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SMART INDUSTRIAL SAFETY SYSTEMS FOR CNG INFRASTRUCTURE: A REVIEW OF REGULATORY REQUIREMENTS, FIRE PROTECTION STANDARDS, AND AI-BASED MONITORING TECHNOLOGIES

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Abstract: This paper examines the provision of industrial and fire safety at compressed natural gas (CNG) infrastructure facilities, with particular focus on automobile gas-filling compressor stations (AGNKSh). The study analyzes international (ISO, NFPA, IEC) and national regulatory documents and evaluates the effectiveness of intelligent monitoring technologies based on RFID, the Internet of Things (IoT), and artificial intelligence (AI). Systematic analysis, comparative analysis, and modeling methods were applied. The results show that, compared with traditional control methods, smart monitoring systems significantly increase the speed of hazard detection and the level of accident prevention, while also improving the economic efficiency of facility operation. The findings support the integrated adoption of digital monitoring technologies aligned with regulatory requirements to ensure the safe and stable operation of gas infrastructure.

Keywords: CNG infrastructure, AGNKSh, industrial safety, fire safety, regulatory standards, IoT, RFID, artificial intelligence, monitoring systems, digital transformation.

1. Introduction

In recent years, the demand for environmentally friendly and economically efficient energy sources in the transportation and energy sectors has been steadily increasing. In this context, compressed natural gas (CNG) has become widely used as an alternative fuel for vehicles, since it produces fewer harmful emissions than conventional gasoline and diesel and enables more rational use of energy resources. Accordingly, the development of CNG infrastructure and the expansion of the network of automobile gas-filling compressor stations (AGNKSh) has become one of the strategic priorities in the Republic of Uzbekistan.

However, the expansion of CNG infrastructure has made industrial safety problems increasingly relevant. At AGNKSh facilities, high-pressure gas storage, compression, and delivery to vehicles are technologically complex processes that may give rise to technogenic risks such as gas leakage,

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explosion, fire, and equipment failure. Because natural gas is highly flammable, even minor technical failures or operational errors can lead to large-scale accidents. Practice shows that traditional control methods cannot fully ensure the rapid detection of hazards in real time.

Consequently, the introduction of digital technologies and intelligent monitoring systems has become essential in modern industrial environments. In particular, RFID, IoT, radar, and AI technologies enable early detection of hazards, real-time monitoring of technological processes, and improvement of the overall safety level.

The aim of this study is to analyze the regulatory requirements, fire safety standards, and modern intelligent monitoring technologies applied to ensure industrial safety at CNG infrastructure facilities — particularly AGNKSh — and to evaluate their effectiveness. The main tasks of the research are as follows:

– to analyze the role of CNG infrastructure in the transportation and energy system;
– to identify and assess the technogenic risks arising at AGNKSh facilities;
– to study international and national regulatory documents on fire safety;
– to analyze the capabilities of monitoring systems based on RFID, IoT, and AI;
– to develop scientifically grounded recommendations for improving safety monitoring.

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2. Literature Review and Regulatory Framework

Since gas-handling technological systems involve high pressure and flammable environments, strict compliance with safety requirements is essential for their management. In the field of fire safety, the standards of the international organizations ISO, NFPA, and IEC play a leading role. In particular, ISO 45001 defines the principles of occupational health and industrial safety management systems; NFPA 52 specifies requirements for using compressed natural gas as a vehicular fuel; and IEC 60079 establishes requirements for electrical equipment in explosive atmospheres.

Table 1. Key international safety standards for CNG infrastructure

Standard	Organization	Scope
ISO 45001	ISO	Occupational health and industrial safety management system
ISO 14001	ISO	Environmental management system
NFPA 52	NFPA	Safety requirements for CNG fuel systems
NFPA 70	NFPA	Electrical safety and explosion-protected equipment
IEC 60079	IEC	Electrical equipment in explosive atmospheres

In the Republic of Uzbekistan, the principal legal act in this field is the Law “On Fire Safety.” In addition, technical regulations on industrial safety, technical operation rules for gas supply systems, construction norms and rules (QMQ), and the fire safety rules approved by the Ministry of Emergency Situations are of considerable importance. National regulatory documents are in many cases based on international standards, which fosters a unified methodological approach.

In the scientific literature, smart sensor systems, digital twin technology, and AI-based predictive models are widely studied for ensuring the safety of gas infrastructure. Effective safety monitoring requires the integrated application not only of technical means but also of regulatory requirements, management systems, and risk-analysis methods.

3. Research Methodology

A complex methodology was applied in this study. The systematic analysis method made it possible to consider the safety system at AGNKSh as a single technological and organizational system and to examine its structure, which consists of sensors, data-transmission channels, processing centers, and alert systems. The comparative analysis method was used to compare international and national standards and to evaluate the effectiveness of different monitoring technologies, while the modeling method was employed to study the mechanisms for detecting and predicting hazardous conditions such as gas leakage and changes in temperature and pressure.

Data sources included scientific articles and monographs, international standards and regulatory documents, statistical data on industrial safety, and data obtained from technological monitoring systems. The collected data were processed using statistical, graphical, and analytical evaluation methods.

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The operating principle of the monitoring system consists of the following stages: *Sensors → Data collection → Transmission via the IoT network → Analysis with AI algorithms → Hazard identification → Alert and control*. Sensors measure gas pressure, temperature, and concentration; the data are transmitted to a central server and analyzed by AI algorithms; and when a hazard is identified, an automatic alert is issued or a safety measure is activated.

4. Smart Safety Monitoring Systems at AGNKSh

Smart safety systems typically consist of sensors, identification technologies (RFID), IoT networks, and AI-based analysis algorithms. Sensors and measuring devices are the core element of the system, continuously monitoring parameters such as gas concentration, temperature, pressure, and vibration in real time. Special gas analyzers are used to detect gas leakage.

Table 2. Technologies used in industrial safety monitoring

Technology	Main function	Field of application
RFID	Identification and tracking of objects	Equipment monitoring
IoT	Real-time transmission of sensor data	Process control
Radar	Detection of motion and hazardous zones	Safety monitoring
Artificial intelligence	Data analysis and prediction	Automated safety systems

RFID technology automatically identifies gas cylinders, equipment, and vehicles and monitors their condition. IoT technology integrates data from various sensors into a single network and transmits them to a central server. AI algorithms (machine learning and neural networks) compare sensor data with historical records to detect deviations from normal indicators and to predict potential accident situations.

Real-time monitoring is usually organized on the basis of a SCADA (Supervisory Control and Data Acquisition) system. SCADA enables operators to monitor processes, observe the condition of equipment, and take prompt measures in emergencies, including automatically shutting down the system.

5. Results and Discussion

The results of the study showed that the introduction of monitoring systems based on IoT, RFID, and AI increases the speed of hazard detection and significantly reduces accidents. The main advantages of smart monitoring systems are real-time hazard detection, continuous process control, reduction of human-factor errors, and the ability to predict accidents in advance.

Table 3. Comparative analysis of traditional and smart monitoring systems

Indicator	Traditional monitoring	Smart monitoring system

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Hazard detection speed	Moderate	High
Data processing	Manual / semi-automatic	Fully automatic
Real-time monitoring	Limited	Fully available
Prediction capability	Not available	Available (AI-based)
Maintenance costs	High	Low
Accident probability	Moderate	Low

According to the results, smart monitoring systems considerably raise the safety level compared with traditional control methods, mainly because of their ability to monitor processes in real time. In IoT-based systems, all equipment operates in an interconnected manner. From an economic standpoint, such systems are also efficient: by reducing accidents, they cut maintenance costs, extend the service life of equipment, and improve energy efficiency.

These findings are consistent with the broader literature on Industry 4.0, which emphasizes that the integration of sensing, connectivity, and analytics yields the greatest safety benefit when combined rather than deployed in isolation. For CNG facilities, this implies that technical solutions should be implemented together with an appropriate regulatory and managerial framework in order to achieve a measurable reduction in overall risk.

6. Conclusion

This study examined, in an integrated manner, the systems for ensuring industrial and fire safety at automobile gas-filling compressor stations (AGNKSh). The results show that, alongside traditional control methods, the introduction of digital monitoring technologies is of great importance at CNG infrastructure facilities. Technologies based on RFID, IoT, sensor systems, and AI enable early hazard detection, real-time process control, and accident prevention.

Scientific and practical recommendations: introduce smart sensors and automated monitoring systems at gas infrastructure facilities; organize real-time monitoring using IoT technologies; apply AI-based predictive algorithms; integrate international standards with national regulatory documents; and link monitoring systems with SCADA.

Future research should focus on the development of digital transformation and smart industrial technologies — in particular, machine-learning algorithms, digital twin technology, and risk prediction based on Big Data analysis. Applying modern digital technologies in harmony with regulatory requirements is of significant scientific and practical importance for ensuring the safe and stable operation of gas infrastructure.

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