Systematized Construction and Practical Path of University Laboratory Safety Management Based on Trajectory Intersection Theory

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Abstract. University laboratories are the core carriers of teaching, research, and the cultivation of innovative talents. Their fire safety is directly related to the safety of teachers and students and the stability of the campus. This paper takes the Trajectory Intersection Theory as the core analytical framework to systematically deconstruct the intersecting causes of human unsafe behavior and material unsafe states in the accident, combined with the indirect catalytic effects of environmental factors and management defects, to reveal the evolution mechanism of laboratory fire and explosion accidents. Based on this, a "four-in-one" laboratory fire safety management system is constructed, which includes personnel control, AI intelligent IoT, "risk grading+dynamic control" management and smart fire protection technology, providing theoretical reference and practical paths for the standardization of laboratory safety management, precise accident prevention, and long-term governance.

Keywords: Trajectory Intersection Theory, University Laboratory, Safety Management

1 Introduction

With the rapid development of Chinese higher education and scientific research, the number of university laboratories, types of experiments, and frequency of hazardous operations have been continuously increasing. Laboratory safety has become a top priority in campus security governance. On March 20, 2026, a sudden flash explosion occurred in a laboratory at the Materials Science and Engineering College, Chongqing University, causing one graduate student to die and three students to be injured, with laboratory equipment destroyed and structural damage. The official preliminary investigation showed that[1] the accident was caused by improper experimental operation, accompanied by multiple issues such as equipment aging, ventilation failure, alarm system malfunction, and delayed emergency response. Based on the existing reports, it can be inferred that this accident was a typical "human-material-management-environment" multiple-factor compounded safety responsibility accident. This incident has sounded another alarm for national university la-

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boratory safety management, posing the urgent need to accurately identify risks, interrupt accident chains, and establish long-term mechanisms.

Foreign university laboratory safety management started earlier, forming a system centered on risk pre-control, standardized operations, and full-process supervision, such as the U.S. OSHA laboratory safety standards and the EU REACH regulations for research premises, emphasizing closed-loop management of personnel qualifications, equipment calibration, hazardous chemical control, and emergency drills. Domestic scholars have conducted extensive research on laboratory safety, focusing on directions such as hazardous chemical management, electrical safety, emergency systems, and digital supervision. However, most studies focus on single-point optimization. There is a lack of systematic and empirical research based on accident causation theories. There is a need for further strengthening in-depth analysis and theoretical transformation of recent typical accidents. The Trajectory Intersection Theory, as a classic accident causation theory, can clearly reveal the core logic of "human-material" intersecting to trigger accidents, making it suitable for the complex safety analysis needs of laboratory scenarios.

This paper applies the Trajectory Intersection Theory to the university laboratory fire safety scenario, improves the accident causation analysis framework for laboratories, and enriches the research results at the intersection of safety science and engineering, and management science, providing theoretical support for laboratory safety management.

2 Theoretical Basis and Empirical Applicability

2.1 The Core Connotation of the Trajectory Intersection Theory

The Trajectory Intersection Theory posits that an accident occurs when the trajectory of human unsafe behavior and the trajectory of material unsafe states intersect in the same time and space[2]. In production and experimental activities, the behavioral trajectory of people and the state trajectory of materials are independent. When they intersect due to management defects and environmental inducements, accidental energy is released, ultimately leading to an accident. Among them: The trajectory of human unsafe behavior includes weak safety awareness, violation of operating procedures, insufficient skills, and errors in emergency response. The trajectory of material unsafe states includes aging and faulty equipment, failure of safety devices, lack of control over hazards, and inadequate fire safety facilities. The indirect causes include missing management systems, ineffective implementation of regulations, inadequate safety training and education, and unreasonable environmental layout, which are key factors that accelerate the intersection of the two trajectories. The theoretical model is shown in Figure 1.

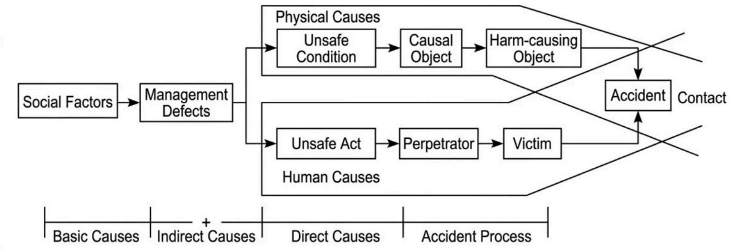

Fig. 1. Schematic diagram of the trajectory crossover theoretical model

University laboratory accidents are characterized by suddenness, coupling, and destructiveness[3]. Most fire and explosion accidents simultaneously involve human violations and equipment/facility hazards. The Trajectory Intersection Theory can accurately locate the direct causes and indirect roots of accidents, helping managers to take targeted actions from the four dimensions of "people, material, management and environment" to interrupt the intersection, eliminate hazards and prevent accidents, providing a clear analytical logic and control thought for laboratory safety management.

2.2 The Empirical Adaptability of Theory in Laboratory Settings

Based on a statistical analysis of 137 laboratory fire and explosion accidents in colleges and universities nationwide from 2020 to 2024 by the Ministry of Emergency Management (Table 1), 89.78% of the accidents involved dual human-object trajectory intersections[4]. Accidents caused solely by a single human factor or a single material hazard accounted for 5.84% and 4.38%, respectively, and accidents triggered by a single factor did not result in serious casualties or significant property damage. In contrast, accidents involving overlapping human-object trajectories combined with management and environmental factors had casualty rates and economic losses 7.6 times and 12.3 times higher than single-factor accidents respectively. The data fully validate the core applicability of the trajectory intersection theory in analyzing the causes of laboratory accidents in colleges and universities and also demonstrate the significant catalytic effect of management and environmental factors on accident evolution.

Table 1. Statistics of Causes of Laboratory Fire and Explosion Accidents in National Universities from 2020 to 2024.

Cause Type	Number of accidents	Proportion(%)	Average casualties per incident	Average direct economic loss / 10,000 yuan
Human-object trajectory crossing	123	89.78	1.82	112.65
A single human factor	8	5.84	0.25	14,82
Single-state hazard	6	4.38	0.17	9.63
Human-object interaction Management/environmental factors	105	76.64	2.15	138.92

3 Hazards Analysis in University Laboratories

3.1 Trajectory of Human Unsafe Behaviors (Direct Cause 1)

Personnel in university laboratories have weak safety awareness and do not strictly adhere to safety operating procedures. When conducting high-risk experiments, they do not comply with the laboratory safety access system and dual-person operation management requirements. They lack the ability to identify and predict risks in dangerous situations such as gas leaks and equipment abnormalities. Most experimental personnel are students with insufficient experience, who have luck and energy-saving psychology, making them prone to carelessness. Some personnel have not received systematic and standardized specialized training in high-risk experimental operations and emergency response, have an insufficient grasp of the operating principles of equipment and the characteristics of hazards, and after discovering abnormal conditions, fail to follow standard procedures to immediately cut off power, evacuate, and raise the alarm, or even engage in incorrect disposal behaviors, which can lead to serious accident consequences.

3.2 Trajectory of Material Unsafe States (Direct Cause 2)

Some equipment and facilities in university laboratories have been in service for too long. For example, the performance of fume hoods has declined, and the exhaust capacity is insufficient, leading to the ineffective removal of flammable vapors. Some electrical wiring insulation layers are damaged, easily causing electric sparks and forming effective ignition sources. The key safety facilities such as flammable gas alarm devices and fire automatic alarm systems are not functioning properly and cannot issue timely warning signals when risks appear. In addition, the storage and management of flammable and explosive reagents and gases are not standardized. The fixing and pressure-reducing devices for high-pressure gas cylinders have safety hazards. Fire extinguishers, emergency showers, eyewash stations, and other fire and emergency facilities are insufficient. The evacuation routes do not meet fire safety standards, which further exacerbate the risk and severity of accidents.

3.3 Management Deficiencies and Environmental Factors (Indirect Causes)

The laboratory safety responsibility system has not been effectively implemented. Daily inspections and hazard investigations are often superficial, and there is a clear absence in the approval process and process supervision for high-risk experiments, failing to curb risks from the source. Safety training and emergency drills are mostly on the surface, failing to achieve full coverage and practical training, resulting in personnel safety literacy and emergency response capabilities that are difficult to meet actual needs. At the same time, the spatial layout of the laboratory is unreasonable, the safety distance between experimental benches, reagent cabinets, and equipment is insufficient[5], and the ventilation and explosion-proof conditions do not meet the standard requirements, further increasing the likelihood of an accident.

4 Construction of a Safety Management System Based on Trajectory Intersection Theory

To intervene in the development of the risk paths of people and things, and to continuously strengthen the management and environment as defense lines, fundamentally preventing disasters caused by the interaction between people and things. Guided by the Trajectory Intersection Theory, a “four-in-one” laboratory safety management system is constructed to interrupt the accident intersection chain, as shown in Figure 2.

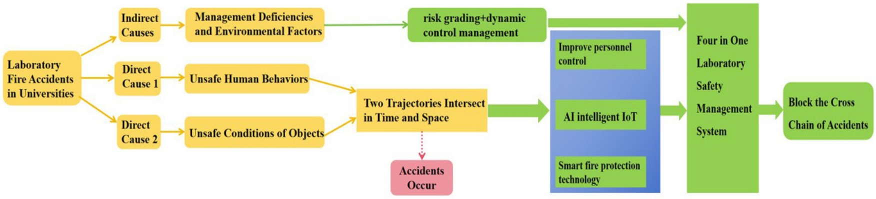

Fig. 2. Trajectory intersection theory model for "four-in-one" laboratory safety management system

4.1 Improve Personnel Control Throughout the Entire Process of Admission, Training and Assessment

Firstly, establish a standardized admission mechanism and a hierarchical classification training system. All personnel entering the experiment must pass the online security assessment module and complete a security knowledge assessment that matches the risk level of their laboratory. Only after passing the assessment can they obtain experimental operation permissions. Implement differentiated training programs for laboratories with different risk levels: set basic safety admission conditions for teachers and students who enter the laboratory for the first time, verify their completion of previous safety learning and signing of safety responsibility agreements; For personnel entering high-risk laboratories such as chemistry and special equipment, they need to complete additional certification of their abilities in hazardous chemical standard operation, special equipment use, fire emergency response, and evacuation to ensure that the training content is highly adapted to the on-site risks.

Secondly, improve the dynamic assessment and permission linkage management mechanism. Implement an annual safety education retraining and review system, and recommend that personnel related to first and second level high-risk laboratories undergo a safety capability review and certification every six months. Establish personal security training files based on the information management platform, and bind the assessment results with experimental operation permissions in real time. Those who fail the assessment will have their admission qualifications automatically suspended by the system.

Thirdly, deepen the cultivation of safety culture and performance incentive orientation. Regularly carry out safety culture publicity and typical case warning education, make fire safety practical training and emergency comprehensive drills mandatory, and create a campus safety culture atmosphere where all staff attach importance to safety and master fire safety skills. At the same time, establish a safety performance integration evaluation system, incorporate the implementation of fire safety into the core indicators of laboratory evaluation and personal evaluation, and implement a safety “one vote veto” system; Strictly implement accountability for units and individuals who fail to fulfill their responsibilities and rectify hidden dangers in a timely manner, promote the formation of a long-term mechanism of “promoting rectification through assessment and construction through evaluation”, and gradually realize the transformation from rigid institutional constraints to conscious safety culture[6].

4.2 Laboratory AI Intelligent IoT

Traditional laboratory safety management relies on manual inspections and discrete information systems, making it difficult to achieve accurate perception and rapid response to dynamic risks. The Internet of Things is a new generation of information technology based on the modes of IoT, human IoT, and human human IoT, with the architecture of perception layer, network layer, and application layer. It is an emerging network technology and industrial model that has received high attention in recent years and has broad prospects. In terms of safety monitoring of university laboratories, Internet of Things equipment such as doors, windows, water, electricity (switches), large precision instruments and equipment (such as confocal microscope, gel imaging system, high-speed freezing centrifuge, Kjeldahl nitrogen meter, etc.) and key mechanical equipment are deployed in the laboratory. Through a series of digital sensors such as light, humidity, smoke, vibration, inductance, temperature, etc., the perception layer can be built through Internet of Things sensing technology to achieve active monitoring, real-time control, and enhance the initiative and accuracy of laboratory risk sensing. Integrate AI systems with existing laboratory management systems (including access control systems, hazardous chemical management systems, safety hazard investigation systems, monitoring systems, etc.) and IoT devices to establish a unified laboratory safety data platform, achieving global awareness and collaborative analysis of laboratory safety situations[7].

Based on IoT sensor data information, AI can be used to intelligently analyze and determine laboratory safety, and generate laboratory safety risk diagnosis reports. If a safety warning threshold is triggered, the diagnostic information will be actively pushed to the AI intelligent dialogue/chatbot end. Then, the AI intelligent robot will actively push warning information to the digital terminal of laboratory safety management personnel to attract their attention and solve the problem of laboratory safety being isolated during holidays. AI pushes relevant safety regulations interpretations, safety tips, and other warm reminders to teachers, guiding students to pay attention to safety precautions and operating procedures[8]. As shown in Figure 3.

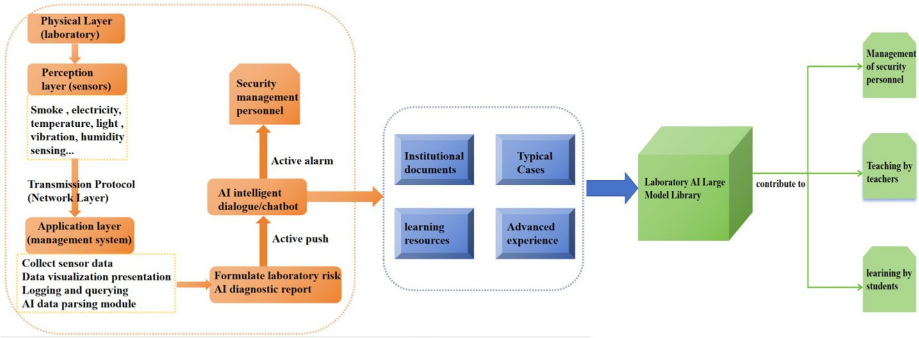

Fig. 3. Laboratory AI intelligent IoT strategy

4.3 Implement the Management System of "Risk Grading+Dynamic Control" Management

Based on risk classification, universities construct a dynamic control system throughout the entire cycle. In the risk classification process, multidimensional evaluation indicators are developed based on the inherent risk characteristics of different types of laboratories: for example, chemical laboratories focus on considering the inventory of flammable and explosive chemicals, reaction hazards and ventilation conditions; Biological laboratories focus on the level of bacterial and toxin species, as well as the protection level of biosafety cabinets; Mechanical laboratories focus on equipment operating loads and the risk of metal dust accumulation; Electronic laboratories focus on circuit complexity and power consumption as core indicators; Special equipment laboratories strictly evaluate equipment calibration results and operating years; For other types of laboratories, the main standard is the completeness of basic fire-fighting facilities.

By conducting comprehensive qualitative analysis, identifying important hazards, semi quantitative job safety analysis and semi quantitative risk level determination, the laboratory risk levels are divided into I to IV, corresponding to major risk, high risk, medium risk, and low risk respectively, as shown in Table 2. In terms of dynamic control, establish a process management and continuous improvement mechanism of level adaptation and real-time adjustment. The I and II level risk laboratories implement a daily self inspection and weekly school campus joint inspection, equipped with intelligent smoke detectors and temperature sensors for real-time monitoring; The III level risk laboratories implement weekly self inspection and monthly hospital level inspection, regularly updates emergency response plans as well; The IV level risk laboratories adopt a monthly self inspection and quarterly department level inspection, approach to strengthen basic safety training. If there are changes such as adding new experimental projects or replacing large equipment in the laboratory, such as introducing new reaction devices in chemical laboratories or expanding electrical equipment in electronic laboratories, the risk level needs to be reassessed and control measures need to be adjusted synchronously.

Table 2. Risk Classification and Typical Examples of University Laboratory Safety.

Risk classification	Risk correspondence	Typical Examples
I level	major risk	(1) Containing toxic, flammable, explosive, and corrosive substances (2) Use Class III pressure vessels with ultra-high pressure (3) Lack of overall and systematic safety management
II level	high risk	(1) Workplace with dust explosion risk (2) Lack of SOP for large instruments and equipment (3) Incorrect classification of experimental waste, mixing can result in severe consequences
III level	medium risk	(1) Flammable materials are stored around small heating equipment such as oven (2) Using glassware or pillows without proper handling according to regulations
IV level	low risk	(1) Improper wearing of personal protective equipment such as lab coats (2) The storage cabinet for items was not closed in a timely manner

4.4 Promote Smart Fire Protection Technology

Build a smart fire comprehensive control platform that integrates real-time monitoring, intelligent warning, and rapid disposal. Intelligent sensing terminals are installed at key points such as laboratory fire-fighting equipment, electrical circuits and ventilation pipelines. Through AI intelligent monitoring equipment, multi-dimensional data such as equipment operating parameters, cable temperature, smoke concentration and personnel operation behavior are collected in real time and transmitted to the centralized management platform through the network. The platform intelligently integrates and analyzes multi-source data to achieve early identification and early warning of fire hazards. For example, when an abnormal increase in electrical line temperature is detected, the system immediately issues a warning and pushes alarm information to urge management personnel to quickly investigate and handle the situation, truly realizing the pre emptive risk prevention and control. On this basis, further deepen the application of big data and artificial intelligence technology. By establishing a data analysis model, deep mining of massive information such as historical fire data and daily safety inspection records is carried out to accurately identify the risk evolution law, and achieve scientific prediction and development trend analysis of fire occurrence probability.

Starting from blocking two key accident trajectories at the source, a “four-in-one” laboratory safety management system covers the construction of an active and three-dimensional safety management system for university laboratories through personnel control, AI intelligent IoT, “risk grading+dynamic control” management and smart fire protection technology.

5 Conclusion

The theory of trajectory intersection provides a scientific and systematic framework for understanding the complex causes of laboratory fire risks in universities. To intervene in the development of the risk paths of people and things, and to continuously strengthen the management and environment as defense lines, fundamentally preventing disasters caused by the interaction between people and things. The construction of a “four-in-one” management system based on this theory, which includes personnel control, AI intelligent IoT, “risk grading+dynamic control” management and smart fire protection technology, can interrupt the two key accident trajectories from the source, achieving precise and long-term control of laboratory safety. In the future, by building a digital twin of lab safety, we can simulate and predict how risks evolve in real time, making the leap from passive response to proactive warning and intervention.

References

1. CNR.com. (2026, March 21). Chongqing University laboratory explosion causes 1 death and 3 injuries; university cites suspected improper operation [News article]. Retrieved from https://www.cnr.cn/newscenter/local/dftj/20260321/t20260321_527558781.shtml.
2. Wang Jiayang. Analysis and Countermeasures of Typical Accidents in Hazardous Chemical Transportation Based on Trajectory Intersection Theory [J]. China Storage & Transportation, 2025, (01): 60-61.
3. Xia Ming, Li Xin, Xu Junjie, et al. Research on the Evaluation of Laboratory Safety Status in Universities Based on the Analytic Hierarchy Process[J]. Experiment and Analysis, 2025, 3(04): 90-97.
4. GUO Zhansheng, DING Yi, LIU Yingying, LI Xia. Statistical Analysis and Countermeasures of Laboratory Accidents inChinese Universities and Research Institutes from 2004 to 2024 [J/OL].Experimental Science and Technology,1-6[2026-03-26].
5. Chen Wenyun, Wang Huiyu, Zhao Quanjian. Exploration of Safety Process Design for Flammable and Explosive Reagent Rooms[J]. New Technology and New Process, 2023, (07): 36-40.
6. Liang Jianlei, Wang Hongyu, Zhai Libo, etc Research on the Construction and Practice Path of Fire Safety Management System for University Laboratories Based on Risk Prevention and Control [J]. Journal of Weifang University, 2026,26 (2): 114-120.
7. Chen Wei, He Jing Research on Optimization Strategy of University Laboratory Safety Management System Integrating AI Agents [J]. China Broadband, 2024, 20 (9): 148-150.
8. Bo L ,Junrui L ,Xuegang L .Multi-dimensional water quality indicators forecasting from IoT sensors: A tensor decomposition and multi-head self-attention mechanism.[J].PloS one,2025,20(7):e0326870.