts stored on a mine car underground. These are 12-foot-long bolts that are being installed in 4-foot-high mine openings (photo by the author)

13 Cable Bolts

One disadvantage of traditional roof bolts is that they are difficult to install when they are longer than the mining height. Various methods have been used to get longer bolts into the roof, but none is without significant shortcomings. Alternatives to longer bolts, like standing supports or truss bolts, are similarly unsatisfactory.

Cable bolts provided the solution, because they are strong and flexible (Fig. 10). Although they had been used in hard rock mines for decades, their application in coal mining was limited before quick-setting resin-grouted systems were developed in the 1990s [53]. Between 2005 and 2013 the use of cable bolts expanded rapidly, from approximately one million units annually to more than four million. During this same period, the number of large roof falls reported to MSHA dropped by 70%, while underground coal production remained essentially constant. The improvement was most noticeable in the Illinois Basin, which has the weakest roof rock of any US coalfield, and once suffered from non-injury roof fall rates that were more than twice the national average [54].

14 Roof Fall Fatalities in 2008–2015

There were 16 fatal roof falls during the 8 years between 2008 and 2015, compared with 36 during the 5 years 1995–1999. The average number of hours worked actually increased slightly during the later period, so the fatality rate had decreased by almost 70%.

Figure 8 shows that the three greatest sources of roof fall fatalities (inadequate safety culture, working inby support, and large roof falls) were largely under control by this time. Of the 16 fatalities, 11 were attributable to the final two categories of loose rock and special projects. In fact, it seems that the fatality rates associated with those two categories had not been significantly reduced since the 1970s.

15 Control of Loose Rock

The 1969 Act prohibited working without roof support. But roof supports like bolts or ATRS are designed primarily to prevent large rock falls and major roof collapses, and do not always protect miners from small, loose pieces of rock that fall from between or around them. During the late 1990s such "roof skin" falls killed one miner and injured 650 others annually [55].

Tighter bolt spacings do reduce potential size of loose rock slabs that can fall between supports. The denser roof bolt patterns employed after Farmington, and later the introduction of canopies and ATRS, explain much of the early reduction in the loose rock fatality rate. But by the early 2000s, it seemed clear that further improvements would require more intensive use of surface controls like straps, headers, large roof bolt plates, and roof screen [55]. Screen in particular covers nearly 100% of the roof surface (Fig. 11), and numerous studies showed that mines that use screen routinely have much lower rates of "struck by" rock fall injuries [45].

Since the turn of the century, the use of screen has increased, particularly in the Illinois Basin [56]. A number of incremental improvements have also been made to the canopies and ATRS that protect miners that operate roof bolters [57]. While falls of loose rock became the single largest cause of roof fall fatalities after 2007 (Fig. 8), there has been just one since 2015. Since 2000 the non-fatal injury

Fig. 11 Installing a roof bolt with screen in a low coal mine (photo by the author)

rate from falls of loose rock has also dropped by more than two-thirds [56].

16 Special Projects

Special projects include cleaning up large roof falls and the construction of conveyor belt drive installations, ventilation overcasts, and other mine infrastructure. Relatively little time is spent on such activities underground (measured as a percentage of the total underground exposure), but that is one reason they have been so hazardous. Special projects often entail a variety of non-routine activities, and unless they are carefully planned and managed, miners may unknowingly venture under unsupported roof or engage in other risky behavior. Special projects also often involve unusually high mine openings that the normal ATRS cannot reach [47].

Today, special projects are normally addressed in a mine's Roof Control Plan on a site-specific basis. For each stage of the project, the hazards are identified together with appropriate controls. A step-by-step procedure is then prepared to manage the project.

17 Summary and Conclusions

In 1968, underground coal miners worked in the most dangerous industry in the US. The industry's safety culture was known to be a big part of the problem. This paper has shown that, even at large mines, more than half of the roof fall fatalities were the direct result of blatantly ignoring "well-known, basic principles" of roof control. Just 8 years later, after the Farmington Disaster and the passage of the Mine Act, the rate of such avoidable fatalities was reduced by nearly 80%.

Even those statistics underestimate the effects of the change in the safety culture wrought by the Farmington Disaster and the Mine Act. The analysis also found that the rate of roof fall fatalities attributable to inadequate technology fell by more than 50% during the same 8-year period. Since the technological innovations that came into use (primarily cabs and canopies) can only account for a portion of that improvement, the bulk of it must be attributed to more intensive use of existing technologies like denser roof bolting patterns.

Two quotes capture this dramatic shift in the industry's safety culture, the first from the Senate Committee that wrote the Act:

> The Nation can no longer accept the fatalistic attitude which permeates this industry that 'coal mining is a hazardous occupation, and we cannot change this fact'…….The Committee is convinced that these hazards can be substantially reduced or eliminated. Many are due to bad practices and a failure on the part of many, including the Federal Government, to act vigorously years ago to change them. [58]

The second was provided 20 years later by Davitt McAteer, who was then heading MSHA as the Assistant

Secretary for Mine Safety and Health. Looking back, he observed that:

> From an overall philosophical standpoint, there's no-question whatsoever that the Act has been of absolutely critical importance in changing the basic mindset of the industry, miners, managers, owners, and government, from saying that 'accidents are inevitable' to saying that 'we can do this without accidents.' Once the Act forced that mindset change, then there could be engineering, structural, mechanical, operational advances [59].

The remainder of the paper homed in on those technological developments that ultimately led to zero. The earliest ones aimed at eliminating the need for any exposure to unsupported roof. The ATRS, which ended the need to set temporary supports manually, was the most important of these.

Major roof falls were the next target. Cable bolts expanded the ability of roof bolting systems to manage difficult ground that required longer supports. Cable bolts also contributed to better safety during pillar recovery, together with better mining practices and Mobile Roof Supports. The data shows that these technologies helped to substantially reduce fatalities from major roof falls during the first decade of the 2000s. A number of incremental improvements ultimately proved sufficient to reduce the hazards from the last two significant sources of roof fall fatalities, loose rock, and special projects.

The Mine Act foresaw this gradual process. It stated that "each operator shall undertake to carry out on a continuing basis a program to improve the roof control system of each coal mine and the means and measures to accomplish such system." Roof control plans played a central part throughout, helping to implement new technologies on a mine-by-mine basis.

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