DEVELOPMENT OF A NOVEL SHIELDING MATERIAL FOR RADIATION PROTECTION IN AIR AND SPACE TECHNOLOGY

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Abstract— Cosmic radiation is the most important and prominent issue for space exploration in modern age because it threatens human health and causes damages to electrical and software systems. Several studies have demonstrated the potential cancer, cardiovascular, and musculoskeletal impact of galactic cosmic radiation. In many fields, lead is known as an ideal shielding material for radiation but it has significant problems such as being extremely expensive, having toxic effects and failing in neutron shielding. Neutron is the most hazardous particle among other radiation types. Keeping all these in mind, the objective of this study is to develop a novel, non-toxic and inexpensive radiation shielding material that protects against neutrons, gamma and X-rays.
Initially, *sodium pentaborate* was synthesized, characterized by using FT-IR, AAS, XRD and B_2O_3 analyses, and applied to the produced fabrics and aircraft canopies. After implementation, those materials were subjected to radiation tests. The fabric which contains only 230 g of sodium pentaborate has reached 75.21% absorption rate of neutron. While sodium pentaborate improved neutron shielding properties of materials outstandingly, it was not an ideal shielding material against gamma-rays. The obtained results prompted us to back it up by another gamma-ray absorber. But it should be emphasized that radiation experiments with sodium pentaborate is a novel implementation in the world to the best of our literature knowledge.

Keywords— Sodium pentaborate, cosmic radiation, neutron, gamma-ray, shielding, absorption, radiation, fabric, lead.

I. INTRODUCTION

It is not difficult to foresee that major and significant developments will be in space technology and Mars journey in 21st century. But the most important, prominent and biggest obstacle on this path is 'cosmic radiation'. Cosmic radiation is the collective term for the radiation which comes from the Sun and from the galaxies of the Universe. Airline pilots, flight engineers and astronauts are occupationally exposed to ionizing radiation of cosmic origin. This radiation exposure has been officially identified and confirmed by the International Commission on Radiation Protection (ICRP) and the US Federal Aviation Administration (FAA). Results of cohort studies on cancer incidence and mortality of civil aviation cockpit crew have been reported from North America, Japan and from several European countries. Even NASA has been funding researches to determine the potential health risks of cosmic rays in an effort to both develop countermeasures for over 25 years. Moreover space radiation has a very significant impact on the technological devices. Some of the high-energy particles can easily penetrate interior of the electronic devices and can cause damages to their electrical and software systems. These effects vary from a single event effect to breakdown of the whole system.
Therefore the potential hazards of cosmic radiation are the motivation for our study. In this context, in accordance with the principle of ALARA (As Low as Reasonably Achievable), radiation protection has great importance in order to tackle possible serious health and environmental problems. Although heavy elements such as lead are known ideal shielding material in radiation shielding; the lack of a shielding material that is effective against both neutron and gamma radiations were showed as the main problem. Also being extremely expensive and heavy and having limited shelf-life are the other disadvantages of these shielding materials. This was the prominent fact that led us to study on radiation shielding. Eventually, the objective of this study was determined as to develop a novel non-toxic, less expensive and more effective radiation shielding material that protects against neutron, gamma and X-ray radiations.
We decided to study on sodium pentaborate in an unexpected way. Sodium pentaborate is a sodium borate mineral and special boron derivative with formula $Na(H_4B_5O_8)$[1]. During literature reviews, it was detected that sodium pentaborate had been used as a capture agent in Boron Neutron Capture Therapy (BNCT) due to its high propensity or cross section (σ) to capture slow neutrons[2]. Also it contains a non-radioactive isotope that doesn't generate secondary radiation in radiation interactions. Considering those facts it was hypothesized that sodium pentaborate can be used as a radiation shielding material.
In this context, *sodium pentaborate* $Na(H_4B_5O_8)$ was successfully synthesized and characterized by FT-IR, AAS, XRD and B_2O_3 (boron oxide) analyses and applied to samples. Fabric production was carried out within the scope of application studies by using sodium pentaborate in different proportions. It has been predicted that if radiation test results are successful, these fabrics will have a very wide area of

[1] S. Menchetti and C. Sabelli (1978). "The crystal structure of $NaB_5O_6(OH)_4$". *Acta Crystallographica Section B* **B34** (1): 45–49.
[2] Yanch, J.C., Shefer, R.E., Busse, P.M., (1999), Boron Neutron Capture Therapy, Science&Medicine, 6, pages 18-27.

usage such as protective clothing for staff, cover and in the construction of a portable protective tent. Also it is a product that appeals to all mankind. Moreover, two separate studies were performed to protect air crews against cosmic radiation. Firstly, aircraft canopy*[3] prototypes were produced by using sodium pentaborate in different proportions. Secondly, canopy parts of an airplane (HURKUŞ) were coated nanotechnologically by using sodium pentaborate in different proportions since there is no production of aircraft canopies in our country. The purpose was to form a judgment about whether it is possible or not to provide radiation shielding property to existing aircraft canopies by nanotechnological coating. Finally, in radiation tests, the neutron, gamma and X-ray attenuation coefficients (μ) of materials were investigated as a function of sodium pentaborate proportion.

II. MATERIALS AND METHODS

1. Synthesis of the Sodium Pentaborate [Na ($H_4B_5O_8$)]

The salt of Na ($H_4B_5O_8$) was synthesized according to the following reaction by mixing the commercially available boric acid and borax pentahydrate in 3:2 molar ratio using deionized water as solvent.



At first, solids (boric acid and borax pentahydrate) were transferred to the solid mixing unit where they will be transformed into a homogeneous mixture. In the meantime water, the mass of which is equal to the total solid mass, was put into the reactor and gradually heated until it reaches the required temperature (80^0C). Then, blended solid solution was fed into water (The temperature of water was kept under control at this stage). After this process the water was housed for 40 minutes at the same conditions. At the end of this time the solution was taken to the crystallization unit wherein macro crystal and granular products were obtained.

2. Characterization Studies

2.1. FTIR (Fourier Transform Infra-Red Spectroscopy)

The FT-IR spectrum of Na($H_4B_5O_8$) crystal was recorded using ATR pellet technique in the range of 450-4000 cm^{-1} by BRUKER Model ALPHA FT-IR spectrometer.

2.2. AAS (Atomic Absorption Spectroscopy)

Firstly, standard boron and sodium solutions of five different concentrations (0.5 - 1 - 2 - 4 - 8 ppm (mg/L)) were prepared. The absorbance of these standard boron and sodium solutions was measured at the wavelength of 249.7 nm and 589 nm, respectively. Then calibration curves were prepared from the values obtained. The standard solutions should produce a straight-line graph. Then the absorbance of the test solutions adjusted in concentration to a measurable range was measured and the concentration of the elements (B% and Na%) was determined from the calibration curves by making stoichiometric calculations. Absorbance is directly proportional to the concentration of the analyte.

2.3. XRD (X-Ray Diffraction)

X-ray diffraction measurements were performed on a PANalytical Empyrean system. The sodium pentaborate samples were placed on the sample holder for analysis at first. Then the XRD data of sodium pentaborate was recorded using CuKα radiation (45 kV and 40 mA) and incident beam optics with a 1/8° fixed divergence and a 1/4° anti scatter slit. The diffraction patterns were collected in the 2θ range of 10°– 80°, the step size was 0.01°, and the exposure time was 98 s.

2.4. Boron Oxide (B_2O_3) Content Analysis

The quality and commercial value of boron products are proportional to the B_2O_3 content of compounds[4]. Therefore boron oxide (B_2O_3) content analysis was performed for powder and crystalline sodium pentaborate samples.

3. Application Studies

3.1. Protective Fabric Production

In our study, impregnation method which is today one of the most widely used method for textile applications was used for the production of protective fabrics. In this method, textile products are impregnated with a solution (liquor) containing chemical substances. The unwanted excess of liquor is removed by squeezing between rollers outside vessel and this solution resumes impregnation vessel. Thus, with the liquor that is transferred to the fabric, substances can also be transferred to the fabric. The impregnation time is extremely short in this application method however this period should not fall below 4 seconds in. The minimum period should be given to discharge of the air in fabric and take the liquor its place during impregnation. Otherwise, it would not be possible to make a proper application. The amount of taken liquor is very important in that method. Some factors such as pressure of roller mangle, fiber type and tissue structure of the fabric, pretreatments applied to the fabric, transition speed of fabric, liquor temperature and the excipients used in the impregnation affect the amount of taken liquor.

[3] * An ***aircraft canopy*** is the transparent enclosure over the cockpit of aircraft. The function of the canopy is to provide a weatherproof and reasonably quiet environment for the aircraft's occupants.(see a canopy in **Fig. 20**)

[4] Briggs, M., (2001), Boron Oxides, Boric Acid, and Borates, Kirk-Othmer Encyclopedia of Chemical Technology.

Therefore, in all applications made by impregnation method, pressure of roller mangle was adjusted for cotton (Table 1).

Table 1: The process parameters used in the impregnation method

	The pressure of roller mangle (Bar)	Received liquor ratio (%)
Cotton	3.5	80

Eventually, *three cotton fabrics* that contain different proportions of sodium pentaborate and *a control sample* were produced. Fabrics are 15x33 cm in size and contain 80 g, 120 g and 230 g sodium pentaborate respectively. The control sample doesn't have any sodium pentaborate at all.

3.2. Aircraft Canopy Prototype Production

Aircraft canopy prototypes were produced by adding sodium pentaborate to *methyl methacrylate monomer* ($C_5H_8O_2$) at different rates in acrylic production stage. In this study, 5 different acrylic production which contains 1%, 3%, 5%, 10% nanoparticulate sodium pentaborate and a control sample (0%) was made. This production was made by applying identical processing so canopy prototypes are of equal size (20x20 cm) and thick (1 cm).
In production studies;

- ⇒ Mould preparation,
- ⇒ Preparation of acrylic resin,
- ⇒ Integration of mixture by adding hardening agent and stirring the mixture to be homogeneous,
- ⇒ Vacuum pumping of air,
- ⇒ Casting of mixture to the mould and
- ⇒ Hardening process were carried out.

3.3. Nanotechnological Coating of Our National Aircraft's (HURKUŞ) Canopy Parts

The principle of screen-printing method which is widely used in surface coating applications was applied. The mixture which contains plexy adhesive and nanoparticulate sodium pentaborate in different proportions was poured onto the canopy part's surface by using a metal spoon. Then using the stripper, 3x5 cm cardboard, coating applications were performed to both surfaces of the canopy parts identically. Finally, 4 canopy parts that belong to our national aircraft (HÜRKUŞ) were coated by using nanoparticulate sodium pentaborate in different rates (1%, 3%, 5%, 10%). Also an identical canopy part didn't receive any treatment as a control sample.

4. Radiation Tests

4.1. Neutron Test

He-3 tube neutron detector was used to determine the neutron absorbing properties of samples. Also ^{252}Cf (Californium) was used as a neutron source. Measurements were carried out with 2.3 MeV neutrons released from ^{252}Cf (Californium) source. If N and N_0 are the measured count rates in detector respectively with and without the absorber of thickness x (cm), the neutron absorption coefficients (μ) can be extracted by the standart equation:

$$\mu = \frac{1}{x} In \frac{N_0}{N}$$

4.2. Gamma Ray Test

The measurement has been done at the photon energies of **662**, **1173** and **1332 keV** obtained from ^{137}Cs and ^{60}Co γ–ray sources respectively. The experiment has been performed using a gamma spectrometer which consists of a 3 in. X 3 in. NaI(Tl) scintillation detector. If N and N_0 are the measured count rates in detector respectively with and without the absorber of thickness x (cm), the linear attenuation coefficients (μ) can be extracted by the standart equation:

$$\mu = \frac{1}{x} In \frac{N_0}{N}$$

III. RESULTS and DISCUSSION

1. Synthesis and Characterization of Sodium Pentaborate

1.1. FTIR (Fourier Transform Infra-Red Spectroscopy)

In order to identify functional groups and learn about the molecular structure of sodium pentaborate, the infrared spectrum was measured (Fig. 1). It is well known that the absorption characteristics of the crystal largely depend on the molecular bonding of the crystal. IR spectra are characteristic for each substance. Therefore, the spectrum obtained in this study was compared with the existing IR spectra in the literature and the analyzed sample have been identified as sodium pentaborate.

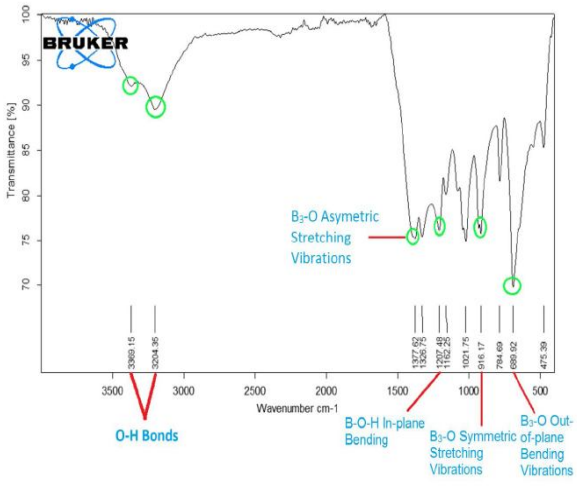


Figure 1: The FTIR spectrum of sodium pentaborate

1.2. AAS (Atomic Absorption Spectroscopy)

It was aimed to determine the concentration of the elements (B% and Na%) in $Na(H_4B_5O_8)$ compound by AAS. The calculated R^2 values of the calibration curves are 0.99. When stoichiometric calculations have been made using the calibration curves; the concentration of the analyte elements have been determined as 7.936±0.9551 (%) and 21.38±0.004937 (%) for Na and B, respectively with 95% reliability degree. When chemical formula was calculated based on the atomic weight and obtained % ratio of elements, the analyzed sample have been identified as sodium pentaborate.

1.3. XRD (X-Ray Diffraction)

Each different crystalline solid has a unique X-ray diffraction pattern which acts like a "fingerprint". Therefore X-ray diffraction analysis of sodium pentaborate was carried out to identify it. Fig. 2 shows the observed XRD patterns of powder $Na(H_4B_5O_8)$. All XRD data were first evaluated by comparisons and searches of the ICDD Powder Diffraction File. In Fig. 2, "*" symbolizes Sodium closo-tetrahydroxohexaoxopentaborate (Reference code-98-000-1386) and "o" symbolizes Sborgite beta (Reference code-98-006-6027) .The chemical formulas and reference codes of phases in the literature are given in detail in XRD analysis table (Table 2).

Table 2: The chemical formulas and reference codes of phases

Reference Code	Phase	Scattering Angle [°2Th.]	Chemical Formula
98-000-1386	Sodium closo-tetrahydroxohexaoxopentaborate	-0.079	$H_4B_5NaO_{10}$
98-006-6027	Sborgite beta	-0.105	$H_{10}B_5NaO_{13}$

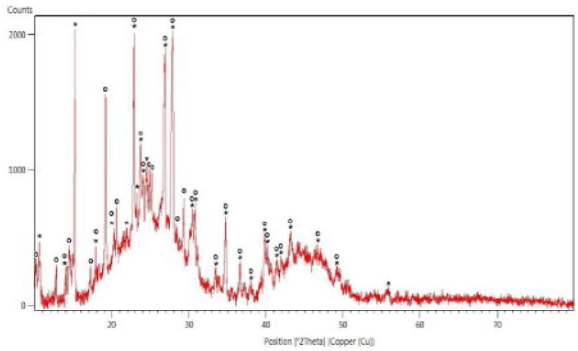


Fig.2: X-ray diffraction analysis of sodium pentaborate

1.4. Boron Oxide (B_2O_3) Content Analysis

The quality and commercial value of boron products are proportional to the B_2O_3 content of compounds. Therefore boron oxide content of $Na(H_4B_5O_8)$ was analyzed. The B_2O_3 content of powder and crystalline sodium pentaborate have been determined as 72.79% and 74.35%; respectively.

2. Radiation Tests

2.1. Neutron and Gamma Ray Tests of Produced Fabrics

a) Neutron Test

N and N_0 are the measured count rates in detector respectively with and without the absorber of thickness x (cm). And the difference between these dose values (N- N_0) is the absorption rate (%).Furthermore, the neutron absorption coefficient (μ) was obtained by Lambert's law using these dose values.

Neutron test results of the fabrics are tabulated in detail in Table 3. According to the results, absorption rate of control sample (sodium free-pentaborate) is **2.51%** and other fabrics that contain 80 g, 120 g and 230 g of sodium pentaborate absorb **27.91%; 58.72%** and **75.21%** of neutrons, respectively. Also R^2 value of the graph is **0.98**. R^2 value's proximity to "1" is crucial in terms of reliability and consistency of test results.

Table 3: The measured linear attenuation coefficients of (μ) fabrics as a function of sodium pentaborate content

Sodium Pentaborate content in fabrics (g)	N_0	N	μ	Absorption rate (%)
control sample (sodium free-pentaborate)	11900	11600	0.017	2.512
80	11900	8578	0.218	27.916
120	11900	4912	0.589	58.722
230	11900	2950	0.929	75.210

b) Gamma (γ) Ray Test

The linear attenuation coefficients (μ) of fabrics in which sodium pentaborate has been used in different rate has been investigated to examine sodium pentaborate effect. The linear attenuation coefficient (μ) of fabric samples were measured for gamma rays of energy 662, 1173 and 1332 keV which have been obtained from ^{137}Cs and ^{60}Co point sources respectively. The measured results are tabulated in Table 4.

Table 4: The measured linear attenuation coefficients of (μ) fabrics as a function of sodium pentaborate content

	662 keV			1173 keV			1332 keV		
Sodium Pentaborate Content (g)	N_0	N	μ	N_0	N	μ	N_0	N	μ
80 g	391973	387711	0.021	167279	166012	0.015	157358	156611	0.009
120 g	391973	384260	0.013	167279	165153	0.008	157358	155892	0.0062
230 g	391973	379508	0.016	167279	163517	0.011	157358	155177	0.0069

2.2 Neutron Test of Nanotechnologically Coated HURKUŞ's Canopy Parts

According to the results, the absorption rate of the control sample (sodium free-pentaborate) is **5.72%** and other canopy parts that were coated nanotechnologically by using 1%, 3%, 5%, 10% sodium pentaborate **absorb 7.25%; 8.09%; 9.33%** and **12.23% of neutrons**, respectively (Table 5).

Table 5: The measured linear attenuation coefficients(μ) and neutron absorption rates of samples as.

Sodium Pentaborate Rate (%)	Thickness (cm)	N_0	N	μ	Absorption Rate (%)
(Control)	0.8	10400	9805	0.073	5.721
1%	0.8	10400	9646	0.094	7.25
3%	0.8	10400	9558	0.105	8.096
5%	0.8	10400	9429	0.122	9.336
10%	0.8	10400	9128	0.163	12.230

2.3. Neutron and Gamma Ray Tests of Produced Aircraft Canopy Prototypes

a) Neutron Test

Neutron test results of the produced canopy prototypes are given in detail below in Table 6.

Table 6: The measured the neutron absorption coefficients (μ) and absorption rates of the produced canopy prototypes.

Sodium Pentaborate Content (%)	Thickness (cm)	N_0	N	μ	Absorption Rate (%)
(Control)	1	10400	8485	0.203	18.413
1%	1	10400	7711	0.299	25.855
3%	1	10400	7170	0.371	31.057
5%	1	10400	6776	0.428	34.846
10%	1	10400	5290	0.675	49.134

As results show, absorption rate of the control sample (sodium free-pentaborate) is **18.41%** and other canopy prototypes that contain 1%, 3%, 5%, 10% sodium pentaborate **absorb 25.85%; 31.05%; 34.84%** and **49.13% of neutrons**, respectively. Also thickness of canopy prototypes is only 1 cm and this leads to the conclusion that sodium pentaborate is an important material to be used in neutron radiation shielding. Also R^2 value of the graph is **0.97** and R^2 value's proximity to "1" is crucial in terms of reliability and consistency of test results.

b) Gamma Ray Test

Gamma test results of the canopy prototypes are given in detail below in Table 7.

Table 7: The measured linear attenuation coefficients (μ) of the produced canopy prototypes as a function of sodium pentaborate content.

		662 keV			1173 keV			1332 keV		
Sodium Pentaborate rate in samples	Thickness (cm)	N_0	N	μ	N_0	N	μ	N_0	N	μ
0%	1	395245	360331	0,092	162734	152976	0,061	154185	145607	0,057
1%	1	395245	352880	0,113	162734	154529	0,051	154185	142242	0,080
3%	1	395245	361242	0,089	162734	151793	0,069	154185	142484	0,078
5%	1	395245	352123	0,115	162734	153701	0,057	154185	142958	0,075

As a result of the discussions and analyses made in collaboration with experts; it has been evaluated that the results are insufficient in terms of consistency. Therefore, it has been decided to repeat the experiment.

As stated previously, neutron is the most hazardous particle for human health among other radiation types[5]. Also gamma radiation which has neither mass nor electric charge penetrates much further through matter than either α or β radiation, thus being able to ionize biological tissues and damage them. Therefore

[5] Akkurt I., El-Khayatt A.M., 2012, *The effect of barite proportion on neutron and gamma-ray shielding*, Annals of Nuclear Energy, 51, 5-9.

the radiation shielding properties of materials (*produced fabrics, produced canopy prototypes and nanotechnologically coated HURKUS canopy parts*) have been tested against both neutron and gamma-rays in order to investigate sodium pentaborate effect on the linear attenuation coefficients (μ).

It is clear that attenuation coefficients and absorption rates of neutron are linearly increased with increasing the proportion of sodium pentaborate in materials. Specifically we noticed that, produced canopy prototypes are more effective than nanotechnologically coated canopy parts in radiation shielding (Tables 5-6) and it can be concluded that sodium pentaborate should be used in canopies not by coating but in the production stage for better shielding. Also the fabric which contains 230 g of sodium pentaborate has reached **75,21%** absorption rate of neutrons. This demonstrates that sodium pentaborate plays an important role in neutron attenuation. Although gamma-ray permeability (N) has decreased with increasing the proportion of sodium pentaborate in materials (Table 4); it is not effective enough to use in shielding. But it should be emphasized that radiation experiments with sodium pentaborate is a novel implementation in the world to the best of our knowledge.

Although lead is effective against gamma and X-rays, it is unable to shield neutrons. Also while sodium pentaborate is effective for blocking neutrons, it is not an ideal shielding material against gamma and x-rays.

CONCLUSION

It can be concluded from this work that while sodium pentaborate improved neutron shielding properties of materials outstandingly, it is not an ideal shielding material against gamma-rays. Eventually these results led us to back up it by another gamma-ray absorber. And in this novel shielding material (sodium pentaboate + gamma-ray absorber) will comprise heavy atoms and light atoms mixed in the proper ratio and this ratio may be varied depending on the field of use and the type of radiation.

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REFERENCES

[1] Alfven, H.,(1939), On the Motion of Cosmic Rays in Interstellar Space, The Physical Review, 55, pages 425-429.

[2] Amirabadi, E.A., Salimi, M., Ghal-Eh, N., Gholam, R.E., Asadi, H., (2013), Study of Neutron and Gamma Radiation Protective Shield, International Journal of Innovation and Applied Studies, 3, pages 1079-1085.

[3] Band PR (1990), Mortality and cancer incidence in a cohort of commercial airline pilots. Aviat Space Environ Med 61:299– 302.

[4] Band PR, Le ND, Fang R, Deschamps M, Coldman AJ, Gallagher RP, Moody J (1996) Cohort study of Air Canada pilots: mortality, cancer incidence, and leukaemia risk. Am J Epidemiol 143:137–143.

[5] Briggs, M., (2001), Boron Oxides, Boric Acid, and Borates, Kirk-Othmer Encyclopedia of Chemical Technology.

[6] Cavallo, D., Tomao, P., Marinaccio, A., Perniconi,B., Iavicoli, S., Pecoriello, V., Moccaldi, R.,(2002), Chromosomal Aberrations in Long-haul Air Crew Members, Mutation Research, 513, pages 11-15.

[7] Cavallo, D., Tomao, P., Marinaccio, A., Perniconi,B., Setini , A., Palmi,S., Iavicoli, S., (2002), Evaluation of DNA Damage in Flight Personnel by Comet Assay, Mutation Research, 516, pages 148-152.

[8] Chung, F.H., (1974), Quantitative Intrepretation of X-Ray Diffraction Pattern of Mixtures, Journal of Applied Crystallography, 7, pages 519-525.

[9] Cullity, B.D., Stock, S.R., Elements of X-Ray Diffraction, Prentice Hall, Third Edition.

[10] Daçe, A., (2013), Gerçekler ve Bilinmesi Gerekenler Işığında Kozmik Radyasyon 2, Kokpit'ten Bakış, 26, sayfa 34-41.

[11] Dayson, N.A., 1993. Radiation Physics with Applications in Medicine and Biology.Ellis Horwood Limited, Chichester.

[12] El-Khayatt, A.M., 2011. NXcom – A program for calculating attenuation coefficients of fast neutrons and gamma-rays. Ann. Nucl. Energy 38 (1), 128–132.

[13] Federal Aviation Administration (FAA), What Aircrews Should Know About Their Occupational Exposure to Ionizing Radiation, FAA Report No: DOT/FAA/AM-03/16, Friedberg W, Copeland K, October 2003.

[14] Fermi, E., (1949), On the Origin of the Cosmic Radiation , The Physical Review, 75, pages 1169-1174.

[15] Flora, S.J., (2002), Lead Exposure: Health Effects, Prevention and Treatment, Journal of Environmental Biology, 23, pages 25-41.

[16] Haldorsen T, Reitan JB, Tveten U (2000) Cancer incidence among Norwegian airline pilots. Scand J Work Environ Health 26:106–111.

[17] Hanawalt, J.D., Rinn, H.W., Frevel, L.K., (1938), Chemical Analysis by X-Ray Diffraction, Industrial&Engineering Chemistry Analytical Edition, 10, pages 457-512.

[18] Hess, W.N., Patterson, H.W., Wallace, R., (1959), Cosmic-Ray Neutron Energy Spectrum, The Physical Review, 116, pages 445-457.

[19] Honda, M., (2009), Ultra High Energy Cosmic Ray Acceleration in the Jet Centaurus A, The Astrophysical Journal, 706, pages 1517-1526.

[20] ICRU, 2010. Reference Data for the Validation of Doses from Cosmic-Radiation Exposure of Aircraft Crew. ICRU Report 84 (prepared jointly with ICRP). Journal of the ICRU 10 (2), 2010.

[21] ICRP, 2013. Assessment of Radiation Exposure of Astronauts in Space. ICRP Publication 123. Ann. ICRP 42(4).

[22] Irvine D, Davies DM (1999) British Airways flightdeck mortality study, 1950–1992. Aviat Space Environ Med 70:548–555

[23] Jun L., Shupping X., Shiyang G., (1995), FTIR and Raman Spectroscopic Study of Hydrated Borates, Spectrochimica Acta, 51A (4), pages 519-532.

[24] Kaji M, Tango T, Asukata I, Tajima N, Yamamoto K, Yamamoto Y, Hokari M (1993) Mortality experience of cockpit crewmembers from Japan Airlines. Aviat Space Environ Med 64:748–750

[25] Kaplan, I., (1964), Nuclear Physics, Addison-Wesley Publushing Company Inc, London, Second Edition.

[26] Mary, S. S., Kirupavathy, S. S., Mythili, P., Gopalakrishnan, R., (2008) , Growth and Characterization of Sodium

Pentaborate [$Na(H_4B_5O_{10})$] Single Crystals, Spectrochimica Acta Part A, 71, pages 1311-1316.

[27] Moorman, R.W., (2002), JAA Adopts Requirments for Assessing Aircrew Exposure to Cosmic Radiation, Flight Safety Foundation-Human Factors& Aviation Medicine, 49, pages 1-4.

[28] NCRP (National Council on Radiation Protection and Measurements). 1957. Protection against Neutron Radiation up to 30 Million Electron Volts. Report No. 20. NBS Handbook, vol. 63. National Bureau of Standards, US Department of Commerce, Washington, DC.

[29] Needleman, H.L., (1991), The Health Effects of Low Exposure to Lead, Annual Review of Public Health, 12, pages 111-140.

[30] Nicholas JS, Lackland DT, Dosemeci M, Mohr LCJ, Dunbar JB, Grosche B, Hoel DG (1998) Mortality among US commercial pilots and navigators. J Occup Environ Med 40:980–985

[31] Parker, S., Coderre, J., Saraf, S., Fairchild, R., Hansrote, R., Perry, H., (1992), Boron Neutron Capture Therapy of Anterior Chamber Melanoma With p-Boronophenylalanine, Investigative Ophthalmology&Visual Science , 33, pages 395-403.

[32] Rinard, P., (1991), Neutron Interactions with Matter, Passive Nondestructive Assay of Nuclear Material, Los Alamos Technical Report NUREG/CR-5550, LA-UR-90, 732, pages 357-377.

[33] Sabelli, C., Menchetti, S., (1978), The Crystal Stucture of $NaB_5O_6(OH)_4$, Acta Crystallographica Section B, 34, pages 45-49.

[34] Singleterry, R.C., (2013), Radiation Engineering Analysis of Shielding Materials to Assess Their Ability to Protect Astronauts in Deep Space from Energetic Particle Radiaton, Acta Astronautica, 91, pages 49-54.

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