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Analysis of Energy Laboratory Safety Management in China Based on the System-Theoretic Accident Model and Processes/System Theoretic Process Analysis STAMP/STPA Model

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Abstract: Laboratory safety in colleges and universities has received wider attention as a critical annual inspection by the Ministry of Education. The laboratory environment is complex and diverse, with many hazard factors. To effectively prevent the occurrence of laboratory emergencies in universities, the STAMP/STPA model is used to analyze the safety of energy laboratory safety management in a resource-based university. Between 2021 and 2022, we carried out laboratory safety inspection and field observation for a mining resource university in China, and identified 16 unsafe control actions in the field of energy laboratory safety management in the university, and identified ten critical causal factors leading to unsafe control actions. Combining the actual situation of the mining resource university, the short-term countermeasures and long-term countermeasures to improve laboratory safety management are proposed to guarantee the university's laboratory safety management. Moreover, the research results have suggestions for the construction and development of laboratory safety management at similar universities.

Keywords: STAMP/STPA model; laboratory safety management; safety analysis

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Citation: Zhong, S.; Du, J.; Jiang, X. Analysis of Energy Laboratory Safety Management in China Based on the System-Theoretic Accident Model and Processes/System Theoretic Process Analysis STAMP/STPA Model. *Sustainability* **2023**, *15*, 11505. https://doi.org/10.3390/su151511505

Academic Editor: Anna Mazzi

Received: 20 June 2023
Revised: 21 July 2023
Accepted: 21 July 2023
Published: 25 July 2023

1. Introduction

In recent years, with the rapid development of China's science and technology and independent innovation capabilities, the laboratory, as an essential basis for scientific research, talent training, and social services of universities and scientific research institutions, has developed and expanded rapidly with the construction of "Double First-Class". Laboratory safety has always been the focus of the stable and harmonious development of colleges and universities and the vital interests of teachers and students [1]. According to the analysis of 140 laboratory accidents publicly reported by the media from 2001 to 2019, the total number of laboratory safety accidents has decreased since the Ministry of Education launched the annual routine safety inspection of laboratories at the end of 2015 [2]. However, safety accidents still occur occasionally, and in December 2018, an explosion in an environmental engineering laboratory at a university in Beijing killed three students on the spot, causing substantial social repercussions [3]. In 2022, the Ministry of Education once again strengthened laboratory safety inspection in colleges and universities in terms of three aspects: improving the laboratory safety management system, strengthening safety education, and strengthening the special actions for laboratory safety in colleges and universities [4]. In addition, the Ministry of Education is studying the drafting of the "Laboratory Safety Code for Higher Education Institutions", which is a two-pronged approach to laboratory management and project management, providing detailed regulations on the responsibility system, management system, safety access, education and training, conditions and security, and hazardous chemical management in university laboratories [5]. Laboratory safety management is a crucial task for universities, and the Ministry of Education attaches great importance to the safety management of university laboratories. Since 2015, the Ministry of Education has organized special safety inspections for university laboratories for eight consecutive years.

With the increase in laboratory safety concerns, domestic and foreign scholars have studied the construction of laboratory safety management systems and the study of crucial laboratory influencing factors. By organizing and summarizing the literature, studies on laboratory safety by previous scholars are broadly classified into three categories. The following scholars focus on analyzing key influences on laboratory safety. Zhan Zonghong et al. applied the "2–4" model and listed factors such as unclear responsibilities and the powers of management organizations, inadequate safety management systems, and a lack of emergency management as critical factors affecting the safety level of laboratories [6]. Du Lili et al. analyzed the unsafe actions of people and the unsafe states of objects, sorted out the problems in the safety management of university laboratories, and put forward countermeasures [7].

A large number of scholars focused on researching countermeasures and recommendations for laboratory safety management. Song Zhijun et al. analyzed the significance of laboratory safety inspection in colleges and universities and discussed the realistic dilemma of laboratory safety inspection and coping strategies [1]. Peng Guiping studied the typical cases of laboratory emergencies in colleges and universities and proposed scenario-building strategies applicable to laboratory safety in colleges and universities [3]. Ye Yuanxing et al. analyzed 150 laboratory accidents and proposed safety management countermeasures for the effective prevention of laboratory accidents [2]. Yunfeng Yang and Genserik Reniers et al. conducted a bibliometric study and found that the key research topics in the field of university laboratory safety are "laboratory risk assessment and management" and "safety culture". The authors concluded that research related to risk perception, human error, or emergency response is an essential part of safety science [8]. Ralph B. Stuart et al. suggest targeting safety skills in teaching, improving laboratory chemical risk assessment education in undergraduate laboratory science, and finally achieving continuous improvement in laboratory safety practices [9]. Md. Tanjin Amin et al. conducted a bibliometric review of research on chemical process safety and risk engineering. It was found that researchers are mostly active in the development of methodologies for safety and risk analysis, hazard identification, accident modeling, and safety management [10]. Liu Jingchao et al. believe that human subjective factors in laboratory safety accidents cannot be ignored and propose countermeasures for laboratory safety management [11]. Li Bingyang et al. expounded on the laboratory safety management concept and practice of Tsinghua University, providing a reference for laboratory safety management in colleges and universities across the country [12]. Based on the data from the questionnaire survey, Xu Zhanghua et al. analyzed the safety management of university laboratories and proposed strategies such as strengthening safety actions management [13]. Tyler S. Love suggested high-quality safety training, safety equipment, and class size control as priorities in laboratory safety management [14]. Pengfei LV et al. proposed to prevent laboratory accidents by reducing laboratory turnover, investing in infrastructure and establishing information platforms [15]. Gao Xiaoming et al. developed Generic Laboratory Safety Metric (GLSM) to effectively identify risk factors and enhance laboratory safety conditions [16].

Another group of scholars, on the other hand, focused on the study of the management system and the exploration of the regulatory model of laboratory safety management. Yang Fuqiang et al. proposed that universities should build a scientific and efficient safety management system according to the characteristics of laboratories [17]. Huang Xiaoyong et al. proposed a model that combines external and internal supervision by the government and schools to improve the safety management capacity of university laboratories [18]. Zhou Yingxin et al. analyzed that the lack of safety management supervision and responsibility system is the overall root cause of the accident [19]. Lu Zisheng put forward the direction of laboratory management reform from the perspective of the safety education system and safety responsibility system [20]. Sun Ye et al. proposed to introduce a third-party safety inspection model into university laboratory safety management [21]. Li Xiangmei et al. proposed to build a laboratory safety education and assessment system to improve the laboratory safety management system [22].

In summary, many scholars have studied the influencing factors, improvement countermeasures, management systems, and regulatory models of laboratory safety and achieved fruitful research results. The previous research results are more generalized and less relevant to different types of university laboratory safety management, and there are fewer studies applying the "Systems Theoretic Accident Model and Process" model to the analysis of university laboratories, especially in mining resource universities. In addition, the university laboratory is a complex system containing many risk factors, and the literature mentioned above lacks a system-based perspective to trace the deep-rooted causes of accidents layer by layer and level by level, and is not specific enough to study the overall range of experimental accidents. Therefore, this paper applies STPA analysis theory to laboratory management, analyzes and identifies its unsafe control actions and causal factors, and proposes coping strategies accordingly to provide references for energy laboratory safety management in mining resource universities.

In this paper, we try to analyze laboratory safety problems in mining resource universities using the STAMP/STPA system causal analysis model. STAMP is based on systems theory and control theory and solves the safety analysis of complex systems as a control problem, considering accidents as due to unsafe situations created by the concurrent operation and interaction of complex dynamic processes. The object of this paper is a mining resource university, which is located in a famous university city in China with a high population density, and laboratory safety is even more indispensable to avoid a loss of people and property. The field of laboratory safety at this university currently suffers from occasional safety accidents, the inadequate implementation of safety inspections, insufficient education on laboratory safety, and aging equipment and wiring. As a hazard analysis technique based on system theory, STPA has a wide range of applications and has been applied by a large number of experts and scholars to analyze the hazardous accidents of complex systems in recent years, and has achieved fruitful research results. Several scholars have compared the STPA analysis technique with other risk analysis methods, and [23] compared four systems thinking about risk analysis methods and found that STPA is best suited for identifying hazardous manual task (HMT) systems. The study in [24] applied FTA and STPA analysis methods to a safety critical BBW system, and a comparison of the two reveals that STPA identifies more causal factors. The study in [25] compared three risk analysis methods to identify threats and vulnerabilities in a CyberShip system, and STPA is good at identifying hazards by looking at the control actions and the structure of the CyberShip system. Therefore, STPA techniques, upon which systems thinking is based, are uniquely suited in the field of hazard analysis of complex systems to accurately and more broadly identify causal factors.

And, by summarizing the literature, it can be found that the STAMP model theory and STPA analysis techniques are applied to the hazard analysis of some complex systems such as the analysis of subway construction [26], the forward modeling of typical accidents in LNG storage tanks [27], the analysis of over-barging operations [28], safety education in science and engineering laboratories [29], laboratory explosions [30], aviation safety accidents [31], crane construction [32], the fatigue analysis of aircrew members [33], the analysis of human factors in aviation [34], fully automated unmanned operation scenarios [35], the analysis of autonomous assembly line system [36], the risk analysis of Lithium-ion battery energy storage system (BESS) [37], the management of multi-controller and autonomous systems [38], and the risk management of coal mine rock burst accident [39]. Overall, the STPA analysis technique based on STAMP theory has a high level of maturity for the application of complex systems such as subway construction, aviation accidents, crane construction, laboratories, assembly and energy storage systems, etc., and can realize the identification of potential risks. For the accident analysis of complex systems, the STPA analysis technique can identify unsafe control actions and the causes of accidents layer by layer and level by level. This can be used as a basis for formulating risk control measures, which can improve the safety of complex systems.

In summary, as a hazard analysis tool based on the STAMP model, STPA was more often applied to accident analysis in projects such as aviation safety, automated manufacturing systems, and engineering construction, as well as laboratory safety management analysis in universities of science and technology; however, relevant studies for energy laboratories in mining resource universities are less common. The STAMP model realizes the interconversion of safety and control problems and considers that safety accidents occur due to missing safety constraints and inadequate safety controls. The STAMP model uses a non-linear mode of thinking to improve the understanding of safety issues and break through the traditional linear mode of thinking, which can well analyze safety issues in complex environments such as university laboratories. The laboratories of mining resource universities are characterized by the intersection of physics, chemistry, biology, and other disciplines, and the experimental materials, conditions, and processes are complex and diversified. This paper identifies the key causal factors of potential risks in laboratory safety management from the system control perspective. It provides a reference for transforming laboratory safety into a preventive and dynamic integrated safety management model in the new era.

2. Principle of STAMP/STPA Model

In 2004, Leveson, a scholar at MIT, proposed the STAMP model, an accident model based on systems theory. In this model, safety constraints and hierarchical safety control mechanisms were introduced in an attempt to model the system process based on the social level and the technical level, and then search and capture the causal factors that may lead to accidents in different stages during the system operation based on different levels. Based on the STAMP model, a safer and more effective system can be constructed, in which a new hazard analysis technique, STPA, is proposed, which can manage and control the social system hazard factors and technical system hazard factors in the same system. In this paper, we observe and think about the problem from the perspective of system thinking, and propose countermeasures based on the perspective of system thinking [40].

The control structure is the basis for the STAMP model to describe the system and to analyze the cause of the accident. The first step in building the control structure is to clarify the concepts of the control hierarchy, control loop, and process model [26]. The STAMP model was widely used in safety research in aerospace, building construction, the energy and chemical industry, transportation, and other fields [29]. Based on STAMP, this paper establishes a safety management control structure for the organizational structure control features of the laboratory security management system. System theoretic process analysis (STPA) is a hazard analysis tool based on the STAMP model; the first step in applying STPA is to define the purpose of the analysis. Defining the purpose of the analysis has three parts: identifying losses, identifying system-level hazards, and identifying system-level constraints. The steps in basic STPA are: defining the purpose of the analysis, establishing the safety control structure, identifying unsafe control actions, and identifying the causes of accidents. The analysis process is shown in Figure 1 [41].

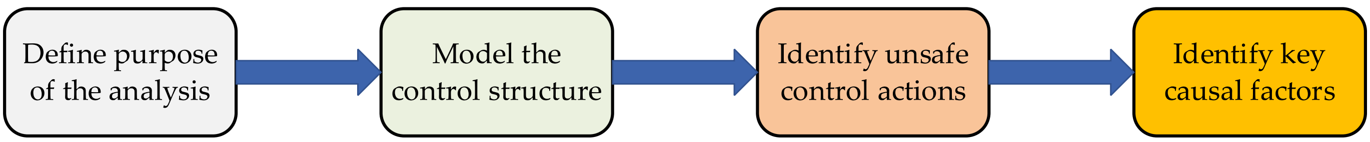

Figure 1. Flow chart of STPA.

The analysis steps of the STPA are: (1) Defining the purpose of the analysis, including identifying system-level hazards and identifying system-level constraints. (2) Modeling the control structure. (3) Identifying unsafe control actions, which are considered unsafe in the STPA safety structure and divided into four categories—not providing the control action leads to a hazard; providing the control action leads to a hazard; providing a potentially safe control action too early, too late, or in the wrong order; and the control action lasts too long or is stopped too soon (for continuous control actions, not discrete ones). (4) Identifying the key causal factors of laboratory accidents.

3. Analysis of Energy Laboratory Safety Management in a Mining Resource University Based on the STAMP/STPA Model

The mining resource university divides its laboratories into chemical, electromechanical, special equipment, and other categories according to the structure of school majors and the experimental projects offered. Chemical laboratories mainly contain chemical, chemical, and chemical reaction laboratories, involving flammable and explosive, toxic, corrosive, and other hazardous chemicals and easily toxic, explosive, and other controlled chemicals, and the "three wastes" generated by the experiments; Electromechanical laboratories contain mechanical, electrical, high-temperature, high-pressure equipment involving high-pressure and high-power equipment, heating and drying equipment, special equipment laboratories containing pressure vessels (including gas cylinders), boilers, etc., The equipment in the university's laboratories is dominated by gas cylinders; the main equipment used in other types of laboratories is electrical equipment.

This paper takes the three national critical laboratories of this mining resource university—geotechnical class, coal resources class, and water damage control class as examples—the experimental projects in the laboratories mentioned above cover the knowledge of many disciplines, such as mechanics, biology, chemistry, and geotechnics. An experimental project often requires a more solid multidisciplinary knowledge base to avoid safety accidents in the experiments. The special characteristics of laboratories belonging to mining resource universities are as follows: multidisciplinary crossover in experimental contents, multi-species integration in experimental materials, multi-dimensional control in experimental conditions, and multi-process convergence in experimental processes. The peculiarities mentioned above cause its daily experiments to be comprehensive, diversified, complex, and dangerous, and if there is a lack of systematic safety management measures, more serious safety accidents are prone to occur. For example, a laboratory had too much trust in the laboratory equipment, for a long time without the control of experimental equipment, which led to continuous heat dissipation of experimental devices, and eventually triggered a fire affecting the surrounding items. The following will summarize the special features and characteristics of the university's laboratory management in three dimensions: organizational structure, operational management, and safety management.

(1) Organizational structure. The laboratory is under the responsibility of the laboratory director and the academic committee review system. The laboratory has a director; three deputy directors, who are responsible to the director and in charge of technical R&D and administrative work; and a full-time assistant director, who assists the director in laboratory management and coordination. The laboratory has an office to handle daily affairs. The office is responsible for the daily unified management of the laboratory, including the implementation of various management and work systems, the construction of conditions, the maintenance of equipment and facilities, scientific research results, internal and external contacts, academic activities, logistical support, environmental health, and other unified management.

(2) Operational management. The laboratory regularly holds academic committee meetings to consider and approve the management rules and regulations of the laboratory. A leadership and coordination group and a laboratory co-construction committee were established. During the preparation and construction stages of the laboratory, the Laboratory Coordination Leading Group discussed and decided on the support work of the supporting units for the construction of the laboratory, including discipline relationships, staffing, welfare treatment, logistical support, and coordinated the allocation of special funds for the laboratory, funds for the construction of the superior discipline platform, and funds for the construction of 211. At the same time, the laboratory invites large-energy

enterprises as members of the co-founding committee and adheres to the policy of scientific research and technological innovation. They are ensuring that it stands at the forefront of international science and technology in the field of coal resources and safe mining and that technological innovation is action-oriented to the needs of national economic construction and the main battlefield of the coal industry.

(3) Safety management. The laboratory has developed a complete system manual to deal with various situations and to improve the safety management of the laboratory, including: "Laboratory Safety Management Regulations", "Laboratory Electricity Safety System", "Laboratory Fire Fighting Organization and Management System", "System of Fire Evacuation Facilities in Laboratories", "Management System of Fire Fighting Facilities and Equipment", "Laboratory Fire Safety Emergency Plan", "Laboratory Fire Safety Education and Training System", "Laboratory Fire Hazard Rectification System", "Laboratory Fire Inspection System", "Laboratory Important Hazardous Source Risk Grading and Control Program", "Laboratory Flammable and Explosive Hazardous Materials Management System", "Management System for the Use of Laboratory Instruments and Equipment", "Procurement of Hazardous Chemicals in Laboratories", "Management System for the Use and Preservation and Disposal of Hazardous Wastes", "Laboratory Accident and Hazard Investigation System", "Laboratory Safety Post Responsibility System", and "Laboratory Security and Confidentiality System". In response to the impact of the coronavirus disease 2019, a series of countermeasures have been developed to effectively guarantee the level of laboratory safety management: "Laboratory Disinfection Guidelines for Prevention and Control of the COVID-19", "Epidemic Prevention and Control Plan", and "Laboratory Hygiene Cleaning and Epidemic Prevention and Disinfection Record Sheet".

The safety management of the university laboratory is mainly responsible for the leading group of laboratory safety work, laboratory safety work group, the leading group of laboratory safety work in each college, and the laboratory administrator, and the organizational structure of laboratory safety management is shown in Figure 2.

3.1. Defining System-Level Hazards and Safety Constraints

Defining system hazards first requires the identification of system-level incidents. The laboratory performs university teaching and experimental research projects and is a necessary place for students and staff to conduct experiments. Through the analysis of school teaching, experimental research projects, the analysis of experimental project risks, and possible accidents, mainly including fire, explosion, poison, corrosion, electric shock, mechanical type damage, equipment damage or failure resulting in the inability to experiment, etc. Moreover, according to the degree of accident damage with five levels of accidents are into divided four aspects, namely personnel injury, economic losses, environmental impact, and instrument damage, as shown in Table 1 [42]. According to the system-level accidents to analyze the conditions that trigger the above accidents, this paper proposes system-level hazards as shown in Table 2, with the statistics of 150 laboratory safety accidents during the period 1986–2019, and the professional characteristics and types of experimental projects of the university. The conditions and requirements to ensure the safety of laboratory safety management and avoid the occurrence of system-level hazards are defined as safety constraints.

As shown in Table 2, the system-level hazards correspond to an "H-number", which may lead to one or more system-level accidents, and each system-level hazard can be traced back to the system-level accident it may have caused, and each system-level accident can be traced back to the losses it may have caused in Table 1.

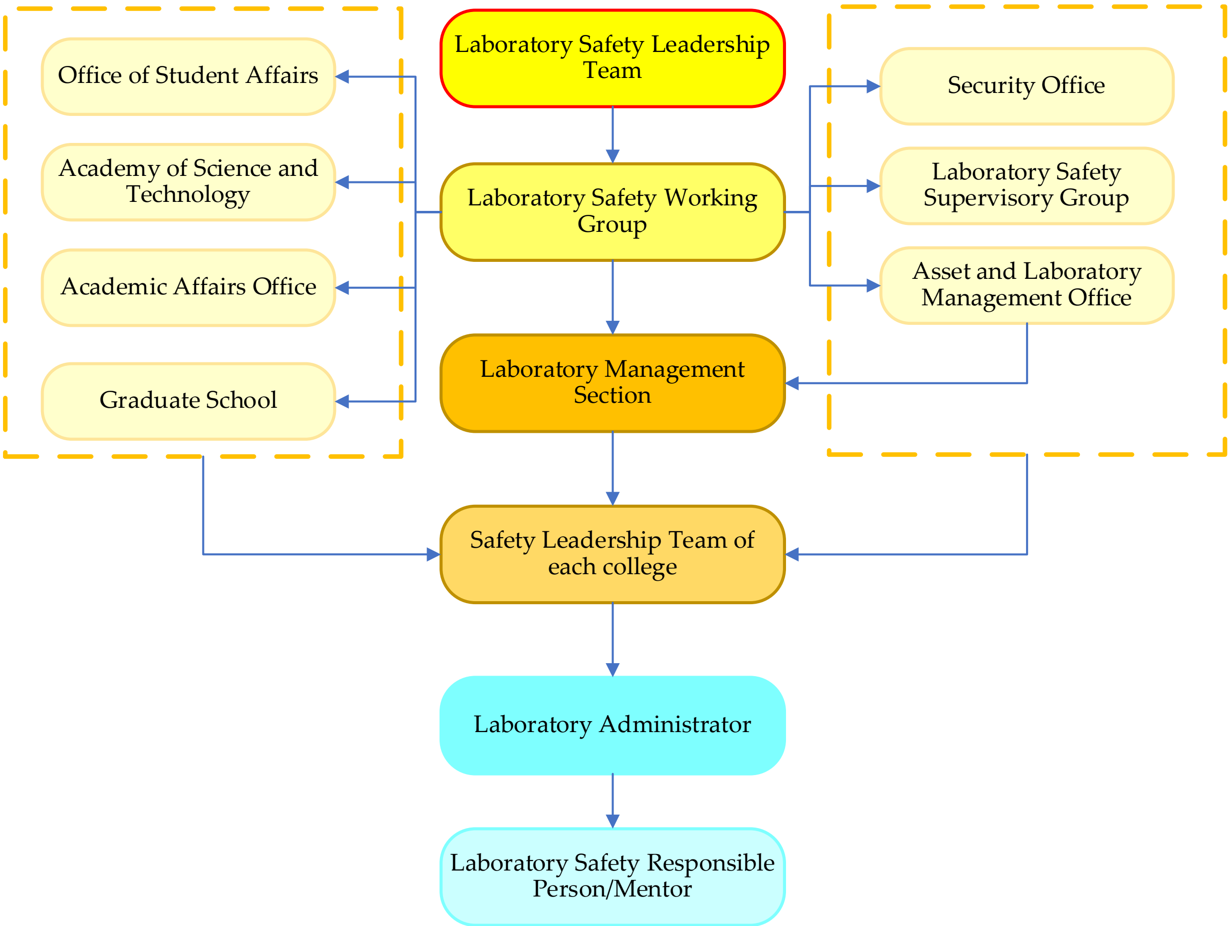

Figure 2. Organizational chart of the laboratory safety management of the mining resource university.

Table 1. Laboratory safety management system-level accidents.

Number	Personal Injury	Economic Losses	Environmental Impact	Instrument Damage
B-1	1–2 deaths or >3 poisonings/serious injuries at a time	Direct economic losses > CNY 1 million	The surrounding environment is seriously polluted, and there are mass incidents	Major instrumentation destruction, infrastructure damage
B-2	Seriously injured <3 people, no deaths	Direct economic losses between CNY 500,000 and CNY 1 million	Environmental pollution in the surrounding area	Major instrumentation destruction, infrastructure damage
B-3	There were minor injuries	Direct economic losses between CNY 50,000 yuan and CNY 500,000	Environmental pollution in the laboratory	Larger instruments and equipment were damaged
B-4	No casualties	Direct economic losses < CNY 50,000	Minor environmental pollution in the laboratory	General instrumentation damaged
B-5	No casualties	No direct economic losses	No environmental pollution	Equipment malfunction

Table 2. System-level hazards for laboratory safety.

Number	System-Level Hazards	Accidents
H-1	Violation of the operation	(B-1, B-2, B-3, B-4, B-5)
H-2	Illegal storage/handling of hazardous chemicals	(B-1, B-2, B-3, B-4)
H-3	Violation of the treatment of three wastes	(B-1, B-2, B-3, B-4)
H-4	Equipment aging, failure, defects	(B-2, B-3, B-4, B-5)
H-5	Aging or short-circuiting of the wire	(B-3, B-4, B-5)
H-6	Reaction out of control	(B-1, B-2, B-3, B-4, B-5)

3.2. Building a STAMP Model for Laboratory Safety Management System

The university's Laboratory Safety Leading Group is responsible for the guidance, supervision, and management of laboratory safety management. The Laboratory Safety Working Group is responsible for the formulation of laboratory safety management regulations, the construction of a laboratory safety management system, laboratory safety management inspection, supervision, and other day-to-day work. The office was set up in the Office of Asset and Laboratory Management, and the university's Laboratory Safety Supervision Group was established. Collaborative management by the Office of Academic Affairs, the Graduate School, the Institute of Science and Technology, and the Office of Student Work. The leading group of laboratory safety work in each college mainly formulates some safety management regulations for the characteristics of college laboratories and implements the daily safety management of college laboratories. According to the job responsibilities of each department of the school management organization structure, as well as the communication and feedback relationship between each level and the safety constraints, the STAMP model of laboratory safety management is constructed as shown in Figure 3. The safety constraints corresponding to the subjects of laboratory safety management in Figure 3 are shown in Table 3 below.

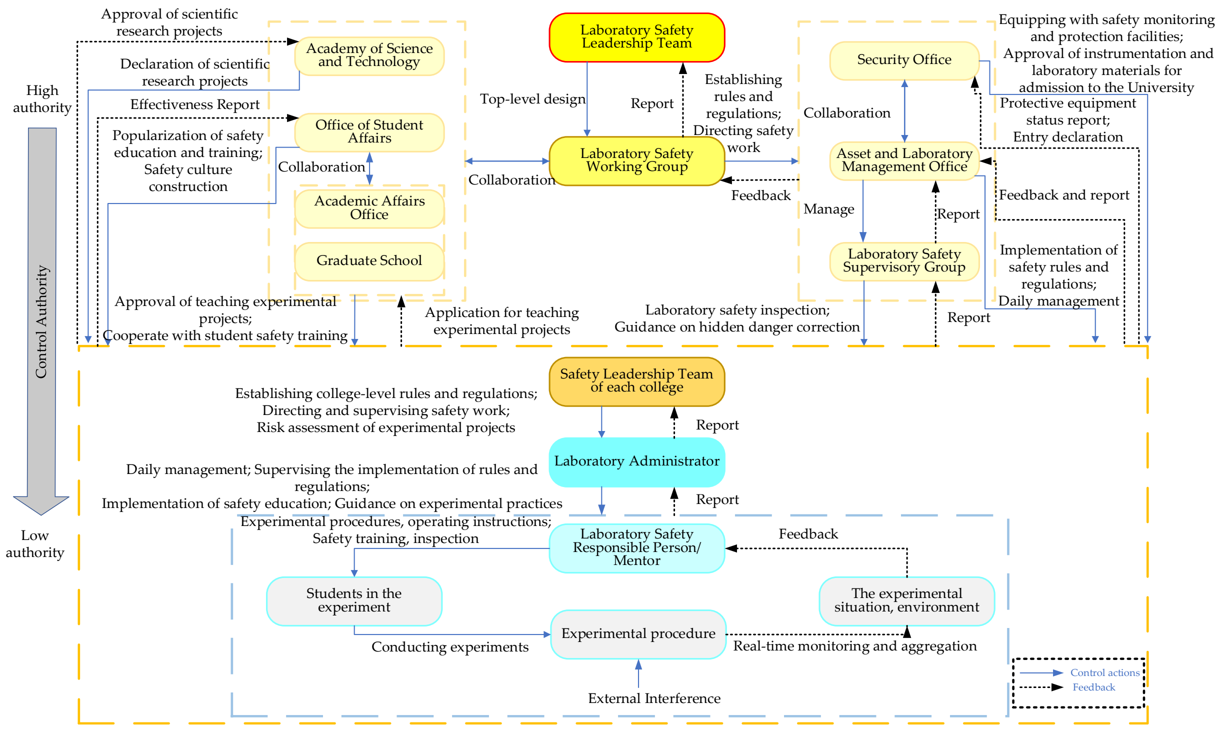

Figure 3. STAMP model for laboratory safety management.

Table 3. Laboratory system-level safety constraints.

ID	The Subject of Laboratory Safety Management	Corresponding System-Level Safety Constraints
1	Laboratory Safety Leadership Team	Zero tolerance for laboratory safety accidents Safety is a top priority
2	Laboratory Safety Working Group	Establish a laboratory safety management system with a clear hierarchy and responsibilities
3	Office of Student Affairs	Laboratory safety training extended to all students The effect of safety culture construction is remarkable
4	Academy of Science and Technology	Strict approval of scientific research projects and adequate identification of dangerous experiments
5	Academic Affairs Office	Laboratory safety training extended to all students Strict approval of scientific research projects and adequate identification of dangerous experiments
6	Graduate School	A rigorous review of teaching experiment projects Timely coordination of safety training
7	Security Office	Strict entry and exit system Standardized access process with strict approval execution
8	Laboratory Safety Supervision Team	The supervisory team is professional in safety inspection and adequate in hidden danger investigation Timely guidance and complete records
9	Asset and Laboratory Management Office	Implementation of safety management regulations, continuous and adequate supervision Professional and continuous laboratory safety education Laboratory classification and management are clear, and the daily management ledger is clear
10	Safety Leadership Team of each college	Faculty laboratory regulations are targeted Guidance and supervision need to be adequate and continuous Risk assessment of experimental projects is professional and accurate Establishment of laboratory classification and management ledger
11	Laboratory Administrator	Laboratory use ledger and material ledger are clear and accurate Timely reporting of safety inspections and hidden dangers Timely reporting of hidden danger rectification status reports Complete implementation of laboratory safety management regulations Supervise the effective and continuous implementation of safety education Laboratory routine safety checks and hidden danger checks are adequate Timely and continuous follow-up of hidden danger correction guidance Professional and conscientious instruction of experimental operation specifications
12	Laboratory Safety Responsible Person/Mentor	Careful instruction of experiments Professional and effective safety education Adequate safety check before the experiment
13	Students in the experiment	Laboratory safety exam passed Well prepared for experiments Proficiency and standardization of procedures in experiments
14	The experimental situation, environment	Accurate and timely feedback on experiments
15	Experimental procedure	The monitoring system is sound and implemented Monitoring equipment is intact and can be monitored in real time

3.3. Identifying Unsafe Control Actions

We investigated the experimental procedures and safety management systems of the school's laboratories on site, for example, the coal resources laboratory and the filling laboratory. In addition, in order to strengthen laboratory safety management and ensure orderly laboratory operation, as a member of the school's Laboratory Safety Supervisory Group, we carried out laboratory safety inspections. We analyzed the operational procedures of the experimenters, including ourselves, when carrying out daily laboratory operations in the laboratory. In conjunction with the laboratory rules and regulations, as well as the process specifications and management norms of the laboratory instructions, we identified the presence of unsafe control actions. We also studied the laboratory safety management rules and regulations issued by the university, such as the "2020 Edition of Laboratory Safety Management System in One Book" and the "China University of Mining and Technology (Beijing) Laboratory Safety Management Measures", and tentatively summarized the unsafe control actions. And, through the Internet, the relevant reports of laboratory accidents were collected and analyzed for their causes, such as: laboratory accidents that occurred in our school and laboratory accidents that occurred in neighboring universities, including fires and explosions.

Analyzing the control and feedback actions of each loop in the laboratory safety management system model in relation to the safety constraints, analyzing the control actions at each control level from top to bottom, and identifying the unsafe control actions in the system. Based on the STPA analysis process, we analyze system-level hazards in university laboratory management systems due to control and feedback errors or inadequacies, starting from four categories of unsafe control actions. Moreover, a total of 16 unsafe control actions at various levels of laboratory management in this university were identified, as shown in Table 4. And, each unsafe control action can be traced back to one or more system-level hazards, as shown in Table 5.

Table 4. Unsafe control actions in the laboratory management system.

Level/Type	Not Providing Causes Hazard	Providing Causes Hazard	Too Early, Too Late, Out of Order	Stopped Too Soon, Applied Too Long
Laboratory Safety Working Group		UCA-1 The established laboratory safety management system is not clear		
Asset and Laboratory Management Office	UCA-2 Did not provide lab safety training for all students and faculty	UCA-3 Unclear grading and classification of laboratory safety management		
Laboratory Safety Supervision Team		UCA-4 Incomplete safety inspection and inadequate guidance for hidden danger rectification	UCA-5 Safety checks are not timely	
Security Office		UCA-6 Inadequate approval rules for entering and exiting the school		
Graduate School, Academic Affairs Office				UCA-7 No ongoing assistance with laboratory safety training
Office of Student Affairs	UCA-8 Laboratory safety training not provided for all students	UCA-9 Inadequate construction of safety culture		
Academy of Science and Technology		UCA-10 Inadequate risk assessment of scientific research experimental projects		

Table 4. *Cont.*

Level/Type	Not Providing Causes Hazard	Providing Causes Hazard	Too Early, Too Late, Out of Order	Stopped Too Soon, Applied Too Long
Safety Leadership Team of each college		UCA-11 Faculty-level laboratory safety management regulations are not well targeted; laboratory grading and classification ledgers are not standardized		
Laboratory Administrator		UCA-12 Inadequate laboratory safety checks; inadequate daily safety management		UCA-13 Laboratory safety education is not continuously carried out; the guidance for the rectification of hidden dangers is not continuously followed
Laboratory Safety Manager/Mentor		UCA-14 Inadequate safety inspection before the experiment; safety training before the experiment is not detailed		UCA-15 No continuous guidance of the experimental process
Students in the experiment		UCA-16 Inadequate preparation of experiments; experimental procedures and operations are not standardized; reporting of experiments is not standardized		

Table 5. Key causal factors of unsafe control actions.

Unsafe Control Actions (UCAs)	Key Causal Factors (CFs)	Corresponding System-Level Hazards
UCA-1	CF-1 Crossed responsibilities of various functional departments, unclear boundaries of responsibilities, different safety management objectives	(H-1, H-2, H-3, H-4, H-5)
UCA-2	CF-2 Lack of professional laboratory safety managers	(H-1, H-2, H-3, H-4, H-5, H-6)
UCA-3	CF-2 Lack of professional laboratory safety managers	(H-1, H-2, H-3, H-4, H-5, H-6)
UCA-4	CF-3 Lack of professional security inspectors and systematic inspection methods	(H-1, H-2, H-3, H-4, H-5, H-6)
UCA-5	CF-2 Lack of professional laboratory safety managers	(H-1, H-2, H-3, H-4, H-5, H-6)
UCA-6	CF-2 Lack of professional laboratory safety managers	(H-1, H-2, H-3, H-4, H-5, H-6)
UCA-7	CF-1 Crossed responsibilities of various functional departments, unclear boundaries of responsibilities, different safety management objectives	(H-1, H-2, H-3, H-4, H-5, H-6)
UCA-8	CF-1 Crossed responsibilities of various functional departments, unclear boundaries of responsibilities, different safety management objectives	(H-1, H-2, H-3, H-4, H-5, H-6)
UCA-9	CF-4 Lack of safety awareness, failure to carry out targeted laboratory safety activities	(H-1, H-2, H-3, H-4, H-5, H-6)
UCA-10	CF-5 Lack of professional experimental project risk assessors	(H-1, H-2, H-3, H-4, H-5, H-6)

Table 5. *Cont.*

Unsafe Control Actions (UCAs)	Key Causal Factors (CFs)	Corresponding System-Level Hazards
UCA-11	CF-6 Lack of professional safety personnel within the leadership team of laboratory safety at the faculty level	(H-1, H-2, H-3, H-4, H-5, H-6)
UCA-12	CF-7 Lack of faculty-level laboratory safety office and insufficient professionalism of laboratory administrators	(H-1, H-2, H-3, H-4, H-5, H-6)
UCA-13	CF-8 Inadequate supervision, the lab manager is a part-time safety manager working part-time on other duties	(H-1, H-2, H-3, H-4, H-5, H-6)
UCA-14	CF-9 Low sense of security responsibility and low security awareness	(H-1, H-2, H-3, H-4, H-5, H-6)
UCA-15	CF-9 Low sense of security responsibility and low security awareness	(H-1, H-2, H-3, H-4, H-5, H-6)
UCA-16	CF-10 Low sense of student safety responsibility, lack of safety awareness, lack of safety education, and weak safety knowledge	(H-1, H-2, H-3, H-4, H-5, H-6)

Based on the system-level safety constraints corresponding to each level in Table 3, the unsafe control actions identified in Table 4 and the hazards traced to them correspond to the safety constraints, as shown in Table 6.

Table 6. UCAs and the corresponding safety constraints in laboratory management systems.

Level/Type	Unsafe Control Actions	Safety Constraints (SCs)
Laboratory Safety Working Group	UCA-1-(H-1, H-2, H-3, H-4, H-5)	SC-1 Establish a laboratory safety management system with a clear hierarchy and responsibilities
Asset and Laboratory Management Office	UCA-2-(H-1, H-2, H-3, H-4, H-5, H-6) UCA-3-(H-1, H-2, H-3, H-4, H-5, H-6)	SC-2 Implementation of safety management regulations, continuous and adequate supervision SC-3 Professional and continuous laboratory safety education SC-4 Laboratory classification and management are clear, and the daily management ledger is clear
Laboratory Safety Supervision Team	UCA-4-(H-1, H-2, H-3, H-4, H-5, H-6) UCA-5-(H-1, H-2, H-3, H-4, H-5, H-6)	SC-5 The supervisory team is professional in safety inspection and adequate in hidden danger investigation SC-6 Timely guidance and complete records
Security Office	UCA-6-(H-1, H-2, H-3, H-4, H-5, H-6)	SC-7 Strict entry and exit system SC-8 Standardized access process with strict approval execution
Graduate School, Academic Affairs Office	UCA-7-(H-1, H-2, H-3, H-4, H-5, H-6)	SC-9 Laboratory safety training extended to all students SC-10 Strict approval of scientific research projects and adequate identification of dangerous experiments SC-11 A rigorous review of teaching experiment projects Timely coordination of safety training
Office of Student Affairs	UCA-8-(H-1, H-2, H-3, H-4, H-5, H-6) UCA-9-(H-1, H-2, H-3, H-4, H-5, H-6)	SC-12 Laboratory safety training extended to all students SC-13 The effect of safety culture construction is remarkable
Academy of Science and Technology	UCA-10-(H-1, H-2, H-3, H-4, H-5, H-6)	SC-14 Strict approval of scientific research projects and adequate identification of dangerous experiments
Safety Leadership Team of each college	UCA-11-(H-1, H-2, H-3, H-4, H-5, H-6)	SC-15 Faculty laboratory regulations are targeted SC-16 Guidance and supervision need to be adequate and continuous SC-17 Risk assessment of experimental projects is professional and accurate SC-18 Establishment of laboratory classification and management ledger

Table 6. *Cont.*

Level/Type	Unsafe Control Actions	Safety Constraints (SCs)
Laboratory Administrator	UCA-12-(H-1, H-2, H-3, H-4, H-5, H-6) UCA-13-(H-1, H-2, H-3, H-4, H-5, H-6)	SC-19 Laboratory use ledger and material ledger are clear and accurate SC-20 Timely reporting of safety inspections and hidden dangers SC-21 Timely reporting of hidden danger rectification status reports SC-22 Complete implementation of laboratory safety management regulations SC-23 Supervise the implementation of safety education in an effective and continuous manner SC-24 Laboratory routine safety checks and hidden danger checks are adequate SC-25 Timely and continuous follow-up of hidden danger correction guidance SC-26 Professional and conscientious instruction of experimental operation specifications
Laboratory Safety Manager/Mentor	UCA-14-(H-1, H-2, H-3, H-4, H-5, H-6) UCA-15-(H-1, H-2, H-3, H-4, H-5, H-6)	SC-27 Careful instruction of experiments SC-28 Professional and effective safety education SC-29 Adequate safety check before the experiment
Students in the experiment	UCA-16-(H-1, H-2, H-3, H-4, H-5, H-6)	SC-30 Laboratory safety exam passed SC-31 Well prepared for experiments SC-32 Proficiency and standardization of procedures in experiments

3.4. Key Causal Factors Analysis

The organizational structure of laboratory safety management, laboratory safety management rules and regulations, the staffing of laboratory safety management personnel in each department and faculty, and the professional quality of personnel in this university are combined. Then, we analyzed the unsafe control actions in the university's laboratories, combining the unsafe laboratory operations and management regulations we captured, and analyzed the unsafe control actions and causal factors from top to bottom in the STAMP model diagram we constructed. And, ten critical causal factors in the laboratory management system of the university were identified that lead to unsafe control actions, as shown in Table 5. The includes the crossing of work responsibilities among functional departments, unclear boundaries in responsibilities and different requirements for safety management objectives; a lack of professional laboratory safety managers; a lack of professional security inspectors and systematic inspection methods; poor safety awareness and a lack of targeted laboratory safety activities; a lack of professional experimental project risk assessors; a lack of professional safety personnel within the leadership team for laboratory safety at the faculty level; a lack of faculty-level laboratory safety office and the insufficient professionalism of laboratory administrators; inadequate supervision, with the laboratory manager being a part-time safety manager working part-time on other duties; a low sense of security responsibility and a lack of security awareness; a low sense of responsibility for safety, lack of safety awareness, lack of safety education, and weak safety knowledge among students.

4. Preventive Measures for Potential Hazards of Laboratory Safety Management System

For the energy laboratory safety management system of the mining resource university mentioned above, through the definition of system-level hazards, safety constraints, and the analysis of safety structure, 16 unsafe control actions of laboratory safety management in this university that may trigger system-level hazards and thus cause accidents were identified, and ten main causal factors were identified. Taking into account the university's financial resources, space, faculty, etc., and with reference to the current status and management level of domestic and foreign laboratory research, we propose countermeasures to improve laboratory safety management and improve potential hazards from both short-term and long-term planning.

4.1. Short-Term Measures to Improve Laboratory Safety Management

(1) Establish a system of responsibility for laboratory safety management with apparent authority and responsibilities. Construct a responsibility system of "horizontal to the edge, vertical to the end, full participation, and clear responsibilities", and learn from the Beijing Institute of Technology to establish a laboratory safety responsibility table [43]. Clearly delineate the responsibilities of the 20 functional departments for laboratory safety management and establish a transparent system of responsibility. The scholar Leveson's perception: "Blame is the enemy of safety. Focus should be on understanding how the system behavior as a whole contributed to the loss and not on who or what to blame for it [40]." To sign a responsibility letter as the basic means must be combined with assessment and evaluation, measures of reward and punishment, and other multi-linkage to ensure that each department has its own role in the implementation of laboratory safety management responsibilities.

(2) Establish a professional technical team for laboratory safety management. The high-quality faculty strength of "Safety Science and Engineering", a double-class construction discipline, is relied upon. The university invites senior professors with profound professional backgrounds and rich practical experience as well as retired professors with ample time, and sets up a safety technical expert group to guide and supervise the laboratory safety management of the university. Furthermore, at the same time, the training of the laboratory managers must be strengthened to enhance the professional level of laboratory safety managers.

(3) Strengthen safety education and training, and incorporate the construction of safety culture into the annual work plans. Laboratory safety education must be included in the syllabus of the compulsory safety education courses for college students as part of the compulsory credits. A combination of online and offline laboratory safety education must be carried out through micro-video, accident cases, thematic websites, and other ways to enhance the fun and vivid intuitive training, and the form of laboratory safety education must be enriched. The publicity and radiation effect of "Safety Culture Month" must be increased to attract the participation of teachers and students of the whole school. Through safety education enhances the sense of safety responsibility of the whole school, the safety awareness of teachers and students must be enhanced and the safety knowledge of students must be strengthened. The safety education and training for teachers and students specializing in high-risk subjects must be significantly strengthened, and a safety education and training ledger must be established to record the participation of personnel and the effectiveness of training [44].

(4) Introduce a professional security assessment agency. Laboratory safety testing and the identification of potential hazards for an essential basis for ensuring laboratory safety. The adequacy of the hidden danger investigation and the comprehensive and timely rectification guidance directly affect laboratory safety work in universities. Third-party assessment organizations have rich practical experience and systematic methods for safety inspection and hidden dangers, which can identify laboratory safety hazards and provide corrective measures on time, which is effective for improving laboratory safety [7]. The East China University of Science and Technology and Shanghai Jiao Tong University have introduced third-party safety assessment companies to conduct laboratory safety inspections. Moreover, the company has developed laboratory safety measures to provide strong support for laboratory safety in schools [45].

4.2. Long-Term Countermeasures to Improve Laboratory Safety Management

(1) Based on the top-level design. Referring to Leveson's perception of system safety: "Operator behavior is a product of environment in which it occurs. To reduce operator "error" we must change the environment in which the operator works [40]". Based upon the system, education, organization, culture, management, facilities, and equipment, a safety management culture system, safety system management system, safety management organization system, safety management security system, safety management education system, and a five-in-one comprehensive laboratory safety management system are built [46]. From the construction of Environment, Health and Safety (EHS) cultural atmosphere, the safety and environmental health awareness of teachers and students can be enhanced, the laboratory EHS system construction can be improved, and a multi-part joint work mechanism can be built. And finally, a laboratory EHS management system must be built in line with the actual situation of universities [47].

(2) Promote the intelligence of laboratory safety management. To quote Prof. Leveson's perception, "High reliable software is not necessarily safe. Increasing software reliability or reducing implementation errors will have little impact on safety [40]". An integrated laboratory safety management system in which schools invest more money while upgrading all aspects of school laboratory security facilities and equipment can be designed to supervise people, machines, materials, methods, and rings through technical means, displaying the current safety status of the laboratory through visualization. The skills and knowledge reserves of experimental personnel, the status of experimental instruments and equipment, the quality and storage of experimental materials, the standardization of the experimental process, the laboratory environment, etc. can all be monitored [48]. The intelligent supervision of the whole process of experiments can be realized, from the application of experimental projects, material entry, laboratory access, pre-experimental preparation, the whole process of experiments, and the disposal of three wastes after the experiments.

(3) Strengthen the construction of a full-time laboratory staff. The quantity and quality of full-time laboratory management technicians are the basis for ensuring laboratory safety. According to the characteristics of each discipline, the authority to recruit full-time laboratory personnel is delegated to the discipline department. Each discipline department, according to the characteristics of the laboratory, sets up full-time laboratory personnel positions for the higher risk level of the laboratory belonging to the discipline to set up an additional college laboratory safety management office to ensure the number of laboratory faculty. At the same time, career development channels are provided for full-time laboratory personnel through guidance and incentives, supervision and assessment, vocational training, etc., stimulating the work enthusiasm of full-time laboratory management technicians. Furthermore, the "Full-time Experimental Personnel Assessment and Incentive Work Methods" are formulated to reduce personnel loss. A "full-time laboratory staff training management approach" can be developed to encourage full-time laboratory staff to actively participate in professional training through continuous training and research to enhance their professional skills while improving laboratory safety management [49].

5. Conclusions

Laboratory safety management in a mining resource university is a complex, diversified, and systematic task which forms the basis of ensuring the orderly development of talents and scientific research. China's resource colleges and universities, while cultivating excellent talents for the country and contributing to the development of the society, have also caused safety hazards in laboratory safety management due to the expansion of the scale of operation and the increasing number of students, and even serious accidents, such as fires and explosions, are caused. Moreover, the safety of college laboratories not only relates to the personal safety of teachers and students and school property safety, but also affects the social security and stability around the university, and may even affect the normal promotion of talent training, research, and teaching. Therefore, enhancing the level of laboratory safety management is the highest priority of the daily work of colleges and universities.

Based on the STAMP/STPA model, we analyzed the safety of laboratory safety management in the mining resource university, took its three types of national critical laboratories as the entry point, and built a STAMP model for laboratory safety management based on the university-wide laboratory safety management. And, using the control structure diagram constructed by the STAMP model, the unsafe control actions were analyzed layer by layer and level by level, and finally, 16 unsafe control actions that existed in the safety management of laboratories in the university were identified, and ten major causal factors were identified. Furthermore, proposing short-term and long-term countermeasures to improve laboratory safety management, considering the funding, space, and faculty of this mining resource university, provides a reference for the construction and development of laboratory safety management in mining resource universities. Finally, with the concept of accident prevention, the potential hazards of laboratory safety management can be improved and prevented before they occur, thus providing a guarantee of safety for the second round of the "double first-class" discipline construction of the university. Subsequently, quantitative analysis can be introduced to establish an accident–cause analysis model to provide laboratory managers with a model basis for tracing accident causes and predicting event outcomes.

This study applies the STPA analysis technique and STAMP theory to systematically analyze the risk factors existing in the energy laboratory safety management of a mining resource university, and logically and clearly sorts out the unsafe control actions and causal factors in the field of laboratory safety according to the vertical structure of the control authority. This expands the application field of the STPA analysis technique, and also introduces new ideas for the analysis of laboratory safety accidents in the energy laboratories of mining resource universities.

Author Contributions: Conceptualization, X.J., J.D. and S.Z.; methodology, X.J., J.D. and S.Z.; validation, X.J. and S.Z.; formal analysis, X.J. and S.Z.; investigation, X.J. and S.Z.; data curation, X.J. and S.Z.; writing—original draft preparation, X.J. and S.Z.; writing—review and editing, X.J., S.Z. and J.D.; supervision, S.Z.; funding acquisition, S.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Key Research and Development Plan (Grant no. 2017YFC1503103) and the curriculum construction and teaching reform project of China University of Mining and Technology (Beijing) (No. J190108).

Data Availability Statement: Not applicable.

Acknowledgments: The authors are thankful to the anonymous reviewers for their kind suggestions.

Conflicts of Interest: The authors declare no conflict of interest.

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