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Theoretical research on hazards and accident prevention

ZHANG Yuebing[1,2,*] WANG Kai[1] ZHANG Ruming[1]

(1. China University of Mining & Technology (Beijing) Beijing 100083, China 2.North China Institute of Science and Technology, East Yanjiao 101601, China)

Abstract

By applying modern safety science viewpoints and accident-causing theory, and based on case studies, the development of hazard theory is briefed, and the structure and concept of hazards are analyzed. While further improving the definition of hazard, the classification of hazards and accident prevention and control model are explored. The position of each type of hazard in the accident control model is further analyzed. The causes of accidents and hazard theory-based measures are pointed out. It is believed that the research on hazard theory should be strengthened, especially the research on identification and control of direct hazard, the first triggering hazard and initial hazard, in anticipation to fully understand all types of hazard resulting in accidents, establish a complete set of hazard theory, and enhance the level of safety management and accident control in coal mines.

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1. Introduction

In recent years, all types of accidents in China, especially coal mine accidents, are frequent, and are characterized by lots of major and catastrophic accidents with serious influence. For example, “1.5”major fire accident in Lisheng Coal Mine in Hunan, “3.1”major water inrush accident in Luotuoshan Coal Mine in Wuhai City, “3.31” major coal and gas outburst accident in Yichuan of Henan, “6.21” major explosives blasting accident in Pingdingshan of Henan in 2010, to name a few. These accidents undoubtedly do not accord with people-oriented scientific outlook on development advocated in China, and also seriously hinder the construction of harmonious society.

* Corresponding author. Email: zyb8562@126.com

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Since hazard concept was proposed, hazard theory plays a good theoretical guiding role for control and prevention of accidents, in particular, major hazard concept provides theoretical foundation for prevention of major accidents. The existence and continual occurrence, failure to timely identify and control hazards are the root cause of frequent accidents[8]. Modern industrial production system becomes ever-complicated. The production system contains a large quantity of hazards. An accident is often as a consequence of the interaction of multiple hazards. Each type of hazard hold different position in accidents, and plays different role, so when preventing a given type of accident, discriminative control means should be taken with respect to all types of hazards leading to the accident. However, as far as present prevention of accidents is concerned, it is hard to find the evident distinction on the control of all types of hazard. As a result, the author made painstaking efforts in researching all types of accident, looking up relevant literatures, and starting from the identification of hazard concept and based on the hazard theory, established the accident control model, and found out the position and role of each type of hazard in occurrence of accidents. Subsequently, pertinent control objectives and means for each type of hazard are researched, used to direct coal mine enterprises in safe production management.

2. Discrimination of hazard concept

Nowadays, the concept of hazard has not been unified yet. Among a lot of hazard concepts available, most of them fail to understand the essential attributes of hazard. In the meantime, there exists much difference in the understanding of hazard concept, so the extension of hazard is unclear, and hazard is often confused with accident potential (or safety potential), accident-causing factor, etc. Hazard literally means a source of danger. That is to say, no hazard, no accident. Therefore, system safety holds that hazard is the precondition on which an accident happens.

(1) Definition I. Willie Hammer defined hazard as “potential unsafe factor that likely leads to casualties or property loss accident”[2]. This definitions accounts of the potential danger of hazard. Then, in order to prevent an accident, we have to find out the hazard, get to know well its harm, study its causing mechanism leading to the accident, and subsequently take preventive measures to control the hazard to make the accident not happen.

(2) Definition II. In China’s *Occupational health and safety management system – specification* (GB/T 28001-2001), hazard is defined as “the root cause or state possibly leading to injury or illness, property loss, workplace damage or their combinations”. Compared with the definition given by Willie Hammer, the author deems this definition is more scientific and reasonable, because: <1> the concept of accident changes. The earlier accidents mainly refer to casualties or property loss, but today’s accident concept also includes illness (occupational illness) and environment damage; <2> Willie Hammer thought the hazard as “unsafe factor”. But it can safely say all factors related to accidents are unsafe factors, including human factor, material factor, environment factor, management factor, social factor, heredity factor, to name a few. The scope is too broad, but “root cause or state” seizes the essence of hazard. “Root cause” means energy carrier or dangerous substance[1,2], “state” is generally in respect of specific root cause hazard. That is to say, some conditions or states (or circumstance, predicament) may result in abnormal transfer of energy or dangerous substance in the specific root cause hazard, and eventually lead to accident or a near-miss. For example, a person suffocates due to oxygen deficit in some circumstances[2].

(3) Other definitions. He Xueqiu thinks hazard is the core producing and strengthening negative effects in subject of knowledge, and the breaking point of dangerous energy[7]. Wang Guangliang opines that, the focus of major hazard is the source, namely, the basic element – dangerous substance leading to accident. Tian Shuicheng believes that, hazard is the core producing and strengthening negative effects in (safety) cognitive object, and the breaking point of dangerous substance, energy and catastrophe information. For example, when the society is in an abnormal period, a bad piece of information may

cause panic among its members and social unrest. During SARS period in China, and after September 11 in USA, some information is highly likely to give rise to social unrest and fluctuating incident. For an individual who is in abnormal period, some bad information can cause his behaviour disorder, functional incapacitation or even death. For example, too joyful or sorrowful news can cause serious influence to cardio-cerebral vascular patients or even lead to their death[8].

3. Extension and classification of hazards

The above is our understanding of the intension of hazards, the purpose of which is to seize the nature of hazards. In order to profoundly study and understand a concept, the people generally will carefully analyze the extension of a concept, without the exception to the hazard concept. From the literatures, presently hazards generally are divided into root hazard, state hazard, material hazard and non-material hazard, category I and II hazard, inherent hazard, triggering hazard , and changing hazard, and so on.

(1) Hazards are classified into root hazard and state hazard. The consequences of an accident are casualties, property loss, occupational illness, environment disruption, etc. The origins leading to such consequences are energy or energy carrier and dangerous substance. State hazard has been described, without repetition here.

(2) Theory on category II and III hazards

In the 1990s, Chen Baozhi et al classified hazards into two categories: Category I and II hazards. Category I hazards mean the energy or dangerous substance that exists in the system and may cause accidental release. In actual work, the people often consider the energy source generating energy or the energy carrier possessing energy as Category I hazard. And Category II hazards mean various unsafe factors leading to malfunction or damage of the measures restraining or restricting energy. The theory believes that[6], an accident is the consequence of the interactions of the hazards in the two categories. The existence of Category I hazard is the precondition on which the accident occurs, determining the severity of the consequence of the accident. Appearance of Category II hazard is the essential condition on which Category I hazard results in the accident, determining the possibility of the accident. The hazards in the two categories are inter-dependent, complementary each other, and jointly determine the danger of the hazards. The focus of accident prevention is how to control Category II hazards.

Based on the theory on the hazards in the above two categories, Prof. Tian Shuicheng from Xi'an University of Science and Technology put forward the concept of Category III hazard. That is, unsafe factors, such as safety management decision, organization fault (organization procedure, organization culture, rule) and people's unsafe behaviour and fault leading to system imbalance, are known as Category III hazards[3]. Later, the hazards in the three categories were revised as: energy carrieor or dangerous substance, namely, Category I hazards; material fault, physical environment factor and individual fault, namely, Category II hazards (focusing on fault of materials like safety facilities, physical environment factor); organization factors – organization factors not conforming to safety (organization procedure, organization culture, rule, system, etc.), namely, Category II hazards, including organizational person's (different from individual person) unsafe behaviour, fault, etc.[8].

The author believes such method of classification is too ambiguous since the causes of accident are considered as the origin of accident, the origin point of accident is expanded to control the all-round three-dimensional space of the origin point, and various unsafe factors leading to failure or damage of shielding measures are called Category II hazards. The method covers all direct causes of accident, is not specific and inoperable in controlling actual hazards. To be more exact, Category II and III hazards are the popular phrases of hidden peril of accidents, which gradually formed in relation to safety and accident prevention by the peoples in their long-term safe production practices, and refer to the unsafe situation of job place, equipment and facilities, mankind's unsafe behaviour and management defects[5]. Hazard is the root cause of danger (or accident). No hazard, no danger, and no accident will happen. On the

contrary, if hazard is available, but if control measures and means are effective, no accident happens either.

(3) Inherent hazard and triggering hazard. Bai Qinhu et al, from another perspective, divided hazards into two categories[6]: one, various kinds of energy that are inevitably existent along with production system (generally from various carriers of energy judge whether the energy exists and its nature and quantity), and dangerous substances. They are physical essence causing system danger or system accident, known as inherent hazards. The other, various faults in hardware or software support system that appear in production activity process and can damage the safety existence conditions of inherent hazards. They are the conditions on which the system transitions from safe situation to dangerous situation, and the triggering causes that lead to system energy release and finally system accident. These faults exist by centering around inherent hazards. Their danger is mainly determined by the nature of inherent hazards, which may be named triggering hazards. The inherent hazards and the triggering hazards determined by the former's nature constitute the hazard structure in the production system. This method of classification mentions "support system fault" is the triggering hazard where an accident happens in the production system, but does not involve the causes of these faults and the prevention and control of the causes. Therefore, further research is needed for the hazard structure of the production system.

(4) Inherent hazard and changing hazard

Ma Guozhong et al[9] classifies the hazards in the transport system into inherent hazard and changing hazard. Inherent hazard means an objective existence is determined by the own nature and structure of the system, which at all times constitute potential peril to the system safety, and under certain conditions will cause major influence on the system operation reliability. Changing hazard means a changing objective existence in the system movement process by which all key elements of the system interact, and which, influenced by various internal and external conditions, may lead to the system state deterioration. Changing hazard means the hazard in the system is changing. Such change possesses three basic features:

1) Variability of danger degree (i.e., the risk degree corresponding to hazard), namely, the danger in the system (i.e., the risk grade corresponding to hazard) changes to some extent along with the change of internal or external conditions of the system.

2) Random migration of danger track, which is embodied from macro perspectives the migration among all the subsystems (i.e., when highly risky hazard moves randomly among all the subsystems, it will randomly appear in different subsystems).

3) Sudden of danger sign. "Restricted by the people's understanding of objective things, some danger signs are always hard to be perceived. After detected, they have become very apparent, so it feels a sudden change." This means changing hazard subjectively gives someone a scene of sudden appearance, but it has existed objectively, except that it is not perceived or found out. This is so-called the sudden features of change.

The method of classification of hazards gives the changing features of changing hazards at length, but it does not account for the relationship between inherent and changing hazards, and falls short of the descriptions of the system hazard structure. It is inconvenient to control the hazards.

(5) Basic and controllable hazard

Zhao Hongzhan et al[2] divided the hazards in the production system into basic and controllable hazard. Basic hazard is also known as inherent hazard (of work system), which means material hazard such as energy (or specific energy source or energy carrier) or dangerous substance. Basic hazard has the same intension as that of Category I hazards. Entity or objective in the actual physical world (especially various kinds of workplace) all may involve basic hazards. For example, a running car (relative motion makes the car carry kinetic energy), a flow production line in operation, a gas filling station (the oil in it is basic hazard), a petrochemical plant (the toxic and harmful chemicals in it are basic hazards), and so on. The peoples need to exercise effective constraints on the basic hazards. And constraints generally come from a controlling mechanism (the functions of the controlling system). At each stage of the system life cycle

(analysis, design, development, operation, etc.), All factors that affect the controlling system to exercise constraints on the controlled objective are all known as controlling hazard. On the whole, controlling hazards are separated from the entity or objective in the real world, and the subsystems of actual work system, which possess specific structure and behavioural features. Controlling hazards contain and surpass the contents of state hazard, Category II hazard and triggering hazard, and are not merely non-material hazard.

4. Research and application of hazard theory

System safety theory holds that, in the system life cycle, system safety engineering and system safety management method should be applied to identify the hazards in the system, and effective controlling measures be adopted to diminish their danger to the minimum, thus making the system reach the optimal safety degree in the stipulated performance, time and cost scope, and effectively preventing and controlling accidents. Hazard theory is an integral part of system safety theory, and main theoretical basis of safety assessment and safety management, so the research on hazard theory is of significance.

(1) Definition of hazard

Literally, hazard is just the origin of danger. This viewpoint is generally recognized. But it can be seen that, through the above-mentioned descriptions of different definitions of hazard, many scholars gave ambiguous definition to hazard, thus making the extension of hazard unclear. According to Mc Farland's theory on accidental energy transfer: "all injury accidents (or damage accidents) are because of: ① getting in contact with excessive energy in a form that exceeding the resistance of tissue (or structure); ② normal energy exchange between the tissue with ambient environment being intervened (e.g., suffocation, drowning)"[9]. This paper believes that, hazard is exactly the origin leading to accidents (including near accidents), while energy or energy carrier and dangerous substance is the origin leading to various accidents. Therefore, energy, energy carrier or dangerous substance possibly leading to accidents is hazard, which conforms to system safety theory. The theory deems that, no accident will occur if there contains no hazard in the system. In fact, no accident will happen if the system contains no energy or dangerous substance leading to accidents. To prevent accidents is to eliminate or control various hazards, then to eliminate or control various kinds of energy or dangerous substance.

According to the above definitions, the extension of hazard is very clear. For example, the people are energy carrier, which may lead to accidents, so the people are hazard. A nail on the ground contains no energy, so it is not hazard. The nail pricking to the foot is caused by the people's energy. However, energy is everywhere. The severity of accidents caused by different kinds of energy is different, and the position and role of various kinds of energy or energy carrier in accidents are varied.

(2) Classification of hazards

1) Classification according to the grade of accident possibly caused by hazards

In practical production, energy or energy carrier is seen everywhere, but all energy or energy carriers do not necessarily lead to accidents, so not all energy or energy carriers are hazards. Under certain conditions, whether the energy in a given form can lead to accidents should depend on: ① the size and concentration degree of the energy; ② time and frequency of action; ③ the location of action. Among them, the size of the energy may be related to the severity of the accident caused by it. So, in safety management, we can manage at different grades the hazards according to the energy size of energy carrier likely causing the accident. For example, China promulgated in 2000 *Identification of Major Hazards* (GB 18218-2000). In 2003, the State Administration of Work Safety (formerly State Administration of Coal Mine Safety) organized relevant agencies drafting *Regulations on Administration of Major Hazard Safety Supervision*, in which the hazards causing above major accidents are named major hazards, and are strictly macro managed and controlled at the national level. However, such grading in enterprises is too rough, and is disadvantageous to reasonable configuration of the limited resources for safety management.

As a result, the hazards in enterprises possibly causing individual casualty can be named general hazards, for example, bricks falling in the air. The hazards likely causing many deaths are named large hazards, for example, pressure container.

2) Classification according to the relationship between hazard and an accident

Production is always accompanied by energy flow. When the energy of hazard transfers and flows according to our wills, no accident will happen. At this time, the energy is in a balance and controlled state. However, because the balance state of the energy of some hazards is poorly stable, when such balance is broken, the energy will begin to release accidentally. When the accidentally released energy acts on the people and equipment, casualty and property loss accident happens. We call the energy or energy carrier leading to the accident and loss as direct hazard. In addition, breaking such balance also needs energy. We call the energy or energy carrier breaking such balance as the first triggering hazard. For example, in a gas explosion accident in coal mines, the coal mine gas reaching the explosion limit is direct hazard, and the ignition source triggering its chemical energy release is the first triggering hazard. The first triggering hazard of coal mine roof accident is mining disturbance. The first triggering hazard of toxic gas leakage accident in a closed container is the energy or energy carrier (men's mistaken operation) leading to leakage, and so on. The energy of first triggering hazard is often in a controlled balance state, while the energy or energy carrier leading to loss of such balance state is the second triggering hazard. If this process is repeated, the ultimate triggering hazard is generally the people, animal or natural energy (e.g., wind, rain, thunder and lightning, earthquake, sunlight). These hazards are called as initial triggering hazards. Being triggering hazards, the people (or animals) are different from other triggering hazards since they have subjective initiative.

(3)The direct hazard control based on accident control model

Occurrence of an accident is the consequence of consecutive triggering and chain reaction of the energy in initial triggering hazard, triggering hazard and direct hazard. Various kinds of hazards possess different position and role in the process of occurrence and development of an accident. Accident prevention is to take pertinent measures as to various kinds of hazards. Direct hazard is pertinent to a kind of accident, and is the main energy or energy carrier leading to a kind of accident loss. For the same kind of accident, its direct hazard is often definite and specific, while there are often many kinds of triggering hazards (e.g., for gas explosion accident in coal mine roadways, its triggering hazard – fire source, is diversified). Therefore, the focus of controlling a kind of accident is to control its direct hazards.

The first triggering hazard is the key to accidential energy release of direct hazard. The first triggering hazard must contain adequate energy level that makes the energy of direct hazard accidentally release. We use the minimum triggering energy, which causes the energy of direct hazard to develop towards an accident, to reflect the stability of direct hazard. The smaller the minimum triggering energy of first triggering hazard, the more stable the direct hazard. Conversely, the more unstable the direct hazard. When the stability of direct hazard reaches to the point where no triggering hazard can accidentally release its energy, the intrinsic safety of the direct hazard is achieved. At the same time, when the stability of the direct hazard cannot reach its intrinsic safety, the triggering hazard must be managed or controlled well, and the first triggering hazard be weakened, eliminated or isolated. Initial triggering hazard is the origin of accident. Combination of a same initial triggering hazard with different triggering hazard and direct hazard will form different accident chain and give rise to different accidents. Therefore, the possible consequence of energy release of various kinds of initial triggering hazard (focusing on the human behaviours) should be investigated so as to take appropriate measures to cut accident chain and prevent accidents.

Control of direct hazard means to make the energy of the direct hazard flow in normal channel. The energy of the first triggering hazard makes that of direct hazard flow towards accidents, while the controlling system makes the energy of direct hazard not towards accidents. The former is negative effect, while the latter is positive effect. Generally speaking, a landmark parameter (e.g., the temperature and pressure of pressure container, or container strength, the speed of speedily running car, gas concentration)

is available which allows the energy of direct hazard to evolve towards accidents. When the parameter reaches a certain value, appropriate controlling measure has to be taken. A typical controlling model consists of automatic controlling system and controlling personnel. Key parameters are measured through testing mechanism (e.g., safety check or/and monitoring system), and then key variables are controlled through the actuation mechanism of the controlling system. When the key parameters are found to exceed the limit, it indicates the stability of direct hazard is poor, the controlling system will send a warning signal and remind relevant staff of the dangerous state of the direct hazard. Refer to Chart 1[10]. The chart illustrates that, two systems exist in the accident control model about the direct hazard: accident triggering system; accident controlling system. The former makes the direct hazard evolve towards accidents, while the latter makes the direct hazard develop towards intrinsic safety. However, because it is unreliable, the controlling system will produce some false operations, thus leading to function failure of the controlling system and even negative effect, making the energy of the direct hazard develop towards accidents. At this time, the controlling system changes into the accident triggering system.

Through the analyses above, the conclusion can be made that in order to prevent the accident occurring, the state of the direct hazard safely running should be kept and enhanced. Further research shows that all direct hazards develop to accidents must have a triggering condition except triggering hazard. For example, there must be an altitude difference in people falling accident, and an entropy difference in chemical explosive. Thus to find and eliminate this difference can also prevent accident occurring.

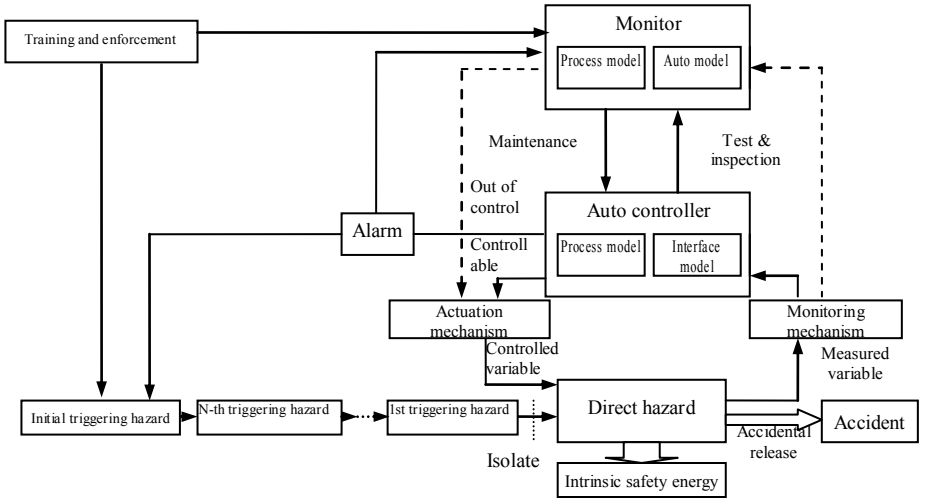

Fig.1 Accident control model based on hazard theory

The role of safety management is to establish a reliable accident control system, and to manage to eliminate or diminish the interference of exterior environment with the normal running of the system (e.g., enclosed management of expressway and railway), or/and eliminate the triggering condition. For example, in the gas explosion accident in coal mines, direct hazard is gas, the first triggering hazard is the fire source initiating gas explosions (e.g., open fire, electric spark, colliding and friction spark), and initial triggering hazards are all men (e.g., violated operation), and the triggering condition is existing oxygen and its concentration reaching a certain level. In order to prevent gas explosion accident in coal mines, at first, a set of reliable gas control system has to be set up, which serves to decrease gas concentration below the explosion limit. In so doing, gas energy will be in a very stable state. No explosion will happen even if fire source is present. However, this set of controlling system cannot be 100% reliable, so it is hard to guarantee gas not exceeding the limit at all times. The excessive gas energy will be in a very unstable state (its triggering energy is 0.28mJ). It has to be isolated with the first triggering hazard – fire

source. Safety management is to establish a set of effective controlling system. For example, set up gas monitoring system, ventilation system, etc., serving to control the gas concentration in mine shaft below the explosion limit (enhancing the stability of direct hazard), and to eliminate all kinds of fire source (isolating). Eliminate or diminish the interference of exterior environment with the normal operation of the system, for example, extract coal seam gas or take outburst prevention measure, restrict irrelevant persons to mine shaft, and so on. Carry out safety education training and enforced management for initial triggering hazards like mine shaft operators, gas monitors, ventilation workers and monitors.

5. Case study

At 13:30 on September 13, 2008, A coach, owned by a transport company in Bazhou City of Sichuan and carrying 51 passengers, was heading from Bazhong City to Ningbo City of Zhejiang. On the midway, due to small turning radius and overspeed, it drove out of the road, dashed against the left wavy rail, and plunged from the cliff and into the valley 100m below, causing 51 deaths.

In this accident, direct hazard is the kinetic energy of the coach, Category I triggering hazard is the kinetic energy of the coach, and initial triggering hazard and monitor are both the coach driver. The controlling system of the accident is: the driver (controller), with his eyes, observed the road condition and ambient environment, by his judgement, decided specific control action (acceleration or deceleration, left turn or right turn), and the wavy handrail on the road left. The accident triggering system was transformed due to the controlling system failure. Main causes contributing to this accident include: ① the controlling system of direct hazard is not reliable. Speed limit mark was available on the road section, but the driver did not decelerated. At the same time, the accident indicated that the strength of the left wavy handrail was too poor; ② Category I hazard was not effectively controlled and managed; ③ control and enforced management of initial triggering hazard failed. Safety education training and enforcement management system was unavailable or invalid, and the warning mark of speed limit was unavailable or invalid.

In order to prevent this accident at first, control system for direct hazard should be established. For example, strengthen the strength of the wavy handrail at the turn, set up buffer zone (planting trees on the hillside), thus, the direct hazard of the bus would be more stable; second, effectively control the first triggering hazard. For example, on the roadside of the speed limit section, install electronic control system to send speed limit signals, mount on-board speed limit device on the coach, allowing the coach to automatically slow down; finally, conduct effective education training and enforcement management for the driver, by the monitoring system, impose stern punishment if he was found speeding.

6. Conclusions

Starting from accident-causing theory and hazard theory and summarizing the author's analysis, the following conclusions are reached:

(1) An accident is often the consequence of the synthetic action of a variety of hazards. The hazard directly responsible for property loss and casualties is direct hazard. Generally speaking, the accidental release of direct hazard's energy also needs consecutive triggering of one or more hazards. These are known as 1^{st}, 2^{nd}, ……N^{th} triggering hazard, which form accident chain and accident triggering system. The earliest triggering hazard is called initial triggering hazard, generally being men, animals or natural energy (e.g., wind, rain, thunder and lightning, earthquake, sunlight).

(2) The minimum triggering energy of the first triggering hazard reflect the stability of the direct hazard. To find and eliminate the triggering condition can also enhance the stability of the direct hazard.

(3) The direct hazard can develop in two directions: one, develop into accident under the action of all categories of triggering hazard; the other, under the controlling role of direct hazard, make the energy of

direct hazard maintain or flow according to the people's will, continuously go stable, and finally transform into intrinsic safety energy. Generally speaking, the controlling system of direct hazard plays the role of positive effect on direct hazard (negative effect, sometimes, thus the controlling system is transformed into triggering system), while the accident triggering system of direct hazard plays the role of negative effect.

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