Design Problems and Knowledge Management

Electronic Journal

Volume 3, Issue 3

May - June 2025

In this issue:

Title page image: Albrecht Dürer (1514) Melencolia I (Public Domain).

Publisher: Society of Aerospace and Nuclear Engineers
Editors: Yuri Spirochkin and Dimitar Popov

Date of publication: 29 June 2025

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Recommended citation format (Harvard style):
<Author> (2025) <Article title>. Design Problems and Knowledge Management, 3(3):<pages>. https://saneorg.wixstudio.com/index/dpkm. Accessed <date>

The Role of Ionizing Radiation and Especially of Small Doses on the Evolution of Life on Earth

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Weak stimuli accelerate vital activity, medium ones promote it, strong ones inhibit it, and very strong ones snuff it out
F. Hueppe

Abstract

Life on Earth has evolved under continuous exposure to ionizing radiation from both terrestrial and extraterrestrial sources. While high radiation doses (HDR) are generally harmful to biological systems—though they played a constructive role in early geological history and though there are some organisms (extremophiles) adapted to, functioning and even profiting from HDR—the effects of low-dose radiation (LDR) on evolution remain complex and intriguing. This article explores the potential evolutionary contributions of LDR, focusing on its role in genetic variability, DNA repair activation, and adaptive responses. We examine Earth's historical radiation environment, analyze biological responses to LDR across diverse living organisms, including radiation hormesis (the proactive role of low doses in the organisms), and assess its implications for adaptation, diversification, and resilience. Additionally, we evaluate evidence of LDR-induced mutagenesis, its impact on genetic diversity, and its role in shaping evolutionary mechanisms. Integrating insights from radiation physics, radiobiology, genetics, and evolutionary biology, this article provides a comprehensive overview of the scientific literature while illuminating the subtle yet significant influence of LDR on life’s evolutionary trajectory.

Keywords: high dose/low-dose (ionizing) radiation, abiogenesis, mutagenesis, DNA repair, radiation hormesis, biological response, adaptation and resilience, transgenerational and epigenetic changes, evolution.

1 DEFINITIONS AND MEASUREMENT UNITS USED

Unit for (geological) time:
Ga – Gigaanum = 1 billion years.
Definitions and units for the radiation doses are given below.

Radiation exposures are measured in terms of the quantity absorbed dose, which equals the ratio of energy imparted to the mass of the exposed body or organ. The unit of absorbed dose is joules per kilogram (J/kg). For convenience this unit has been given the special name gray (Gy). Ionizing radiation can consist of electromagnetic radiation, such as X-rays or gamma rays (γ-rays), or of subatomic particles, such as protons, neutrons, and α-particles. X- and γ-rays are said to be sparsely ionizing, because they produce fast electrons, which cause only a few dozen ionizations when they traverse a cell. Because the rate of energy transfer is called linear energy transfer (LET), they are also termed low-LET radiation. In contrast, the heavier particles, such as neutrons, α-particles, or heavier ion particles are termed high-LET radiation because they transfer more energy per unit length as they traverse the cell. For high-LET radiation—such as neutrons, α-particles, or heavier ion particles—equivalent dose or effective dose equals the absorbed dose multiplied by a weighting[1] factor to account for biological effect of different types of radiation on human tissue (National Research Council 2006).

Equivalent dose is calculated for individual organs. It is based on the absorbed dose to an organ, adjusted to account for the effectiveness of the type of radiation, i.e. the equivalent dose is equal to the absorbed dose times a quality or weighting factor, which is different for the different organs. Effective dose is calculated for the whole body. It is the addition of equivalent doses to all organs, each adjusted to account for the sensitivity of the organ to radiation (ICRPaedia 2025).

Since the weighting or quality factors are dimensionless, the unit of equivalent dose is also joules per kilogram. However, to avoid confusion between the two dose quantities[2], the special name Sievert (Sv) has been introduced for use with equivalent dose[3]. The units for dose are given in Table 1 below.

Table 1 Units of dose (National Research Council 2006)

Units of Dose	Unit	Symbol Conversion Factors
Becquerel (SI)	Bq	1 decays/s = 2.7×10^{-11} Ci
Curie	Ci	3.7 × 1010 decays/s = 3.7×10^{10} Bq
Gray (SI)	Gy	1 J/kg = 100 rads
Rad	rad	0.01 Gy
Sievert (SI)	Sv	1 J/kg = 100 rem
Rem	rem	0.01 Sv

Note: SI in brackets indicates belonging to the International System of units (Système International d'unités, SI, French). Gray is the special name of the unit (J/kg) to be used with absorbed dose; Sievert is the special name of the unit (J/kg) to be used with equivalent dose. Equivalent dose equals absorbed dose times weight (quality) factor (National Research Council 2006).

2 FOREWORD

During my student years (1980-85), I had a friend whose father was a doctor of biological sciences. He told me that the topic of his dissertation was related to the impact of radiation from nuclear tests in French Polynesia on humans. Naturally, this aroused my curiosity as student in Sofia University on physics of Earth, Atmosphere and Space, but in those years the topic was classified, and the only thing my friend whispered to me was, that 20 years after the first explosions (i.e., in the 1980s), the next generation people on some atolls like Moruroa were quite tall – over 2 meters. Later, I realized that this information was false, as data from various sources

[1] Also called quality factor.
[2] Absorbed vs. effective or equivalent dose.
[3] And effective dose as well.

indicates that the average height for men in French Polynesia is around 1.78 m, and for the women – 1.72 m (Worlddata 2025). However, due to the long-term consequences of nuclear tests, the Polynesian people have suffered from some diseases including thyroid cancer, leukemia, lymphoma, breast cancer and stomach cancer (Disclose 2021). Thyroid cancer has been a particular area of focus due to the known release of radioactive iodine during the tests. There was a small but statistically significant increase in the risk of thyroid cancer associated with exposure to radiation from the French nuclear testing program (Drozdovitc et al. 2021).

In 1993, my wife's thyroid gland was operated (two-thirds of it was preventively removed as for doubts of future papillary carcinoma), and this was generally believed to be related to the consequences of the Chernobyl accident at that time. A recent study proves that the frequency of thyroid cancer among Bulgarian population has increased twice within the period 1986-93 relative to the period 1980-86 (Ivanova et al. 2020).

In the mid of 1990s, I was already working at a nuclear power plant, where I met a man from the reactor equipment maintenance team who told me that he had accumulated an effective dose of 1.04 Sv[4], from which 8.6 mSv he had received as an acute dose during a small radiological incident. However, this person had divorced and remarried and had two daughters from his second marriage who were completely normal, i.e., there were no mutations in his offspring.

These few examples from my life made me think about and explore the role of radiation and in particular low doses of radiation on life on Earth and its evolution. In my work and preparation of this article I relied on the help of my daughter, who is molecular biologist. In submitting the article to the journal DPKM, published by SANE, I was guided by an important provision of the stated policy of this Society, which aims to achieving "a synergistic effect – especially in complex, interdisciplinary research and development". The interdisciplinary research in this case is on the frontier between the ionization radiation physics and evolutionary biology.

3 INTRODUCTION

The emergence and diversification of life on Earth, spanning nearly four billion years, have been shaped by a myriad of environmental factors, including climate change, geological events, biotic interactions, and intrinsic genetic predispositions. Among these, ionizing radiation, originating from primordial radionuclides in the Earth's crust and cosmic radiation from space, has been a persistent presence. The cosmic radiation primarily consists of positively charged ions from protons to iron and larger nuclei coming from outside the Solar System. This radiation interacts with atoms in the atmosphere to create an air shower of secondary radiation, including X-rays, muons, protons, alpha particles, pions, electrons, and neutrons. The immediate[5] (or acute) dose

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[4] Equal to ~432 average annual doses due to the radiation background.

[5] "Immediate dose" refers to the radiation exposure that occurs at the time of the event or shortly thereafter, from particles that directly interact with and deposit energy in the organism. Oppositely, "non-immediate dose" refers to: 1. A chronic exposure (accumulated dose) which is a continuous exposure to low levels of radiation over an extended period (e.g. background radiation); while each individual interaction might be "immediate" at a microscopic level, the overall dose is accumulated over time. 2. Internal contamination: If radioactive material enters the body (e.g., through inhalation, ingestion, or through a wound), it can deposit energy over time as it decays within the body. 3. Delayed effects from acute exposure: while the initial exposure might be immediate (an "acute"

from cosmic radiation is largely from muons, neutrons, electrons and this dose varies in different parts of the world based largely on the geomagnetic field and altitude. Low-energy transfer (LET – see below) effects are coming also from X-rays, γ-rays and UV-rays. In Fig. 1 the electromagnetic spectrum of LET ionizing radiation is shown.

The study of life’s origins and diversification is a complex endeavor, encompassing a multitude of environmental factors that have shaped biological processes over billions of years. Among these factors, radiation, particularly in small doses, presents a subtle yet potentially significant influence on the evolutionary trajectory of life on Earth. Understanding this influence requires a clear definition of what constitutes low-dose radiation and an appreciation for the ubiquitous presence of natural background radiation in the environments where life has emerged and evolved.

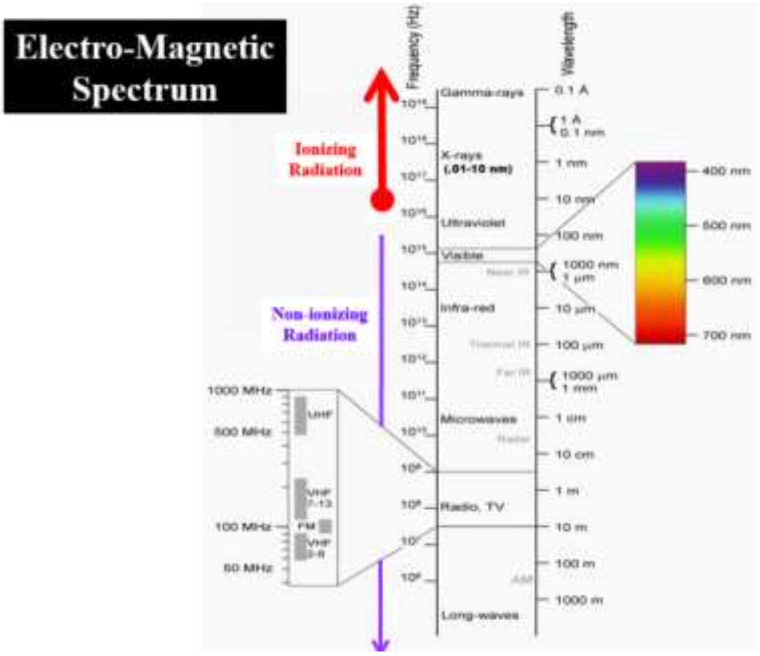

Fig. 1 Electromagnetic spectrum and ionizing radiation (Metting 2016)

Low-dose radiation (LDR) is generally defined as a radiation dose of 100 mSv or less, while low-dose-rate ionizing radiation is characterized by a rate of exposure at <6 mSv/h (Tang et al. 2017). These definitions are often based on animal experimental studies that have indicated that exposures within these ranges can induce genetic and epigenetic changes, potentially leading to various physiological disturbances but also variations in natural selection. Other works (Mahesh et al. 2023) aim to define health-effect (low-dose-response) less than 10 mGy and dose rate < 0.5 mGy/h.

The concept of 'low dose' can also be understood from a microdosimetric perspective, referring to an average frequency of charged-particle traversals substantially less than unity in cells. An important consequence is that in this case the probability of any effect on autonomous cells must be proportional to the absorbed dose and independent of dose rate. However, this definition may be unnecessarily restrictive because-especially in the case of low-LET[6] radiation-

dose, like from a single large event), the biological effects (e.g., cancer development) may not appear until much later (years or even decades).

[6] LET - Linear Energy Transfer (keV/μm). In the context of radiation biology and medicine, LET refers to the average amount of energy deposited by ionizing radiation in a material (such as tissue) per unit of distance traveled.

only a small fraction of events may cause the effects under consideration, e.g. cell lethality (Zaider 1998). This physical definition emphasizes the probabilistic nature of radiation interactions at very low doses.

While the destructive potential of high-dose radiation (HDR) is well-established (although there are some exceptions, showing the adaptation of some organisms to HDR – see Sect. 0) and especially the mutational impact of exposure to high doses of radioactivity (Dubrova et al. 1996; Ziegler et al. 1993), the effects of chronic exposure to low doses of radiation (LDR) on biological systems and their evolutionary trajectories are often controversial and have been a subject of ongoing scientific debates, especially related to the inapplicability of LNT (Linear no Threshold) model for low doses[7] (Tubiana et al. 2009). For instance, the investigations of Prof. Emer. Dr. Antone Brooks from Washington State University have clarified that at low doses, biological reactions are unique and often unrelated to those that occur at high levels (Brooks 2018). The hugely influential LNT model- which predicts acute exposure damage can be extrapolated linearly to low dose exposures - is estimated to be flawed (see also Fig. 8). In fact, small amounts can have even an adaptive protective effect. In addition, "hit theory," the idea that radiation only affected cells it directly traversed, yielded to a new "bystander theory", which hypothesizes that cells communicate with each other and a dose to one affects the cells around it (2018).

Also, another alternative hypothesis, the radiation hormesis (see Sect. 0), suggests that low levels of radiation can elicit beneficial biological responses, including the stimulation of DNA repair mechanisms, antioxidant defenses, and immune responses, ultimately leading to enhanced resistance to various stressors (Luckey 1991; Feinendegen 2005).

Life on Earth has always existed in a world permeated by ionizing radiation from natural sources. This background radiation originates primarily from cosmic radiation bombarding the Earth from space and terrestrial radiation emanating from radioactive elements within the Earth's crust, such as uranium, thorium, and potassium. The average annual effective dose from natural background radiation is approximately 2.4 mSv worldwide, with variations depending on geographical location and altitude. For instance, some regions, like the Kerala Coast in India exhibit almost five times higher natural radiation levels (CNSC 2020). Furthermore, naturally occurring radioisotopes, such as potassium-40 and carbon-14, are present within the human body and in many common foods. Given this constant exposure, it is plausible that evolutionary processes have been continuously influenced by this environmental factor, leading to the development of mechanisms to cope with or even potentially benefit from low levels of radiation.

4 RADIATION LEVELS ON EARLY EARTH. ABIOGENESIS AND THE DAWN OF LIFE

Understanding the role of LDR in evolution requires considering the historical context of Earth's radiation environment, which was considerably more intense than it is today. High

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It's a measure of the density of energy transfer along the radiation's track. Low-LET radiation refers to types of radiation that deposit energy sparsely along their path, causing less dense ionization. Examples include X-rays, gamma rays, and electrons. High-LET radiation deposits energy more densely, causing more ionization in a smaller volume. Examples include alpha particles and neutrons.

[7] See also Fig .7, Sect. 6.

concentrations of short-lived primordial radionuclides and a weaker geomagnetic field, offering less shielding from cosmic radiation, contributed to elevated background radiation levels. The early history of Earth was characterized by intense geological activity and a very different atmospheric composition compared to the present day. In this primordial environment, natural radioactivity, stemming from the decay of long-lived isotopes present in the Earth's crust and oceans, is hypothesized to have played a significant role in the planet's evolution, potentially even influencing the very origins of life (Ershov 2022).

The radiation environment on early Earth was significantly different from what exists today, primarily due to the decay of long-lived radioactive isotopes and the evolution of the planet's crust. Factors contributing to this change include the chemical evolution of the continental crust, alterations in the relative abundances of the heavy isotopes like uranium-235[8], uranium-238[9] and thorium-232[10] as well as the light potassium-40[11] and their decay products present in rocks, soil, and water (Eisenbud and Gesell 1997). These isotopes, called also primordial, as their half-life is comparable to the life of Earth, are a matter of special interest, because of their high specific radioactivity. The energy released through the radioactive decay of these isotopes would have served as a potent internal energy source for the early Earth, contributing to the melting and differentiation of its matter, as well as driving tectonic activity (Ershov 2022).

Large Ion Lithophiles[12], including potassium, uranium, and thorium, were preferentially incorporated into the continental crust as it formed and increased in size over geological time. Consequently, the abundance of these radioactive elements at the Earth's surface increased initially. However, due to their radioactive decay, with half-lives shorter than the age of the Earth (except for thorium-232), their activity concentrations in the continental crust are now lower than at any point in the distant past. As it is seen from Fig. 2, the radiation dose from geological emitters has changed considerably over the past four billion years. The concentration of the above isotopes also varies geographically, leading to regional differences in background radiation levels. This implies that early life forms, thought to have evolved between 3.5 and 4 billion years ago, and eukaryotic life[13], which emerged as early as 2.1 billion years ago, existed under significantly higher levels of external gamma radiation from contact with the continental crust, potentially up to four times the current levels (Karam and Leslie 1999).

Beyond the large-scale geological effects, the radiation emitted from these decaying isotopes could have directly influenced chemical reactions in the early oceans and atmosphere. The oceans, acting as a vast reservoir and converter, would have provided an environment where the initial chemical transformations could occur, potentially paving the way for the emergence of more complex prebiotic molecules and eventually the first self-replicating entities.

The decay of radioactive isotopes of thorium-232, uranium-238, uranium-235 and potassium-40 penetrated in the Global Ocean is theorized to have initiated key processes like the oxygenation of the hydrosphere and atmosphere. One compelling hypothesis suggests that the radiolysis of water, induced by this natural radioactivity, could have led to the formation of

[8] Half-life of U-235 is 0,7 Ga
[9] Half-life of U-238 is ~ 4.5 Ga
[10] Half-life of Th-232 is ~14.05 billion years.
[11] Half-life of K-40 is 1,25 Ga.
[12] Tending to be concentrated in the silicate outer shell of the Earth.
[13] Cells with nuclei.

radical species, like H^+, OH^-, H_2O_2, which are highly reactive. These radicals, in turn, might have been involved in the synthesis of simple organic molecules, such as amino acids, sugars, and nitrogenous bases, which are the fundamental building blocks of all known life (Ershov 2022).

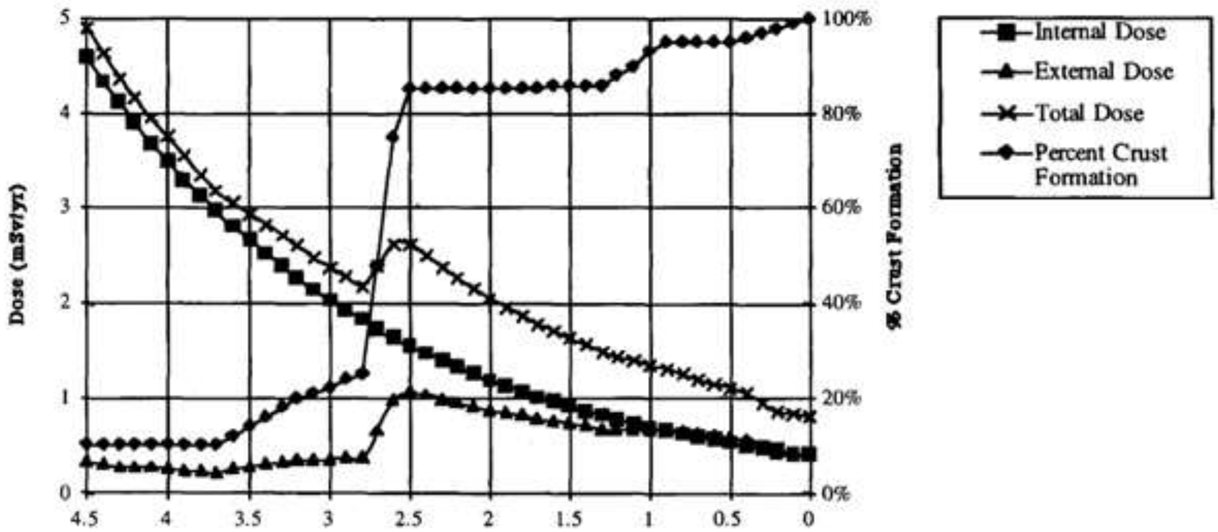


Fig. 2 Radiation dose change within geologic time (Karam and Leslie 1995)

The internal radiation from potassium-40, which emits γ-rays and β-particles especially within organisms, has undergone a substantial decrease over time. Potassium-40 decays with its half-life of 1.25 billion years, resulting in a significant reduction in its activity over Earth's 4.6-billion-year history. Currently, humans receive about 0.40 mSv per year from internal potassium-40 and a human contains average about 17 milligrams of potassium-40, what makes 4,000 decays per second (Upton and Silverman 2025). However, around 4 billion years ago, the specific activity of potassium-40 was much higher, potentially resulting in an internal dose four to eight times greater than present levels during the existence of prokaryotic[14] and eukaryotic life (Karam and Leslie 1995). It is estimated that the radiation exposure from geological materials has decreased from approximately 1.6 mGy per year to 0.66 mGy per year over this vast period.

This decrease in both external geological radiation (Fig. 2) and internal radiation from potassium-40 indicates that the overall radioactive environment in which life has evolved has changed considerably. According to Fig. 3, the content of potassium-40 decreased approximately 10-fold relative to the initial amount. The radioactive isotopes that quantitatively prevail now are those of thorium and uranium (approximately 80% and 50% relative to the initial amounts).

Alongside the internal energy provided by natural radioactivity from the soil and oceans, the early Earth was also subject to intense ultraviolet (UV)-rays from the early Sun. The prebiotic atmosphere, lacking significant amounts of oxygen and constituting mainly from nitrogen, ammonia, carbon oxide and dioxide, hydrogen and water vapor (Hayes 2025) would not have had a substantial ozone layer to filter out this harmful UV radiation. Consequently, the surface of early Earth would have been bathed in much higher levels of UV radiation than today (Karam and Leslie 1995). While this intense UV radiation could have been detrimental to early forms of life, it is also proposed that it might have acted as a significant selection factor.

[14] Cells without nuclei.

Organisms that could develop effective defense mechanisms against UV damage, such as the ability to repair DNA (Sinha and Häde 2002) or find refuge in shielded environments like rock interiors, would have had a selective advantage. Therefore, the interplay between the terrestrial radiation from radioactive elements and the external radiation from the Sun likely shaped the chemical evolution of the early Earth and the initial evolutionary steps of the first life forms.

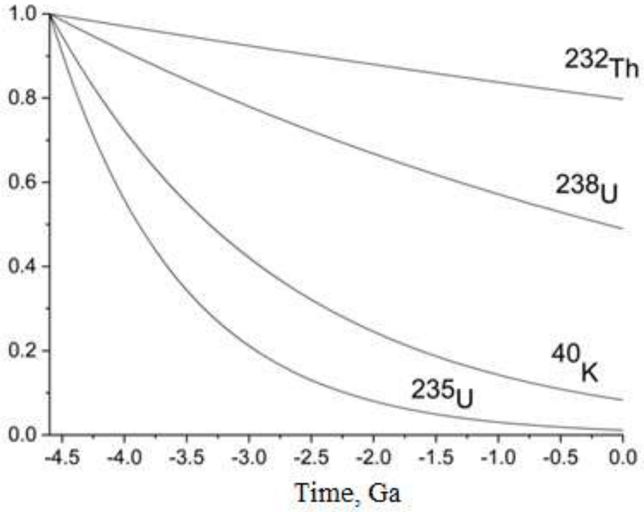


Fig. 3 Relative change of decay rate of ^{232}Th, ^{238}U, ^{40}K and ^{235}U isotopes since the origin of Earth (Ershov 2022)

UV radiation has played also crucial role for the down of complex forms of life – the abiogenesis. In the 1920s Russian biochemist Aleksandr Oparin and British scientist J.B.S. Haldane (Fig. 4) independently set forth similar ideas concerning the conditions required for the origin of life on Earth (Oparin 1924; Haldane 1929). Both believed that organic molecules could be formed from abiogenic materials in the presence of an external energy source (e.g., ultraviolet radiation) and that the primitive atmosphere was reducing[15] and contained ammonia and water vapor, among other gases. Both also suspected that the first life-forms appeared in the warm, primitive ocean were heterotrophic[16] rather than autotrophic[17]. Oparin believed that life developed from coacervates, microscopic spontaneously formed spherical colloid aggregates of lipid molecules that are held together by electrostatic forces and that may have been precursors of cells. Oparin’s work with coacervates confirmed that enzymes, fundamental for the biochemical reactions of metabolism, functioned more efficiently when contained within membrane-bound spheres than when free in aqueous solutions.

Haldane, unfamiliar with Oparin’s coacervates, believed that simple organic molecules formed first and in the presence of ultraviolet light became increasingly complex, ultimately forming cells. Haldane and Oparin’s ideas formed the foundation for much of the research on abiogenesis that took place in later decades (Rogers 2025).

Especially, the Miller–Urey experiment carried out in 1952, confirmed the ideas of Haldane and Oparin. It is seen as one of the first successful experiments demonstrating the

[15] Having very low amounts of free oxygen.
[16] Obtaining preformed nutrients from the (bio)compounds in existence on early Earth.
[17] Generating food and nutrients from sunlight or inorganic materials.

synthesis of organic compounds from inorganic constituents in an origin of life scenario. The experiment used methane (CH_4), ammonia (NH_3), hydrogen (H_2), in ratio 2:1:2, and water (H_2O). Applying an electric arc (simulating lightning) resulted in the production of amino acids (Miller 1953).

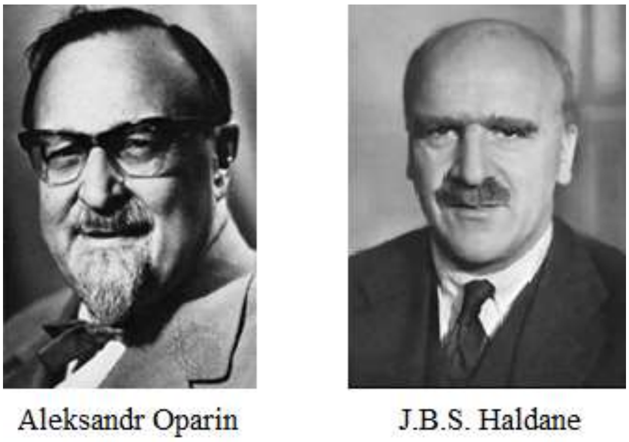


Fig. 4 The fathers of abiogenesis concept (photos from Encyclopaedia Britanica)

As the Earth's atmosphere has evolved over time, especially after the Great Oxygenation Event[18] (Fig. 5) which led to the appearance of massive quantities of O_2 in the atmosphere, thus influencing (decreasing) the amount of high-energy radiation coming from space and reaching the surface. This augmented amount of oxygen permitted an ozone layer to be formed, mainly due to solar but also to cosmic γ-rays causing the dissociation of oxygen molecules, and following combination of oxygen ions with oxygen molecules (Cooke et al. 2022). Therefore, the intensive γ-radiation played also a non-destructive role further to protect through forming ozone layer the organisms from UV radiation coming from the Sun and ensuring further evolution of more complex forms of life on Earth.

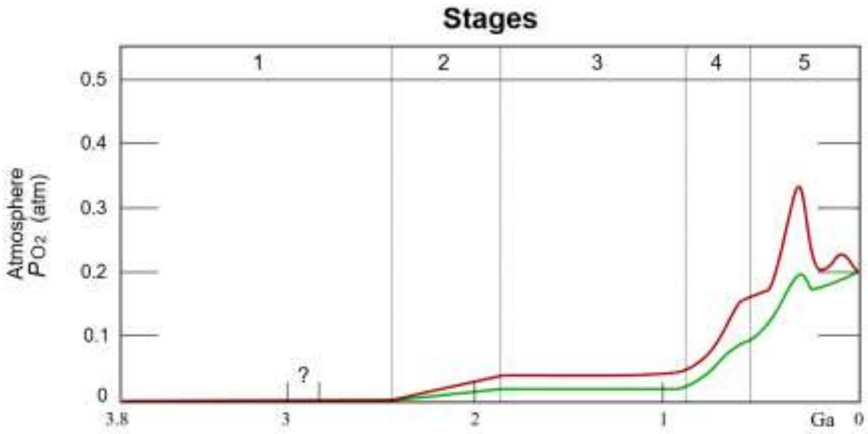
At the last stage #5 (Fig 5) happened the Neoproterozoic Oxygenation Event (NOE), also called the Second Great Oxidation Event, which was a geologic time interval between around 0,85 and 0,54 Ga ago during the Neoproterozoic era, which saw a very significant increase in oxygen levels in Earth's atmosphere and oceans (Och and Shields-Zhou 2012). Marine deposits record a very significant positive carbon isotope excursion, especially of carbon-13. Its elevated values are believed to be linked to an evolutionary spread of eukaryotic plankton and enhanced organic burial, which in turn indicate a spike in oxygen production during this interval (Shields-Zhou and Och 2011).

5 MUTAGENIC EFFECTS OF LOW-DOSE RADIATION AND GENETIC DIVERSITY

Ionizing radiation is a well-established mutagen, capable of damaging the genetic material within reproductive cells and leading to the transmission of mutations across generations (BEIR V 1990). While high doses of radiation can lead to overwhelming DNA damage and cell death, low

[18] GOE, which happened approximately 2.460 – 2.426 Ga ago, is inferred to have been caused by cyanobacteria, which evolved chlorophyll-based photosynthesis that releases dioxygen as a byproduct of water photolysis due to Sun and space radiation.

doses can induce a more manageable level of DNA lesions[19]. These lesions, if not perfectly repaired, can result in mutations – permanent changes in the DNA sequence. The mutagenic potential of LDR, which includes also single- and double-strand breaks, base modifications, and cross-links (Friedberg et al. 2006), has been recognized since the early 20th century, with radiation being utilized as a tool in genetic research to induce novel mutations in experimental organisms.



Red and green lines represent the range of the estimates while time is measured in billions of years ago (Ga). Stage 1 (3.85–2.45 Ga): Practically no O_2 in the atmosphere. The oceans were also largely anoxic—with the possible exception of O_2 in the shallow oceans. Stage 2 (2.45–1.85 Ga): O_2 produced, rising to values of 0.02 and 0.04 atm., but absorbed in oceans and seabed rocks (Great Oxidation Event). Stage 3 (1.85–0.85 Ga): O_2 starts to gas out of the oceans, but is absorbed by land surfaces. No significant change in oxygen level. Stages 4 and 5 (0.85 Ga – present): Other O_2 reservoirs filled; gas accumulates in atmosphere. Stage 4 is known as the Neoproterozoic Oxygenation Event.

Fig. 5 Production of oxygen (relative pressure) vs. geological time (Holland 2006; The Wonder of Science 2025)

Studies on animals have demonstrated that both acute and chronic exposure to low-dose radiation can induce a variety of genetic and epigenetic changes. These changes include alterations in gene expression, the occurrence of chromosomal inversions, and modifications to metabolic profiles. For instance, prenatal exposure to low doses of ionizing radiation (as low as 10 mGy) has been shown to induce reversion events in mice[20] with a specific mutation, while, exposure to slightly higher low doses (100 mGy) has been linked to changes in metabolic profiles in mice (Tang at al. 2016).

In natural settings, organisms exposed to elevated radiation levels have also exhibited signs of increased mutation. A study on populations of Daphnia water fleas in Chernobyl found that genetic diversity was significantly higher in lakes experiencing the highest radiation dose rates, suggesting that the radiation-mediated supply of new mutations outweighed the effects of natural selection and genetic drift in that environment (Goodman et al. 2022). Various taxonomic groups within the Chernobyl Exclusion Zone have displayed evidence of elevated rates of genetic damage and mutation and reduced population sizes.

[19] Lesions in DNA may consist of breaks or other changes in chemical structure of the helix, ultimately preventing transcription.
[20] Reversion events in mice, particularly concerning the "pink-eyed unstable" (p(un)) mutation, refer to the return of a mutant phenotype to a wild-type phenotype. These events are often detected as black spots on the fur of mice with the pun/pun genotype, appearing as partially black hair against a background of colorless hair.

Similarly, around Fukushima, population censuses of birds, butterflies, and cicadas suggested that abundances were negatively impacted by exposure to radioactive contaminants, while other groups (e.g., dragonflies, grasshoppers, bees, spiders) showed no significant declines, at least during the first summer following the disaster (Mousseau and Møller 2014). However, it is important to note that the efficiency and spectrum of mutations induced by LDR might differ from those induced by high doses or other mutagens. Furthermore, the cellular response to LDR, including the activation of sophisticated DNA repair pathways (see next Section), can significantly modulate the ultimate frequency and types of mutations that are fixed in the genome.

Even at the cellular level, research has indicated that a single alpha particle traversing the nucleus of a cell has a high probability of resulting in a mutation. An experiment held the Radiological Research Accelerator Facility at Columbia University with human–hamster hybrid cells by either a single α-particles have shown that the induced mutant fraction averaged 110 mutants per 10^5 survivors (Hei et al. 1997). The inherent mutagenic potential of even very low-dose radiation implies that it could serve as a continuous source of genetic variation, providing the raw material upon which natural selection can act, thereby driving evolutionary change.

In normal environmental conditions, the directly attributing specific evolutionary changes to low-dose radiation exposure is a complex challenge. It is difficult to isolate the effects of radiation from the myriads of other environmental factors that influence evolution. Moreover, the rate of spontaneous mutations in organisms is already significant, making it challenging to definitively identify the small increment of mutations induced by low-dose radiation above this background level (BEIR V 1990). The effects of low-dose radiation can also vary considerably depending on an organism's genetic background, age, sex, and the specific characteristics of the radiation exposure, such as whether it is acute, fractionated, or chronic (Tang at al. 2016).

Despite these complexities, the observation that genetic diversity can be higher in environments with elevated radiation levels, as seen in the Chernobyl Daphnia study, suggests that in certain contexts, radiation might play a more dominant role in driving evolution by significantly increasing the mutation rate. This enhanced mutation rate could potentially lead to rapid adaptation to the specific challenges of a radioactive environment or even contribute to speciation over longer periods. However, it is crucial to remember that natural selection remains the primary guiding force of evolution, acting upon the phenotypic variations that arise from these mutations, whether induced by radiation or occurring spontaneously (Bergman 2021). The interplay between the mutagenic effects of low-dose radiation and the selective pressures of the environment ultimately determines its contribution to the evolutionary trajectory of life.

6 BEYOND DAMAGE: ADAPTIVE RESPONSES AND RADIATION HORMESIS

Living organisms have evolved intricate mechanisms to detect and repair DNA damage caused by various environmental stressors, including radiation. Exposure to low doses of radiation has been shown to trigger the upregulation of these DNA repair pathways, as well as other cellular defense mechanisms such as antioxidant enzymes and stress response. This phenomenon, known as the adaptive response, suggests that pre-exposure to a low dose of radiation can render cells more resistant to subsequent exposure to higher, otherwise damaging doses. The evolutionary implications of this adaptive response are significant. Organisms living in environments with chronic low-level radiation exposure might have been selected for more efficient and inducible DNA repair systems, providing a survival advantage not only against radiation but also against other DNA-damaging agents. Furthermore, the activation of these defense mechanisms might have broader pleiotropic[21] effects, potentially enhancing overall cellular resilience and longevity. This could have indirectly influenced evolutionary trajectories by affecting life history traits and reproductive success.

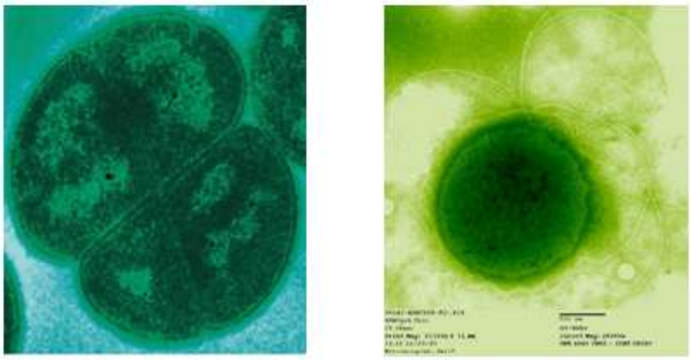
Concerning high doses radiation, it worths to review how living organisms have developed adaptive response. The existence of organisms that thrive in environments with exceptionally high levels of ionizing radiation provides compelling evidence that life can adapt to this extreme stressor. These radioresistant extremophiles have evolved remarkable mechanisms to survive and even, in some cases, utilize high radiation levels. One of the most well-studied examples is the bacterium *Deinococcus radiodurans*, renowned for its ability to withstand extreme doses of ionizing radiation, including UV and gamma rays, far exceeding typical background levels and lethal doses for most other organisms. Following the Chernobyl nuclear disaster, radiotrophic fungi growing within the destroyed reactor have been discovered (Fig. 6). These fungi, containing the pigment melanin, can utilize the energy from radioactivity as a source for growth, in a process analogous to photosynthesis. The melanin appears to play a role in both radiation protection and energy harvesting (Mironenko et. al. 2000). Similar melanized fungi have also been found in environments with high UV radiation, suggesting a broader protective role for this pigment.

Fig. 6 A black fungus (*Cladosporium sphaerospermum)* feeding on γ-radiation, discovered in Chernobyl NPP site (Reddit 2024)

Certain archaea[22], such as *Thermococcus gammatolerans*, found deep within the ocean around hydrothermal vents, also exhibit high levels of radiation resistance (the most radiation-resistant organism known to exist[23]), often coupled with thermophilic adaptations (Gronstal 2023). The remarkable ability of these organisms to survive high radiation environments is attributed to a suite of sophisticated genetic and physiological adaptations. A key adaptation is the presence of highly efficient DNA repair mechanisms (Prekeges 2003). *Deinococcus radiodurans* (Fig. 7, left), for instance, possesses multiple copies of its genome and highly effective DNA repair enzymes that can quickly and accurately mend radiation-induced DNA damage (Gronstal 2023). The system of its chromosomal DNA repair shows that *Thermococcus gammatolerans* (Fig. 7, right) can slowly or quickly rebuild damaged chromosomes without loss

[21] Conditions in which a single gene or genetic variant influences multiple phenotypic traits.
[22] Ancient organisms' predecessors of the eukaryotes (the cells with nuclei)
[23] While a dose of 5 Gy is sufficient to kill a human, and a dose of 60 Gy is able to kill all cells in a colony of E. coli, Thermococcus gammatolerans can withstand doses up to 30,000 Gy, and an instantaneous dose up to 5,000 Gy.

of viability (Tapias et al. 2009).



Deinococcus radiodurans Thermococcus gammatolerans

Fig. 7 Organisms highly resistant to HDR (photos from Wikipedia Commons)

Many other radioresistant organisms have robust antioxidant defense systems. Radiation generates reactive oxygen species (radicals) that can damage cellular components, and these organisms have evolved mechanisms to neutralize these harmful molecules, often through the production of high levels of antioxidants (Prekeges 2003). The diverse array of adaptations found in these radioresistant organisms underscores the power of natural selection to drive the evolution of specific survival strategies in response to the selective pressure imposed by high background radiation.

Coming back to low doses radiation, as mentioned in Sect. 5, another complex of mechanisms is developed in living organisms – the radiation hormesis, which posits that low doses of ionizing radiation can produce stimulatory or beneficial effects in biological systems. A growing body of evidence supports[24] the concept of radiation hormesis. It is interpreted to be adaptation to background radiation exposures, combined with adaptation to higher radiation exposures dependent upon metabolic protection from the array of other abiotic stresses in the environment (Parsons 2012). This idea, rooted in the broader field of toxicology where low doses of substances, toxic at high levels, can have opposite effects at low levels, suggests that radiation exposure at levels comparable to or slightly above natural background might not be inherently harmful and could even trigger protective or even stimulation mechanisms within organisms.

The Arndt–Schulz law and Hueppe’s rule[25], early observations in toxicology, hinted at this biphasic dose-response relationship, where weak stimuli can enhance biological activity (Baldwin and Grantham 2015).

[24] For instance, P. A. Parsons brings in his letter 17 scientific articles, besides his own ones, which unambiguously support the radiation hormesis and that the low-doses radiation effects contradict with the linear-no-threshold (LNT) concept (Parsons 2012).

[25] In early 1900s, advances in the toxicology field demonstrated that variable doses of toxic substances either showed no effect or in some cases had a beneficial effect. Professor Hugo Schulz, who worked at the University of Greifswald in Germany in the 1890s, observed that at low dosages various chemical and biologic toxicants appeared to stimulate metabolism. His work became known as the Arndt–Schulz law, which states, “*Weak stimuli accelerate vital activity, medium ones promote it, strong ones inhibit it, and very strong ones snuff it out*.” This relationship was also seen in the works of the German physician, bacteriologist and hygienist Prof. Ferdinand Hueppe and became known as Hueppe’s rule. Because of this research, as well as governmental concern about high-dose effects and the difficulty of proving low-dose effects, the idea of hormesis began to fade and threshold models became better accepted in toxicology (Baldwin and Grantham 2015). Similarly, LNT model was accepted widely in radiation protection and radiobiology in XX century.

Furthermore, stress-derived hormesis suggests that metabolic adaptations to various environmental stresses throughout evolutionary time, including climate-based extremes, might have inadvertently conferred protection against the effects of low-dose radiation (Parsons 2002). One of the fundamental principles of evolutionary biology dictates that organisms tend to become progressively adapted to the environments they are most frequently exposed to, making a hormetic response to a ubiquitous environmental factor (like background radiation) a logical expectation (Parsons 1990).

Several cellular mechanisms have been proposed to explain the beneficial effects observed at low doses of radiation. One prominent mechanism is the stimulation of DNA repair capacity. Low-dose radiation might activate enzymes and pathways involved in repairing DNA damage more efficiently, potentially reducing the accumulation of mutations and genomic instability. Another key mechanism involves the induction of antioxidant activity. As discussed in Sect. 4, radiation can generate reactive oxygen species (ROS), by direct hydrolyze of the water in the cells, which can damage cellular components. Low doses of radiation might stimulate the production of antioxidants, helping to neutralize these harmful molecules and protect cells from oxidative stress (de Toledo et al. 2006). The concept of radiation hormesis proposes a U-shaped or J-shaped (as it is on Fig. 8) dose-response curve, where low doses of radiation produce beneficial effect.

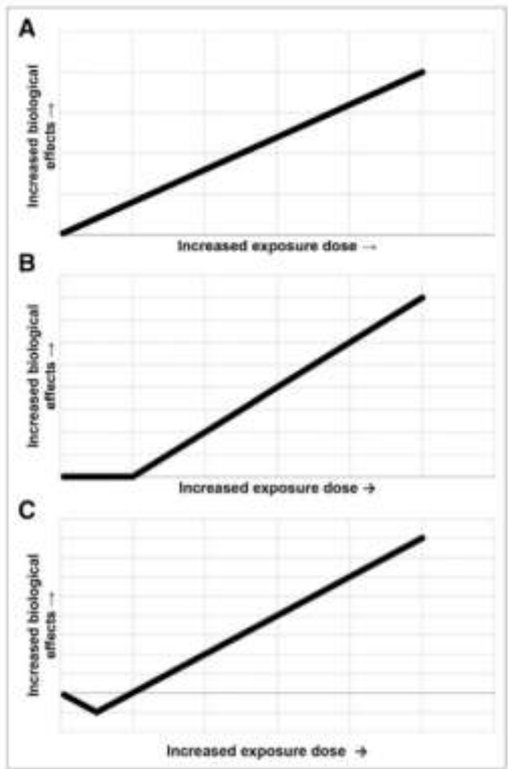


Fig. 8 Examples of: **A** Linear No-Threshold model (LNT), **B** Threshold model and **C** Hormetic model (Baldwin and Grantham 2015)

Furthermore, low-dose radiation has been shown to modulate immune functions, potentially enhancing the body's ability to fight off infections and even cancer (Baldwin and Grantham 2015). In some cases, it has also been observed to stimulate cell proliferation, which could be beneficial in tissue repair and regeneration (Lau et al. 2021).

A particularly relevant phenomenon is the radio-adaptive response, where a prior exposure to a low dose of radiation can induce resistance to the effects of a subsequent, higher dose (Metting 2016). This suggests that exposure to low levels of radiation might prime cellular defense mechanisms, making organisms more resilient to future radiation stress. Understanding these cellular mechanisms is crucial for appreciating the potential evolutionary significance of radiation hormesis and adaptive response.

From an evolutionary standpoint, radiation hormesis can be viewed as an expected phenomenon. Given that all life on Earth has evolved under constant exposure to background radiation, it is plausible that organisms have developed adaptive responses to these levels of radiation. The hormetic responses to LDR could have provided a selective advantage to organisms inhabiting radioactive environments.

If hormetic effects of LDR were prevalent in early Earth's more radioactive environments, they could have acted as a positive selective force, favoring organisms that could effectively harness the subtle stimulatory effects of radiation. This could have contributed, among the other factors for the natural selection, to the diversification and success of early life forms in challenging conditions.

7 TRANSGENERATIONAL AND EPIGENETIC EFFECTS

Beyond the direct effects of radiation on exposed organisms, there are evidences that low-dose radiation can have transgenerational effects, leading to phenotypic changes in subsequent generations that were not directly exposed. Studies in animal models have shown that parental exposure to low doses of radiation prior to conception can result in various adverse outcomes in their offspring, including increased genomic instability, reproductive impairments, and morphological abnormalities. For example, paternal or prenatal exposure to low-dose ionizing radiation has been associated with reduced fertility, a decrease in the number of live fetuses, and the occurrence of transgenerational genomic aberrations in animal studies (Tang et al. 2017). In butterflies around Fukushima, a higher level of morphological abnormalities was observed in progeny compared to their progenitors, with the frequency of abnormalities increasing across generations, suggesting a role of non-targeted effects of radiation (Hancock et al. 2018).

A key mechanism proposed to mediate these transgenerational effects is epigenetics, which involves heritable changes in gene function that occur without alterations to the underlying DNA sequence. Low-dose radiation has been shown to induce various epigenetic modifications, including alterations in DNA methylation patterns[26], histone modifications[27], and the expression of non-coding RNAs. The epigenetic changes can affect gene expression and have been linked to a range of biological outcomes, including altered cellular functions, genomic instability, and impairments in reproductive cells (Tang et al. 2017). Furthermore, radiation-induced epigenetic modifications in parental germ cells have been shown to be transmitted to subsequent generations, potentially contributing to the observed transgenerational effects (Leung et al. 2021).

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[26] DNA methylation is a biochemical process where a methyl group (CH_3) is added to a DNA molecule. Methylation generally leads to gene silencing or "turning off" the gene expression.

[27] DNA in eukaryotic cells is not just a free-floating strand; it's tightly wound around proteins called histones. These DNA-histone complexes form structures called nucleosomes, which are the fundamental units of chromatin (the packaged form of DNA in the nucleus).

Besides the above-described negative transgenerational effects, epigenetic effects are highly relevant to the ongoing discussion regarding potential "beneficial" effects at low doses of radiation. Studies indicate that LDR exposure during gestation can elicit specific epigenetic alterations that lead to positive adaptive phenotypic changes (Belli and Tabocchini 2020).

A notable example comes from the *Avy* mouse model, where LDR significantly increased DNA methylation at the viable yellow agouti (*Avy*) locus in a sex-specific manner. This epigenetic change resulted in a concomitant shift in offspring coat color towards pseudo-agouti, which is considered an adaptive phenotypic change (Bernal et al. 2013). The observation that maternal dietary antioxidant supplementation mitigated both these DNA methylation changes and the coat color shift further supports the hypothesis that oxidative stress partially mediates these epigenetic and phenotypic changes.

This provides direct evidence of LDR-induced epigenetic changes leading to a positive adaptive phenotypic outcome. The fact that antioxidants can mitigate these effects points to oxidative stress as a key mediator, linking the initial radiation exposure to the epigenetic modification and subsequent adaptive phenotype. This demonstrates a clear cause-and-effect chain involving epigenetics, suggesting that LDR can "reprogram" the epigenome in a way that confers a selective advantage or adaptive capacity, potentially through the activation of stress response pathways, thereby providing a molecular basis for the hormetic hypothesis. Several state-of-the art investigations, proving the positive effects of LDR on some animals are summarized on Table 2.

The ability of low-dose radiation to induce heritable epigenetic changes suggests a mechanism by which environmental radiation levels could have long-lasting evolutionary consequences, influencing the traits of organisms across multiple generations without necessarily requiring permanent alterations to the DNA sequence itself. This epigenetic inheritance could provide a degree of flexibility in how organisms respond and potentially adapt to changes in their radiation environment over relatively shorter evolutionary timescales compared to traditional genetic mutations.

8 SCIENTIFIC DEBATES ON THE ROLE OF LOW-DOSE RADIATION IN EVOLUTION

While radiation undoubtedly plays a role in mutagenesis, its precise influence on evolutionary transitions remains a complex and open question. Continued interdisciplinary research is necessary to refine our understanding of LDR's contributions to life's evolutionary history.

The impact of low-dose radiation (LDR) on the evolution of life remains a subject of ongoing scientific discourse. While there is substantial evidence supporting the mutagenic effects of radiation, distinguishing its specific evolutionary role from other environmental factors presents significant challenges.

Table 2 Summary of Positive Transgenerational Effects (Hormesis) in animal models

Effect	Model organism(s)	Observed outcome	Dose Range/Context	References
Reduction in Tumorigenesis / Cancer Incidence	Mice, human (suggested by epidemiological data but debated)	Reduced cancer incidence, protection from spontaneous neoplastic transformation, suppression of spontaneous cancers.	Low doses, doses above individual-specific stochastic threshold, 1 mGy to 100 mGy (gamma-ray photons).	(Vaiserman 2010)
Prolonged Lifespan	Flour beetles, house flies, fruit flies, guinea pigs, mice, rats, chipmunks, dogs	Increased mean/median lifespan, reduced early mortality.	Acute X-ray (5-10 Gy), daily exposures (0.3-2.5 Gy/day), chronic gamma irradiation (0.6-0.8 Gy, 7-14 cGy/year, 0.35-1.2 mGy/hour), single doses (200-400 rads).	(Vaiserman et al. 2021)
Enhanced Fertility / More offspring	Rodents	Increased number of offspring.	Exposure to inhaled uranium dust (Manhattan Project).	(Vaiserman et al. 2021)
Adaptive Phenotypic changes	*Avy* mouse model	Shift in coat color (pseudo-agouti), increased DNA methylation at specific locus.	Gestational LDR (0.7-7.6 cGy, max effects at 1.4 and 3.0 cGy).	(Bernal et al. 2013)

Radiation is just one of many variables that have influenced life’s evolutionary trajectory, alongside climate shifts, geological processes, and ecological interactions. Identifying whether radiation-induced mutations significantly shaped adaptive diversification requires detailed comparative genomic studies and refined evolutionary modeling.

Some of the key debates surrounding LDR include:

♦ The Linear No-Threshold (LNT) Model vs. Radiation Hormesis: The LNT model assumes that any radiation exposure—even at low doses—increases risk proportionally. In contrast, the radiation hormesis ypothesis suggests that LDR might activate protective biological mechanisms, potentially leading to beneficial effects. The validity of these models remains controversial, with research supporting both perspectives (Mahesh et al. 2023).

♦ Adaptive Radiation vs. Radiation-Induced Evolution: Classical examples of adaptive radiation—such as Darwin's finches—are primarily attributed to ecological factors rather than radiation-induced genetic changes. Determining the extent to which radiation actively drives diversification versus acting as a background factor requires further empirical evidence (DAAL 2025).

♦ Transgenerational Mutations: Some studies suggest that radiation exposure can lead to transgenerational effects, while others argue that such mutations do not significantly shape evolutionary trends. Evidence from Chernobyl and Fukushima indicates increased genetic variability, but whether this translates into long-term evolutionary advantages remains unclear (Hancock et al. 2018).

To resolve these debates, scientists need to perform long-term studies tracking genetic adaptations in radiation-exposed populations. Advanced genomic analyses comparing radiation-exposed and non-exposed species are needed as well. Reconstructions of historical radiation environments and their potential influence on major evolutionary events would help. And finally, experimental testing of radiation hormesis at the molecular level would definitely close this issue.

CONCLUSION

Radiation has played a significant yet often overlooked role in Earth's evolutionary history. While high doses of ionizing radiation are largely recognized as detrimental, low-dose radiation presents a more nuanced influence on biological processes. Life has continuously evolved under exposure to natural radiation, both from terrestrial sources and cosmic origins, making it a persistent environmental factor.

LDR has been shown to contribute to genetic variability through mutagenesis, activate cellular defense mechanisms, and potentially promote adaptive responses. The concept of radiation hormesis, suggesting that small doses may stimulate protective biological functions rather than cause harm, challenges traditional radiation risk models. Some organisms have developed resilience to radiation through enhanced DNA repair systems, efficient antioxidant production, and epigenetic modifications—mechanisms that could have shaped evolutionary trajectories over time.

From the earliest stages of abiogenesis, when radiation was significantly more intense than today, to modern ecosystems experiencing chronic exposure, radiation has exerted subtle but continuous evolutionary pressures. The existence of radioresistant extremophiles, such as *Deinococcus radiodurans* or radiotrophic fungi *Cladosporium sphaerospermum*, found in Chernobyl site, underscores the adaptability of life under high radiation stress. Furthermore, transgenerational effects and epigenetic inheritance suggest that radiation-induced changes may extend beyond individual exposures, influencing future generations without direct genetic mutations.

Despite ongoing scientific debates regarding the extent of radiation's role in evolution, its presence as a constant environmental factor makes it a relevant force in shaping life's complexity and resilience. While radiation alone is not the sole driver of evolutionary transitions, its interplay with other selective pressures – such as climate changes, geological shifts, and ecological interactions—contributes to the broader framework of biological adaptation.

In conclusion, radiation represents both a challenge and a potential catalyst for biological innovation. The inherent mutagenic potential of even very low-dose radiation implies that it could serve as a continuous source of genetic variation, providing the raw material upon which natural selection can act, thereby driving evolutionary change. Its influence has undoubtedly contributed to life's diversity, adaptability, and long-term survival. As research continues to uncover its evolutionary significance, the story of radiation in shaping life remains an evolving scientific inquiry that bridges physics, genetics, and evolutionary biology.

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Advanced Concept for Designing Technical Systems: SPARS (Smart ProActive Resilient System)

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Abstract

This article describes an advanced concept of engineering design: Smart ProActive Resilient System (SPARS). It is applicable to the development of aircraft, nuclear facilities and other complex, safety-critical and expensive technical systems. Their long-term operating conditions may be characterized by uncertainty. It ranges from statistical dispersion of system properties and values of factors acting under typical operating conditions to the lack of knowledge about all possible adverse events. Errors in predicting extreme impacts and the system's ability to withstand them create a threat of a catastrophe that may be accompanied by significant material losses, environmental damage, and human casualties. There is no doubt that such a threat must be minimized. Below, a number of common approaches to reducing uncertainty at the design stage are analyzed and their shortcomings are identified. The SPARS concept seems to be the most effective tool, since it allows designers to cope with uncertainty and ensure safety to a greater extent than other approaches. It combines defense in depth against predictable hazards, in-service monitoring and diagnostics of anomalies with the ideas of a biologically similar (bionic) response of the system to adverse events, including unexpected ones, providing it with the ability to recover from destructive impacts. The SPARS concept is illustrated by an important design case – an emergency landing of an aerospace vehicle.

Keywords: design, technical system, uncertainty, safety, aircraft, nuclear facility, automatic control, neural network.

INTRODUCTION

To ensure safety of complex technical systems, such as aircraft, space and aerospace vehicles, nuclear facilities, transport, industrial and social infrastructure objects, designers use – explicitly or implicitly – the concept of multi-level protection, or *defense in depth*, against hazard factors that may manifest themselves at the operation stage. These factors may be specific to each class of technical systems. They are associated with the release of energy possessed by the system and/or explosive, flammable, toxic or radioactive substances contained within the system. Such release can occur when the structural elements of the system lose their load-bearing capacity and collapse. Thus, the technical systems under consideration are potentially dangerous.

The concept of defense in depth was developed in nuclear power industry to ensure safety of nuclear power plants (NPPs) taking into account the main hazard factor characteristic for them – ionizing radiation. This factor is countered by "a number of consecutive and independent levels of protection that would have to fail before harmful effects could be caused to people or to the environment" (IAEA 2006). Some levels of protection are *physical barriers* constructed from structural elements, while others are implemented through the use of *safety systems* and organizational measures (IAEA 2016). When one level of protection fails (one barrier is overcome), the next one comes into play. Properly organized multi-level protection ensures that no single failure due to technical malfunction or human error could lead to harmful effects and that a combination of failures threatening such consequences is of very low probability.

The number of independent levels of defense in depth can (up to 5) in combination with control, monitoring and diagnostic tools, as well as limitations on the manifestation of human factors, allows us to characterize nuclear power as a whole as a fairly safe branch of technology (Spirochkin 2019). Similar principles of protection, but against other hazard factors and expressed in different terms, are used in aviation, aerospace technology and other industries dealing with potentially hazardous technical systems.

An essential part of defense in depth is integrity of the system structure. It is substantiated at the design stage using assumptions about operational loading factors (static and dynamic loads, temperature, corrosion, erosion, etc.) as well as assessments of the system response to them. The assumptions are based on data obtained from operating experience of systems similar to the one being developed (serving as prototypes) and previously produced specimens, as well as from research experiments. The system response is assessed through calculations with the use of mathematical models and (or) through testing of physical objects that reflect, to varying degrees, the properties of the system. But even with such substantiation, design decisions are made under conditions of uncertainty. It ranges from statistical dispersion in system properties and values of known operational loading factors to the lack of knowledge about all possible impacts during operation and the behavior of the system in unforeseen situations. The left boundary of this range includes repetitive, frequently occurring and predictable events that fit into the category of *aleatory uncertainty*. The right boundary corresponds to adverse events that are unknown at the time of design and therefore unpredictable – they are covered by the category of *epistemic uncertainty*. Between these boundaries are impacts of a known nature with extreme but unknown intensity, rare combinations of random events that can disrupt the operation of the system or make it unusable, errors in analyzing the behavior of the system in poorly defined conditions, and other variables that are difficult to estimate.

Underestimation of load values, combined with errors about the ability of the system to withstand them, or ignorance of any adverse loading factors, can lead to its destruction with the release of accumulated energy and hazardous substances, not to mention the loss of an expensive system as such. It is obvious that the uncertainty that exists at the design stage and creates such a threat during the operation of the system must be minimized.

The necessary conditions for minimizing uncertainty are the possibility of its quantitative assessment (quantification) and controllability – in the direction of reduction. Quantification is achievable for aleatory uncertainty. Its measure is *risk*, which is interpreted as the probability of an adverse event, the severity of the harm caused by it, or a combination of these two indicators, for example, their product. Accordingly, to take into account aleatory uncertainty in design, an approach is used that involves assessing the probability of expected events based on accumulated statistical data. But since the result of design must be clearly defined geometric characteristics and physical and mechanical properties of all elements of the system, the probabilistic approach is usually implemented indirectly – through deterministic safety factors, strength safety factors or reliability factors[28]. Their values are specified depending on statistical dispersion of the loading parameters and the properties of elements characterizing resistance to them, the corresponding probability distribution laws and the required safety or reliability indicators (Taylor 1965; Makarevskii et al. 1975; Rzhanitsyn 1978; Gladkii 1982; Spirochkin 2019). Due to the control of statistical dispersion under conditions of standardized mass production and normal operation, the statistical validity of distribution laws, and conservatism of the values of the above factors specified in regulatory documents, the target risk indicators in modern projects are very low – they correspond to the probability of an accident 10^{-6} and a catastrophe 10^{-7}. The question of how much these indicators correspond to reality remains open, as a consequence of – among other circumstances – the insufficient duration of operating experience of some systems, for example, NPPs (Spirochkin 2023).

However, predictions about the future based on past experience, even long-term, can be wrong due to epistemic uncertainty inherent in our knowledge of the world. Beyond the boundaries of knowledge lie adverse events not captured by existing experience and statistics. The metaphor of a “black swan” has become generally accepted to characterize such events (Taleb 2007). It is applied to any unexpected and large-scale disaster, including the one that occurred at the *Fukushima Daiichi* NPP in 2011. The unexpectedness of such events, coupled with the extreme severity of their consequences, raises doubts about the applicability of the probabilistic approach, and proposals to change the design paradigm based on it appear (Dédale 2013). In this regard, it should still be noted that the real cause of the disaster at the *Fukushima Daiichi* NPP was the underestimation by the designers of the maximum tsunami wave height, based on the available statistical data. Since tsunami phenomena are known and recurring, the possibility of their probabilistic assessment is, in principle, beyond doubt. The problem that caused that disaster was the insufficient conservatism of the assessment made in design and the incomplete implementation of defense in depth (Spirochkin 2023).

The application of probabilistic methods to rare adverse events for which there is little or no statistical data is possible on the basis of the Bayesian approach, which operates with subjective probabilities that are refined as new relevant data becomes available (Ventsel 1969). Using this approach or other analytical tools, attempts are made to account for uncertainty with a significant epistemic component (Haug et al. 1986; Nielsen 1994; Lempert et al. 2003; Stirling 2007; Aven and Steen 2010; Beer et al. 2013; Patelli et al. 2014; Saunders et al. 2015; Pierre 2015; Beer et al. 2016; Gupta 2021; Sotiropoulos and Tserpes 2022; Blumsack 2023; Gong et al. 2023). In areas where safety is of particular importance, the precautionary principle is used (Stirling 2007; EUR-Lex 2017), and the worst-case scenario method is applied (Schneier 2010; Capitanescu and Wehenkel 2013).

The reduction of epistemic uncertainty is facilitated by the accumulation of experience, its theoretical generalization and transformation into knowledge. However, as the scope of application of technologies is constantly expanding, and the world is undergoing uncontrollable

[28] Different branches of technology use different terms, the essence of which is the same.

changes, epistemic uncertainty shows no tendency to decrease. When the operating conditions of the created system change significantly relative to those specified during design, such properties as resistance to unexpected adverse effects and the ability to recover from them are in demand.

The purpose of this article is to introduce a new concept for the design of technical systems that meets this challenge – Smart ProActive Resilient System (SPARS). It emerged from the combination of advances in two high-tech and safety-critical areas – aerospace industry and nuclear power – with ideas from bioengineering. Below, Section 1 characterizes uncertainty in design and discusses existing engineering approaches to reduce it. Section 2 presents the basic provisions of the SPARS concept. Section 3 illustrates its application to ensuring safety in emergency landing of aerospace vehicle.

1 UNCERTAINTY IN DESIGN AND EXISTING ENGINEERING APPROACHES TO ITS REDUCTION

1.1 Uncertainty in design

Uncertainty in the design of technical systems is caused by many factors. Table 1 lists the main sources of uncertainty and shows what components of uncertainty they generate.

Table 1: Characterization of uncertainty in design

Source of uncertainty	Generated components of uncertainty	
	Aleatory uncertainty	Epistemic uncertainty
1. Statistical dispersion of system properties and loading parameters	To the full	
2. Hidden imperfections in the system and operating documentation	As part	As part
3. The emergence of new properties		To the full
4. Uncontrolled impacts on the system and changes in operating conditions	As part	As part
5. Human factors	As part	As part
6. Errors in the substantiation of design decisions	As a minor part	As the dominant part
7. Unknown factors		To the full

As can be seen from this table, only one of the seven sources of uncertainty generates exclusively aleatory uncertainty – the first. It covers many difficult-to-control deviations in the processes of manufacturing system elements, system assembly and normal operation. The sources 2 and 4 to 6 generate such an uncertainty component in part. The risk associated with aleatory uncertainty is reduced through high quality of design and production work, compliance with prescribed operating rules, performance of operational control, maintenance and repair, and timely decommissioning. All sources except the first create epistemic uncertainty to varying degrees. Such sources as the emergence of new properties, or unknown factors are characterized by it to the fullest extent. This circumstance limits the range of approaches to reducing uncertainty based on probabilistic methods. Although the level of their development is quite high, the area of applicability can hardly be expanded beyond the boundaries established by the stochastic nature of known properties and phenomena. Below we analyze existing engineering methods for reducing uncertainty – both aleatory and epistemic – that allow designers to manage it in order to ensure safety of the created system at the operation stage.

1.2 Refinement of probabilistic characteristics

Reducing uncertainty in design is facilitated by refinement of probabilistic characteristics of variables that determine the parameters of the system being created and have a stochastic nature. Such refinement is especially in demand when the system differs significantly from prototypes in terms of operating conditions, configuration, dimensions, materials and manufacturing technologies. In this case, it should be expected that the statistical dispersion of geometric characteristics of elements, properties of materials and external loads may go beyond the data of prototypes.

The refinement is achieved by obtaining new experimental data – statistical series, specific for the system being created, and processing these data in order to find reasonable distributions and other probabilistic characteristics. They should ensure less error in estimating the parameters of the state and behavior of the designed system in predicted operating modes. The corresponding procedures are aimed at reducing aleatory uncertainty generated by the first source – see Table 1.

New experimental data can be obtained during tests related to the category of *phenomena-exploration experiments* (Oberkampf et al. 2003). These include tests to determine the properties of basic materials and joints (mechanical, welded and others), which are carried out in a laboratory on material samples and structural elements. These tests can be one of the intermediate stages of design, preceding the adoption of final design solutions. A methodology for handling aleatory uncertainty using testing is standardized (ASME PTC 19.1-2005 2006). If such tests reveal increased statistical dispersion of properties compared to prototypes, then it may be necessary to improve technological processes, strengthen structural elements, or increase safety factors.

Similar experiments allow designers to obtain data on statistical dispersion of the geometry of elements and connections. The main contribution to such dispersion is made by initial technological imperfections: thinning of walls, deflections, eccentricities and other deviations from the design forms and sizes, which are often combined with residual stresses after various technological operations.

Statistical data on the loads during operation can be obtained in research facilities using small-scale physical models or full-size mock-ups, on prototypes of the system manufactured before the start of its serial production, as well as on systems already put into operation, equipped with appropriate recording devices. The degree of reproduction of real processes using experimental objects of the first two types in research facilities is determined by compliance with the similarity criteria. Full-scale experiments on prototypes have no limitations in terms of similarity, but they are usually expensive and can only be carried out when the system design has been completed and the manufacturing stage has begun. If the results of these experiments require any changes to the system, this can become a problem due to additional costs and time constraints.

Along with its undoubted advantages, the approach under consideration has a significant shortcoming – the result is not the actual state of each element of a certain system or the actual values of loads, but parameters of the probabilistic approximations of the corresponding statistical populations. Thus, it is possible to reduce uncertainty for the entire fleet of similar systems and the range of typical operating conditions within predictable limits corresponding to reasonable values of probability. However, it is impossible to guarantee that a certain system has precisely known properties or that it will not be subject to loads exceeding probabilistic estimates during its service life.

1.3 Experimental determination of the actual system properties and loads

Actual properties of a certain specimen of the system can be determined in the performance check experiments, in which performance indicators include static strength, resistance to vibration and impact, etc. Such experiments fall under the category of *system and certification tests* (Oberkampf 2003). Actual properties are also obtained in experiments aimed at identifying or refining mathematical models – they are called *mathematical-model-development experiments* and *calibration* (*model-updating*) *experiments* (ibid).

This approach eliminates the shortcoming noted in Subsection 1.2 – generalization of data across the entire statistical population – and can provide a reduction in aleatory uncertainty as applied to a certain specimen of the system (within the limits related mainly to the first source of uncertainty in Table 1). However, it has its own inherent problems – 1) significant costs for conducting experiments for each specimen, and 2) the data obtained determine only its initial properties, and there is no information on their degradation during the operation of the system.

1.4 Pilot Projects

Innovations aimed at implementing scientific ideas in new technical systems may have a high level of epistemic uncertainty. To lower it, the concept of a *pilot project* is used. Within this concept, neither the probabilities of various outcomes of innovation nor any other measurable indicators are assessed, but uncertainty as such is investigated empirically. A pilot project may be a stage of a large long-term project or a large-scale program and follow any of the strategies below:

1) exploration of the space of possible outcomes through parallel promotion of several innovation options (by separate project teams) and identification of the most successful of them (Pich et al. 2002);
2) limiting the scope of innovation to an area corresponding to low (acceptable) risk, interpreted as the amount of potential losses, learning lessons and identifying corrective measures (Cocron and Aronhime 2022);
3) modeling key actions typical for implementing an idea in question, using a small representative example to identify emerging problems and find ways to solve them.

The last strategy is familiar to the author from his participation in 2006-2008 in a program aimed at introducing a promising approach – *information support for the life cycle* in the design of transport-type nuclear reactors. The complexity, novelty, and degree of responsibility of this program necessitated a pilot project in the form of design and engineering work on a certain pipeline system as part of a specific reactor, with data exchange between the stages of work and the departments of the design organization performing them.

Direct “confrontation with uncertainty” in a pilot project allows designers to investigate such sources of uncertainty as the emergence of new properties (source 3 in Table 1), errors in substantiation of design decisions (source 6), and unknown factors (source 7).

1.5 In-service monitoring and diagnostics

As noted in Subsection 1.3, one of the problems inherent in determining actual properties by system and certification testing is that this approach only provides initial properties, i.e. before commissioning of the system, and does not provide information on their degradation during operation. This problem can be solved by *in-service monitoring and diagnostics*.

In-service monitoring includes observing, recording and collecting data that characterize the current health (operability) of the system, as well as its operating conditions. Raw data are harvested using sensors located in certain points of the system, with a specified periodicity in time. Diagnostics involves analyzing the collected data and assessing the health of the system based on certain signs in them that may indicate possible malfunctions. The data that allow such an assessment to be carried out are both directly observable defects and the parameters of the system’s response to loads acting during normal operation or used in special tests. Deterioration of properties under the influence of some operational factors can lead to adverse changes in operating conditions and loads applied to structural elements. Therefore, diagnostics also includes the analysis of such conditions and loads. In-service monitoring and diagnostics operations, carried out both periodically and after extreme events are or can serve as a source of data on current geometric parameters, properties of system elements and loads acting on them.

Currently, these operations are performed by automated monitoring and diagnostic systems, which are a necessary part of each safety-important technical object (each specimen of a serially produced technical system). For example, all modern nuclear reactors are equipped with such systems. The vibration and noise diagnostics tools included in them detect signs of anomalies in broadband mechanical vibrations accompanying the operation of reactor and identify these signs as evidence of certain deviations in its health (Arkadov et al. 2004; Spirochkin 2019).

The development and implementation of similar systems in various fields of technology form a separate engineering discipline: *structural health monitoring* (SHM). For example, guidelines have been developed for its use in aerospace industry (SAE 2021). However, it is premature to declare the widespread practical application of SHM in this area (Sause and Jasiūnienė 2021).

In-service monitoring and diagnostics can reduce aleatory uncertainty for each specimen of a serially produced system and increase the level of safety due to knowledge of its current state and the possibility of more accurately predicting its future – based on the assessment of the remaining service life. In addition, in-service monitoring and diagnostics facilitates to reduce epistemic uncertainty – by detecting hidden imperfections of the system at the operational stage (part of source 2 in Table 1), emerging properties (source 3), uncontrolled impacts and changes in operating conditions (source 4), as well as possible manifestations of previously unknown factors (source 7).

The described approach has some inherent problems. Firstly, the scope of monitoring and diagnostics is limited to observing a relatively small number of safety-critical elements and recording a narrow set of key parameters. Otherwise, the complexity and energy consumption of the distributed structure of the system increase significantly, and its operation in real time becomes difficult. Another problem is the resistance of components (sensors, communications and data processing devices) to adverse operational factors, which must be maintained throughout the entire service life. The latter problem is especially relevant for nuclear power plants and spacecraft that operate for a long time without the possibility of repair or replacement of elements. In addition, the recording of physical processes is inevitably accompanied by errors, for the assessment and reduction of which the signals coming from the sensors must be periodically calibrated.

The first of these problems can be solved within an advanced approach – *information support for the life cycle*. It was developed in the Russian nuclear power industry with the participation of the author (Spirochkin and Evropin 2008; SPiR-O-2008; Evropin et al. 2009; Spirochkin and Atroshchenkov 2009; VERLIFE 2013; OTT 1.5.2.01.999.0157-2013; Spirochkin 2019). Its effectiveness is based on the use of detailed mathematical models reflecting the actual geometry of NPP elements and their current properties (with periodic updating through operational monitoring and diagnostics). Such models allow designers who supervise NPP operation to overcome the scope of directly recorded parameters and analyze the condition and operability of each element, as well as assess the operability of the facility as a whole.

2 INTRODUCING THE SPARS CONCEPT

2.1 General characterization

As follows from previous section, none of the common engineering approaches to reducing uncertainty in design solves the problem completely, especially given the presence of the epistemic component associated with ignorance. The SPARS design concept presented below is based on the obvious point of view that it is impossible to eliminate uncertainty when creating technical systems intended for a long-term service under insufficiently known operating conditions that may conceal unpredictable events. Therefore, solutions to the issues of safety, as well as efficiency, caused by uncertainty, in particular, when systems are complex, safety-critical and expensive, should be sought by giving them properties similar to those of biological organisms – properties that increase chances of survival in a dangerous, difficult-to-predict environment. These properties include: *smartness*, i.e. a sense of the environment and internal state, including an understanding of emerging threats, preparedness for such threats – what can be named *proactivity*, situational response to events, inter alia unexpected ones, and the ability to reduce damage from adverse impacts (of course, in a certain range of their intensity), as well as to recover – the latter corresponds to the idea of *resilience*.

The desired properties can be transformed into the following requirements: a system designed according to the SPARS concept must:

1) “observe” the environment, evaluate external conditions in comparison with acceptable ones (specified for design) and draw a conclusion about the “safety of being here”;
2) “feel” its integrity, assess the operability of elements and draw a conclusion about the “safety of being in the current state”;

3) assess the possible danger of changes occurring outside and inside by comparing their parameters with the system's potential for resistance to impacts based on actual (also subject to change) properties, and select a response mode that is acceptable from the prospect of "no loss of safety";
4) adequately respond to an adverse event (possible culmination of the above changes), i.e. implement actions aimed at minimizing the danger, for example, avoid extreme external impacts if the system is mobile and allows such avoidance, or reduce damage caused by them by absorbing and dissipating energy;
5) assess in real time the development of an adverse event and the internal state according to safety criteria (taking into account the possibility of an accident); in case of a safety deficit, perform special actions to protect people and maintain the operability of elements important for safety, including localization and passivation of hazard factors, ensuring evacuation from the accident zone, as well as other actions that prevent an accident from escalating into a catastrophe;
6) assess the state of the system and the environment according to safety criteria after an adverse event; draw a conclusion on life cycle management applicable to its subsequent interval, taking into account the efficiency criteria;
7) be able to recover, at least partially, if avoidance of extreme external impacts or their reduction were not fully successful and damage to the system occurred.

The design approaches within the SPARS concept that meet these requirements are based both on ideas and technologies already in use and on a number of innovations. As for the former, these approaches implement the concept of multi-level protection, or defense in depth, against hazard factors – see Introduction.

More specifically, the first two requirements from the above list correspond to the SHM technology, as well as information support for the life cycle (see Subsection 1.5). The corresponding system properties, as well as the properties partially related to items 4 – 6, are close to the principles of Integrated System Health Management (ISHM) (Xu and Xu 2017) and Intelligent Health and Mission Management (IHMM) (Ranasinghe et al. 2022). The SPARS concept incorporates these principles and in turn develops them.

An important advance from the level of safety achievable by the traditional design approaches (see Introduction) to the desired higher indicators can be considered the property of proactivity corresponding to requirement 3. The idea of proactivity originates in socio-economic studies (Bateman and Crant 1999) and has since begun to penetrate into engineering sciences – see, for example, (Bea 2005), but it has not yet been sufficiently developed in the latter.

Achieving higher levels of safety is also facilitated by improving the reactive properties of the system, as provided for in requirements 4 – 6. These properties, given the high speed of physical processes characteristic of many accidents, should obviously be implemented using AI tools. To reduce damage from extreme external impacts by absorbing and dissipating their energy, which is part of requirement 4, the principles of *crashworthiness* are incorporated into the SPARS concept. They were developed in military aviation – see, for example, (Zimmerman and Merritt 1989) – and then began to be applied to a wide range of vehicles for ensuring safety in accidents (Frings 1998; Du Bois et al. 2000; Ambrósio 2001; Spirochkin 2023).

Requirement 7 is fulfilled based on the principles of *resilience engineering* (Hollnagel et al. 2006, 2010). Their implementation within the SPARS concept includes supplementing the properties of crashworthiness, largely achieved through controlled destruction of selected structural elements, by another generally accepted technology – constructing a system from replaceable or repairable modules. Such modules should be, first of all, physical barriers that absorb the energy of extreme loads and localize the damage zone, as well as other structural elements and safety devices that can be destroyed in adverse events.

Innovative aspects of the SPARS concept, complementing the above mentioned principles and technologies, are presented in Subsection 2.2.

2.2 Innovative aspects

One of the innovative aspects of the SPARS concept can be considered the *supra-disciplinary nature* of its approaches, which are based on the achievements of one industry and find their application in another. This is precisely the case with the concept of defense in depth. It originated and was most developed in nuclear power industry (see Introduction), and when applied in other areas it can have a significant effect on safety. A corresponding example is given in Section 3. The same applies to the principles of crashworthiness. They are currently used only in the design of mobile technical systems, i.e. vehicles. The use of the SPARS concept, which encompasses these principles, could expand their application area, e.g. to nuclear facilities.

Another innovation in the SPARS concept is bio-inspired design, in which bionic ideas are applied mostly to the behavior of the system, rather than to its structure, as is usually done. This aspect, which primarily covers the properties of smartness and proactivity, can be called *behavioral bionic design*. Such properties are implemented in the designed technical system by equipping it with a special automatic control system that combines sensors, information processing devices and actuators (devices that generate control forces).

The SPARS concept assumes that information processing should be carried out using such an artificial intelligence (AI) tool as neural network. The example analysis of an aircraft emergency landing given in Section 3 shows that the neural network approach is preferable not only because of the high speed of the accident development, to which the control system must respond, but also based on the possibility of using heterogeneous information, the nature of which makes it difficult to process it by classical mathematical methods. The use of neural network constitutes the third innovative aspect of the SPARS concept.

Finally, the fourth innovation is related to design measures that facilitate the recoverability of a technical system after adverse events, but go beyond its modular construction. They increase resilience by improving physical barriers and safety devices and include, for example, the use of metamaterials with advanced properties that traditional structural materials do not have. The metamaterials in question should provide sufficient energy absorption with little geometrical changes of structural elements, localization of hazard factors associated with uncontrolled movements of components of the human-machine system in accident, and the ability of machine components to self-heal. The creation and application of metamaterials for ensuring safety within the SPARS concept is an area of ongoing research and development (R&D).

3 APPLICATION OF THE SPARS CONCEPT TO ENSURING SAFETY IN EMERGENCY LANDING OF AEROSPACE VEHICLE

3.1 Shortcomings of the existing system of protection against hazard factors in emergency landing

The possibility of emergency landing poses a serious challenge to designers of various types of aircraft. Airworthiness standards for the transport category airplanes require that the designed structure ensure the safety of occupants in the event of a “minor crash landing”, i.e. an emergency landing which results in minor damage and injury (CFR Part 25; AP-25 2009; CS-25 2018). However, the conditions of such a landing (properties of the landing surface, the velocity vector and rotation angles of the aircraft axes), which, in addition to the structure parameters, affect safety, are not clearly defined in regulatory documents. The choice of these conditions remains with the pilot. It should be noted that due to the high speed of the accident development and the psychological pressure exerted on the pilot by the perceived threat of a catastrophic outcome (FAA-H-8083-3C 2021) not all aspects of the situation are within his control.

Besides this, the loads acting on the aircraft structure when it hits the landing surface with the landing gear retracted, as specified, for example, in (CFR Part 25), § 25.561, i.e. directly by the fuselage, are uncertain. Emergency landing is *not a design case* for the fuselage structure (with the exception of structural elements that contribute to ensure buoyancy in ditching – such as external doors and windows). So the applied loads may exceed the values allowed in design for normal operating conditions and cause destruction of structural elements. The behavior of this structure, which collapses on impact, is difficult to predict. Even if regulations and design approaches “give each occupant every reasonable chance of escaping serious injury” (ibid) in the particular case mentioned above, in many other possible scenarios the chances of survival are not guaranteed and there is a safety deficit.

The shortcomings of the existing system of protection in the event of emergency landing are even more obvious for aerospace vehicles – such as the American *Space Shuttle* or the Soviet *Buran*. They were designed to transport astronauts, or cosmonauts, and large payloads into orbit and return them to Earth. On return, these vehicles flew in the atmosphere like airplanes, using aerodynamic surfaces (wings, rudders, ailerons, etc.), and they had other basic features of airplanes. Therefore, the design specifications for *Space Shuttle* or *Buran*, as well as for new aerospace vehicles being developed for commercial orbital flights and suborbital transportation of people and payloads (cargo) correspond to the requirements for transport category airplanes. However, the range of potential cargo necessitates an expansion of existing requirements – along with the safety of occupants, the integrity of particularly valuable or dangerous payloads (for example, containing toxic, flammable or radioactive substances) must also be ensured and environmental pollution must be prevented, bearing in mind the possibility of damage during an emergency landing.

In such an abnormal landing, the following hazard factors must be taken into account:

1) maximum values of accelerations acting on passengers and crew members, as well as acceleration profiles over time, since they may exceed human tolerance limits;

2) destruction of cargo and equipment attachment units under the action of inertial forces, which may cause uncontrolled movements of the torn off mass items with the threat of damage to the aircraft compartments and injury to people inside them;
3) injuries to people during their uncontrolled movements caused by contact with interior elements of the cockpit or passenger cabin;
4) deformations of the aircraft structure, which can lead to a reduction in the life volume of the cockpit and passenger cabin or contacts of large-sized cargo with structural elements of the cargo compartment, and also complicate the evacuation of occupants;
5) destruction of pipelines and tanks of the aircraft or transported cargo with flammable, toxic or radioactive contents, threatening fire, explosion and environmental pollution;
6) destruction of fuselage elements, leading to the sinking of the aircraft in the event of ditching, i.e. emergency landing on water.

These factors are counteracted by a system of protection, which includes a number of physical barriers and technical and organizational measures. Its task is to limit the intensity of hazard factors to values that exclude fatalities, reduce injuries to occupants and damage to the structure. Thus, in the path of the accelerations that constitute the first group of hazard factors, a transport category airplane has two physical barriers: the fuselage structure and the passenger or crew member seat equipped with restraining safety belts. The fuselage structure is not designed to withstand impact with a hard landing surface without the use of landing gear, so its behavior in emergency landing is a priori uncertain. It should be noted that the crashworthiness concept used in the design of military helicopters, provide for a special energy-absorbing structure of the lower part of the fuselage as the first physical barrier against impact accelerations (Jackson and Fasanella 2003; Jackson et al. 2006; Lau et al. 2012; Guida et al. 2018). The behavior of this part is analyzed through calculations and experiments, which allows designers to minimize the mentioned uncertainty and construct a sufficiently reliable first barrier.

Other hazard factors from the above list are also resisted by different physical barriers, but their number is less than that used in the defense in depth of nuclear facilities. A detailed analysis of the system of protection provided by regulatory documents for the postulated design case “emergency landing” shows that (Spirochkin 2025):

- this system is characterized by a small number of physical barriers, uncertainty of the properties of some of them, uncertainty of the relationship between landing conditions and hazard factors, and underdevelopment of active safety systems;
- the maximum values of accelerations used to specify requirements for most physical barriers were likely derived from statistics on emergency landings of light airplanes, and their application to new types of aircraft, especially aerospace vehicles, seems insufficiently substantiated;
- this system is inferior in depth and reliability to the indicators typical for nuclear facilities and in a number of indicators for the crashworthiness concept, which is used in the design of military helicopters;
- therefore, the protection cannot be considered sufficient – it does not ensure safety to the extent that is achievable with the current state of science and technology.

In fact, safety in emergency landing of a transport category airplane is ensured in form, but not in substance, and this leads to a safety deficit. The listed shortcomings are aggravated by the risks created by prospective payloads of the aerospace vehicles under design. Eliminating these shortcomings to improve safety is an urgent design problem.

3.2 Key features of the SPARS concept as applied to emergency landing

Given the diversity of possible causes of emergency landing and aircraft states, the variability of pilot actions and landing conditions, as well as the insufficient study of nonlinear processes of deformation and destruction of the structure under impact loads, it is obvious that at the design stage it is impossible to foresee all possible scenarios for the development of such an accident and assess their outcomes. In this case, designers are dealing with a combination of aleatory and epistemic uncertainty. The application of the SPARS concept is aimed at minimizing uncertainty and compensating for the safety deficit by giving the aircraft properties of "smartness", "proactivity" and "resilience" to assess emerging, including previously unknown, dangers in real time and respond to them with minimal negative consequences.

The main design measure for implementing these properties is equipping the aircraft with a special automatic tool – the Critical and Emergency Control System (CECS), capable of recognizing a critical situation in flight, preventing it from turning into emergency landing, and, and in case of failure, minimizing the negative consequences of such a landing. CECS uses sensors, communications, processing devices and actuators, the combination of which solves these tasks in real time. A significant portion of the equipment necessary for this purpose is already applied in modern advanced airplanes. The SPARS concept envisages the inclusion of CECS into the integrated Flight Control System (FCS)[29] and its interaction with other components of this system, including avionics.

CECS may require the installation of additional sensors to expand the range of parameters recorded, as well as innovations in their processing, in particular, the elimination of fragmentation caused by data gaps due to the absence of sensors at certain points on the aircraft or large time intervals between successive sensor records. In the latter case, the incorporation of ideas developed within the framework of information support for the life cycle (see Subsection 1.5) is used. This enables early, subtle signs of changes that could lead to potentially dangerous deviations from normal flight conditions to be recognized and proactive (hazard-preventing) control actions to be developed and taken. For deviations that have reached critical values, reactive (responding to an emerging danger) control is applied. Both proactive and reactive control actions should be carried out mainly in automatic mode.

If these actions fail to prevent an emergency landing, CECS determines in real time acceptable conditions for its performing, as well as measures capable of minimizing the expected values of hazard factors. For this, quantitative dependencies between aircraft parameters, emergency landing conditions and hazard factors $\{H\}$ are used – they are covered by the concept of a generalized function $\mathcal{F}$:

$$\{H\} = \mathcal{F}(\{S\},\{P\},\{V\},\{\Psi\},\{\mathcal{S}\},\{\mathcal{H}\},\{\mathcal{A}\}), \tag{1}$$

[29] If the FCS is equipped with elements of AI, it is considered an Intelligent Flight Control System (IFCS) – see, for example (Stengel 1992; NASA 2002).

where $\{S\}$ is the set of parameters of the aircraft structure and its cargo (configuration, dimensions, mechanical properties of structural materials, etc.); $\{P\}$ describes the landing surface; $\{V\}$ is velocity vector when touching the landing surface: $\{V\} = \{V_x, V_y, V_z\}$; $\{\Psi\}$ includes rotation angles of the aircraft axes: the yaw angle ψ, the pitch angle ϑ and the angle of roll γ,: $\{\Psi\} = \{\psi, \vartheta, \gamma\}$; $\{\mathcal{S}\}$ contains parameters of safety systems and other safety means (if they are used); $\{\mathcal{H}\}$ reflects the influence of human factors (including pilot actions); $\{\mathcal{A}\}$ describes automatic control actions.

Specifications for design an aircraft must contain allowable values for all hazard factors $\{H_a\}$. Therefore, having $\mathcal{F}$, for known argument values, it is possible to evaluate hazard factors $\{H\}$ and check the fulfillment of safety conditions:

$$\{H\} \leq \{H_a\}. \tag{2}$$

On the other hand, based on $\{H_a\}$ and known parameters of the aircraft structure $\{S\}$, for known or expected values of some arguments – $\{P\}$, $\{V\}$, etc., it is possible to determine the required values of other arguments, for example, parameters of safety systems and other safety means $\{\mathcal{S}\}$ (what is feasible at the design stage) or automatic control actions $\{\mathcal{A}\}$, that could ensure safety in the event of emergency landing – for example, using aerodynamic control surfaces.

If, when performing emergency landing, the existing (and structurally improved) physical barriers exhaust their ability to withstand hazard factors, then CESC can activate engineered safety systems. The SPARS concept envisages equipping an aircraft with safety systems whose functions are similar to those used at NPPs: a *controlling safety system*, a *protecting safety system* and a *localizing safety system*. A detailed algorithm for the operation of CESC, as well as some ideas for improving physical barriers and building safety systems for transport category airplanes can be found in the article (Spirochkin 2025).

The methodology for determining the quantitative relationship between aircraft parameters, emergency landing conditions and hazard factors, i.e. generalized function $\mathcal{F}$, was created during R&D aimed at ensuring safety in a possible (and postulated) emergency landing of the Soviet aerospace vehicle *Buran* in the 1980s. This methodology was based on dynamic analysis of the behavior of the aircraft with payload (Fig. 1) when interacting with the landing surface. The finite element method was used to model all components of this dynamic system (Spirochkin 1987, 2023). As a result of the analysis, dynamic response is determined, including time histories of accelerations at different points: $\{a(t)\} = \{a_{1x}(t), a_{1y}(t), a_{1z}(t), a_{2x}(t), \dots\}$.

This methodology is applicable in design, however, due to high requirements for computing resources and long time to determine dynamic response, it cannot be used by the CESC system on board the aircraft and in real time.

As studies conducted for *Buran* have shown, under the accepted scenarios of emergency landing, assessment of safety is possible based on the maximum value of vertical acceleration at the center of gravity of the payload, i.e. $\{H\} = a_{y\,max}$. For given structural characteristics $\{S\}$ and reasonable rotation angles of the aircraft axes $\{\Psi\}$, the arguments, which mainly determine this value, are the ultimate strength of the landing surface σ and the vertical velocity V_y. Then it is possible to obtain an approximate representation of the generalized function $\mathcal{F}$ in the form of a *response function*:

$$a_{y\,max} = \mathcal{F}_{ay}(\sigma, V_y)|_{\{S\},\{\Psi\}}. \tag{3}$$

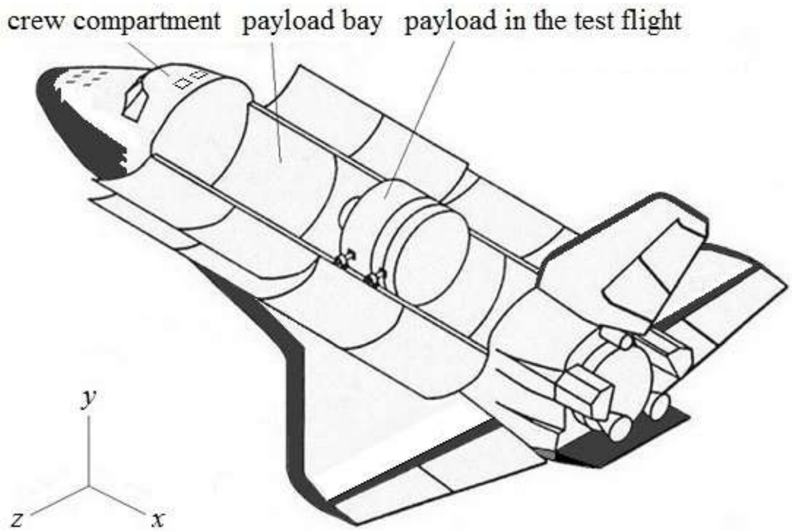

Fig. 1 The *Buran* aerospace vehicle with payload

This response function can be visualized as a *response surface*. Fig. 2 shows a response surface constructed from the results of a multivariate dynamic analysis of the *Buran* emergency landing.

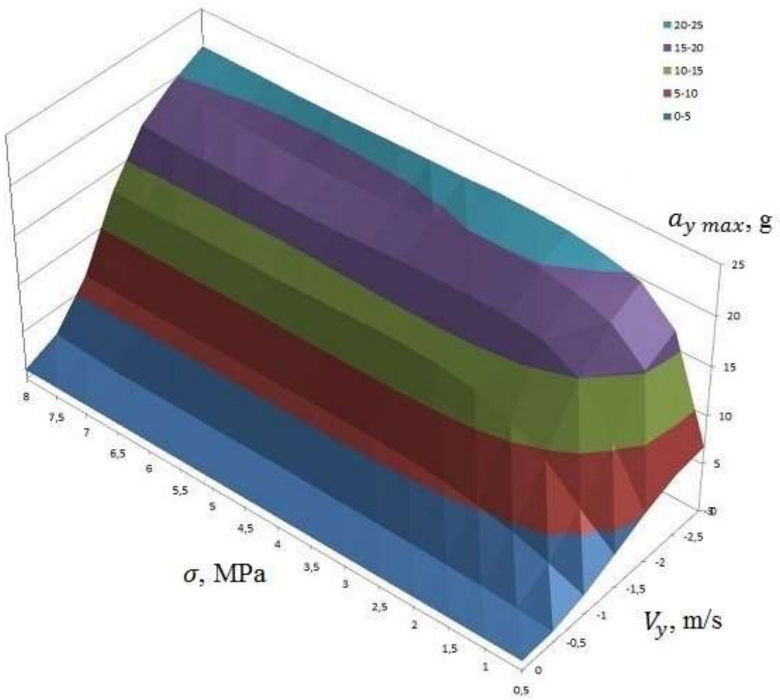

Fig. 2 Response surface for the *Buran* emergency landing

If necessary, response functions can be determined in terms of other hazard factors and taking into account a larger number of arguments. In the latter case, the response surfaces lose the ability to be presented visually, but the important advantage of this method remains – it allows for fast forecast of the aircraft structure behavior and assessment of hazard factors during emergency landing. The corresponding computational operations, mainly related to interpolation, can be performed by the onboard computer, providing substantiation for the choice of landing surface and kinematic parameters of the aircraft in real time. Tables containing the nodal values of response functions and thereby determining the generalized function $\mathcal{F}$ must be generated at the aircraft design stage based on dynamic analysis of a set of expected states of its structure, various payloads and emergency landing scenarios.

The response surface method can be implemented in CECS, however its use may be complicated by non-smoothness or discontinuity of the response functions, preventing the differentiability required for interpolation. These features may be related, for example, to the fact that the actual structural characteristics are presented in a range of possible values pointwise, rather than continuously. In some intervals, they, as well as the values of other arguments of the response functions, may be completely absent.

3.3 Testing the application of neural network

R&D on emergency landing, ceased with the closure of the *Energia-Buran* program, has recently received new impetus from the prospect of commercial orbital flights and suborbital transportation projects, as well as new technological advances, including in the field of AI.

Thus, the principles of critical and emergency control implemented in CECS using response surfaces can be implemented more effectively based on neural network technology. The idea of determining the response of a structure when its actual state and loading conditions changed during operation without conducting new finite element analyses, but using a neural network, was noted in regulatory documents of nuclear industry, in the preparation of which the author took part (SPiR-O-2008; VERLIFE 2013; OTT 1.5.2.01.999.0157-2013). This idea was tested in a pilot project on the practical application of the SPARS concept. The goal was to develop a neural network and study its ability to predict hazard factors in an emergency landing.

The neural network was developed by engineer Igor Uspensky. He also trained it based on the results of dynamic analysis for the *Buran* emergency landing processed the forecasts generated by the neural network for other, arbitrary data (Spirochkin 2025). The forecasts for a number of the *Buran* emergency landing scenarios are shown in Fig. 3 in comparison with the values obtained from dynamic analysis. As can be seen, these forecasts agree quite well with the results of dynamic analysis, thus, they can replace the latter with acceptable accuracy. Once the neural network has been trained, its forecast of the structure behavior in each emergency landing scenario is generated very quickly – within a second or less. So, it competes with the response surface method and is another candidate analytical tool for use in CESC – as software loaded into the onboard computer as part of this system. At the same time, neural network approach has a significant advantage – it does not require differentiability or continuity of data to construct a generalized function $\mathcal{F}$. Another advantage of this approach over the response surface method is the expansion of the range of sources for training data – in addition to the results of dynamic analysis it is possible to use data from research experiments and statistics of real emergency landings, presented in the form of text, hypertext, graphs, etc.

Training a neural network, i.e. constructing a generalized function $\mathcal{F}$, should be carried out at the pre-operation stages of the aircraft life cycle, including flight tests. The training set should contain data for a variety of assumed states of the aicraft and emergency landing scenarios. If necessary, before transporting cargo with previously unforeseen characteristics, additional training can be carried out.

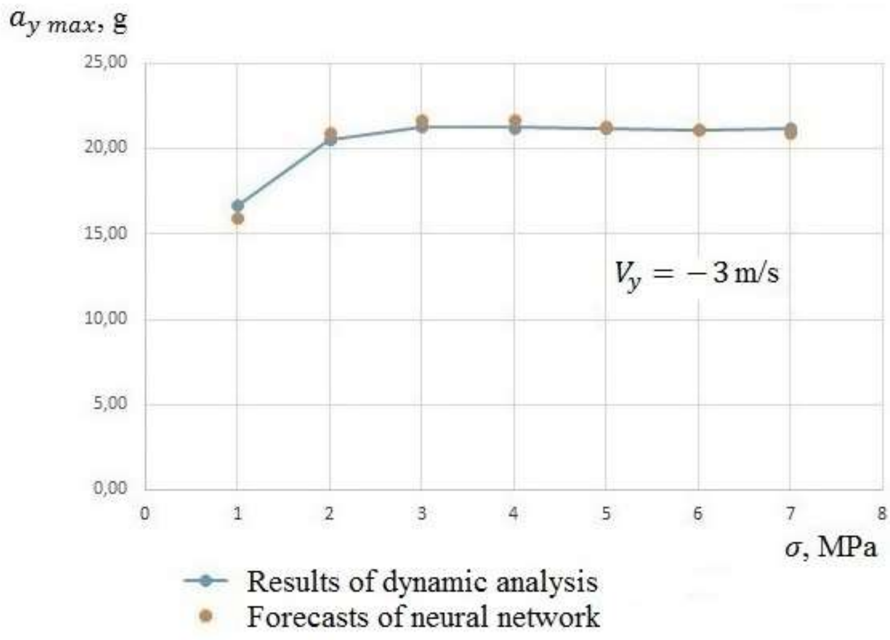

Fig. 3 Forecasts of neural network in comparison with the results of dynamic analysis for a number of the *Buran* emergency landing scenarios

In addition to forecasting the behavior of the structure and hazard factors in emergency landing, neural network used in CECS is obviously applicable to performing other control operations in critical and emergency situations, for example: recognizing changes occurring outside and inside the aircraft that may cause deviations, assessing the danger of these changes, determining proactive control actions, etc.

3.4 Consideration of bionic aspects

As noted in Subsection 2.2, the SPARS concept implements behavioral bionic principles. They are embodied in CECS, which work should replace the pilot actions in situations where possible negative manifestations of human factors – such as erroneous assessments and decisions, delayed reaction, stress or inaction – can lead to fatal consequences. Substantiating decisions on automatic control actions during emergency landing can be performed by using a neural network – software loaded into the onboard computer. According to modern notions, this AI tool is similar to the brain of a living being, therefore, its application directly reflects the behavioral bionic principles. In addition, the neural network is capable of training when receiving new information characterizing each emergency landing performed.

Another of the bionic aspects can be the recovery of aircraft after emergency landing. Such possibility depends on the degree of damage to its structure, adequate damage assessment and the ability of repairing or replacing damaged parts. Providing emergency landing with minor damage is a task of CECS. Another task is damage assessment as part of the post-accident analysis. Both these tasks, as well as the ability of repairing or replacing damaged parts, are related to bionic principles not at the level of functions, but through the overall goal of ensuring a long life cycle. This goal is achieved due to the properties corresponding to the principles of resilient engineering, and the latter are incorporated into the SPARS concept.

CONCLUSION

The traditional paradigm of engineering design is based on a priori, statistically validated knowledge about the operation phase. This knowledge allows designers to cope well with aleatory uncertainty inherent in operational factors of stochastic nature and, in most cases, to ensure safety at a level acceptable to society. However, from time to time, rare or completely unpredictable adverse events occur that do not fit into statistics, the intensity of which exceeds the system's ability to withstand them, and the consequence is an accident or catastrophe. To prepare for expected adverse events, designers equip the created systems with in-service monitoring and diagnostic tools, what makes accident management possible. However, such measures are unlikely to help cope with dangerous situations of unknown nature, i.e. with epistemic uncertainty, or ignorance.

The application of the SPARS concept allows designers to address safety and efficiency issues caused by uncertainty by giving the created system properties similar to those of biological organisms, increasing the chances of survival in a dangerous, unpredictable environment – smartness, proactivity and resilience. This concept can be considered a kind of "synergistic effect" of advances in two high-tech and safety-critical areas – aerospace industry and nuclear power, combined with ideas from bioengineering. And it looks very promising.

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