FAULT TREE ANALYSIS OF SPONTANEOUS COMBUSTION
OF SULPHIDE ORES AND ITS RISK ASSESSMENT

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Abstract A logic fault tree of mine spontaneous combustion of sulphide ores was built by the fault tree analysis (FTA) based on a lot of mechanism investigation of sulphide ore spontaneous combustion in more than ten mines and review of a great amount of relevant literature. The fault tree is composed of 17 key contributory factors. After making a qualitative analysis of the fault tree, the minimum relevant factors for assessment of inherent self-heating potential and the optimal paths for controlling fire were put forward. A mathematical model based on the heat transfer and diffusion theory is recommended to pre-estimate quantitatively the fire risk in field.

Key Words fault tree analysis; sulphide ores; spontaneous combustion; risk assessment

A fire disaster from the spontaneous combustion of sulphide ores in a mine can produce large quantities of toxic gases and heat to pollute the whole mine, lead to large economic losses and death. Some mines of iron, copper, lead, zinc and tin in China are high sulphide-bearing ore bodies. It is of great importance to know the spontaneous combustion potential and take necessary preventive and protective measures with an overall integrated fire control strategy, by employing systematic risk assessment and any other appropriate techniques at mining planning and design stages. Up to now, a variety of laboratory methods have been proposed to evaluate the self-heating potential. Techniques for dealing with outbreaks of spontaneous combustion are well developed in monitoring, sealing, cavity filling, inactivation, ventilation and extraction. However, some problems still exist about how to determine the most important one among all the relevant factors and how to arrange the order of these factors. After these problems are solved, the optimal scientific fire control program will be achieved. In this paper, the FTA is used to solve these problems.

1 FAULT TREE BUILDING

In FTA, an undesired event is selected as top event. Its contributory events are drawn below, branching downwards as in a tree. They are connected to the top event through different logic gates. For example, if all the events listed below are needed to make the top event possible, the AND gate is used, which shows that this and this and this are all needed

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to make the top event possible. If only one of the events is needed to make the top event possible, then the OR gate is used, which shows that either this or this is needed. The built fault tree is an excellent tool to order graphically the causes and effects involved in a mishap and provide direction to gather information. In this paper, the spontaneous combustion of sulphide ore pile in stope is taken as the top event. The needed events to make the top event happen are as follows. The ore is easy to be oxidized; ore reacts with humid air (that is oxygen and water) fully and the temperature in the ore pile continuously rises to the ignition point of ore or smoking. They are connected to the top event through the conditioning AND gate. The branching event can be subdivided into more detailed events according to the conductive method and are connected through correspondent logic gates. Fig. 1 shows the built fault tree of spontaneous combustion of sulphide ore pile depending on a lot of mechanism investigation of sulphide ore spontaneous combustion both in laboratory and field[2].

![Fault Tree Diagram]

**Fig. 1** Fault tree of spontaneous combustion of sulphide ore pile in stope

2 QUALITATIVE ANALYSIS OF THE FAULT TREE

2.1 Minimum Cut and Path Set Analysis

According to the logic algebra and the symbols in Fig. 1, the fault tree can be expressed as equation (1) after simplification by Boolean laws.

\[
T = RX_1X_2X_3X_12X_17, (X_1 + X_2 + X_3 + X_4 + X_5 + X_6)(X_9 + X_{10})
\]

\[
(X_{12} + X_{13} + X_{14} + X_{15} + X_{12} + X_{13} + X_{14} + X_{15})
\]

(1)
It can be seen from equation (1) that there are 48 minimum cut sets in the fault tree. According to the definition of minimum cut set, in this tree, all basic events in the fault tree lead to the result of fire in 48 cases.

Let \( S = \{ R, X_7, X_4, X_{11}, X_{16}, X_{17} \} \). The achieved minimum cut sets are listed below.

\[
\begin{align*}
K_1 &= \{ S, X_7, X_4, X_{11} \}, K_2 = \{ S, X_7, X_4, X_{16} \}, K_3 = \{ S, X_7, X_4, X_{17} \}, \\
K_4 &= \{ S, X_7, X_4, X_{16} \}, K_5 = \{ S, X_7, X_4, X_{12} \}, K_6 = \{ S, X_7, X_4, X_{13} \}, \\
K_7 &= \{ S, X_7, X_4, X_{11} \}, K_8 = \{ S, X_7, X_4, X_{16} \}, K_9 = \{ S, X_7, X_4, X_{12} \}, \\
K_{10} &= \{ S, X_7, X_4, X_{13} \}, K_{11} = \{ S, X_7, X_4, X_{16} \}, K_{12} = \{ S, X_7, X_4, X_{12} \}, \\
K_{13} &= \{ S, X_7, X_4, X_{11} \}, K_{14} = \{ S, X_7, X_4, X_{16} \}, K_{15} = \{ S, X_7, X_4, X_{12} \}, \\
K_{16} &= \{ S, X_7, X_4, X_{11} \}, K_{17} = \{ S, X_7, X_4, X_{16} \}, K_{18} = \{ S, X_7, X_4, X_{12} \}, \\
K_{19} &= \{ S, X_7, X_4, X_{11} \}, K_{20} = \{ S, X_7, X_4, X_{16} \}, K_{21} = \{ S, X_7, X_4, X_{12} \}. \\
K_{22} &= \{ S, X_7, X_4, X_{11} \}, K_{23} = \{ S, X_7, X_4, X_{16} \}, K_{24} = \{ S, X_7, X_4, X_{12} \}, \\
K_{25} &= \{ S, X_7, X_4, X_{11} \}, K_{26} = \{ S, X_7, X_4, X_{16} \}, K_{27} = \{ S, X_7, X_4, X_{12} \}, \\
K_{28} &= \{ S, X_7, X_4, X_{11} \}, K_{29} = \{ S, X_7, X_4, X_{16} \}, K_{30} = \{ S, X_7, X_4, X_{12} \}, \\
K_{31} &= \{ S, X_7, X_4, X_{11} \}, K_{32} = \{ S, X_7, X_4, X_{16} \}, K_{33} = \{ S, X_7, X_4, X_{12} \}, \\
K_{34} &= \{ S, X_7, X_4, X_{11} \}, K_{35} = \{ S, X_7, X_4, X_{16} \}, K_{36} = \{ S, X_7, X_4, X_{12} \}. \\
K_{37} &= \{ S, X_7, X_4, X_{11} \}, K_{38} = \{ S, X_7, X_4, X_{16} \}, K_{39} = \{ S, X_7, X_4, X_{12} \}, \\
K_{40} &= \{ S, X_7, X_4, X_{11} \}, K_{41} = \{ S, X_7, X_4, X_{16} \}, K_{42} = \{ S, X_7, X_4, X_{12} \}, \\
K_{43} &= \{ S, X_7, X_4, X_{11} \}, K_{44} = \{ S, X_7, X_4, X_{16} \}, K_{45} = \{ S, X_7, X_4, X_{12} \}, \\
K_{46} &= \{ S, X_7, X_4, X_{11} \}, K_{47} = \{ S, X_7, X_4, X_{16} \}, K_{48} = \{ S, X_7, X_4, X_{12} \}. 
\end{align*}
\]

Based on equation (1) and the definition of minimum path set, 9 minimum path sets are achieved, which means that there are 9 plans to control the spontaneous combustion of sulphide ore pile in stope. The minimum path sets are listed as follows.

\[
\begin{align*}
P_1 &= \{ R \}, P_2 = \{ X_7 \}, P_3 = \{ X_4 \}, P_4 = \{ X_{11} \}, P_5 = \{ X_{16} \}, \\
P_6 = \{ X_{17} \}, P_7 = \{ X_7, X_4, X_{11}, X_{16}, X_{17} \}. 
\end{align*}
\]

2.2 Vital Series Analysis of Basic Event

According to the architecture of the built fault tree and the approximate critical method, the vital series of all basic events is \( I(R) = I(X_7) = I(X_4) = I(X_{11}) = I(X_{16}) > I(X_{17}) > I(X_7) \). Since the structure vital series analysis does not take into account the fault probability of each basic event, this analyzing result is just for reference. In practical experiences, events \( X_1, X_7, X_{12}, X_{16} \) are more important than the others.

2.3 Factors of Characterizing the Spontaneous Combustion Potential

Depending on the minimum cut set of the fault tree, some characterizing factors for criticizing the spontaneous combustion tendency of sulphide ores in laboratory are \( X_1, X_7, X_{12}, X_{16}, X_4, X_7, X_4, X_{11}, X_{16} \) and \( R \). \( X_1, X_7, X_{12}, X_{16}, X_4, X_7, X_4, X_{11} \) and \( R \) can be tested by mineralogical analysis and chemical composition analysis. \( X_7, X_4 \) and \( R \) can be determined by the special devices described in [2]. To know whether the fire breaks out in a stope, other factors, e.g. \( X_{12}, X_{17}, X_{13}, X_{14}, X_{13}, X_{11} \) should be taken into considerations.

2.4 Pathes of Spontaneous Combustion Control

In order to control the ore pile spontaneous combustion, the following effective measures may be achieved by the minimum path sets.

- Reduce the piling time of ores in stope after blasting to control \( X_{17} \);
- Use various effective inactive materials to control \( X_7 \) and \( X_{17} \);
- Control blasting parameter to prevent the excessive ore fragmentation;
3 QUANTITATIVE PRE-ESTIMATION OF FIRE

In order to pre-estimate fire, both field monitoring and mathematical model can be employed. In field test methods, the most effective one is to determine the temperature in the center of ore pile continuously and it can be explained clearly in Fig. 1 since the condition R in the first AND gate can determine whether a fire breaks out. The mathematical model for pre-estimating fire is based on the heat transfer and diffusion theory. In this method, the direct relevant factors are as follows: Self-heating flux of ore \((HF, \ W \cdot \text{m}^{-2})\); Average fragmentation of ore \((FD, \ m)\); Ore pile volume \((OV, \ m^3)\); Average depth of ore pile \((OPD, \ m)\); Air temperature \((AT, \ ^\circ\text{C})\); Air velocity in stope \((AV, \ \text{m} \cdot \text{s}^{-1})\); Heat transfer coefficient between air flow and ore pile \((HTC, \ W \cdot \text{m}^{-2} \cdot \text{K}^{-1})\); Virgin strata temperature \((VST, \ ^\circ\text{C})\); Thermal conductivity of ore \((OTC, \ W \cdot \text{m}^{-1} \cdot \text{K}^{-1})\); Ore density \((OD, \ \text{kg} \cdot \text{m}^{-3})\); Ore specific heat \((OSH, \ J \cdot \text{kg}^{-1} \cdot \text{K}^{-1})\); Ore ignition or smoking point \((OIP, \ ^\circ\text{C})\); Ore pile loose factor \((OLF)\); Water content of ore \((OWC, \ %)\); Water specific heat \((WSH, \ J \cdot \text{kg}^{-1} \cdot \text{K}^{-1})\); Water density \((WD, \ \text{kg} \cdot \text{m}^{-3})\); Virgin strata thermal conductivity \((VTC, \ W \cdot \text{m}^{-1} \cdot \text{K}^{-1})\); Virgin strata density \((VD, \ \text{kg} \cdot \text{m}^{-3})\); Virgin strata specific heat \((VH, \ J \cdot \text{kg}^{-1} \cdot \text{K}^{-1})\); Surface area of ore pile \((OSA, \ m^2)\); Hydraulic radius of stope \((SR, \ m)\). Using these factors, the time \((t/d)\) from blasting to ignition of ore can be obtained by the following equation.

\[
t = (\sqrt[3]{\frac{1}{4} \left(\frac{c_2}{c_1} \right)^2 - \frac{c_3}{c_1}} - \frac{c_1}{2c_1})^2 / 86400
\]

where \(c_1 = HTC \cdot SR / (OTC \cdot (OIP / 2 - AT) - 6OPD \cdot HF / FD)\),
\(c_2 = VTC \cdot (OIP / 2 - VST) / (\pi \cdot VTC / (VD \cdot VH))^{1/4}\),
\(c_3 = OPD \cdot OD \cdot OSH \cdot (OIP - VST) + OPD \cdot OWC \cdot WD \cdot WSH \cdot (OIP - VST) / OLF\).

If \(t\) is much greater than that of ore extraction or unlimited, there is no risk of ore spontaneous combustion. If \(t\) is shorter or approximate equal to the time of ore extraction, effective measures should be employed to prevent the spontaneous combustion.

4 CONCLUSIONS

The built fault tree in the paper expresses graphically the causes and effects involved in the spontaneous combustion of sulphide ores clearly and simply. Based on the analysis of the fault tree, optimal safe program can be achieved for testing self-heating potential, pre-estimating fire and taking scientific measures to prevent and extinguish the spontaneous combustion of sulphide ores. The proposed mathematical model for fire pre-estimation and the risk assessment method were verified in field.

References