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Critical Situations Created by Humans in Aircraft Flight: About the Possibilities of Control

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Abstract

This article addresses safety in potentially dangerous situations created by negative manifestations of human factors during aircraft flight. These manifestations include erroneous actions by the pilot, delayed reaction to rapid changes in flight conditions, inattention, fatigue, illness, inaction, suicidal intent, hijacking of the aircraft by intruders, including terrorists, who are among the passengers, panic behavior of passengers, etc. The escalation of such a situation, considered critical, into an accident can be prevented if the aircraft is designed as a “smart” human-machine system with a high level of robotization. The automatic part of this system must be able to recognize dangerous human behavior and perform autonomous measures aimed at minimizing the risks. In the most extreme case, it must block human actions and transfer aircraft control to a fully automatic mode – until the end of the flight with a safe landing. The purpose of the article is to formulate the problem of developing an onboard automatic control system that meets such tasks, and a preliminary analysis of the possibilities of its solution. The specific features of the problem under consideration determine the choice of artificial intelligence elements, in particular neural network technology, for its effective solution.

Keywords: aircraft, automatic control, critical situation, human factors, neural network, safety.

1 INTRODUCTION

In modern aircraft, a significant portion of the flight control functions is performed or can be performed automatically, without the participation of a human operator (pilot). The prospect of civil aviation moving to fully unmanned transport air vehicles or passenger planes without crews is not clear – it has both advantages and disadvantages (McLean 2003; Harris 2003). Without making any additional contribution to their consideration, it should be noted that research and development (R&D) aimed at reducing human participation in aircraft control is largely motivated by the need to minimize negative manifestations of human factors during flight and the risks associated with them. The range of these negative manifestations covers erroneous actions of the pilot, delayed reaction to rapid changes in weather or air traffic conditions, inattention, fatigue, illness, inaction, suicidal intentions, hijacking of an aircraft by intruders, including terrorists, who are among the passengers, panic behavior of passengers on board, etc. If the escalation of a critical situation caused by any of these initial events – we will call such a situation anthropogenic – is not stopped, it can lead to a serious flight accident and even a

catastrophe. Some examples of catastrophes of this genesis, which resulted in the destruction of aircraft and human fatalities, are given in Table 1.

Table 1 Some aviation catastrophes caused by negative manifestations of human factors in flight

Date	Location	Aircraft, airline and flight	Probable ¹ cause
2001-09-11	USA, Washington, DC	Boeing 757-223, <i>American Airlines</i> , Flight 77	Hijacking of the aircraft by terrorists (ASN 2006a)
2001-09-11	USA, PA	Boeing 757-222, <i>United Airlines</i> , Flight 93	Hijacking of the aircraft by terrorists (ASN 2006b)
2001-09-11	USA, New York	Boeing 767-222, <i>United Airlines</i> , Flight 175	Hijacking of the aircraft by terrorists (ASN 2006c)
2001-09-11	USA, New York	Boeing 767-223ER, <i>American Airlines</i> , Flight 11	Hijacking of the aircraft by terrorists (ASN 2006d)
2009-06-01	Atlantic Ocean	Airbus A330-203, Air France, Flight 447	Misunderstanding of critical situation by pilots and erroneous actions to get out of it (ASN 2025c)
2013-08-14	USA, BHM	Airbus A300F4-622R, UPS, Flight 1354	Pilot fatigue (ASN 2013)
2013-11-29	Namibia, Bwabwata National Park	Embraer ERJ-190AR, <i>Linhas Aéreas de Moçambique</i> (LAM), Flight 470	The pilot's suicidal intentions (ASN 2024c)
2015-03-24	France, Prads-Haute-Bléone	Airbus A320-211, <i>Germanwings</i> , Flight 9525	The pilot's suicidal intentions (ASN 2025b)
2016-03-19	Russia, Rostov Airport (ROV)	Boeing 737-8KN, <i>flydubai</i> , Flight FZ981	Pilot fatigue (ASN 2025a, Yakimovich 2024)
2021-07-06	Russia, Kamchatka, Palana	Antonov An-26B-100, Kamchatka Aviation Enterprise	Lack of time to perform the required maneuver (ASN 2024b, Yakimovich 2024)

Fortunately, not every critical situation that arises in flight leads to catastrophe – sometimes a safe outcome is possible. It is the bifurcation nature of a critical situation that is its distinguishing feature – a control action applied rightly in spatial and temporal terms can prevent it from turning into a disaster. This is the difference between a critical situation and an emergency one – the latter, as a rule, is irreversible and results in an accident that is associated with destruction and material losses. An example of a critical situation created by humans and resolved safely is that which occurred on 17 February 2024, involving *Lufthansa* Airbus A321-231, flight LH1140. It was en route from Frankfurt to Seville. Near Madrid, the captain left the cockpit and shortly after, the co-pilot suddenly lost consciousness. The plane flew without pilot control for about 10 minutes. When the captain returned to the cockpit, he decided to divert to Madrid-Barajas Airport, where he landed without further incident (ASN 2024a).

¹ In the terminology of investigation reports.

Anthropogenic critical situations are characterized by uncertainty of occurrence, development and outcome. This uncertainty includes both aleatory and epistemic components. The first of them primarily encompasses pilot behavior patterns that are deviations from normal piloting but are predictable and associated with erroneous actions, delayed reactions, inattention, or fatigue. The uncertainty of the occurrence of a critical situation arising from any of these causes can be characterized by an appropriate probability estimate based on statistics accumulated in aviation. Based on the known causes of critical situations of this type and reasonable probability estimates, standard design and organizational measures can be implemented in order to minimize the risk of an accident or catastrophe.

Other negative manifestations of the human factor during aircraft flight – sudden illness of the pilot, inaction, suicidal intentions, hijacking, etc. – are more of an epistemic nature. They are difficult to predict and almost impossible to control, however, some preventative design and organizational measures are feasible.

The reversibility of critical situations provides a fundamental opportunity to cope with them and ensure a safe outcome. The purpose of this article is to explore this possibility and present the results in the form of an engineering formulation of the problem of creating a special on-board automatic control subsystem, intended to maintain safety in anthropogenic critical situations that may arise during the flight of a civil aircraft.

2 EXISTING APPROACHES TO MANAGING ANTHROPOGENIC CRITICAL SITUATIONS

2.1 Traditionally used approaches

Design measures aimed at minimizing the risk associated with aleatory uncertainty in pilot behavior (behavioral patterns of the first type – see Introduction) include constructing the cockpit interior and the human-machine interface according to ergonomic principles. These principles are established in existing standards and are being developed through ongoing research – some aspects of ergonomic design are discussed in the author's book (Spirochkin 2023). Organizational measures are implemented in accordance with national and international regulatory documents, for example, (Air Code 1997), (CFR Part 91), (ICAO 2020). These measures cover pilot education and training, selection based on professional suitability criteria upon recruitment and subsequent certification, periodic physical and mental health screening (Yakimovich 2024), pre-flight health checks of pilots, as well as the implementation of safety culture in airlines. Important elements of the latter include the private and commercial pilot responsibility to perform IMSAFE health assessment (FAA 2023; Kingsky Flight Academy 2023) and mutual monitoring achieved through the presence of two pilots in the cockpit.

Regarding the second type of negative human behavior patterns, the potential manifestation of which is characterized, rather, by epistemic uncertainty, but is, in principle, predictable (see Introduction), design measures to reduce risk are limited. They mainly include protection against intruders entering the cockpit or against penetration of small arms bullets and fragments of explosive devices with specified parameters (CFR Part 25, § 25.795). Organizational measures cover profiling carried out by airport security services to identify intruders, as well as the use of technical means for screening passengers and baggage.

In the event of an anthropogenic critical situation of any origin during aircraft flight, the traditional approach to flight safety, cultivated in civil aviation, is applied. This approach assumes that any hazards in flight, including those caused by crew errors, must be managed by highly qualified pilots and their appropriate training (ICAO, 2020). However, this approach, as well as the design and organizational measures described above, cannot ensure safety across the entire range of possible anthropogenic critical situations. This disappointing conclusion is confirmed by the list of aviation catastrophes in Table 1. Moreover, the existing system of ensuring flight safety in civil aviation, while generally quite reliable, apparently cannot guarantee the prevention of any anthropogenic critical situation or a safe exit from it in the future. Such a guarantee is hindered by the very nature of human factors, which are insufficiently studied and limited in control.

2.2 Alternatives

Understanding the limitations of managing potential negative manifestations of human factors in civil aviation motivates the search for alternatives to traditionally used approaches.

In situations created by humans in flight, an alternative approach can be implemented through intervention in the process of human control, which has become inadequate, by the automatic part of the human-machine system. The form of intervention may vary depending on the specifics of the situation. For example, if the cause of a critical situation is the unintentional erroneous actions of the pilot, for example, due to a lack of understanding of the complex flight situation, but these actions do not create an instantaneous threat of an accident, then the intervention can be “soft” – in the form of a recommendation to the pilot to correct his actions or in a slight automatic modification of the pilot’s control actions to improve the flight (Rogalski 2010).

In situations of a more serious nature and rapidly developing in a negative direction, their development can be stopped and a safe outcome ensured by blocking dangerous human behavior and transferring aircraft control to automatic mode. This “hard” intervention can also be used in a critical situation of the first category if the pilot did not follow the recommendation and (or) missed the time to correct his errors. The second type of intervention is of primary interest, since it is the most complex and applicable to the most extreme cases. For cases such as an obvious hijacking attempt or an aircraft deviation from its flight plan noticed by the air traffic control center, not attributable to the actions of the authorized flight crew, a number of technical solutions have been proposed – see, for example (Pizzo 1974; Shear 2003; Gleine 2005; Conner 2009). These solutions are typically based on the crew’s or air traffic controllers’ assessment of the critical situation, as well as their involvement in control, including remote control of the aircraft from the ground. To the author’s knowledge, none of the proposed solutions have been implemented in serial products.

The alternative proposed in this article is the situational replacement of human control, which turns out to be insufficiently reliable or even dangerous, with automated control. This idea goes beyond the traditional design and organizational measures used in civil aviation. It only partially overlaps with the alternative technical solutions presented in the aforementioned publications. The approach implementing this idea is aimed at ensuring safety in the entire range of the anthropogenic critical situations and is based, rather, on the philosophy of space technology. Given the extreme nature of the physical processes when launching a spacecraft into

orbit or re-entering the atmosphere, as well as the complexity of maneuvers in orbit, which limits the control capabilities of the human operator, this philosophy provides for predominantly automatic control. The participation of the human operator in control is only an option, implemented in a limited number of space operations.

For example, no cosmonaut (pilot) was present on board the Soviet aerospace shuttle *Buran* during its test flight and return to Earth on November 15, 1988. Its landing on the airfield runway was carried out automatically (Brovkin and Kravets 2014). A similar concept is currently being implemented to varying degrees in unmanned aerial vehicles, including military ones. However, the approach described below differs from fully automatic control of an aircraft. Its essential distinguishing features are as follows:

- the automatic control system has a special component which works simultaneously with the pilot – it monitors not only the flight conditions, but also carries out a kind of supervision over his actions, as well as the situation in the cockpit and passenger cabin from a safety point of view;
- this component intervenes in the control performed by the pilot when a critical situation arises and carries out autonomous actions – up to the complete exclusion of the pilot from the control loop and the implementation of other protective measures.

To ensure this situational takeover of control, an aircraft – plane, helicopter or airspace vehicle – should be designed as a human-machine system with a high level of robotization. The special component of the automatic control system should be capable to recognize critical situations (in the context under consideration, anthropogenic), determine an automatic control algorithm adequate to a specific situation and aimed at a safe outcome from it, and also perform appropriate control actions. All these functions must be carried out in real flight time. The current level of science and technology makes it possible to implement the component in question as part of an on-board automatic control system.

The current stage of R&D carried out in this direction with the participation of the author includes an engineering formulation of the problem and an analysis of the possibilities of its solution.

3 THE PROBLEM STATEMENT

The problem of situational takeover of control when an anthropogenic critical situation arises in flight in order to ensure a safe way out of it can be formulated as follows: it is necessary to equip the onboard automatic control system with a special component that must solve three tasks, or lower-level problems, in real time:

- 1) recognition of the situation;
- 2) determination of the algorithm for managing the situation and
- 3) implementation of this algorithm.

The first task is essentially similar to that solved during the investigation of an aviation accident post-factum, but differs from it because it must be solved directly in flight, and the result of the solution must be unambiguous – in the form of an algorithm of automatic actions that would ensure a safe way out of the situation. Reliable recognition of the situation in both cases requires information obtained through several channels: sound recordings, video data, and sensor data characterizing the flight parameters, as well as control actions and the state of the

aircraft systems. All sounds in the aircraft cockpit are currently gathered by the cockpit voice recorder (CVR) and sensor data by the flight data recorder (FDR). These recordings assist accident investigators. Video recordings of the cockpit or passenger cabin are not generally made.

Automatic recognition of the situation in real time is possible using electronic processor devices capable of identifying certain markers (or patterns) in the data coming through each channel that characterize its occurrence and course, and of generating integrated judgments about the nature and probable development of the situation. The solution to this task (the first of the low-level problems in our list) is, according to available information, in the early stages of research and development in global civil aviation. No serial-produced electronic devices of this kind were found.

The second low-level problem that requires a solution after recognizing an anthropogenic critical situation is to determine the algorithm for managing it in order to achieve a safe outcome (a safe way out of the situation). Such algorithm should provide for the following groups of operations:

- blocking dangerous or potentially threatening actions of pilots and (or) passengers;
- transferring aircraft control exclusively to automatic mode and
- performing the automatic control with a certain spatial scheme of force application and time profile.

The solution to this problem may not be easy, given the variety of critical situations that may arise in flight due to human fault. For the second problem, as for the first, no ready-made solutions applicable to the entire range of possible situations were found in the available sources of information. It is reasonable to assume that the algorithm appropriate to a particular situation can be determined by selecting from a pre-developed set of algorithms, taking into account established criteria of applicability and effectiveness.

The selected algorithm must be implemented (the third of the low-level problems in the list above) by the relevant control circuits including actuators and secondary flight controls, that are capable of generating the necessary control forces. Air vehicles are currently equipped with control circuits that use mechanical, hydraulic or electromechanical actuators and aerodynamic rudders. These elements can produce the control actions needed to manage some critical situations. However, in the event of failure of the aerodynamic secondary controls, their actuators, or the entire control loop, there are no proven technical solutions that guarantee a safe outcome. In such cases, other design solutions are required.

The absence of ready-made technical solutions on a number of issues indicates the significant novelty of the problem at hand. There is an obvious need to develop appropriate practical proposals for solving these issues in order to create the required component of the automatic control system for an aircraft. The proposals should cover solutions to the following tasks:

- 1) implementation of video recording of the situation in the cockpit and passenger cabin;
- 2) development of methods for recognizing anthropogenic critical situations in real time using all three data recording channels: CVR, FDR and video;
- 3) an experimental study of the sufficiency of information received through these channels, and in case of insufficiency, a proposal to obtain additional information;

- 4) embodiment of recognition methods in on-board electronic devices (including the choice of the most effective combination of software and hardware);
- 5) development of control algorithms for a conceivable set of anthropogenic critical situations, including all three groups of operations that must be performed in real time, and a technique for selecting the best algorithm for a specific situation using certain selection criteria;
- 6) development of appropriate control circuits for the implementation of these algorithms, including actuators and elements generating control forces;
- 7) development of the architecture of an on-board automatic control system for anthropogenic critical situations, and linking it with the flight control systems currently in use or under design.

4 ANALYSIS OF THE SOLVABILITY OF THE PROBLEM

The analysis of the solvability of the problem of creating a component of an aircraft automatic control system for managing anthropogenic critical situations is carried out by considering the individual tasks within this problem, which are listed at the end of the previous section.

The first of these tasks (implementation of video recording) seems quite simple from a technical point of view. However, as attempts to equip cockpits with video cameras have shown, pilots are opposed to such measures, and overcoming their resistance can be a significant organizational challenge. The solution lies in the intersection of industrial and organizational psychology and maintaining a safety culture in airlines.

Methods for recognizing anthropogenic critical situations based on available flight records from CVR and FDR (see the second task in our list) have so far been developed mainly for use in aviation accident investigations. In particular, it is possible to recognize the mental state of pilots by analyzing the recording of their conversations in the cockpit (Yakimovich 2025b). There are also attempts to identify abnormal pilot behavior based on data from FDR, characterizing the process of manual control through deviations of the aerodynamic secondary controls in an emergency situation (Klyuev 2024). The key issue for the use of these methods in flight conditions is their applicability on board an aircraft and in real time.

Information obtained from the CVR, FDR, and video (if video recording is feasible) may be insufficient to recognize critical situations caused by certain unhealthy conditions of the pilot, his inaction, or suicidal intention, especially when these conditions have no audible or visible signs of manifestation. If the pilot is alone in the cockpit, and if he loses consciousness, remains silent, or shows no visible intention, it is extremely difficult to determine what is happening to him based on this information. Given such situations, it may be necessary to conduct experimental studies to find additional sources of information that can fill this gap (the third task). The best source of information is the one that provides a clear picture of the processes in the pilot's mind that initiated the anthropogenic critical situation.

Methods for identifying processes occurring in pilots' minds, which are used by aviation psychologists in accident investigations and professional suitability assessments (Yakimovich 2024, 2025a, 2025b), are unlikely to be applicable to recognizing critical situations in flight. However, these processes must inevitably manifest themselves in some physical, but non-mechanical, phenomena, which, if identified, can be considered diagnostic signs. Such signs could include, for example, specific patterns in the electromagnetic field emitted by the brain.

Despite the weak intensity of the electromagnetic field generated by neurophysiological processes, modern technology makes it possible to record it using instrumental methods. It is possible that additional sources of information required for reliable recognition of some anthropogenic critical situations in real time should be based on the development of these methods and their implementation in the automatic control systems of aircraft.

The solution to the fourth task (embodiment of recognition methods in on-board electronic devices) should involve the choice of a combination of software and hardware based on the criteria of their seamless inclusion in the automatic control system of aircraft and the minimum time spent on recognizing a critical situation.

When solving task 5 (development of control algorithms for a conceivable set of anthropogenic critical situations and a technique for selecting the best algorithm for a specific situation), it is necessary to take into account:

- the nature of each critical situation in question and the human behavioral parameters characterizing it;
- variables describing the current flight conditions;
- the current state of the aircraft in terms of operability and safety (integrity, controllability, degradation of the properties of elements, etc.);
- the control forces necessary to implement a safe way out of the situation;
- available characteristics of control circuit elements;
- changeability of the situation over time and the time reserve available for control actions;
- the emergence of additional loads at a certain combination of spatial scheme of control forces and their time profiles with the dynamic properties of the aircraft;
- limitations imposed by the environment (flight altitude, terrain, meteorological conditions, etc.).

In many respects, this task is similar to that which must be solved when ensuring the safe emergency landing of an aircraft (Spirochkin 2025). Therefore, a solution should likely be sought within the SPARS (Smart Pro-Active Resilient System) concept described there. The functions of the component of the aircraft automatic control system in question, which is intended to provide control in anthropogenic critical situations, fall within the range of functions of the Critical and Emergency Control System (CECS) (ibid). At this stage of R&D, it is difficult to determine whether it should be implemented as an autonomous subsystem within CECS or integrated into this system as a set of additional options.

In any case, the component that provides control in anthropogenic critical situations will use, among many onboard equipment elements, actuators and elements generating control forces – both aerodynamic secondary flight controls and new ones not yet used in aviation. The latter could include, for example, small solid-fuel rocket engines similar to those applicable in emergency rescue systems (launch escape systems) or soft landing systems for spacecraft. Technical proposals for these elements can be prepared as a result of solving task 6. These proposals, as well as results of solving task 7, which should determine architecture of the component in question and its interface with the integrated Flight Control System (FCS)², can form the content of the corresponding conceptual design.

² If the FCS is equipped with elements of AI, it is considered an Intelligent Flight Control System (IFCS) (Stengel 1992; NASA 2002).

5 PREFERENCE FOR NEURAL NETWORK TECHNOLOGY

The key features of the problem of creating a component that provides control in anthropogenic critical situations from the point of view of information technology are the following:

- 1) the heterogeneous nature and multiplicity of data required to recognize the situation and determine an effective control algorithm and, thus, subject to processing;
- 2) continuous updating of these data during the development of a critical situation, and, accordingly, the need to process them and obtain results in real time;
- 3) requirement for installation of the component on board the aircraft.

Similar features are inherent in the problem of ensuring safety during an aircraft emergency landing. To solve that problem, the choice was made in favor of neural network technology (Spirochkin 2025). This technology also appears preferable for control in anthropogenic critical situations. Indeed, effectively recognizing such situations is unlikely to be possible without the use of a neural network. The challenge lies in training it. Given the variety of situations, training is not an easy task, but it will be carried out not in flight conditions, but on the ground and in advance.

Recognizing patterns based on a set of characteristic elements is a typical task that a neural network can solve. In our context, the pattern to be identified is a set of data of different modalities (audio, video and sensor signals). Determining an algorithm for control in an anthropogenic critical situation is possible using classical methods of applied mathematics and mechanics, including solving the differential equations of aircraft motion. However, this requires extensive computational resources unavailable onboard the aircraft and is not applicable under the time constraints typical of a developing critical situation. Using a neural network, pre-trained on a representative set of examples corresponding to a conceivable set of anthropogenic critical situations and flight conditions, ensures the algorithm can be determined with minimal time expenditure.

Another preferred area of application of neural network technology is the processing of the results of experimental study aimed at discovering additional channels of information for the purpose of more reliable recognition of an anthropogenic critical situation.

An important argument in favor of neural network technology is the ability to process fuzzy data, which will inevitably be present in information flows of various natures.

It remains to be added that the development of a neural network and its training for the above-mentioned applications should be an integral part of the project to create the control system component in question. An aircraft that implements the control in anthropogenic critical situations acquires the properties of a robotic system and can be called a “smart” aircraft. The idea described is reminiscent of the first of the three fundamental Rules of Robotics, formulated by Isaac Asimov in his book *I, Robot*: “A robot may not injure a human being, or, through inaction, allow a human being to come to harm.”

CONCLUSION

The presented research shows that the design and organizational measures currently used in civil aviation do not ensure safety across the full range of critical situations that may arise during an aircraft flight due to negative manifestations of human factors. Aviation accident statistics

confirm the existence of the problem. The proposed solution to it is to give the aircraft the properties of a “smart”, i.e. highly robotic system, capable of recognizing the emergence of an anthropogenic critical situation on board and taking control to ensure a safe outcome. The article describes the engineering formulation of the problem of creating a special on-board automatic control subsystem intended to perform the corresponding functions. The formulation of the problem is accompanied by an analysis of its technical feasibility.

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Implementation of Artificial Intelligence in Nuclear Industry Short Overview

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Abstract

Artificial intelligence (AI) is rapidly emerging as a transformative technology in the nuclear energy sector, offering unprecedented opportunities to enhance safety, operational efficiency, and reliability. This overview examines the main domains where AI is being implemented in nuclear power plants, including predictive maintenance, process optimization, digital twins, and autonomous robotics. AI-driven predictive maintenance enables early detection of equipment anomalies, reducing unplanned shutdowns and improving plant reliability. Process optimization through AI allows for dynamic adjustment of reactor operations, maximizing electricity generation while minimizing fuel consumption and equipment's wear. The development of digital twins – virtual replicas of physical assets – facilitates advanced simulation, operator training, and risk-free testing of modifications. Autonomous robotic systems, powered by AI, are revolutionizing inspections and interventions in hazardous environments, significantly reducing human exposure to radiation. The integration of AI into nuclear safety and accident management is also discussed, highlighting its role in early warning systems, reduction of human error, and proactive risk analysis. Despite its promise, the adoption of AI faces challenges related to cybersecurity, regulatory compliance, and the need to build trust among operators. Real-world examples from leading industry players demonstrate the tangible benefits and ongoing evolution of AI applications in nuclear energy industry. The review concludes that while AI will not replace human expertise, it will serve as a powerful augmentation tool, supporting safer, more efficient, and more resilient nuclear power operations.

Keywords: AI, data analytics, digital twins, nuclear safety optimization, accident management support, predictive maintenance, robotics, risk analysis, design optimization, human-machine interface, decision support systems, risk-free testing, continuous monitoring, cybersecurity, regulatory compliance.

1 INTRODUCTION

Artificial intelligence (AI) is increasingly recognized as a transformative force in the nuclear energy sector, offering the potential to significantly enhance safety, operational efficiency, and reliability of nuclear power plants. The nuclear industry, characterized by its conservative approach and stringent safety requirements, has traditionally been slow to adopt new technologies. However, the growing complexity of plant operations and the need for improved risk management have accelerated the development and deployment of AI-based solutions in

several critical areas. These critical areas, which will examine in more detail with examples further on, can be summarized as follows (Tuhin 2025; Ejigu et al. 2024):

1. Reactor Design Optimization

AI techniques, including generic algorithms and neural networks, are used to optimize reactor core configurations, fuel arrangements, and thermal-hydraulic parameters to improve efficiency and safety.

2. Autonomous Control and Operation

AI enables real-time monitoring and autonomous control of reactor systems, reducing reliance on human operators and enhancing responsiveness to abnormal conditions.

3. Equipment Prognostics and Health Management

Machine learning models predict equipment failures and assess component health, allowing for predictive maintenance and reducing downtime.

4. Nuclear Safety Analysis and Accident Management

AI supports risk assessment, scenario modeling, and decision-making during emergencies, improving the robustness of safety systems.

5. Big Data Analytics for Plant Monitoring

AI and big data computing are used to process vast amounts of sensor and operational data to detect anomalies, optimize performance, and support decision-making.

6. Digital Twin Technology

Digital twins—virtual replicas of physical systems—are enhanced by AI to simulate and predict plant behavior under various conditions, aiding in diagnostics and planning.

7. Human-Machine Interface Enhancement

AI improves operator support systems, reducing cognitive load and enhancing situational awareness through intelligent interfaces and decision aids.

AI technologies, including machine learning, deep learning, and advanced data analytics, are now being integrated into nuclear facilities to support decision-making, automate routine and complex tasks, and provide predictive insights that were previously unattainable through conventional methods (Kantarcioglu 2024; Ejigu et al. 2024). This paradigm shift is driven by technological advancements and the increasing availability of large-scale operational data, which AI systems can leverage to uncover hidden patterns, optimize processes, and proactively address safety concerns (Jendoubi & Asad 2024; Ejigu et al. 2024).

2 MAIN TECHNOLOGICAL AREAS FOR AI IMPLEMENTATION

The implementation of AI in the nuclear industry encompasses a wide range of applications, all centered around the analysis of vast and complex datasets generated by plant operations. AI systems are capable of processing real-time data streams from thousands of sensors distributed throughout a nuclear facility, enabling the identification of subtle anomalies, prediction of equipment failures, and automation of both routine and emergency procedures. By leveraging sophisticated algorithms, AI can reveal correlations and trends that are often missed by human operators, thereby supporting more informed and timely decision-making. These capabilities are particularly valuable in environments where safety is paramount and the consequences of human error or equipment malfunction can be severe.

2.1 Predictive Maintenance

One of the most promising applications of AI in nuclear power plants is predictive maintenance, which utilizes machine learning algorithms to analyze real-time operational data from critical equipment such as pumps, turbines, and valves (Gohel et al. 2021; Walker et al. 2023). These algorithms are trained to recognize the normal operating states of various components by continuously monitoring parameters like vibration, temperature, pressure, and flow rates. When deviations from established norms are detected, the system can alert operators to potential issues long before they escalate into failures. This approach enables a shift from traditional scheduled maintenance to a more dynamic, condition-based strategy that optimizes the timing of repairs and replacements. The result is a substantial reduction in unplanned shutdowns, lower maintenance costs, and enhanced safety, as critical failures are prevented before they occur (Picot 2023; Gruenwald et al. 2024). Furthermore, predictive maintenance supported by AI contributes to the overall reliability of the plant, ensuring that essential systems remain operational and reducing the risk of accidents caused by equipment malfunction (Gohel et al. 2021).

2.2 Optimization of processes and efficiency

AI-driven optimization extends beyond maintenance to encompass the entire spectrum of plant operations, including power management, fuel cycle optimization and the efficiency of cooling systems (Zhang et al. 2024; Deng et al. 2024). By integrating data from operational sensors, electricity grid consumption patterns, and external factors such as weather forecasts, AI systems can recommend optimal operating modes for reactors and turbines (Seurin et al. 2023).

This holistic approach allows nuclear plants to maximize electricity generation while minimizing fuel consumption and equipment wear, thereby improving both economic and environmental performance (Seurin et al. 2023; Picot 2023). Advanced AI models can also simulate various operational scenarios, enabling operators to evaluate the impact of different strategies on plant efficiency and safety (Zhang et al. 2024; Deng et al. 2024). The continuous feedback provided by these systems supports adaptive management, allowing plants to respond dynamically to changing grid demands and operational conditions without compromising safety margins (Seurin et al. 2023).

2.3 Digital twins

The concept of digital twins represents a significant advancement in the application of AI to nuclear energy. A digital twin is a highly detailed, virtual replica of a physical asset – such as an entire nuclear power plant or individual components – continuously updated with real-time data from operational sensors (Kropaczek et al. 2023; Mondal et al. 2024). This technology enables operators to simulate a wide range of scenarios, including accident conditions, equipment modifications, and routine operations, in a risk-free virtual environment (Yadav et al. 2021; Al. Rashdan et al., 2022).

Digital twins also play a crucial role in operator training, providing an immersive and realistic environment where personnel can practice responding to complex situations and develop

the skills necessary to manage both normal and emergency operations (Kropaczek et al. 2023; Mondal et al. 2024).

Additionally, proposed design changes can be tested virtually before implementation, allowing for a thorough assessment of their impact on plant safety and efficiency (Kropaczek et al. 2023).

2.4 Process management

AI-driven process management in nuclear power plants encompasses intelligent fuel management, dynamic efficiency optimization, and advanced nuclear waste management strategies. These applications leverage real-time data and predictive analytics to optimize plant performance while maintaining strict adherence to safety standards.

2.4.1 Intelligent fuel management

AI algorithms are increasingly used to calculate the optimal configuration of fuel assemblies within the reactor core, balancing the goals of maximum fuel burnup and strict compliance with safety regulations. By simulating various core configurations and operational scenarios, AI can recommend fuel loading patterns that enhance efficiency, extend fuel life, and minimize waste generation (Zhang et al. 2024). This intelligent approach to fuel management not only improves the economic performance of nuclear plants but also supports the safe and sustainable operation of reactors over their lifespan (Deng et al. 2024).

2.4.2 Dynamic efficiency

The ability of nuclear plants to operate flexibly and adapt their output to the needs of the electricity grid is critical for modern energy systems. AI systems enable dynamic efficiency by continuously monitoring grid demand, operational parameters, and external factors such as weather conditions (Seurin et al. 2023). By adjusting reactor and turbine settings in real time, AI ensures that plants operate within safe limits while maximizing electricity generation and minimizing wear on equipment (Picot 2023). This adaptive management capability is particularly valuable in the context of increasing renewable energy integration, where grid stability and responsiveness are essential.

2.5 Nuclear waste management

The management of spent nuclear fuel and radioactive waste is a complex logistical challenge that requires thorough tracking, categorization, and long-term planning. AI technologies are being deployed to streamline these processes, providing automated systems for inventory management, waste classification, and the optimization of storage and disposal strategies. By integrating data from multiple sources and simulating various scenarios, AI can help ensure the safe and efficient handling of nuclear waste, reducing risks to both personnel and the environment (Ejigu et al. 2024).

3 THE ROLE OF AI IN NUCLEAR SAFETY AND ACCIDENT MANAGEMENT

The integration of AI into nuclear safety and accident management represents a paradigm shift in how risks are identified, assessed, and mitigated within nuclear facilities. Rather than replacing human expertise, AI acts as a powerful augmentation tool, providing operators and engineers

with advanced analytical capabilities and real-time decision support. This synergy between human judgement and machine intelligence is crucial, given the complexity and high stakes of nuclear operations.

AI systems can process vast amounts of operational and historical data, enabling the early detection of anomalies, the reduction of human error, and the proactive identification of emerging risks that might otherwise go unnoticed. By leveraging global incident databases and learning from operational experiences across the nuclear industry, AI can help standardize best practices and improve the overall safety culture within nuclear organizations.

3.1 Nuclear safety

AI's contribution to nuclear safety is multifaceted, encompassing early warning systems, human error reduction, and proactive risk analysis.

3.1.1 Early warning

Preventive maintenance systems powered by AI, such as vibration monitoring and thermal cycle tracking, serve as sophisticated early warning mechanisms for critical equipment (Gohel et al. 2021; Walker et al. 2023). By continuously analyzing sensor data, these systems can detect subtle deviations from normal operating conditions – such as changes in vibration patterns or temperature fluctuations that may indicate impending equipment failure (Walker et al., 2023).

For example, an AI system might identify an anomaly in a main circulation pump weeks before it becomes a safety concern, allowing for timely intervention and repair (Gruenwald et al. 2024). This predictive capability is especially vital for safety-related components, which are routinely tested and monitored to ensure their reliability in emergency situations (Walker et al. 2023). The early identification of potential failures not only prevents costly unplanned shutdowns but also significantly reduces the risk of accidents caused by equipment malfunction (Gohel et al. 2021).

3.1.2 Reduction of human error

Human error remains a leading contributor to nuclear incidents and accidents, often arising from procedural lapses, misinterpretation of data, or cognitive overload during high-stress situations (Shanahan et al. 2023; Kim 2024). AI systems can function as “co-pilots” in the control room, continuously monitoring operator actions and providing real-time feedback if a procedure is performed incorrectly or if an action could lead to a risky situation (Kim 2024). By cross-referencing operator inputs with established protocols and procedures and historical incident data, AI can issue timely warnings and suggest corrective actions, thereby reducing the likelihood of mistakes (Kim 2024). This collaborative approach also supports ongoing training and skill development for plant personnel (Kropaczek et al. 2023).

3.1.3 Proactive risk analysis

AI's ability to analyze incident reports and operational data from nuclear power plants worldwide enables a proactive approach to risk management (Ejigu et al. 2024). By identifying recurring patterns, hidden correlations, and emerging threats, AI systems can uncover risks that may be overlooked by traditional human analysis (Ejigu et al. 2024; CNSC&ONR&NRC 2024). These insights (facts from incidents or accidents, conclusions and recommendations) are

disseminated through international platforms such as the International Atomic Energy Agency's INIS system, facilitating the sharing of lessons learned and the continuous improvement of safety practices across the industry. Proactive risk analysis supported by AI not only enhances the resilience of individual plants but also contributes to the global advancement of nuclear safety standards (CNSC&ONR&NRC 2024).

3.2 Accident management

Accident management is arguably the most critical area where AI can deliver substantial benefits to nuclear safety and operational resilience. AI-powered decision support systems (DSS) and robotic intervention technologies are transforming the way nuclear plants respond to emergencies, enabling faster, more informed, and more effective actions during crisis situations.

3.2.1 Decision Support Systems (DSS)

During an accident, operators are confronted with an overwhelming volume of data and must make rapid decisions under intense pressure (IAEA 2025). AI-based DSS can process thousands of signals in real time, analyze the evolving situation, and predict the most likely progression of the event, such as the spread of radioactive contamination following a primary circuit leak (IAEA 2025; Shanahan et al. 2023). These systems draw on emergency plans, historical incident data, and advanced simulations to recommend the most effective response strategies, presenting operators with a shortlist of optimal actions supported by robust data analysis (IAEA 2025). While the final decision remains with human operators, the guidance provided by AI-based DSS enhances situational awareness, reduces cognitive load, and supports more effective crisis management (Shanahan et al. 2023).

3.2.2 Robotic intervention

AI-powered autonomous systems and robotics are revolutionizing the way inspections, maintenance and repairs are conducted in nuclear facilities, particularly in areas with high radiation levels where human access is hazardous or impossible. Equipped with advanced computer vision and image analysis capabilities, these robots can identify structural defects such as cracks, corrosion or other anomalies in equipment and infrastructure (Shanahan et al. 2023; IAEA 2025).

In severe accident scenarios, such as those experienced at Fukushima or Chernobyl, the deployment of AI-powered robots can be lifesaving (Shanahan et al. 2023; IAEA 2025). These autonomous systems are capable of entering highly radioactive environments to assess damage, close valves, perform repairs, and carry out other critical tasks that would be lethal for human responders (Shanahan et al. 2023). Equipped with advanced sensors and computer vision, AI-controlled robots provide real-time feedback to operators, enabling precise and timely interventions during emergencies (IAEA 2025).

The deployment of AI-controlled robots significantly reduces the radiation exposure of personnel, enhances the precision and reliability of inspections, and enables the execution of complex tasks in environments that would otherwise be inaccessible (IAEA 2025). In addition to routine maintenance, autonomous systems are increasingly being used for emergency response, providing real-time situational awareness and performing critical interventions during accident scenarios (Shanahan et al. 2023).

4 CHALLENGES TO AI IMPLEMENTATION IN NUCLEAR IDUSTRY

Despite its transformative potential, the implementation of AI in the nuclear industry is not without significant challenges. Key issues include cybersecurity, regulatory compliance, and the establishment of trust between operators and AI systems.

4.1 Cybersecurity

AI-related systems in nuclear facilities must be rigorously protected against cyber threats, given the potential consequences of unauthorized access or manipulation. The integration of AI introduces new attack vectors, including vulnerabilities in data transmission, algorithm integrity, and system interfaces (CNSC&ONR&NRC 2024). Ensuring robust cybersecurity requires the adoption of advanced encryption, continuous monitoring, and the development of resilient architectures that can withstand sophisticated hacking attempts. Regulatory bodies are increasingly focused on establishing guidelines and standards for the secure deployment of AI in critical infrastructure, recognizing the importance of safeguarding both operational and safety-related systems (CNSC&ONR&NRC 2024).

4.2 Regulations

Regulatory compliance is a major hurdle for the adoption of AI in nuclear power plants, particularly for safety-critical applications. Nuclear regulators demand that all safety-related systems be fully understandable, predictable, and transparent - a requirement that is often at odds with the “black box” nature of many AI models (CNSC&ONR&NRC 2024). The lack of accessible source code and the complexity of machine learning algorithms pose significant challenges for verification, validation, and licensing. To address these concerns, the industry is exploring the development of explainable AI (XAI) techniques and collaborative frameworks that facilitate regulatory oversight while preserving the benefits of advanced analytics (CNSC&ONR&NRC 2024).

4.3 Trust

Building trust between operators and AI systems is essential for its successful implementation and adoption. Operators must have confidence in the recommendations provided by AI, which requires extensive testing, validation, and ongoing involvement in the development and deployment process. Transparent communication, user-friendly interfaces, and continuous training are critical for fostering trust and ensuring that AI systems are perceived as reliable partners rather than opaque or unpredictable entities (Mondal et al. 2024). The establishment of trust not only supports operational effectiveness but also enhances the overall safety culture within nuclear organizations (Kropaczek et al. 2023).

5 EXAMPLES OF IMPLEMENTING AI IN NUCLEAR ENERGY IDUSTRY

The practical implementation of AI in the nuclear industry is rapidly expanding, with a diverse array of applications and pilot projects now underway across the globe. These initiatives span predictive maintenance, process optimization, digital twins, robotics, regulatory compliance,

operator training, nuclear waste management, and grid integration, demonstrating the versatility and transformative potential of AI in nuclear power.

5.1 Predictive maintenance and real-time monitoring

AI-driven predictive maintenance is now a cornerstone of modern nuclear plant operations. For example, in USA Exelon (now Constellation Energy Group) has deployed machine learning algorithms for real-time monitoring and predictive maintenance at several of its nuclear facilities, including Peach Bottom NPP and Limerick NPP in Pennsylvania. These systems analyze sensor data to detect anomalies and forecast equipment failures, enabling maintenance to be scheduled proactively and reducing unplanned outages. Blue Wave AI Labs estimates that such tools save over \$1.6 million per year per reactor by cutting fuel costs, minimizing downtime, and reducing time spent on analysis and planning (Walker et al. 2023; Gruenwald et al. 2024; Jendoubi & Asad 2024; Picot 2023; Nuclear Business Platform 2024).

Similarly, the U.S. Department of Energy's Idaho National Laboratory has demonstrated explainable AI technologies for predictive maintenance, focusing on performance, explainability, and trustworthiness. These systems have been shown to improve decision-making and reduce operational costs (Walker et al. 2023).

5.2 Process optimization and grid integration

AI is increasingly used to optimize plant operations, including dynamic load-following and grid integration. For instance, AI systems at Constellation Energy and other operators process operational data, grid demand, and weather forecasts to recommend optimal reactor and turbine settings, maximizing electricity generation while minimizing fuel consumption and equipment wear (Seurin et al. 2023; Jendoubi & Asad 2024; Nuclear Business Platform 2024).

AI also supports flexible operation, allowing nuclear plants to adapt output to grid needs, which is critical as other renewable energy sources (wind farms, solar plants) become more prevalent (Jendoubi & Asad 2024).

5.3 Digital twins and simulation

Digital twin technology is revolutionizing nuclear reactor management. In US, Argonne National Laboratory has developed advanced digital twins for reactors, including the Experimental Breeder Reactor II and the Fluoride-salt-cooled High-temperature Reactor, using graph neural networks to simulate reactor behavior under various conditions. These digital twins enable continuous monitoring, predictive maintenance, and real-time decision-making, enhancing safety and efficiency (Kropaczek et al. 2023; Mondal et al. 2024; Cohen 2025; Hu et al. 2025; Huber 2025).

In UK, Rolls-Royce is integrating digital twins into the design and operation of its Small Modular Reactors (SMRs), allowing for risk-free simulation of operational scenarios, prediction of maintenance needs, and optimization of plant performance (Kropaczek et al. 2023; Mondal et al. 2024).

5.4 Robotics and autonomous systems

AI-powered robotics are increasingly deployed for inspection, maintenance, and decommissioning in hazardous environments. The UK's RAIN Hub and Robotics and AI Collaboration Laboratory (RAICo) have developed and deployed first-of-a-kind robots at Sellafield, Dounreay, Chernobyl, and Fukushima, performing autonomous radiometric surveys and remote handling tasks that would be dangerous for humans (Shanahan et al. 2023; Lennox 2021; Lopez Pulgarin et al. 2025).

Lancaster University and other research groups have proposed cyber-physical architectures for nuclear decommissioning, integrating sensor networks, robotics, and AI for efficient and safe operations (Shanahan et al. 2023).

5.5 Nuclear waste management

AI is transforming nuclear waste management by optimizing waste classification, treatment, storage, and disposal. Advanced machine learning algorithms enhance the precision of waste categorization and support predictive modelling for risk assessment and strategic planning (NEA 2023; Abulifa et al. 2025; Chenniappan & Devarajan 2024). AI-driven platforms, such as NuclearAI, use graph neural networks and the integration of the neutron-physics computer code Monte Carlo to model isotopic transmutation, minimizing radiotoxicity and heat load (Boyyey 2025).

In the US, multi-agent systems with AI are also being developed for regulatory compliance and decision-making in nuclear waste management, as demonstrated in a case study of the uranium mining area near Winslow, Arizona (Chang et al. 2025).

5.6 Operator training and simulation

AI is increasingly used for operator training and simulation. Argonne National Laboratory has explored the use of generative AI models to enhance operator interaction with diagnostic information, providing clear explanations of faults and supporting decision-making (Vilim et al. 2024; Jendoubi & Asad 2024). AI-guided reasoning-based operator support systems, such as those developed by Hanna et al. (2024), use logic programming to assist operators in fault identification and management during incidents.

5.7 Administrative automation and regulatory compliance

AI is also being leveraged to streamline regulatory compliance and enhance cybersecurity. Platforms like Nuclearn³ automate documentation, compliance, and procedure writing, freeing engineers from repetitive administrative tasks and increasing engineering capacity. Nuclearn's *Agentic AI* and *AI Marketplace* solutions provide tools for automating regulatory correspondence, license extensions, and compliance screening (Fox & Vincent 2025; Connor 2025).

The U.S. Nuclear Regulatory Commission (NRC), UK Office for Nuclear Regulation (ONR), and Canadian Nuclear Safety Commission (CNSC), as well as the International Atomic Energy Agency (IAEA), have published guidelines and principles for deploying AI in nuclear

³ Based in Phoenix, Arizona, United States.

applications, emphasizing safety, security, and transparency (CNSC&ONR&NRC 2024; IAEA 2025).

5.8 Fuel management and core design

AI is being applied to optimize nuclear core and fuel designs. Vattenfall Nuclear Fuel in Sweden has explored the use of neural networks for in-core fuel management, predicting key reactor parameters and accelerating design evaluation (Åsman 2025). Texas A&M University has developed advanced thermo-mechanical phase-field models to simulate fuel behavior under stress, supporting longer fuel cycles and improved efficiency (Aquino et al. 2025).

6 CONCLUSION

The integration of AI into the nuclear energy sector marks a pivotal advancement in how nuclear facilities are operated, maintained, and safeguarded. As demonstrated by a growing number of real-world applications, AI is no longer a theoretical concept but a practical tool that is actively enhancing nuclear safety and accident management, predictive maintenance, process optimization, digital twin development, autonomous robotics, operator training, regulatory compliance, and nuclear waste management. Leading operators in U.S. such as Exelon, Constellation Energy, along with technology partners like Westinghouse, Rolls-Royce, and major research laboratories, have shown that AI-driven solutions can significantly reduce unplanned outages, improve safety margins, serve as decision support system and optimize resource utilization. The deployment of digital twins and AI-powered simulation platforms enables risk-free testing and continuous monitoring, while robotics and autonomous systems are revolutionizing inspections and interventions in hazardous environments. AI's role in nuclear waste management and regulatory compliance is also expanding, with advanced algorithms supporting more accurate classification, documentation, and strategic planning.

Despite these advances, challenges remain in the areas of cybersecurity, regulatory transparency, and building trust among operators and stakeholders. Addressing these issues will require ongoing collaboration between industry, regulators, and technology providers, as well as the development of robust frameworks for explainable and secure AI.

In summary, AI is set to become an indispensable component of the nuclear industry's future, augmenting human expertise and enabling safer, more efficient, and more resilient nuclear power operations. Continued investment in research, pilot projects, and cross-sector investigations and partnerships will be essential to fully realize the transformative potential of AI in nuclear industry.

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Design of a Training Program for Civil Aviation Pilots Aimed at Increasing Their Stress Resistance in Flight

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Abstract

The article discusses a way to reduce the emotional response of pilots to the occurrence of abnormal situations in flight. It consists in simulating various abnormal situations on a computer simulator and proposing the pilot to recognize the current flight threat factor in ambiguous situations. To reduce emotional reactions in pilots and to prevent stress, which usually occurs due to the lack of understanding of which threat factor caused the abnormal situation, ICAO recommends developing a computer program "Threat and Error Management" (TEM). The article presents a specific technology used in the design of a TEM program for one of the Russian airlines.

Keywords: amygdala, emergency situation, emotional response, stress resistance, flight threat factors, TEM program.

INTRODUCTION

Usually, civil aviation pilot training programs are aimed at transferring professional knowledge and skills to pilots. These programs do not include special classes that can improve such mental qualities as stress resistance in pilots' work. However, even with sufficient piloting skills, there are still problems with pilots' behavior in emergency situations. In particular, it remains unclear whether pilots will become stressed when they suddenly detect a dangerous flight situation, or whether they will respond to it relatively calmly (without stress)? At the same time, it is known that the effectiveness of their thinking, i.e. the speed and correctness of finding solutions to get out of a dangerous situation, largely depends on how strong emotions pilots will experience in an emergency situation.

In this regard, the task of designing such training programs for pilots, which would be aimed at reducing the level of their emotional response to the emergence of dangerous situations in flight, becomes relevant. This article is devoted to the technology of designing such a training program for training civil aviation pilots with the aim of more effective interaction with aircraft equipment. But first, we need to consider what determines a person's (pilot's) stress resistance and whether it can be improved through special training.

1 POSSIBILITIES OF CORRECTION OF STRESS RESISTANCE

Many neuropsychologists believe that stress resistance is an innate quality and depends on the degree of reactivity, i.e. responsiveness to external influences of such a brain structure as the

amygdala. The amygdala is part of the limbic system of the brain (Fig.1), which is generally responsible for a person's emotional reactions. It is the amygdala that produces feelings of fear and anxiety when an external situation is perceived as potentially dangerous (Wiesel 2017).

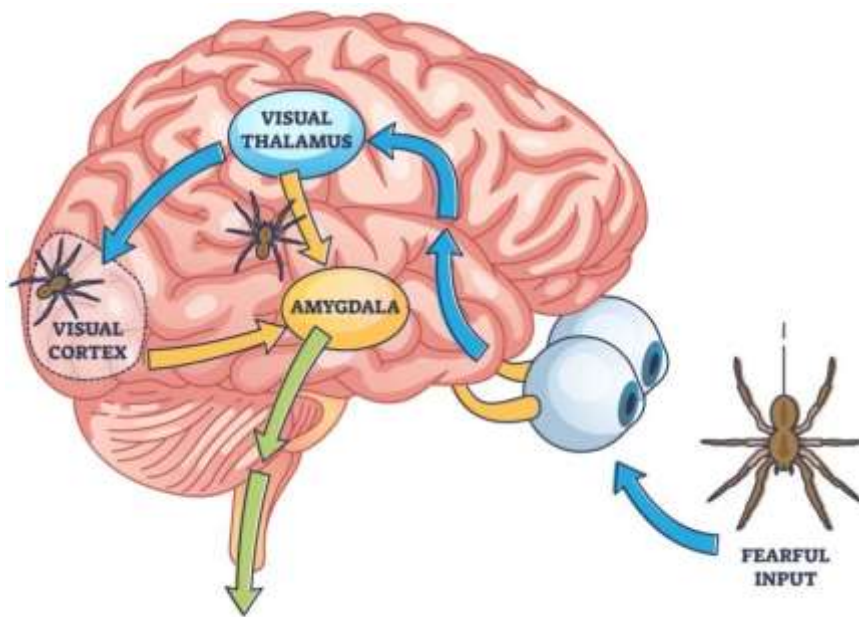


Fig. 1 Location of the amygdala in the limbic system of the brain (by O. Guy-Evans, MSc, reviewed by S. McLeod, PhD; <https://www.simplypsychology.org>)

How quickly the amygdala will be excited and to what extent it will generate a feeling of fear and anxiety depends on the innate properties of the nervous system in a particular person. One of the properties of the nervous system is called lability: it means the speed and intensity of the nervous system's response to external influences. Thus, if the limbic system, including the amygdala, is highly labile, there will be an increased emotional reactivity (sensitivity) in response to external danger factors. In this case, it is said that a person is highly unstable to stress. Conversely, if the amygdala is less labile, the person is more resistant to stress.

For this reason, it is impossible to change a person's stress resistance in general, as it is a physiological characteristic of the individual's nervous system. However, it is possible to reduce their emotional response to certain professional situations, particularly dangerous emergencies. How can this be achieved?

As we know, when a person finds themselves in a dangerous and unfamiliar situation, they tend to become more anxious than when they are in the same situation but have experienced it before. It is the factor of "personal acquaintance" with a particular emergency situation that can help prevent the pilot from becoming stressed when the situation occurs again during a flight. Therefore, virtual immersion of pilots in possible emergency situations (using a computer simulator) and training them on how to handle them can help reduce negative emotions in real flights. Renowned neuroscientist Catherina Pittman also says this (Pittman 2021).

Here, it is necessary to make a small digression and explain which degree of emotional arousal has a positive effect on the quality of professional activity, and which degree of arousal has a negative effect, i.e., it impairs the process of information analysis: it narrows the scope of thinking, slows it down, and provokes errors in activity.

According to the well-known Yerkes-Dodson law of psychology, the best performance is achieved when a person is in a state of nervous arousal that is slightly above average. The average level of nervous excitement is observed in a person in a normal working condition. If some factors appear in the process of activity that complicate this process, then nervous excitement increases and the individual's mental resources are activated to solve a complicated task. This mental state is called the “mobilization” state, and it is characterized by an even higher level of mental performance than in the normal calm state of an employee.

However, a further increase in nervous excitement leads to the development of other types of mental states: mental tension, then stress, and then panic. All of these conditions, unlike mobilization, are unfavorable for professional activity, as they are dominated by emotional processes in the brain that suppress (inhibit) the functioning of other mental functions. This manifests itself in the incomplete (limited) functioning of perception, attention, thinking, and memory, resulting in errors, omissions, delays, and inadequate decisions in activities. The phenomenon of poor mental performance under stress was clearly demonstrated in the experiments conducted by American psychologists Yerkes and Dodson, and later by other scientists (Bodrov 2006; Khanin 2010).

Based on this, it is important for the training of civil aviation pilots to ensure that they experience only a state of mobilization when flight conditions become more challenging, rather than entering a state of stress when an emergency situation arises on board the aircraft.

This can be achieved by immersing pilots in simulated (virtual) emergency situations that can be modeled on a computer simulator. It is advisable to simulate only those emergency situations that often cause stress. These situations are at the initial stage of any emergency, where the pilot needs to understand the cause of the situation and identify the threat to the flight. It is more difficult for a pilot to determine the true cause of a flight deviation, especially in situations where different threat factors may be behind the same symptoms, than it is to choose an action plan to deal with the situation.

Unfortunately, many pilots have a psychological tendency to rush into correcting a dangerous situation as quickly as possible, which forces them to accelerate and shorten the process of analyzing possible flight hazards. They tend to focus on the most common flight hazard, such as assuming that a decrease in aircraft speed is caused by a malfunctioning autopilot and acting accordingly. However, the actual cause of the flight hazard may be different, such as icing on the speed sensors, which requires different actions from the pilot to correct the situation. If the pilot “struggles” with the wrong cause of an emergency, he will move the flight situation from the “dangerous” status to the “catastrophic” status, when the plane’s destruction becomes inevitable.

A similar disaster due to the misidentification of a flight threat factor occurred, in particular, with the French A-330 in 2009, which crashed into the Atlantic Ocean, as well as with the Russian An-148, which crashed due to a collision with the ground in 2018.

The insidiousness of some abnormal situations lies in the fact that they have the same initial symptoms, i.e., the same set of deviations, although they may be caused by completely different threat factors. In this regard, it is necessary to familiarize pilots with such “ambiguous” abnormal situations in advance and teach them algorithms for recognizing various threat factors on a computer simulator.

2 TRAINING PROGRAM FOR STRESS PREVENTION

To create such a training program, the International Civil Aviation Organization (ICAO) provides relevant recommendations in the document “Personnel Training” – Doc. 9868, 2008 (Appendix C). This document proposes that all airlines develop a computer program called “Threat and Error Management” (TEM), which is aimed at modeling various emergency situations in which it may be difficult to determine the threat factor to a flight, and therefore stress in pilots. As experience in investigating aviation accidents has shown, stress occurs when pilots fail to understand the true cause of an emergency situation, leading to fear of not finding the right way out and potentially losing themselves and their passengers.

If the pilots are already familiar with a set of the most difficult abnormal situations to recognize in advance, try to analyze the possible threat factors themselves, find among them the actual threat factor and successfully build a plan for its parrying, then they will feel more calm and confident when facing a similar situation in a real flight. Due to such training on a computer simulator, it will be possible to lower the degree of emotional response of pilots (to prevent stress) to the emergence of dangerous flight situations directly in their activities. Moreover, moderate nervous excitement will lead to a state of mobilization that is beneficial for pilots, and knowledge of the algorithm for finding the current threat factor will speed up the pilot’s thinking process.

A similar computer program, TEM, was developed by the Russian airline *Aeroflot – Russian Airlines* (Yakimovich 2024). To simulate 20 flight situations, the monitor displayed images of the A-320 instrument panels, showing various changes in the readings of the flight instruments, engineering displays, and emergency lights. The pilot was first presented with a normal flight scenario at a specific stage, followed by the onset of an abnormal situation. The pilot should have noticed the deviations from the normal flight mode (Fig. 2).

After that, on the adjacent monitor, paired with the first monitor, a question was asked about what signs of an abnormal situation he noticed. The adjacent monitor also offered options for answering this question, while the first monitor retained the image of the analyzed situation.

Next, the TEM program sequentially asked the pilot a number of other questions, which he had to answer (Fig. 3).

In particular, the following questions were asked:

1. What hypotheses can you make about the flight threat factors?
2. What verification actions do you intend to take to test the first hypothesis (or the second)?
3. Which threat factor is active in this situation?
4. What plan of action will you choose to counter the identified threat factor?

It is important to add that when the pilot wanted to perform virtual verification actions to confirm the presence of a suspected threat factor, they selected the necessary verification actions from the provided list. The selected verification actions were then conditionally executed, and the pilot could see on the first screen the consequences of these actions, such as changes in flight parameters or the appearance of warning messages or displays. After summarizing the information received, the pilot was able to either accept the hypothesis under consideration and choose a plan of action, or reject it and then proceed to test the next hypothesis.



Fig. 2 Dynamic image on the monitor screen when deviations in flight parameters from the normal mode begin

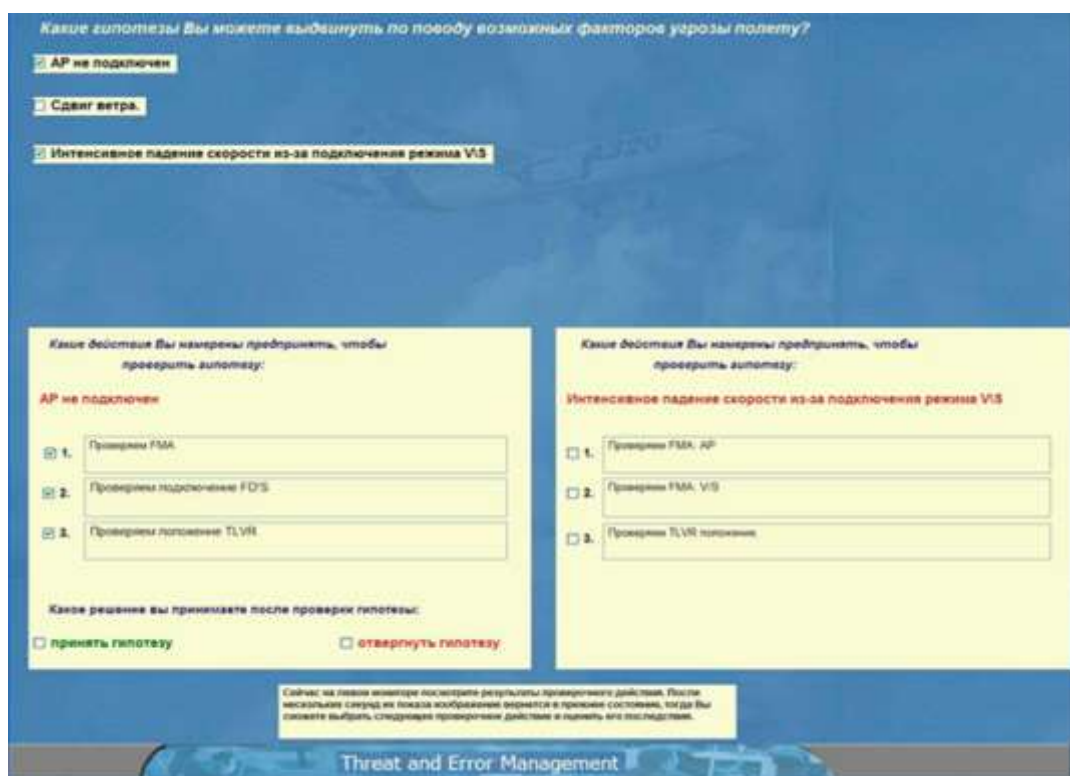


Fig. 3 Image on the second monitor, where questions were presented to test various hypotheses about possible threat factors

These questions and answers guided the pilot's thinking in the right direction when it came to finding an answer about the current threat factor. However, these were not just leading questions; they represented a specific thinking algorithm that the pilot should follow when analyzing an emergency situation. In essence, the pilot was encouraged to adopt a universal approach to thinking in situations where flight threats were identified (Yakimovich and Gorodetsky 2013).

The inclusion of the TEM program in the professional training of pilots helps, firstly, to direct the pilot's thinking in an emergency situation in the right direction, i.e., it helps to avoid confusion and immediately start diagnosing the causes of the incident. Secondly, the program teaches pilots to conduct diagnostics according to a specific scheme: to generate possible hypotheses and sequentially test them until the actual flight hazard factor is identified. Only then can they proceed to take action to mitigate the hazard. Thirdly, this program allows you to familiarize yourself with the most difficult situations in advance (during ground training), when there are similar initial symptoms of flight hazards and it is difficult to identify the actual hazard.

In conclusion, I would like to emphasize that the design and implementation of the TEM program in airlines for various types of aircraft will reduce the percentage of aviation accidents caused by human error and make a significant contribution to improving flight safety in civil aviation as a whole.

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