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SUBJECT: Evaluation of the Potential for a Roof Fall to Ignite a Methane-Air Mixture at the Wolf Run Mining Company, Sago Mine, Upshur County, West Virginia, MSHA I. D. No. 46-08791

An explosion initiated in the sealed 2 Left area in the northern portion of the Sago Mine on January 2, 2006. Maps indicate that three roof falls occurred in this area prior to seal construction. Examinations after the explosion determined that additional roof falls had occurred that were not shown on the mine maps. The precise timing of these falls relative to the mine explosion is not known.

The Sago Accident Investigation Team requested that Roof Control Division (RCD) personnel assess the likelihood that these roof falls ignited explosive concentrations of methane at the Sago Mine. The RCD evaluated the possibility of a roof fall initiation through background literature searches and in-mine investigations.

Background

Roof Control - The primary roof support consisted of ¾-in. x 6-ft., fully grouted bolts on approximately 4-ft. centers. The bolts were installed with 8- x 8-in. bearing plates which were typically supplemented with larger "Spider" or "Pizza Pan" plates for additional surface control. In some areas, welded wire mesh was installed with the 8- x 8-in. plates for improved roof surface control. Cable bolts also were noted in the sealed 2 Left area. In the areas investigated by RCD, the cable bolts were only used occasionally and there was evidence that wood cribs and wood Propsetter standing supports also had been used on an infrequent basis. Explosive forces had warped and folded the "Spider" and "Pizza Pan" plates, torn welded wire mesh from the roof in places, and dislodged wood supports.

Pillar stability was evaluated using Analysis of Retreat Mining Pillar Stability (ARMPS) software. For the typical 55- x 80-ft. center pillar, 18-ft. mining width, 15-ft. bench mining height, and 320-ft. overburden, the pillar stability factor (SF) is 2.2. The effective pillar stability is actually higher because the 15-ft. mined height only applies to the panel entries and not the crosscuts. The crosscut mining height of only 7 to 8 ft. serves to reinforce and improve the pillar stability. In the areas traveled, no evidence of abnormal pillar stress or pillar dilation was encountered. This observation is consistent with the satisfactory SF value. The pillar rib conditions in the entries and crosscuts appeared to be stable.

2 Left Roof Falls

Mining was completed in 2 Left in late October and the seals were completed on December 11, 2005. Prior to the January 2nd explosion, three pre-sealing roof falls had been identified on the mine map. Roof Control Division personnel visited the mine on January 30, 2006, and observed that these three pre-sealing roof falls had extended (see Drawing 1). Also, four additional roof falls were observed that were not shown on the mine map prior to seal completion (see Drawing 1 green shaded falls labeled "Before 1/27/06"). It is not known exactly when these four newer roof falls occurred. The roof fall areas observed were consistent with roof fall information collected by other investigators during initial exploration on January 27, 2006. Roof Control Division personnel again observed the 2 Left area on May 11, 2006, and found additional roof falls that were not present on January 27 or 30 (see Drawing 1 purple shaded falls labeled "After 1/27/06").

Other investigators have determined that the explosive forces propagated in every direction from the area near surveying spads 4010, 4011, 4047, and 4048 (see Drawing 1). The seven roof falls that were observed during the January 30 investigation range in distance from approximately 150 ft. to 470 ft. from this area. The rubble and exposed fall cavity of the five closest roof falls (within 440 ft.) were inspected. Access to the two roof falls beyond 450 ft., was obstructed by deep water in bench mined entries.

The roof falls extended 7 to 12 ft. above the mining horizon. Gray shale was the predominant rock type visible in the fall rubble and in the exposed cavity of the roof falls. However, thinly bedded sandstone beds, interspersed with shale layers were exposed at the top of the fall rubble, roughly 8 to 12 ft. into the immediate roof in three locations (see Drawing 1).

The fall rubble consisted of rock slabs of varying thickness and geometry. The falls encompassed the entire entry width and primarily affected the entries and adjoining intersection(s) as opposed to crosscuts. Thus, there appears to be a general tendency for north-south migration of the roof fall areas (see Drawing 1). Roof support in the vicinity of the roof falls consisted of ¾-in.-diameter, 6-ft.-long, fully grouted resin bolts installed with 8- x 8-in. roof bearing plates and "Spider" or "Pizza Pan" plates. Cable bolts were installed near some of these roof falls, wire mesh had been installed near the perimeter of two of the roof fall cavities, and wire mesh was noted under the fall rubble of a third roof fall. The fully grouted bolts were the only roof support that could be observed within the roof fall rubble.

Geology

The Sago Mine is developed in the Middle Kittanning coal seam. The overburden, measured from the base of the seam to the surface, ranges from 230 to 320 ft. in 2 Left and the immediate roof consists of gray shale grading upward into sandy shale and sandstone with shale bedding.

Exploratory Drill Hole SF17-97 is situated immediately adjacent to the sealed area (Drawing 1). Drill core from this hole was used to assess the stratigraphy above the Middle Kittanning coal seam (see Table 1). The roof falls noted in the course of the investigations are within an 800-ft. radius of this hole. It is reasonably likely that the same sequence of units is present above the coal seam in the vicinity of the roof falls in the sealed area. Coal measure geology is known to change substantially over short distances (e.g. due to depositional features such as sand channels). However, the rubble observed in the falls appeared to be gray shale overlain by bedded sandstone (i.e. generally consistent with Table 1). Table 1 provides an example of the thickness of individual lithologic units, the distance from the top of the Middle Kittanning seam, and the distance from the top of the typical mining horizon to the lithologic units based on information from Drill Hole SF17-97. In much of 2 Left, 3 to 5 ft. of shale roof (3.6 ft. average) typically was mined with the coal.

Table 1
Drill Hole SF17-97 Lithology
Example of Immediate 40 ft. of Roof above Middle Kittanning Coal Seam

Lithologic Description	Thickness, ft.	Distance to Lithologic Unit from Top of Coal Seam, ft.	Distance to Lithologic Unit from Top of Mining Horizon(1), ft.
Dark Gray Shale	15.70	41.39	37.8
Dark Gray Sandy Shale	9.30	32.09	28.5
Shale	5.30	26.79	23.2
Dark Gray Shale	5.40	21.39	17.8
Sandstone with Shale Streaks	3.30	18.09	14.5
Dark Gray Sandy Shale	7.20	10.89	7.3
Dark Gray Shale	8.30	2.59	Top of Mining Typically Within this Unit
Shale	2.59	0	Typically Mined
Bone – top unit of coal seam	0.30		

Note (1) = Top of mining at 3.6 ft. average depth into overlying shale

Shale Description - Shale samples from the immediate roof in the vicinity of spad 4010 were studied microscopically for the Sago Mine explosion investigation. The samples were classified based on grain size and bedding spacing as "laminated siltstone" according to Potter's 1980 textural classification of shales. They are characterized by very similar textures having a matrix composed of very fine-grained (0.005-0.2 mm) muscovite lathes, which are randomly oriented, but arranged in thin bedding layers. Contacts between adjacent bedding layers are gradational, defined by different grain sizes or mineral contents. The very fine-grained, muscovite-dominated layers host approximately 8-12% angular quartz grains, which are approximately 0.01 mm in diameter and isolated by the surrounding matrix. Coarser-grained layers are dominated by angular quartz grains, which are approximately 0.1 mm in diameter and touch along tangential contacts to leave angular interstices that are filled with finer-grained muscovite. The very finest-grained layers host very fine-grained, clay sized (<0.003 mm) muscovite with no quartz, and represent planes of preferential weakness along which delamination preferentially occurs.

Sandstone Description - Three sandstone samples (RCD-SSA, RCD-SSC, and RCD-SSD) collected from the fringe of the roof fall rubble are described below. The sample locations are depicted in Drawing 1.

Sample RCD-SSA is characterized by 1/16-in. to 1/8-in. crossbedded laminations of light-colored, fine-grained quartz sandstone that form beds ¼ in. to ½ in. thick, and are bounded by 1/64-in. dark-colored laminations that host abundant muscovite and biotite flakes. The sandstone laminations are well indurated, although scratch marks from a knife blade are visible. Sandstone laminations commonly pinch down from ¼ in. to 1/16 in. over a distance of 3 in., to be bounded by dark-colored micaceous laminations.

Sample RCD-SSC is characterized by 1/16-in. to 1/32-in. laminations of alternating light-colored, fine-grained quartz sandstone and dark-colored siltstone. The light-colored quartz sandstone laminations are well indurated, and alternate with moderately indurated dark-colored siltstone laminations, which host very fine-grained flakes of biotite mica. Fine-grained flakes of muscovite mica are commonly distributed within the light-colored quartz laminations, which may also host microcline or orthoclase grains, due to a faint pink tint. Very thin (1/64-in.) carbonaceous bedding partings are distributed at approximate 1½-in. intervals. Laminations of all compositions can be easily scratched with a knife blade, indicating that quartz grains are not sutured.

Sample RCD-SSD is characterized by 1/16-in. to 1/8-in. crossbedded laminations of light-colored, fine-grained quartz sandstone that alternate with 1/32-in. dark-colored laminations of very fine-grained siltstone, which hosts abundant 1/16-in. flakes of muscovite mica. The sample also hosts a ¾-in.-thick bed of fine-grained, dark-colored, well indurated siltstone that hosts fine-grained biotite and muscovite mica, and contains 1/64-in. stringers of light-colored quartz siltstone. The entire sample is approximately 2 in. thick, and is bounded by muscovite-rich bedding partings.

Historical Research on Roof Falls and Ignitions

The majority of methane-air ignitions can be attributed to frictional ignitions by some form of machine or mechanical action. [d,f] However, within the time frame from 1960 to present, four instances were found where the most likely source for the ignition was a roof fall[c, d, k, l]. One instance involved a roof fall on a mining section and three instances referred to falls of ground within the extracted area of a longwall panel. The precise ignition mechanisms could not be determined conclusively. However, the most likely scenario from these cases was determined to be ignition through rock-on-rock frictional forces.

The factors involving ignition from roof falls have been studied with laboratory testing where the ignition capability (incendivity) of both mine roof rock and steel roof support materials were investigated. In addition, the ignition potential from compression of methane–air-coal dust mixtures has been studied in the laboratory.

Steel Roof Support Incendivity - Tests have been performed in which roof bolts and cable bolts were broken in tension and roof bolt heads were pulled through plates in an explosive methane-air mixture. Tests on roof bolts and plates produced no sparks or ignitions [c]. However, sparking was observed in tests on cable bolts. In fact, sparking had been observed from breaking cable bolts in underground coal mines in the U. S. in the early 1990's. In response to these observations, laboratory testing was conducted to assess cable bolt failure incendivity. The test results indicated that although sparks are produced by breaking cable bolts these sparks are not hot enough, not large enough and are not of sufficient duration to ignite an explosive methane-air mixture [a, b].

Tests have also been performed to try to determine the possibility of igniting an explosive methane-air mixture by impact friction. These tests evaluated the incendivity of various combinations of materials when impacted together (i.e. by dropping one from a fixed height onto another). Samples included sandstone, shale, roof bolt steel and aluminum. Several combinations produced sparks, but the only ignitions were initiated by dropping aluminum on a rusty steel plate [c]. Despite these findings, however, the researchers determined that sparks from failing steel roof supports cannot be conclusively ruled-out as an ignition source because of the limitations of laboratory testing simulating the actual underground environment.

Rock-on-Rock Frictional Incendivity - Laboratory work indicates that specific rock types (e.g. sandstones) do have an incendivity potential [c, d, f]. Studies have attempted to determine whether or not an ignition could occur due to heat and/or sparks produced by the friction of rocks rubbing together during a roof fall. In laboratory settings, two rock specimens have been rubbed together by pressing a rock against another rotating rock wheel. Ignitions have been produced in these experiments with varying rock types under varying test conditions. Video records of these experiments indicate that the ignitions appeared to be from the heat trail behind the hot spot on the rocks and not the sparks that are produced [d]. Rocks high in quartz content appear to be most susceptible to producing the friction required for heating but, rock composition is also a large factor [d]. The study indicated that the rock composition, (ie. the overall proportion of quartz, feldspar and rock fragments in the grain framework) was a better indicator than quartz content alone of the incendivity of a particular rock [d].

It has been noted that quartz-rich rock types (sandstones and quartzites) can produce a voltage when minutely deformed by applied mechanical stress. The mechanism known as piezoelectricity was discovered in 1880 by Pierre and Paul-Jacques Curie. They found that when certain types of crystals including quartz, tourmaline, and Rochelle salt, were compressed along certain axes, a voltage was produced on the surface of the crystal. In a piezoelectric crystal, the positive and negative electrical charges are separated, but symmetrically distributed, so that the crystal overall is electrically neutral. When a mechanical stress is applied, this symmetry is disturbed and the crystals are polarized, and the charge asymmetry generates a voltage across the material. The charge separation may be described as a resultant electric field and may be detected by a voltmeter as a voltage between the opposite crystal faces. The phenomenon of piezoelectricity is widely used in a variety of electronic devices, including igniters. Currently, synthetic material such as carefully prepared ceramics are used as igniters since they exhibit the most efficient piezoelectric properties (g,i).

As a geologic phenomenon, piezoelectricity has been invoked to explain certain effects associated with earthquakes, such as "earthquake lights", the lightning or fireballs that have been reported in the vicinity of earthquake epicenters. Piezoelectricity also has received some attention in the field of earthquake prediction, where some suggest that the mechanical stress imparted by shifting tectonic plates my induce voltages in rocks, which might be recorded as a precursor to earthquakes. Although it is thought that in rock types where crystals are randomly oriented the piezoelectric effect is self canceling, it may be that in rock types with preferentially oriented quartz crystals (such as gneiss or quartzite), such voltages may be generated (j).

Methane-Air and Coal Dust Compression - Computer simulations have predicted that air temperature could increase rapidly to the point of igniting methane or coal dust during a roof fall. Subsequently, laboratory tests simulated air compression from a confined falling object and verified that ignitions could occur with certain methane and coal dust mixtures. The laboratory tests had no ignitions with any methane-air mixture in the absence of coal dust. Also, the numerical simulation for a full-scale mine scenario indicated that ignition could only be achieved with a falling block of at least 65- x 65-ft. planar area falling simultaneously (e).

Summary

It is difficult to definitively exclude a roof fall as a potential ignition source for the explosion at Sago Mine. However, it appears to be an unlikely source for the following reasons:

- Shale is the predominant rock type visible in the roof fall rubble. Specifically, the material referred to as shale is classified as "laminated siltstone" with low quartz content in a soft matrix that inhibits quartz grain-to-grain contact. This rock type is not as conducive to frictional heating or piezoelectric sparking as sandstones that have been suspected as ignition sources in roof falls (d). An exploration drill hole in the vicinity indicates that rock classified by core logging as sandstone exists above the mining horizon. Three roof fall cavities had sandstone beds exposed at the top of the fall rubble roughly 8 to 12 ft. into the immediate roof above the underlying shale. The samples collected from the roof fall rubble are a variety of sandstone that is micaceous, and characterized by thin, alternating laminations of fine sand, silt, and mica partings. In contrast, the sandstones associated with piezoelectric sparking and rock-on-rock frictional heating are commonly considered to be dominated by quartz, exhibit stronger cementing or even quartz grain fusing (i.e. the metamorphic rock "quartzite"), and occur in more massive beds. Furthermore, the roof falls observed are outside the area where the explosion is inferred to have originated. Thus, rock-on-rock or piezoelectric ignitions are unlikely ignition sources.

- The only metal roof supports noted in the fall rubble were fully grouted bolts and the wire mesh noted under the rubble of one fall. These steel roof support materials have not been associated with ignitions in experiments or in documented observations of gob ignitions. It was not possible to determine whether cable bolts noted near the roof falls could be hidden in the fall rubble. However, previous laboratory testing of the sparks from cable bolt failure did not ignite methane-air explosive mixtures.

- All of the roof falls observed in the 2 Left seal area that were not noted on the mine maps prior to sealing, encompassed a much smaller area than the 65- x 65-ft. highly confined area required in computer simulations to ignite methane by compression.

Attachment

References

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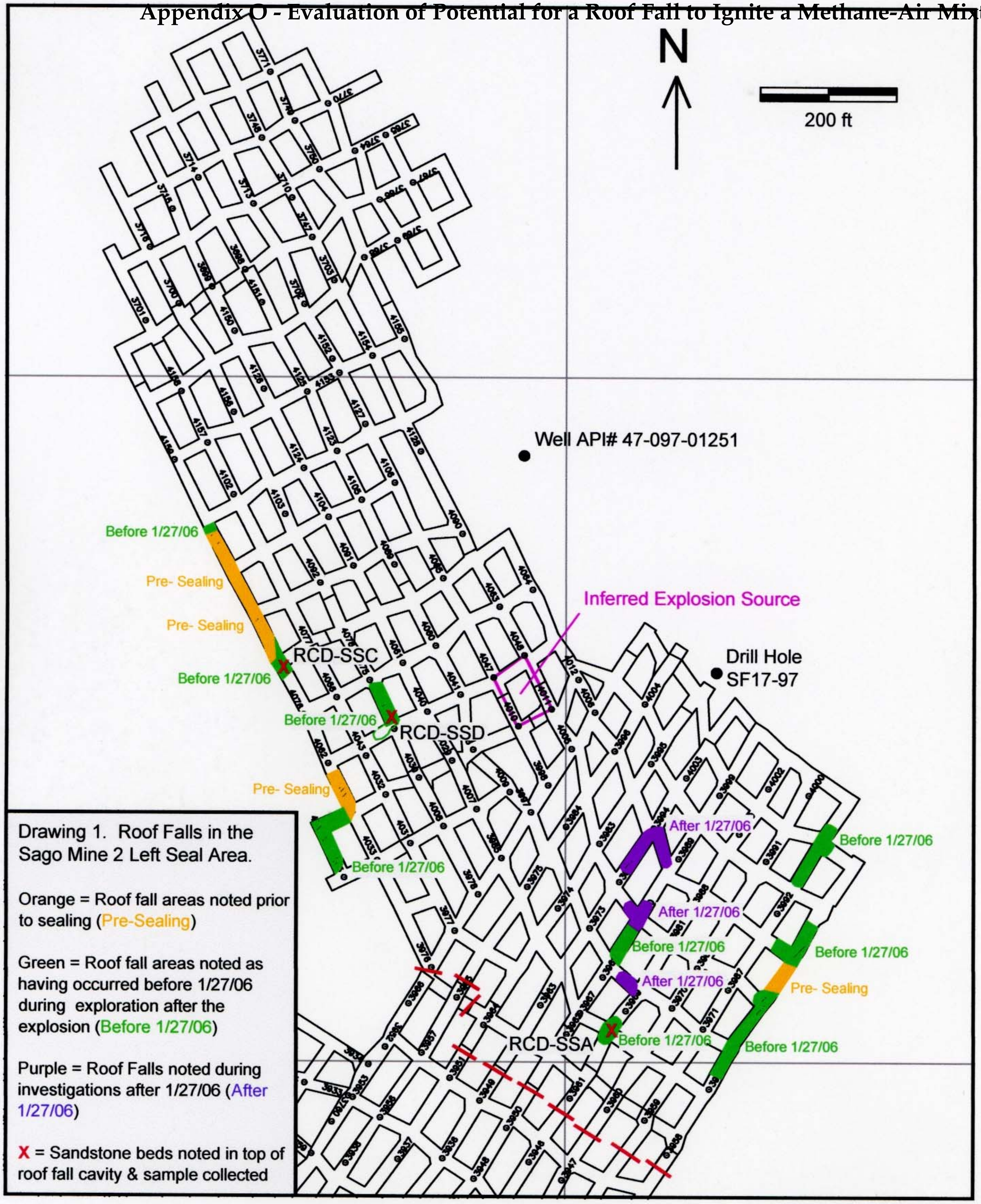
N
200 ft
Well API# 47-097-01251
Inferred Explosion Source
Drill Hole
SF17-97
RCD-SSC
RCD-SSD
RCD-SSA
Before 1/27/06
Pre- Sealing
After 1/27/06
Drawing 1. Roof Falls in the Sago Mine 2 Left Seal Area.
Orange = Roof fall areas noted prior to sealing (Pre-Sealing)
Green = Roof fall areas noted as having occurred before 1/27/06 during exploration after the explosion (Before 1/27/06)
Purple = Roof Falls noted during investigations after 1/27/06 (After 1/27/06)
X = Sandstone beds noted in top of roof fall cavity & sample collected