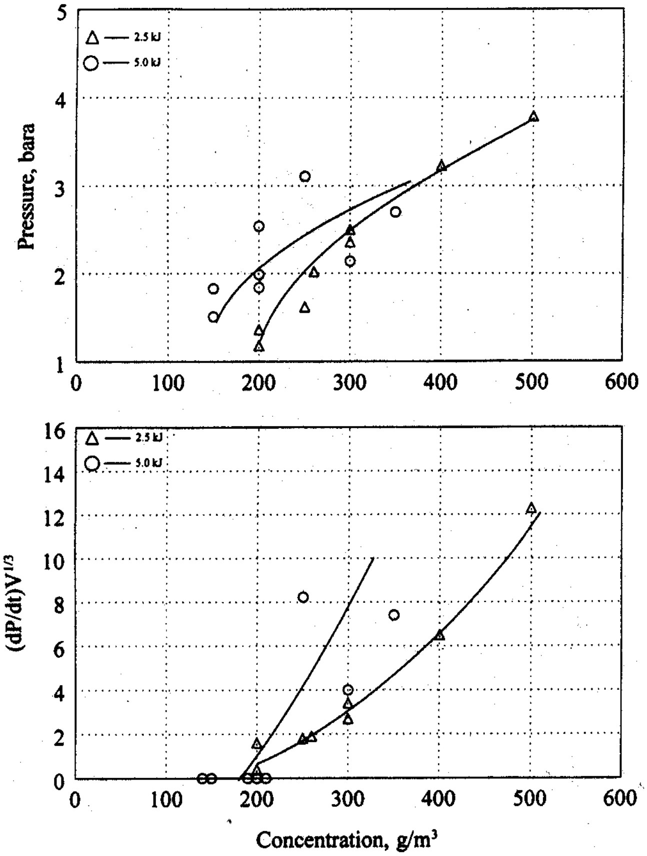

Fig. 9. MEC data for iron powder from the 20-L chamber.

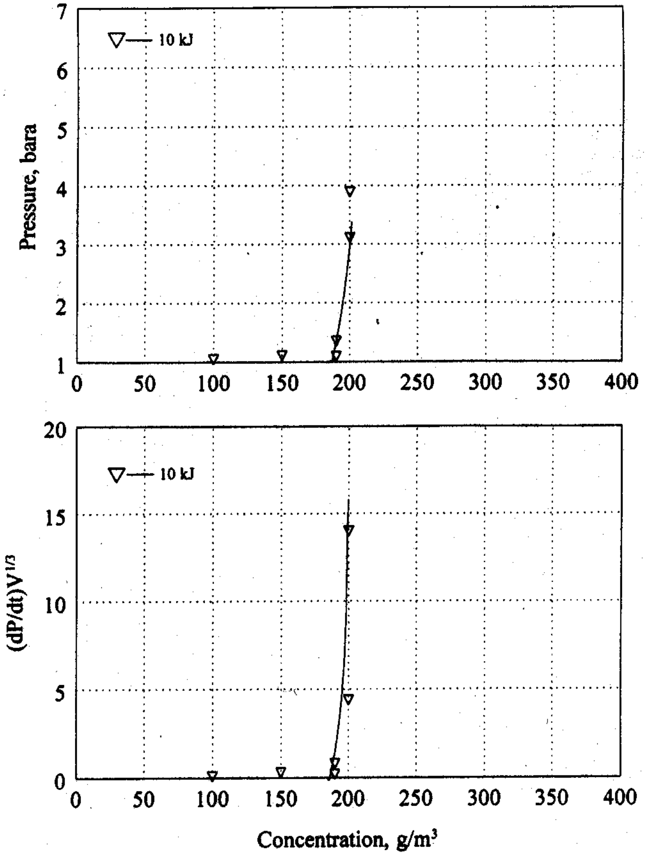

Fig. 10. MEC data for iron powder from the 1-m^3 chamber.

1-m^3 results for the carbonaceous dusts. This is a result of overdriving the smaller vessel with too strong an ignition source. For the carbonaceous dusts, the closest agreement to the 1-m^3 data was found with a 2.5-kJ ignitor in the 20-L vessel.

The iron results appear to be somewhat different in that the 20-L MEC at 2.5-kJ ignition energy was higher than the 1-m^3 MEC. It must be noted that these MEC values are three to five times higher than those found with the carbon-based fuels. The data in Fig. 11D show that for the more difficult-to-ignite dusts (such as this iron powder) with higher MEC values, the use of a 5-kJ ignitor in the 20-L chamber may be more appropriate for agreement with the 1-m^3 data at 10 kJ.

Siwek (1988) compared the MEC values measured with a 10-kJ ignitor in 20-L and 1-m^3 vessels. He concluded that there was no significant effect of vessel volume on the measured MECs, i.e. that the MECs from the two vessels agreed to within one concentration increment. However, in his MEC tests, the dust concentration increment was 10 g/m^3. A close examination of the data in Fig. 8 of his paper, however, suggests that the MECs for six of the 16 dusts studied were between 10 and 30% lower in the 20-L vessel than in the 1-m^3 vessel. Two of the dusts were less than 10% higher and the rest were about the same. This suggests that some overdriving was occurring, at least for some of the dusts. Another difference between Siwek's data and the data presented in this paper is that he reports the MEC as the highest concentration that does not produce an explosion rather than as the lowest concentration that just produces an explosion.

In conclusion, the MEC data presented in this paper show that overdriving can occur in the 20-L vessel using 5-kJ or 10-kJ ignitors. For the dusts tested, the MEC data using 2.5-kJ or 5-kJ ignitors in the 20-L vessel agreed best with the MEC data from the 1-m^3 vessel using a 10-kJ ignitor. The extent of overdriving in the 20-L vessel is dependent on the type of dust. There was less of an effect (Fig. 11) for the RoRo93, gilsonite, and lycopodium, all of which have a high volatility. The overdriving in the 20-L vessel was greatest for the coal dust, which had a much lower volatility.

4. LOC data and discussion

All of the LOC testing in the 1-m^3 vessel was conducted with the 10-kJ ignition source and the 20-L tests were conducted mainly with 2.5- or 5-kJ ignition sources. The criteria for ignition were unchanged from the MEC testing. LOC testing also incorporated the effect of fuel con-

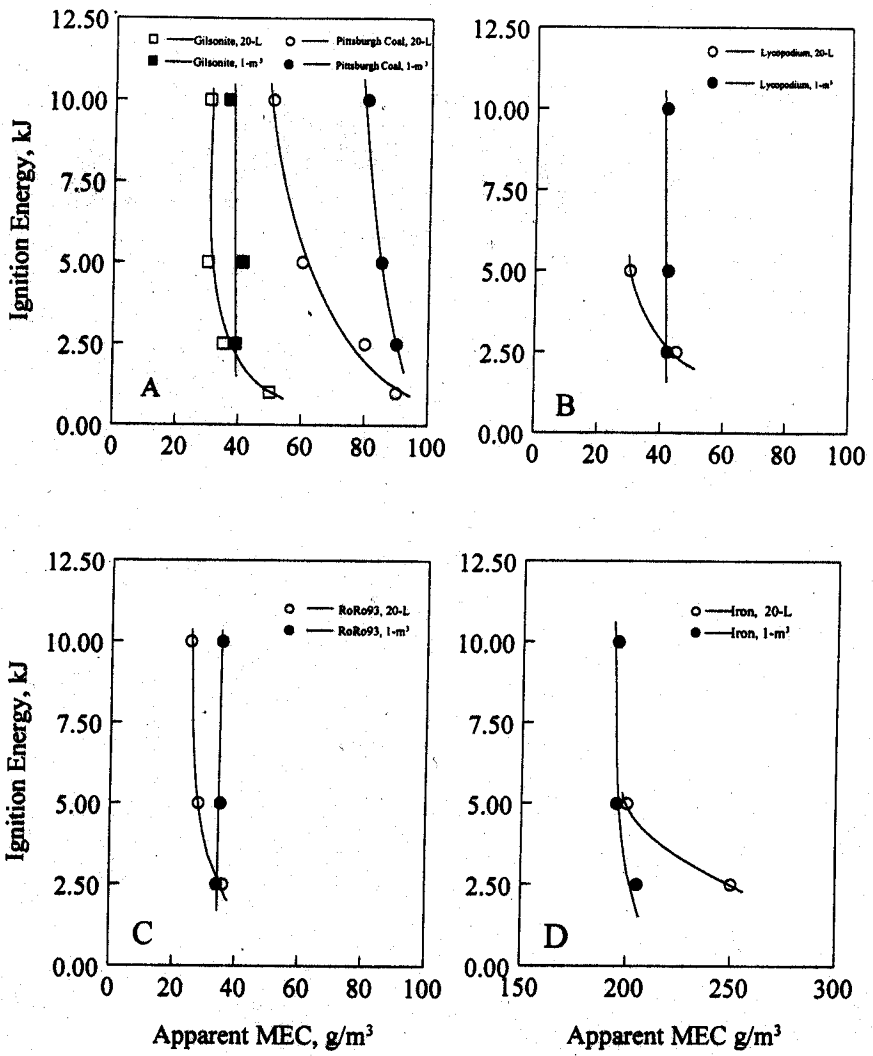

Fig. 11. Effect of ignition energy on apparent MEC.

centration on the measurement. In effect, the fuel concentration was varied in order to determine the lowest possible LOC at any concentration, i.e. the "worst" case. The oxygen concentration was reduced by adding nitrogen to the air. This was done in both test vessels as well as in the dust injection gas reservoirs for the 20-L and 1-m^3 chambers. This approach eliminated any question about the actual O_2 concentration in the initial stages of dispersion and ignition.

The LOC data for the RoRo93 dust are shown in Fig. 12. Tests were made over a range of dust concentrations in order to determine the LOC at the "worst" case. The ignitions/explosions are shown as the solid data symbols and the nonignitions/nonexplosions are shown as the open data symbols. The 1-m^3 chamber data using 10-kJ ignitors are shown in the top part of the figure and the 20-L data using 2.5-kJ ignitors are shown in the bottom of the figure. In the 1-m^3 chamber, the RoRo93 dust ignited and burned at 11% oxygen but not at 10% oxygen. The reported LOC value is then taken as the average of these values or 10.5%. In the 20-L chamber, the RoRo93 also ignited at 11% but not at 10% oxygen, so the LOC value is also 10.5%. In this case the LOC value determined in the 20-L chamber using a 2.5-J ignitor was in agreement with the data from the 1-m^3 chamber using 10-kJ ignitor. All of the LOC data are summarized in Table 3.

The 20-L data for Pittsburgh coal in Fig. 13 clearly show that the effect of the ignition source is significant in this volume. As ignition energy increases, lower quantities of fuel and oxygen are required to create 1 bar overpressures. A comparison of the 14% oxygen and 150 g/m^3 coal coordinates on the three 20-L graphs provides a good example of the effect of ignition source. With a 1-kJ ignition source, the 14% oxygen and 150 g/m^3 point is outside the flammability envelope. With a 2.5-kJ ignition source, this point is just inside the flammable envelope and with a 5-kJ ignition source, this point is well within the flammability envelope. Increasing the ignition energy increases the size of the flammability zone. As listed in Table 3, the LOC in the 20-L chamber decreased from 13.5% at 1 kJ to 11% at 2.5 kJ and 9.5% at 5 kJ. In the 1-m^3 chamber, the LOC is 13.5% at 10 kJ.

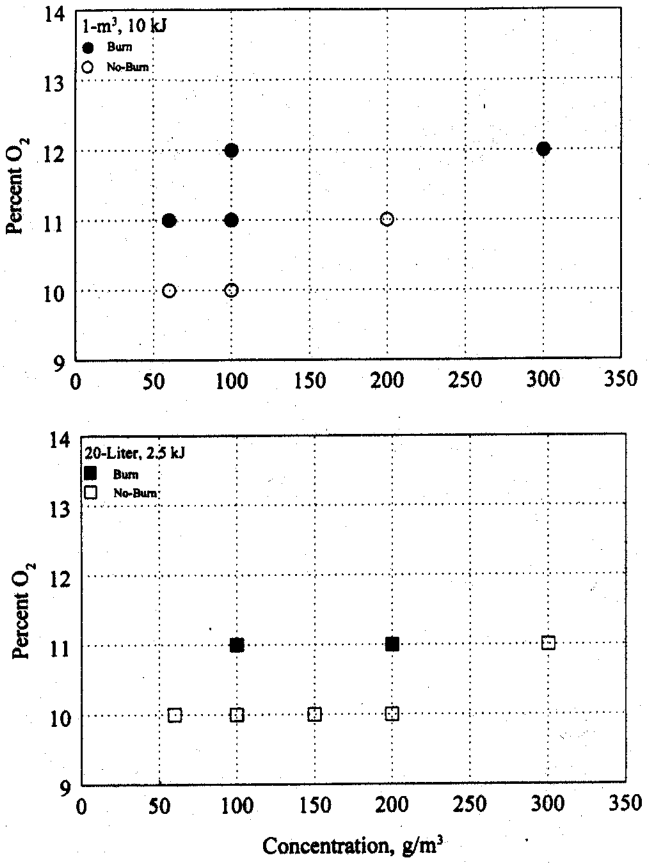

Fig. 12. LOC data for RoRo93.

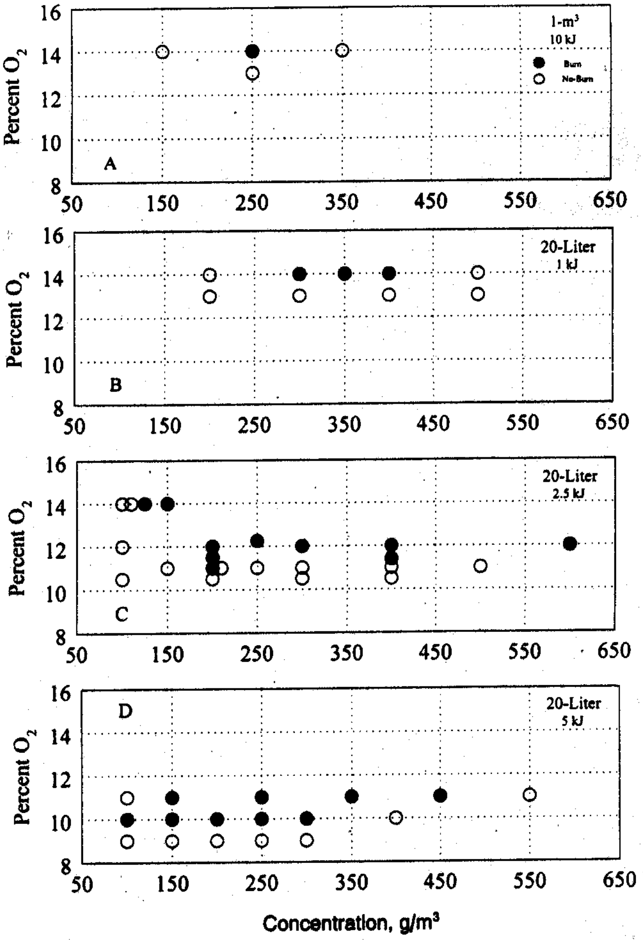

Fig. 13. LOC data for Pittsburgh coal.

Table 3
Results of LOC testing (% O_2)

Dust	20-L vessel			1-m³ vessel
	1 kJ	2.5 kJ	5 kJ	10 kJ
RoRo93	–	10.5	8.5	10.5
Pittsburgh coal	13.5	11	9.5	13.5
Gilsonite	–	10.5	8.5	11.5
Aluminum	–	9.5	8.5	9.5

The results of the gilsonite tests are shown in Fig. 14 and illustrate the effect of concentration on the LOC. For example, the 20-L data show an ignition at 11% O_2 at 100 and 200 g/m³ but failure to ignite and burn at 300 g/m³. The dust did not ignite at 10% O_2 at any concentration tested. The data show that the LOC in the 20-L chamber with a 2.5-kJ ignitor was 10.5% compared to 11.5% measured in the 1-m³ with a 10-kJ ignitor.

As shown in Fig. 15, the LOCs for the aluminum dust were found at much higher dust concentrations than for the carbonaceous dusts. This shows the importance of LOC testing over a wide range of dust concentrations. The measured LOCs for this aluminum were 9.5% using a 10-kJ ignitor in the 1-m³ and 9.5% at 2.5-kJ and 8.5% at 5-kJ in the 20-L chamber. In both cases, the lowest LOC value was found at a very high dust concentration of ~1000 g/m³.

Comparing the LOCs of aluminum and RoRo93 measured in the 20-L chamber with the LOCs measured in the 1-m³ chamber leads to the conclusion that 2.5 kJ is an appropriate ignition source for the 20-L chamber. The 2.5-kJ ignition source appears to neither overdrive nor underdrive the aluminum and RoRo93 systems. However, comparing the gilsonite and Pittsburgh coal LOCs leads to the conclusion that 2.5 kJ does overdrive these dusts in the 20-L chamber. The 1-m³ LOCs for gilsonite and Pittsburgh Coal are 11.5% and 13.5%, respectively, compared with the 20-L LOCs of 10.5% and 11% at 2.5 kJ.

All of the LOC data reported here support the conclusion reached by Siwek (1988), i.e. that the 10-kJ ignition source is inappropriate for LOC measurement in the 20-L vessel. Furthermore, the data also indicate that the 5-kJ ignition source is inappropriate for LOC measurement in the 20-L chamber, for the dusts studied. Both the 10-kJ and the 5-kJ sources will overdrive the explosion in the 20-L vessel for most dusts. The results reported here (Table 3) and in Siwek's paper (figure 20 in Siwek, 1988) indicate that the 1-kJ or 2.5-kJ ignition

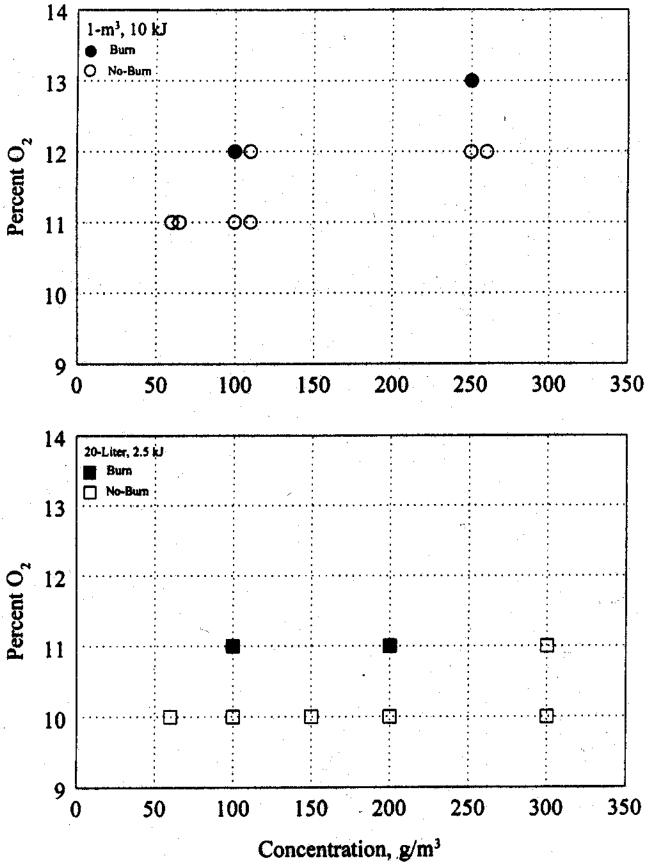

Fig. 14. LOC data for gilsonite.

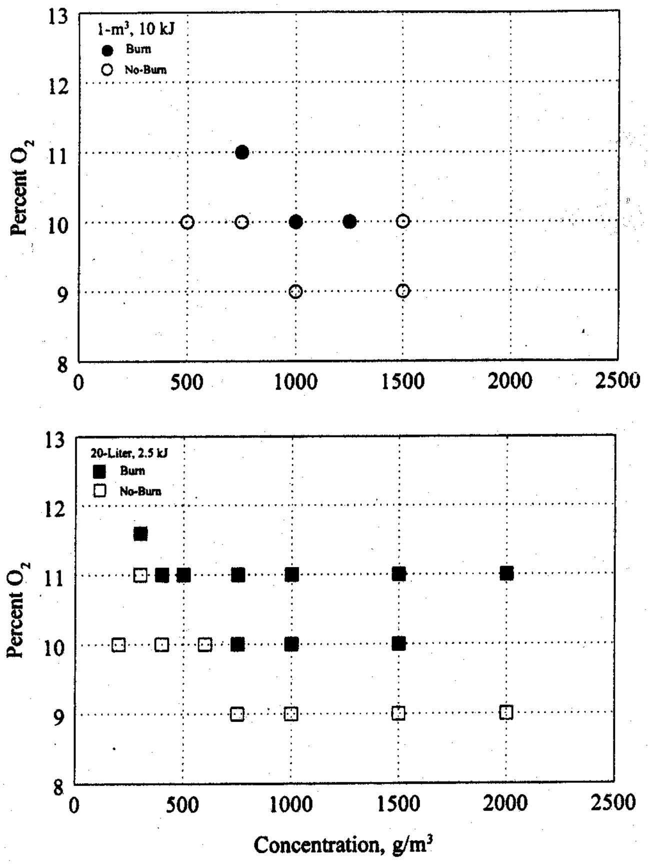

Fig. 15. LOC data for aluminum.

source may be the most appropriate ignition source to use for LOC measurement in the 20-L vessel to match the LOC data from the 1-m³ vessel using a 10-kJ ignitor. However, there may be some dusts for which overly conservative LOC values will be obtained in the 20-L chamber with the 2.5-kJ ignitor.

Siwek (1988) recommended that a 5-kJ ignition source should be used for dusts with LOC values below 10%. However, neither the current study nor Siwek's work investigated dusts with LOC values significantly below 10%. This is an area of LOC measurement that needs further study. If it is assumed that dusts with LOC values below 10% are highly reactive and the effect of the ignition source is to either overdrive or underdrive these systems, then it might be expected that a 5-kJ ignition source would more likely overdrive these systems. Additional data need to be gathered for dusts with LOC values below 10% to establish a clear recommendation.

To obtain unambiguous and practically usable LOC values, the 1-m³ chamber is preferred, especially when LOC values are below 10%. The 20-L LOC values may be somewhat more uncertain, but the 2.5-kJ data from the 20-L vessel appear to be conservative, at least for LOC values above 10%.

In applying the LOC data, one should use a reasonable safety margin. NFPA 69 recommends keeping the oxygen concentration at least 2% below the measured LOC value when protecting equipment. It is important to remember that the LOC values listed in Table 3 are only for the specific dusts tested and may not be applicable to other particle sizes of the same materials. Often, finer sizes of dusts have lower LOC values. It is also important to recognize that these LOC data are for nitrogen inerting of air. Inerting with other gases such as carbon dioxide may give different results.

5. Conclusion

The data from this study and the previous work (Cashdollar & Chatrathi, 1992) demonstrate that overdriving can occur when using strong chemical ignitors in the 20-L chamber. The result is that apparent MEC values are found which are lower than the "true" values. For most dusts tested, the best agreement is found between 20-L chamber data with 2.5-kJ ignitors and 1-m³ data with 10-kJ ignitors. Overdriving is not a concern when testing with 10 kJ in the 1-m³ vessel. The advantage of the 20-L chamber is that the explosion tests can be conducted more quickly and with much smaller dust samples. In practice, therefore, the 2.5-kJ ignitor is recommended for initial testing in the 20-L vessel. For hard-to-ignite dusts with higher MEC values, a 5-kJ ignitor may be more appropriate. If there are significant differences in the MEC values obtained at 2.5-kJ and 5-kJ energies, it may be advisable to go to the 1-m³ vessel for a final MEC determination. If the dust does not ignite with a 2.5-kJ ignitor, but does ignite with a 5-kJ or 10-kJ ignitor in a 20-L vessel, it is necessary to use a 1-m³ vessel with a 10-kJ ignitor for the final determination.

Similar conclusions can be drawn regarding overdriving the 20-L vessel when making LOC measurements. These and previous data indicate that both 5- and 10-kJ energies are too strong for the 20-L chamber. From the studies carried out to date, the 2.5-kJ ignitor is the most appropriate energy level for 20-L LOC testing, and in fact, the 2.5-kJ data may be slightly conservative for some dusts. Additional LOC studies are needed, particularly for dusts with LOC values below 10%.

Acknowledgements

The authors wish to acknowledge the assistance of G.M. Green and PRL in the collection of the 20-L data and Frankie Terry, Thomas Klug, and Jack Creager of Fike in the collection of the 1-m³ data.

References

Amyotte, P. R., Chippett, S., & Pegg, M. J. (1989). Effect of turbulence on dust explosions. *Progress in Energy and Combustion Science, 14*, 293–310.

Bartknecht, W. (1989). *Dust explosions: course, prevention, protection.* New York: Springer.

Cashdollar, K. L., & Chatrathi, K. (1992). Minimum explosible dust concentrations measured in 20-L and 1-m³ chambers. *Combustion Science and Technology, 87*, 157.

Cashdollar, K. L., & Hertzberg, M. (1985). 20-Liter explosibility test chamber for dusts and gases. *Review of Scientific Instruments, 56*, 596–602.

Cashdollar, K. L., Sapko, M. J., Weiss, E. S., & Hertzberg, M. (1987). Laboratory and mine dust explosion research at the Bureau of Mines. In *Industrial dust explosion, STP 958.* Philadelphia, PA: ASTM pp. 107–123.

Chawla, N., Amyotte, P. R., & Pegg, N. J. (1996). A comparison of experimental methods to determine the minimum explosible concentration of dusts. *Fuel, 75*, 654–658.

Hertzberg, M., & Cashdollar, K. L. (1987). Introduction to dust explosions. In *Industrial dust explosions, STP 958.* Philadelphia, PA: ASTM pp. 5–32.

Hertzberg, M., Cashdollar, K. L., & Zlochower, I. A. (1988). Flammability limit measurement for dust and gases. In *21st Symposium (International) on Combustion* (pp. 303–313). Pittsburgh, PA: The Combustion Institute.

Rice, G. S., & Greenwald, H. P. (1929). Coal dust explosibility factors indicated by experimental mine investigations 1911 to 1929. Bureau of Mines Technical Paper 464.

Siwek, R. (1988). Reliability determination of the safety characteristics in 20-L apparatus. *Flammable dust explosion.* St. Louis, MO.