HHS Public Access
Author manuscript
Min Eng. Author manuscript; available in PMC 2016 December 22.

Published in final edited form as:
Min Eng. 2016 October ; 68(10): 55–59. doi:10.19150/me.6802.

Refuge alternatives relief valve testing and design

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Abstract

The U.S. National Institute for Occupational Safety and Health (NIOSH) has been researching refuge alternatives (RAs) since 2007. RAs typically have built-in pressure relief valves (PRVs) to prevent the unit from reaching unsafe pressures. The U.S. Mine Safety and Health Administration requires that these valves vent the chamber at a maximum pressure of 1.25 kPa (0.18 psi, 5.0 in. H_2O), or as specified by the manufacturer, above mine atmospheric pressure in the RA. To facilitate PRV testing, an instrumented benchtop test fixture was developed using an off-the-shelf centrifugal blower and ductwork. Relief pressures and flow characteristics were measured for three units: (1) a modified polyvinyl chloride check valve, (2) an off-the-shelf brass/cast-iron butterfly check valve and (3) a commercially available valve that was designed specifically for one manufacturer's steel prefabricated RAs and had been adapted for use in one mine operator's built-in-place RA. PRVs used in tent-style RAs were not investigated. The units were tested with different modifications and configurations in order to check compliance with Title 30 Code of Federal Regulations, or 30 CFR, regulations. The commercially available relief valve did not meet the 30 CFR relief pressure specification but may meet the manufacturer's specification. Alternative valve designs were modified to meet the 30 CFR relief pressure specification, but all valve designs will need further design research to examine survivability in the event of a 103 kPa (15.0 psi) impulse overpressure during a disaster.

Background

The Mine Improvement and New Emergency Response Act of 2006, known as the Miner Act (U.S. Department of Labor, 2006), was enacted in the wake of three mine accidents involving explosions or fire that claimed 19 lives that year. Intended to help improve underground coal mine accident preparedness, the Miner Act includes provisions that target mine safety issues in areas such as emergency response planning; adoption of new technology; training and education; and mine safety standards enforcement. Section 13 of the Miner Act specifically directed the U.S. National Institute for Occupational Safety and Health (NIOSH) to provide for research into the effectiveness and viability of refuge alternatives (RAs) for underground coal mines, and the U.S. Department of Labor to act on the results of such research, as appropriate. These mandates culminated in the 2009 adoption

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of changes to the Title 30 Code of Federal Regulations, or 30 CFR, mining health and safety regulations (U.S. Department of Labor, 2008), requiring underground coal mines to supply mine emergency RAs and associated components so as to provide a life-sustaining environment for persons trapped underground. Such RAs can be either self-contained mobile units or built-in-place facilities. The regulatory changes also include provisions establishing requirements for the approval of RAs and their components by the U.S. Mine Safety and Health Administration (MSHA), among which are numerous criteria for providing a safe breathable atmosphere under positive pressure within the RAs. One criterion for maintaining a safe RA atmosphere is the inclusion of an air pressure relief valve that will activate at a maximum of 1.25 kPa (specified as 0.18 psi, or approximately 5.0 in. H_2O), or as specified by the RA manufacturer, above mine atmospheric pressure in the RA (U.S. Department of Labor, 2008).

The primary purpose of the required relief valve is to limit the maximum positive pressure within the RA to prevent damage to its systems or components as well as provide for occupant safety and comfort during use. Relief valve design and operation, however, must also account for other critical factors, such as meeting minimum RA airflow requirements based on maximum occupancy, preventing reverse airflow before positive pressure is established or if it is lost during RA use, surviving MSHA-specified overpressure and flash fire conditions prior to RA deployment, preventing overpressure that may interfere with personnel entry into and exit from the RA, and in some cases allowing necessary unobstructed airflow prior to RA deployment.

Research to date by the NIOSH Pittsburgh Mining Research Division on mobile RAs as well as built-in-place RA installations for coal mining suggests that the design and implementation of RA relief valves have not yet had sufficient performance analysis or technical development. In response, the division began studying and testing the use of relief valves in RAs. Work thus far has focused primarily on the relief pressure and flow characteristics of a commercially available, purpose-built RA relief valve and adaptations of two relief valve designs normally used in other applications. This paper details the laboratory testing and the specially built test apparatus used to measure and study relief pressures while controlling valve configurations, flow levels and duct characteristics. The testing reported here lays the groundwork for anticipated followup research on valve design reliability, adequacy of valve flow capacity, and valve survivability in the events of overpressures and flash fires.

Experimental setup

To test the performance of a variety of relief valves, a pressure relief valve test stand was developed, consisting of a 1.12-kW (1.5-hp) centrifugal blower fan able to produce a maximum pressure of 1.62 kPa (6.5 in. H O) at 24.9 m^3/min (880 ft^3/min), standard ductwork with inside diameters of 10.2 cm (4.0 in.) and 12.7 cm (5.0 in.), candidate pressure relief valves (PRVs), a pressure gauge and an air velocity transducer (Figs. 1 and 2). The blower fan provides the airflow to test each relief valve. The bleed-off leg and gate provide a means to reduce the flow to the relief valve. The pressure gauge and airflow transducer measure the operating parameters of the relief valve being tested. The pressure gauge was installed according to the manufacturer's recommendations, with +/−2 percent mechanical accuracy, and the accuracy of the flow meter is +/−3 percent of reading. Results are verified with a second set of flow and pressure gauges substituted into the test setup. The different angle configurations provide different relief pressures and flows depending on the angle of the flap and resulting force required to open the relief valve.

The system is modular in that its ductwork can be extended or reduced and the valves can be quickly switched out. This allowed for each PRV to be tested at 0°, 45° and 90° orientations, in terms of the angle of flow with respect to horizontal.

The pressure at which the PRV relieved was measured using a Magnehelic gauge rated up to 2.5 kPa (10.0 in. H_2O). A modular airflow probe adapter was designed and fabricated with a 3D printer, which allowed for the probe to be positioned at various distances from the center of the duct by installing different-sized inserts. An example of one insert is shown in Fig. 3. The air velocity was measured using a Kanomax 6332D air flow transducer. Four different inserts were used to measure the air velocities at distances of 0.0 mm (0.0 in.), 12.7 mm (0.5 in.), 25.4 mm (1.0 in.) and 38.1 mm (1.5 in.) from the center of the duct. Measuring the air velocities at these four locations allowed for the average velocity to be determined across the ductwork cross section. The actual cubic feet per minute, or ACFM, air velocities were measured using the test setup. Standard cubic feet per minute, or SCFM, would change the values by less than 5 percent, so the values were not adjusted. The average velocity for the polyvinyl chloride (PVC) check valve was within 10 percent of all measured velocities, making multiple readings unnecessary for the other relief valves.

Valve designs

Three valve designs were tested using the benchtop set-up: (1) A commercially available 10.2-cm (4.0-in.) Schedule 40 PVC check valve (Fig. 4) was tested in its original configuration and modified to increase the relief pressure. These valves are normally used in water systems to prevent backflow in waste water applications. Weights were added to the plastic check valve flap, and the valve was tested in different orientations. The flap seals with an O-ring that is captured in the outer edge of the flap. (2) A brass/cast-iron butterfly check valve (Fig. 5) was modified by removing the torsion springs to lower the relief pressure to an acceptable level and orienting the valve to use the weight of the brass parts to create a relief pressure. These valves are also used for backflow prevention in waste water systems. (3) A commercially available valve that was designed for RAs and is currently installed in steel prefabricated portable RAs and one mine operator's built-in-place RA was also tested (Fig. 6). The valve was tested in as-received condition as well as a modified configuration that aimed to reduce the relief pressure in an attempt to meet the 30 CFR maximum opening pressure of 1.25 kPa (0.18 psi) above mine atmospheric pressure in the RA. The unit is steel cased and has a steel flap design that is spring loaded and sealed with an elastomer gasket.

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Measurements and analysis

The setup was used to measure the pressures and air velocities for a number of configurations. Table 1 shows the test results for the NIOSH modified off-the-shelf PVC check valve that had weights added to the lightweight flapper to increase resistance to air flow, allowing for the relief pressure to be controlled by simply adding or removing weights and changing the angle. All values were recorded after airflow was established and had stabilized. Nine configurations in total were tested by adjusting the angle and the amount of weight added to the flapper. Air velocities were measured using all four of the different velocity probe inserts at all nine configurations. The volumetric flow rate was calculated based on the cross-sectional area of the 10.2-cm (4.0-in.) ductwork at the PRV. The air velocity was corrected for the ductwork reduction based on the Venturi effect and continuity equation (Pope, 1996):

$$Q = v_1 A_1 = v_2 A_2$$

where Q is the flow rate in m^3/s, v is the velocity in m/s and A is the cross-sectional area of the pipe in m^2.

From the results of changing the angle in conjunction with the added weight shown in Table 1, it can be seen that the relief pressure can be adjusted up or down within the MSHA requirements as desired.

Table 2 shows the test results for the brass/cast-iron butterfly PRV. Two different configurations were tested: (1) 45° orientation with no spring return and (2) 90° orientation with no spring return. For both configurations, the air velocities were measured at the center of the ductwork. The unit was not tested at 0° because it would not be capable of sealing without a spring return. For the 45° configuration, the pressure relieved right at the 30 CFR limit of 1.25 kPa (5 in. H_2O). For the 90° configuration, the pressure exceeded the 30 CFR limit.

Table 3 shows the test results for the commercial PRV that was purpose-built for RAs. Three different configurations were tested: (1) original, or as-received, (2) with preload washers removed and (3) with the factory spring replaced with a 17.9-g/mm (1-lb/in.) spring and a washer.

For all three configurations, the air velocities were measured at the center of the ductwork. Pressures exceeded the limit of 1.25 kPa (5.0 in. H_2O) for all three configurations. The most noteworthy result of this testing is that this unit did not relieve any pressure up to 1.62 kPa (6.5 in. H_2O), the maximum pressure available for the test apparatus, in the original configuration. Even with modifications to reduce the load on the valve by replacing the spring, the unit did not relieve until 1.44 kPa (5.8 in. H_2O). The manufacturer was contacted and stated the valve was not calibrated. They use a compressed air source that only allows testing of the opening pressure of the valve and not airflow. The users of this commercially available RA valve did pass purge testing for a portable RA during their harmful gas removal component testing. The valve was only tested at the 0° orientation because the other angles would have increased the relief pressure due to the weight of the flap.

Although the adequacy of RA relief valve flow capacity has not been directly addressed at this stage, the test results do begin to shed light on this topic. Specifically, 30 CFR requires an airflow of at least 0.35 m^3/min (specified as 12.5 ft^3/min), per occupant to a built-in-place RA when breathable air is supplied by compressed air cylinders, a fan or a compressor. The average flow rate for the modified PVC check valve configured at 45° with no added weight (Table 1) represents a breathable air throughput sufficient for approximately 49 RA occupants.

Discussion

Testing was conducted on three different valve designs to be used for pressure relief in built-in-place RAs. Two of the units, a PVC check valve and a brass/cast-iron butterfly check valve, were purchased off the shelf and modified to evaluate compliance with 30 CFR regulations for relief pressure. A commercially available valve that was designed for steel portable RAs and is currently installed in a number of mines was also examined.

Of the three PRVs tested, only the modified PVC check valve complied with the 1.25 kPa (0.18 psi, 5.0 in. H_2O) limit. The commercially available valve would not operate at the test setup maximum pressure of 1.62 kPa (6.5 in. H_2O) until a lighter spring was installed, although the relief pressure was still above the 30 CFR limit. The manufacturer did demonstrate the ability to purge with this valve installed in a portable RA, in previous testing. Additionally, the airflow through the PVC check valve as tested is sufficient to meet the built-in-place RA requirement of 0.35 m^3/min (12.5 ft^3/min) per RA occupant, for RA capacities as high as 49 people.

The purpose of the testing was to investigate the airflow and pressure relief characteristics of the three PRVs. No research was performed on the survivability of the PRVs to comply with the 103 kPa (15.0 psi) impulse overpressure specification. Future research is necessary to address the survivability of PRVs and may warrant significant valve housing and flap redesign.

Conclusions

The commercially available valve that was tested is used in steel prefabricated portable RAs and one mine operator's built-in-place RA. The vast majority of PRVs that are in use are servicing tent-type units and were not part of this research. The commercially available relief valve does not comply with the 1.25 kPa (0.18 psi) limit as stated in the 30 CFR specifications but may meet specifications set by the manufacturer. This valve needs to be reevaluated by the manufacturer to ensure it meets the 30 CFR specifications.

The PVC check valve that was tested offers a viable solution for relief valves in RAs. It can be modified to adjust the relief pressure as needed. The size of the relief valve can be chosen to allow sufficient airflow out of the RA to meet the airflow requirement based on the number of miners in the chamber.

The brass/cast-iron butterfly check valve may be an alternative to the PVC check valve with further modifications.

Future research is necessary to examine the survivability of PRVs subjected to a 103 kPa (15.0 psi) impulse overpressure. The PVC check valve housing and flap may need to be redesigned in order to withstand the mine atmosphere and a potential catastrophic event.

Acknowledgments

The authors gratefully acknowledge the assistance of Joe Ducarme and Tim Matty and other researchers at the Pittsburgh Mining Research Division for their assistance in completing this work.

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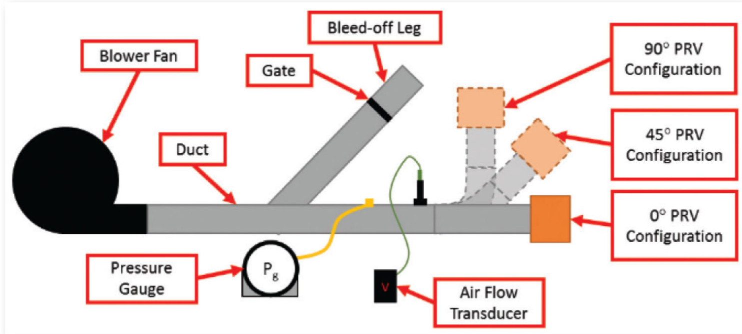

Figure 1.
Schematic of setup.

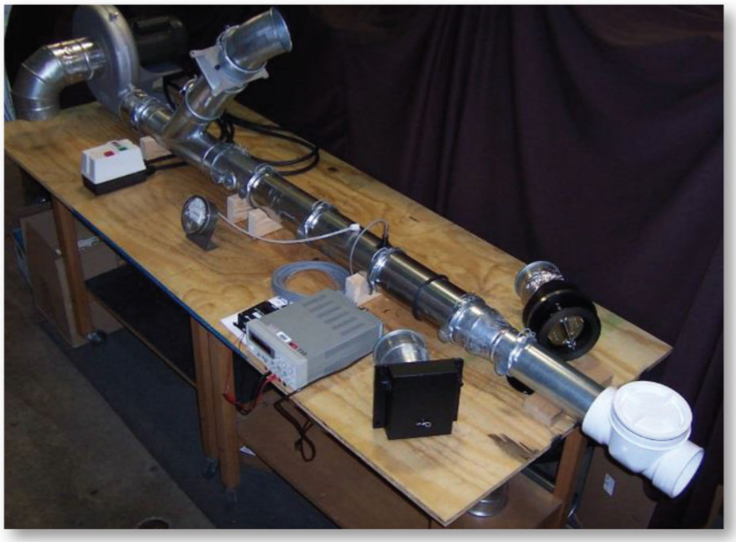

Figure 2.
Photograph of setup.

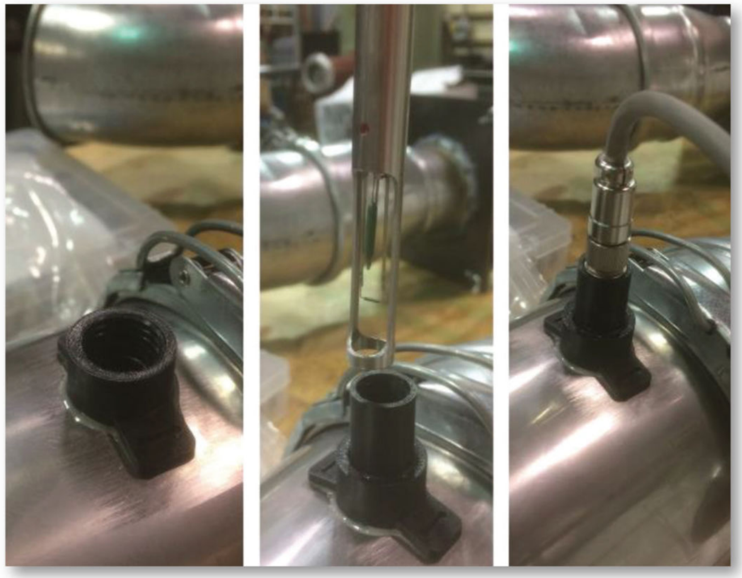

Figure 3.
From left to right: Probe adapter, probe adapter with insert, probe installed ready for testing.

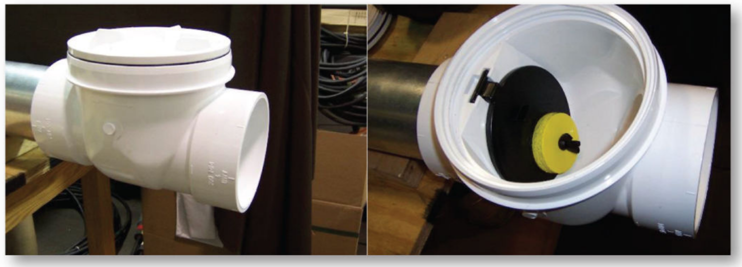

Figure 4.
PVC check valve.

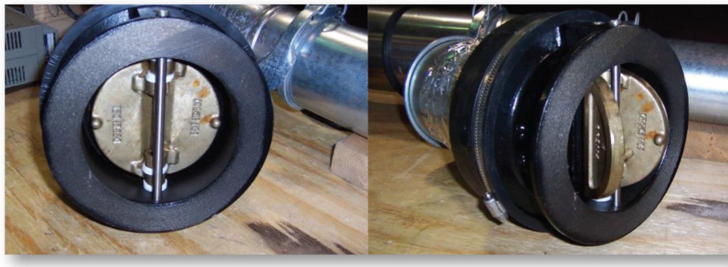

Figure 5.
Brass/cast-iron butterfly check valve.

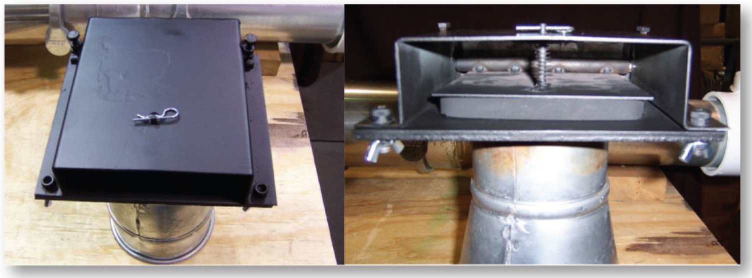

Figure 6.
Commercially available relief valve.

Table 1

Pressure and velocity data for the NIOSH modified PRV.

		XL insert (1.5 in. from center)			L insert (1.0 in. from center)			M insert (0.5 in. from center)			S insert (0 in. from center)			Average		
Angle	**Added weight to fapper (kg)**	**V (m/s)**	**Q (m^3/min)**	**P (kPa)**	**V (m/s)**	**Q (m^3/min)**	**P (kPa)**	**V (m/s)**	**Q (m^3/min)**	**P (kPa)**	**V (m/s)**	**Q (m^3/min)**	**P (kPa)**	**V (m/s)**	**Q (m^3/min)**	**P (kPa)**
0°	0.00	21.4	16.3	0.3	23.0	17.5	0.3	22.9	17.4	0.3	23.7	18.0	0.3	22.8	17.3	0.3
	0.43	20.0	15.2	0.5	19.9	15.1	0.5	21.0	16.0	0.5	20.9	15.9	0.5	20.4	15.5	0.5
	0.87	18.9	14.3	0.7	19.5	14.8	0.7	20.9	15.9	0.7	20.0	15.2	0.7	19.8	15.1	0.7
45°	0.00	20.9	15.9	0.3	23.2	17.6	0.3	23.0	17.5	0.3	23.8	18.1	0.3	22.7	17.3	0.3
	0.43	19.7	15.0	0.6	21.5	16.4	0.6	21.4	16.3	0.6	22.1	16.8	0.6	21.2	16.1	0.6
	0.87	18.3	13.9	0.7	20.0	15.2	0.7	19.9	15.2	0.7	20.8	15.8	0.7	19.8	15.0	0.7
90°	0.00	21.1	16.0	0.3	22.3	16.9	0.3	22.4	17.0	0.3	23.8	18.1	0.3	22.4	17.0	0.3
	0.43	21.9	16.6	0.4	21.3	16.2	0.4	22.9	17.4	0.4	22.3	17.0	0.4	22.1	16.8	0.4
	0.87	19.7	15.0	0.5	22.4	17.0	0.5	22.5	17.1	0.5	21.7	16.5	0.5	21.6	16.4	0.5

Table 2

Brass/cast-iron butterfly PRV test results.

Angle	Confguration	V (m/s)	Q (m^3/min)	P (kPa)
45°	No springs.	15.1	11.5	1.25
90°	No springs.	14.1	10.7	1.30

Table 3

Commercial PRV test results.

Angle	Confguration	V (m/s)	Q (m^3/min)	P (kPa)
0°	Original.	0.0	0.0	1.62
	Preload washers removed.	0.0	0.0	1.62
	Factory spring replaced with 1-lb/in. spring and washer.	11.3	8.6	1.44