RISK ASSESSMENT OF FLYING THROUGH A ZONE WITH INCREASED RADIOACTIVE RADIATION

by

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This research deals with the assessment of the risk to which air traffic is exposed in zones of increased level of radioactive radiation. Natural disasters and war conflicts, which take place around nuclear power plants and the radioactive area (Chernobyl), create fear that large amounts of radioactive material may be released into the atmosphere. The paper analyzed the effects of: the efficiency of the HEPA filter in relation to the size of the radioactive dust particles, radioactivity on the aircraft instrumentation, radioactivity on the engine and the contribution of the engine in the spread of radioactivity to the crew in the aircraft. An assessment of the risk of exposure to radioactive radiation in the aircraft was put in perspective, depending on the type of aircraft and the dose of radiation.

Key words: airbone particulate radioactivity, monitoring, sampling, atmospheric distribution, contaminated area

INTRODUCTION

As the impact of radiation on the environment is the subject of a large amount of research [1], this study is concentrated only on the impact of radioactivity on aircraft and persons transported in them, but with an emphasis on radiation originating from zones with an increased dose of radiation which spreads in the form of dust, and not cosmic radiation, whose influence has been investigated many times so far [2-5]. A special phenomenon which may be interesting to be observed, especially with his impact on aircraft, is solar flares phenomenon [6, 7].

There are a number of aviation studies related to the occurrence of volcanic ash near aircraft [8, 9]. Thanks to the huge energies at the moment of ejection into the atmosphere, ash can reach great heights and, consequently, be carried by air currents to appear at distant locations. This type of contamination causes the appearance of static charge, as well as, the formation of deposits on aircraft engine parts and aerodynamic surfaces [10].

By its movement through the zone of intense radioactive radiation, the aircraft exposes itself to the risk of radiation affecting the operation of the propulsion unit and instruments. This risk is greater than that caused by the static charge of alkaline dust, which is known to disable the engine, disrupt the power supply and adversely affect the operation of navigation and measuring instruments.

The idea of research was initiated by rumors from the beginning of the conflict in Ukraine and speculations that nuclear material had been released from certain power plants [11, 12]. Based on these events, initial research assumptions related to possible sources of unwanted elevated radiation: accidents in nuclear power plants with uncontrolled release of radioactive material or emission of radiation, accidents in facilities for the enrichment of radioactive material, storage of waste or weapons, intentional release of radioactive particles on high altitude eider a low, or high radioactivity.

The spread of radioactive particles through the atmosphere and penetration through the materials

Focus is not on radioactivity in the zone of the immediate explosion of a nuclear warhead, because it is clear that in that zone the risk is huge, and it is not at all questionable. Also, the topic is not an assessment of the spread of radioactive pollutants from radiation sources through the atmosphere, given the fact that

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there are a large number of studies on this topic, both from an earlier date [13], and those that were done in recent times [14-17]. These studies deal with the spread of pollutants through the so-called low atmosphere, and they would be significant for aircraft if they were to take off or land near compromised zones.

There are also studies dealing with the assessment of the concentration of radioactive pollutants at high altitudes, those altitudes at which aircraft could be found during commercial flight [18, 19], but also meteorological systems that monitor the flow of air and aerosols, so they would also be suitable for evaluating the spread of radioactive particles, although they are most often captured by aerosols. There are also volcanic ash monitoring systems in high atmosphere zones. One such was developed by the European Aviation Safety Agency (EASA). A similar system could be used to track the movement of radioactive particles, at those altitudes at which aircraft could be found during flight [18, 19].

The movement of radioactive particles in the layers of the upper atmosphere depends on air currents at given levels, which in turn, depend on temperature. The dependence of temperature and pressure at height is given in fig. 1 [20-22].

In accordance with the generally known facts related to the penetration of radioactive particles, the range of particles can be described using fig. 2., that is important because it can be concluded which of those particles can be stopped by the shell of an aircraft.

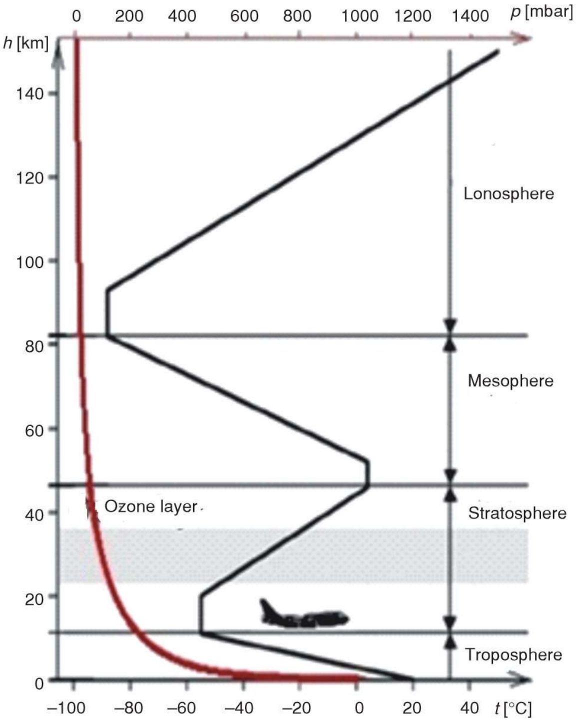

Figure 1. Layers of the atmosphere – dependence of temperature and pressure on height in relation to the Earth's surface and the flight zone of civil aircraft

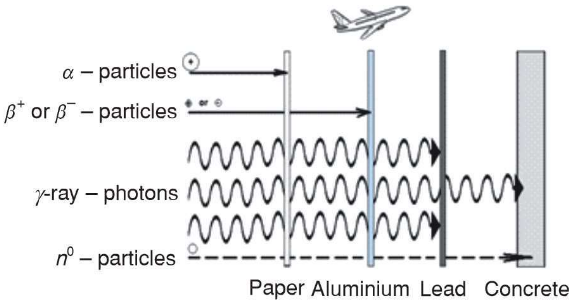

Figure 2. Particles and materials that will stop them

MATERIALS AND METHODS

Flying through a zone with an increased level of radioactive radiation is a risk. The risk depends on the distance from the source, weather conditions, and the thickness and type of material the aircraft is made of. Flying through a zone where the radiation intensity is high, even at very long distances from the source, the risk is huge, so such zones are definitely avoided when planning the flight.

However, if there is an assessment that the intensity of radioactive radiation at the mentioned height is not that high, then a risk assessment should be carried out depending on the type of air interceptor and the duration of the flight from entering the *dangerous* zone for landing. The time interval is not limited only to the time of flight through the zone of interest, because even after exiting it, certain objects may remain irradiated/contaminated and play the role of a source of radiation.

Our goal is to use methods related to risk assessment and risk management [23], to come up with an equation by which we could assess in which situations a flight through a potential zone with increased radioactive radiation should be avoided. In short, coefficients should be determined for risk assessment with the aim of determining the level of risk.

Assessments are mainly carried out to analyze the risk of some objects that are exposed to risk of any kind, to support decision making. Decision-making has also taken root in aviation [24, 25]. So it is actually a matrix intersection of the parameters of importance. These parameters include: object value, threats, object vulnerability and impact (likelihood that threats will exploit the vulnerability). Each of the parameters in eq. (1) is a dimensionless quantity whose values range from 1 to 5, where 5 most often represents the most unfavorable variant in terms of impact on risk, and 1 is the most favorable variant for which the risk is small [26, 27].

$$R_r = AV\sum T_i \tag{1}$$

where R_r is the relative risk, A – the object value, V – the object vulnerability, and T – the threats. The disadvantage of this method lies in the fact that it is not particularly precise because it contains a large number of uncertainties and it could be said that it represents a subjective assessment of the situation. The shortcomings can be compensated for by applying complex mathematical models, but this is not easy to implement in practice and is therefore rarely used. For this reason, the most unfavorable parameters are chosen during the evaluation, thus avoiding indeterminacy.

Risk assessment when flying through a zone with increased radioactivity can be done in a similar way. The parameters that affect the risk are: the time of exposure to radiation, the type and intensity of radiation, and the level of protection in the aircraft. However, it should be emphasized that the plane will certainly not be at the very source of radiation and that it cannot be considered that the total flight time is also the total time of maximum exposure, nor that the radiation dose is the same in the plane as, for example, over the Chernobyl power plant, if we take for example a flight over chimney of this power plant. Even if the plane passes through a radioactive cloud, there is a certain degree of protection that will reduce the penetration of particles and make the dose not be as high inside as it is outside. However, there are possible risks due to the probability that the elements of the aircraft can become new sources of radiation even after leaving the zone of interest. For the above reasons, the authors of the paper analyzed the risk, as if the source of radiation was inside the plane, and based on that and eq. (1), they derived the following eq. (2)

$$R_R = \frac{K_D K_T}{K_p} \tag{2}$$

where R_R is the risk factor, which can have values from 1 to 25 (25 is the highest risk, and 1 is negligible risk), K_T – the exposure time factor, from 1 to 5, where 1 is characteristic for short flights through a contaminated zone, and 5 for a stay in an aircraft that lasts more than 2 hours after its entry into a radioactive zone; although flights can last up to 20 hours, it should be said that the time factor is related to the duration of the flight from entering the zone to landing (the time before entering the zone is not taken into account, and the time spent in the aircraft after leaving the zone is counted, because then parts of the aircraft are irradiated and take the role of a source), K_D – the radiation dose factor, ranging from 1 to 5 (1 is for the lowest dose of radiation, and 5 for an extremely high dose of radiation; the dose is actually the equivalent dose intensity and represents the equivalent dose per unit of time [μSvs^{-1}], and K_P – the coefficient of the degree of protection (damping) and has values from 1 to 5 (it depends on the distance and thickness of the walls between the source and passengers, *i. e.* the crew), value of 1 if it concerns aircraft with the least protection, and a value of 5 for those with the highest protection. Compared to the basic model, K_D represents threat (T), while factor K_p represents vulnerability (V), the time factor K_D cannot be equated with the value (A), but it in the intersection with K_D represents a total threat that indicates that as time increases, the probability that people's health and life will be endangered, increases, the value (A) should not be taken into account, because it is not an object, but a human life for which the value (A) cannot be determined.

In tab. 1 are values that determine this factor, K_D.

The dose rate expressed here is given for the case where a person would be in the immediate vicinity of the source (filter, particles deposited anywhere on the aircraft or an engine that emits a large amount of radioactive particles). The total risk factor is taken into account, also degree of protection, so the actual dose received by a person will depend on all the mentioned parameters. For example, since the helicopter has no protection, we can consider that the crew will receive the maximum dose for a given type of radiation in a unit of time. It is obvious that the engine is positioned behind their back or above their head, and the main rotor pushes all the air together with pollution particles to the cabin itself.

Table 2 refers to the factor that depends on the time spent in the air trap after entering the radioactivity zone K_T.

Table 3 shows the values of the protection factor K_p.

Depending on the risk factor, we can classify the relative risk into several categories. We determine the category, size and level of risk according to tab. 4.

If a decimal number is obtained for the risk factor, the value of the factor is rounded to a whole number, which can introduce an error in the assessment, so another method of calculation is proposed so that the relative risk, R_R, is expressed as a product as provided by the general eq. (2). This approach requires certain corrections in the categorization of factors and/or the relative risk itself. Namely, it could be done in two ways: to represent the protection factor as a decimal number and so, that its maximum value is such that

Table 1. Values that determine K_D

Equivalent dose rate [μSvs^{-1}]	Radiation dose coefficient, K_D
Under 1	1
1 till 10	2
10 till 100	3
100 to 1000	4
Over 1000 (over 1 mSvs^{-1})	5

Table 2. Values that determines K_T

Time spent in the aircraft	Exposure time coefficient, K_T
Less than 30 minut	1
30 up to 1 hours	2
1 hour up to 1.5 hours	3
1.5 hour till 2 hours	4
More than 2 hours	5

Table 3. K_p factor based on type of aircraft

Aircraft type	Protection level, K_P
Helicopter	1
Propulsion engine in fuselage	2
Propulsion engine in tail section	3
Engine mount on wing of a high wing	4
Engine mount on wing of low or mid wing	5

Table 4. Categorization of risks

Category	Relative risk	Level of risk, R_R
1st	Unnoticeable, infinitesimal	1, 2
2nd	Small	3, 4, 5
3rd	Reasonable high	6-9
4th	Great risk	10-16
5th	Dangerously high risk	17-25

when multiplied by the maximum values of other factors, R_R does not exceed 25, meaning the maximum value of K_p would be 1 or that the protection factor be presented in the reverse mode, that 1 be the value that is characteristic of maximum protection, and 5 be the value of aircraft that have very weak protection, and that R_R goes from 1-125. The risk levels would then be determined differently, but in the same way as in the table above, the limits would be determined by norming.

The obtained formula, according to which the risk is calculated is eq. (3)

$$R_R = K_T K_D K_P \tag{3}$$

where K_T and K_D are the smoothing time coefficient and radiation dose coefficient respectively. These parameters take the same values they had in eq. (2).

Analysis of possible risks from radioactive radiation when flying through zones of interest

The following are recognized as possible risks when an aircraft passes through a zone with an increased level of radioactive radiation:

– the ability of the HEPA filter to stop radioactive particles but not elektromagnrtic radiation,
– the risk of radioactive dust settling on parts of the aircraft,
– the impact of radioactive particles on the engine, as well as the role of the engine in spreading these particles on the interior (cabin) of the aircraft, and
– the impact of radioactivity on the instruments of the aircraft.

During the risk assessment, we will consider the objects in the first three points as new sources of radiation. The fourth point will not enter the risk equation, because the risks from this point do not represent a direct threat to human health. As such, they directly endanger the aircraft, but not the crew or passengers. This does not mean that these risks are small, on the contrary, if the proper operation of the instruments or controls is compromised, it can lead to fatal consequences for the people in the aircraft. However, in terms of contamination and endangering health through contamination, this risk does not play a role.

Categorization of possible risks

The categorization of possible risks from radioactive radiation is given in tab. 5. and in the algorithm in fig. 3.

Table 5. Categorization of direct risks

Source of risk	Risk in time
HEPA as source	Postponed effect
Deposits as source	Postponed effect
Engine as source	Immediate impact

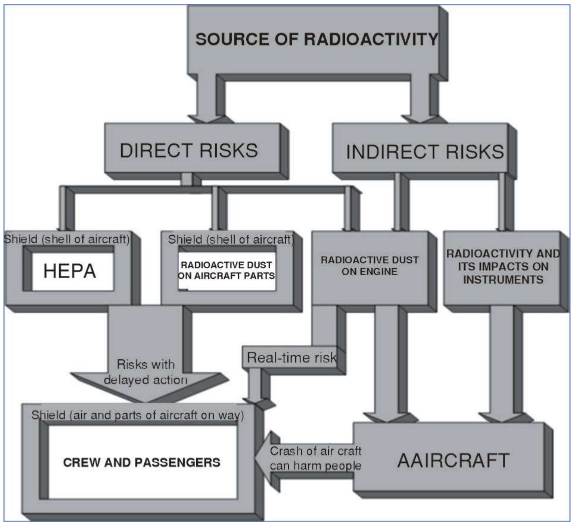

Figure 3. Algorithm of risks

Possibility of stopping radioactive particles with HEPA filter

Since the nucleus is an integral part of atom, radioactive particles are mostly found in the dimensions of the entire atom, which is of the order of 0.1 nm. However, when they are found in nature, either by emission from nuclear waste, or from a nuclear disaster, these particles do not appear individually but bind to dust, moisture and air molecules and other particles from the environment.

The diameter of radioactive particles in the air is in the order of μm in most studies. Some studies show that the dimensions of radioactive aerosols are between 1.1 μm and 2 μm [28], while other studies show that the diameter of radioactive aerosols and other radioactive particles in the environment range from 4-14 μm [29], in some cases they are much bigger, in the range of a couple of mm [29, 30], and in some studies they are even smaller from 1 μm [30].

Aircraft filters, although having pore openings of the order of tens of micrometers and are capable of stopping particles of 0.3 μm and up [31], should be capable of stopping radioactive atoms themselves, along with dust and aerosols to which they are attached. However, the filters are hardly capable of stopping gamma radiation or neutrons, or even beta and alpha particles. Airplane flight should be limited through areas affected by radioactive disasters, but if its use is necessary, then decontamination should be carried out after flying, because the filter that stopped the radioactive atoms, would be contaminated and will not stop their decay and the emission of ionizing radiation into the surrounding space. In such conditions, the filter would act as a source of radioactive radiation and would directly endanger the health and life of crews, of the traveler, but also of the living world that is in his vicinity. Because of this, special procedures would have to be prescribed for the operation and disposal of such contaminated filters. Under conditions of normal exploitation, the filter is changed in extremely long periods (after several months). As in this situation the filter becomes a source of harmful radiation, this should not be the practice after flying over zones with an increased level of radioactive contamination.

Risk of deposition of radioactive dust on aircraft parts

In order to assess the risk of deposition of radioactive particles on aircraft parts, it is important to know what their construction is and how air flow is achieved in their vicinity.

It is necessary to analyze all the known concepts related to the positions of aircraft engines, fig. 4 [32, 33]. The smallest possible protection, *i. e.*, the shortest distance from the engine group to the cabin, was taken as representative for the appropriate geometry of the fixed-wing aircraft, and the most unfavorable position of the passengers or crew members in relation to the source of radiation was taken for this assessment. It is the seat closest to the engine group.

Any of type aircraft from fig. 4, has position of the engine that does not affect the increase in radiation inside the aircraft cabin. Namely, most of the engines are installed in engine nacelles, and even those that are not, but are part of the fuselage and have non-coaxial air flow, are separated from the cabin space, which implies that the crew and passengers are at a relatively safe distance from a potential source of radiation. Observing radioactive particles as a part of the whole, related to dust, sand and other particles that can be found in the air, we can state that they too, considering the fact that they belong to the group of particles PM2.5 and possibly to the group PM10 as well as other particles of pollutants, they do not have any significant contribution in disrupting the operation of the engine, except for an infinitesimal reduction in flow, like other deposits [33-35]. Regarding deposition, just as other particles cannot stick together, neither can radioactive ones [36, 37].

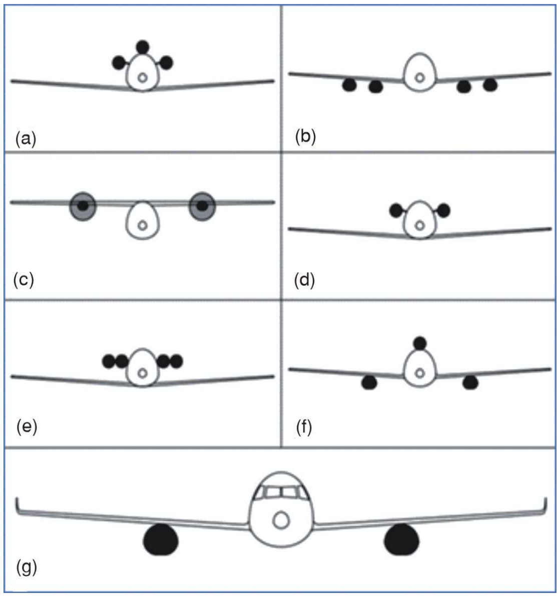

Figure 4. Aircraft type by position of engine mount: a) tail mount and one in fuselage, b) engine mount below wing, c) propeller jet mount, d) tail mount e) double tail mount, f) wing mount and one in fuselage, g) now days most common concept engine mount below wings

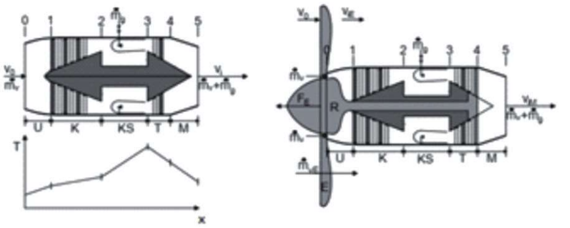

Figure 5. Dependence of temperature on the position in the engine (T = T(x)); Tags: U-intake, K-compressor, KS-combustion chamber, T-turbine, M-nozzle

The influence of radioactive particles on the engine and the role of the engine in spreading these particles to the interior of the aircraft

During the movement of air through the engines that are in use today, both commercial and military, we can notice that, in a short period, there is a big jump in temperature, and then a large part of the thermal energy is converted into kinetic energy. The monitoring of the temperature and its sudden increase during its flow through the engine is shown by a diagram on fig. 5 [33, 38, 39].

The drawing shows the volume of air and the paths through which the air-flows. The maximum temperature is reached in the combustion chamber at the end, before entering the turbine, and theoretically it reaches around 2000 ºC [39, 40]. Earlier research related to the influence of pressure and temperature on radioactivity carried out by Curie and Onmers [41] and those of more recent date [42], show that radioactivity does not depend on external parameters such as temperature and pressure. In theory, temperature can affect the change of these parameters only in the case of extreme values that are measured in millions of Kelvins. Temperatures to which radioactive particles are exposed in our observation are far below the level that could affect the level of radiation.

From the previous analysis, it follows that the operation of the engine itself has no effect on the change in the level of radiation. However, as the place where the air-flow is the highest, we will consider it and the cabin air filter as sources of radiation, both because of the flow and because of the possibility of deposition.

The influence of radioactivity on aircraft instruments

Today's commercial aviation relies heavily on the rapid exchange of large amounts of data, between aircraft and ground and between aircraft. Loss of communication and unreliability in this exchange would automatically lead to a duplication of separation norms and *the sky would become smalle*r, more precisely, we could accommodate fewer users in the same space. Therefore, the requirements for more efficient and economical flights and the very dimensions of the aircraft led to the development of a system called fly-by-wire in aviation jargon, and it is intuitively clear what it refers to. Namely, the command modules from the cockpit give information to the devices that turn it into control and control for the control of electro or electro-hydraulic servo devices that command all parts of the aircraft. The conclusion here is that kilometers of cables, integrated circuits, sensors and other semiconductors are still exposed (and threatened) by ionizing radiation. This practically means that the integrity of the aircraft is compromised [43, 44].

The resistance of such systems to ionizing radiation would still have to be tested, and what we know for sure is that they are not resistant to electromagnetic pulse (EMP) caused by the detonation of nuclear weapons.

RESULTS AND DISCUSSION

The risk factor that one of the crew or passengers will be irradiated with a dose that may cause health issues and even death is represented by eq. (2).

Analysis of modeled scenarios with maximum and minimum limit values

Case 1 – helicopter flight through a radioactive zone with a high level of radiation (1 $\mathrm{mSvs^{-1}}$), and maximum time (2 hours). According to the data we presented earlier, the dose coefficient in this case would be 5, the time coefficient 5 and the protection coefficient would be 1. According to the formula, we get

$$R_R = \frac{5 \cdot 5}{1} = 25$$

So, the risk here is maximum, as expected.

Case 2 – helicopter flight through a radioactive zone with a low level of radiation (up to 1 $\mu\mathrm{Svs^{-1}}$), maximum time (2 hours). According to the data we presented earlier, the dose coefficient in this case would be 1, the time coefficient 5 and the protection coefficient would be 1. According to the formula, we get

$$R_R = \frac{1 \cdot 5}{1} = 5$$

This is a risk from the second category and is considered a small risk, but still unacceptable, because according to the risk management methodology, only the first category is acceptable. After all, for this case it is easy to calculate the radiation dose that would be received by passengers and aircraft personnel. Namely, if we assume that the dose per second is 1 μSv, then the total dose for 2 hours will be H = 7200 seconds · 1 $\mu\mathrm{Svs^{-1}}$ = 7200 μSv = 7.2 mSv. It was said earlier that the helicopter is considered to have virtually no radiation protection, and that is why we do not even take it into account in this simple calculation. Therefore, the dose received by the helicopter crew is higher than the annual dose received by each of us (6.2 mSv). This practically means that with just three such flights, the helicopter pilot would exceed the annual maximum dose for professionally exposed persons (20 mSv is the maximum dose allowed for persons professionally exposed to radiation).

Case 3 – flight of an aircraft with a nacelle on a low or medium wing through a radioactive zone with a high level of radiation (1 $\mathrm{mSvs^{-1}}$), maximum time (2 hours). According to the data we presented earlier, the dose coefficient in this case would be 5, the time coefficient also 5, while the protection coefficient would be 5. According to the formula, we get

$$R_R = \frac{5 \cdot 5}{5} = 5$$

In this case, the risk belongs to the second group and it is an unacceptable risk.

Case 4 – flight of an aircraft with a nacelle on a low or medium wing through a radioactive zone with a low level of radiation (1 $\mu\mathrm{Svs^{-1}}$), maximum time (2 hours). According to the data we presented earlier, the dose coefficient in this case would be 1, the time coefficient 5, while the protection coefficient would also be 5. According to the formula, we get

$$R_R = \frac{1 \cdot 5}{5} = 1$$

In this case, the risk belongs to the first group, which is a negligible risk.

In this way, in principle, the risk of flying through a radioactive zone could be determined. Of course, for detailed analyzes of the possible received dose, it is necessary to use a very complex mathematical apparatus, which would also include attenuation formulas. For such a thing, it is necessary to form a model that would take into account a large number of input sizes that would differ according to the construction of the aircraft and the type of material. Nevertheless, the goal of risk assessment is to find a simple model that would provide quality risk assessments that are applicable in practice.

CONCLUSIONS

Through the analysis, we came to the following conclusions: HEPA filters can become sources of radiation if the plane passes through a radioactive cloud, radioactive particles have no greater tendency than other pollutants to stick to surfaces and aircraft engines, the impact of radioactivity on the instrumentation would be manifested through the action of ionizing radiation to the semi-conductor elements of the aircraft.

The risk factor would not be particularly meaningful if the monitoring of the environment and atmosphere in the flight area of the aircraft was not sufficiently developed, because without it, it is not possible to determine the potential dose of radiation that will reach the aircraft before the flight itself. This problem could be solved by introducing the monitoring of radioactive particles in order to prevent and ban or redirect risky flights, but also by introducing a more serious detector system in aircraft, which would alert the appearance of radioactive particles at the very beginning of the zone, which would lead to the decision to stop the aircraft in progress, redirect flights to less risky paths.

The main contributions of the paper are the proposed equations for risk assessment, but also the recognition of the need for faster development of areas in aviation that would deal exclusively with radiation protection in zones with an elevated level of radioactive radiation, which is higher than usual, that is, the development of nuclear safety management in the field of aviation. The results of the analyzes presented in the paper should be guidelines that would include the mentioned risks in the risk management manual issue.

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AUTHORS' CONTRIBUTIONS

A. S. Ivković conceived the idea for the study, participated in writing, image processing and data analysis. S. D. Ilić contributed by collecting data and references, processing images, writing the paper and analyzing the results. R. V. Radovanović contributed by collecting literature, directing the study, and analyzing the results. S. D. Milić contributed with image processing, data systematization and analysis of results.

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ПРОЦЕНА РИЗИКА ПРИЛИКОМ ЛЕТЕЊА КРОЗ ЗОНУ СА ПОВЕЋАНИМ РАДИОАКТИВНИМ ЗРАЧЕЊЕМ

Рад се бави проценом ризика којем је изложен авио саобраћај у зонама повећаног нивоа радиоактивног зрачења. Елементарне непогоде и ратни сукоби, који се воде око нуклерних електрана и радиоктивног подручја (Чернобиљ) стварају бојазан да може доћи до ослобађања у атмосферу већих количина радиоактивног материјала. У раду су анализаирани: ефикасност „ХЕПА“ филтера у односу на величине честица радиоактивне прашине, утицај радиоактивности на инструментацију ваздухоплова, утицај радиоактивности на мотор и допринос мотора у ширењу радиоактивности на људство у ваздухоплову. Извршена је процена ризика од излагања радиоактивном зрачењу у ваздухоплову у зависности од врсте ваздухоплова и дозе зрачења. Циљ рада је да укаже на потребу за развојем алата у ваздухопловству који би се бавио праћењем и заштитом од радиоактивног зрачења у зонама са повишеним нивоом радиоактивног зрачења.

Кључне речи: радиоактивне честице у ваздуху, праћење, узорковање, дистрибуција у атмосфери, контаминирана област