Article

Not peer-reviewed version

Production of Nano and Micro Powders and Composites from Radioactive Waste for the Space Industry

Valeriy Kizka *

Posted Date: 19 September 2024

doi: 10.20944/preprints202409.1466.v1

Keywords: radioactive powders, radioactive composites, radioactive devices, radioactive waste, disposal, space industry

Article

Production of Nano and Micro Powders and Composites from Radioactive Waste for the Space Industry

V. A. Kizka

Institute for Safety Problems of Nuclear Power Plants, Chornobyl, Ukraine; v.kizka@ispnpp.kiev.ua

Abstract: Taking into account modern technologies in the mining industry and in the processing of industrial waste, we propose to reprocess cemented low- and intermediate level radioactive waste by extracting all chemical compounds from them. Because of the low cost of space flights in the near future, we propose to use chemical compounds, extracted from radioactive waste, in the production of space electronics and structural materials for automatic space probes and rovers. At the same time, since nano- and micro powders, as well as composites with these fillers, are widely used today in electronics and technology, including in the space industry, the production of radioactive powders and composites will provide new scientific results in the field of materials science and solid-state physics, since nothing is known today about the properties of radioactive powders and composites containing radioactive sources inside.

Keywords: radioactive powders; radioactive composites; radioactive devices; radioactive waste; disposal; space industry

---

1. Introduction

Disposal of radioactive waste (RW) remains a current and largely unsolved problem due to the increasing volumes of this waste and the continuing threat of leakage of radioactive contamination into the environment at RW storage sites. The time of disposal of RW at disposal sites, ranging from several hundred to thousands of years, remains questionable due to the lack of practical experience of mankind in such long-term control of hazardous objects. No state has existed for so long without the destruction of its industry and economy due to wars, crises and revolutions. The ever-increasing amounts of RW remain as a legacy for future generations, onto whose shoulders we shift the solution to the problem of radionuclide leaks into the environment, protection and monitoring of RW storage facilities. And all this against the backdrop of growing terrorist threats. The latter will inevitably increase due to the trends already observed today in coalition of terrorist organizations with drug trafficking, which gives terrorists huge financial profits [1], and this will inevitably give access to weapons of mass destruction [2]. The main method used by terrorists to influence the authorities and the population is fear. The more dangerous weapons terrorists possess, the greater the effect will be achieved. It is necessary to take into account the peculiarities of the psychology of modern terrorism. Participants in terrorist organizations are represented mainly by mentally ill people, with an inferiority complex and poor people trying to solve their material problems and improve their social status through criminal methods [3]. Today, the number of such citizens is growing catastrophically around the world due to escalating international conflicts, the development of scientific and technological progress, accompanied by the emergence of distorted spiritual values [4,5], which indicates the inevitable increase of terrorism in the future. The presence of a "dirty bomb" in the hands of terrorists can be eliminated if we begin now to solve the problem of disposing of RW into space using unconventional methods.

In the mid-20th century, the idea of sending RW into space as passive ballast arose, but it was abandoned due to the high cost. Now the cost of sending a payload into space has decreased several

 doi:10.20944/preprints202409.1466.v1

times and is about $1500/kg compared to $6000/kg in the 1960s [6]. If the Starship project is successfully completed, the cost of sending a payload will be about $200/kg [6]. Given the further decrease in the cost of space flights, the question arises about the possibility of sending RW into space as a payload. That is, taking into account the current level of technology development, is it possible to consider RW stored in cemented and vitrified form as an artificial rock from which we can isolate all the main chemical compounds that could be used for the manufacture of devices and structural materials for spacecraft?

Since space equipment is designed to operate under the influence of ionizing radiation, the presence of the equipment's own radioactivity should theoretically not disrupt its operation. The idea of using radioactive silica and silicon, extracted from cemented and vitrified RW, for the creation of space electronics was expressed in [7]. Since scientific research studies the properties of the radiation resistance of various materials (semiconductors, dielectrics, metals) under the influence of external irradiation, information about the properties of these same materials, but containing radionuclides inside them, would be a completely new scientific and technical result. The production of radioactive powders of various levels of dispersion would also be a new result from a scientific and technical point of view.

2. Review of Modern Technologies

To immobilize low- and intermediate-level radioactive waste (LLW, ILW), cementation is used, and for high-level radioactive waste (HLW), vitrification is used. When cementing RW, Portland cement is mainly used, the composition of which is as follows, wt.% [8]: 65 – CaO, 23 – SiO_2, 8 – Al_2O_3, 4 – Fe_2O_3. During vitrification, various glasses are used - aluminophosphate, borosilicate, aluminosilicate, etc. One of the most common is borosilicate glass with the composition, wt.% [9]: 47 – SiO_2, 24 – Na_2O, 12 – B_2O_3, 10 – CaO, 5 – Al_2O_3, 2 – TiO_2. The amount of radioactive waste encapsulated in cement is up to 30% by weight, in glass - no more than 20% [10]. During the storage of RW, radionuclides migrate into cement or glass and the matrix containing the RW also becomes radioactive. Let us assume that we have the technology for extracting these compounds from radioactive waste. Where can these compounds be used in space industry?

CaO, Ca: From [11] it is known that the addition of CaO nanoparticles (0.5-1 wt.%) to the Mg-1Zn alloy improves its mechanical and anti-corrosion properties, and magnesium alloys are used in the aerospace industry [12]. In addition, the addition of Ca (0.6-1 wt.%) to magnesium alloys (ZAX421, ZAX422 alloys) not only improves their mechanical properties, but also increases their ignition temperature [13].

SiO_2, Al_2O_3: Silicon dioxide is the main source of silicon for electronics. In addition, SiO_2 nanoparticles themselves are used in the space industry [14]. In particular, SiO_2 is used in polymer composites for thermal control coatings of spacecraft [15]. Alumina Al_2O_3 in the form of sapphire is widely used in electronics due to its high hardness, good electrical insulating and optical properties, in particular, in SOS (silicon on sapphire) technologies that are used in space industry [16].

Fe_2O_3: In radio electronics, polymer composites with fillers made from a mixture of alumina and hematite are used [17]. Hematite is the main ore of iron. Iron-based alloys are used in space industry, such as Incoloy MA956, PM2000, etc. [18].

Na, Ti, TiO_2: Alloys based on the Al-Si, Al-Si-Mg systems, which are used in space industry, are modified with sodium additives in amounts up to 0.1 wt.% and Ti – up to 0.05 wt.% to improve ductility [19]. Titanium alloys are used in space technology [20]. A composite with a matrix of vinyl methyl silicone rubber and a TiO_2 filler is used as protection against gamma radiation [21]. The space industry uses NaS batteries in flying vehicles [22] and plans to use them on future rovers [23].

B, B_2O_3: Boron oxide is used to produce boron, boron carbide, boron nitride. Boron, boron nitride and boron carbide fibers are used to strengthen metal composites in space technology [24,25]. Additions of boron and boron carbide to aluminum alloys are used to reduce the radiation permeability of the alloy to neutron and gamma radiation [26].

By treating cemented and vitrified RW as an artificial rock, we can apply mining technologies to extract the above compounds. Or we can apply technologies for recycling industrial and household waste - ash and slag. A review of these technologies is given in [27]. We shall complement them here with a few examples.

The rock-forming minerals of kaolin clays are kaolinite and quartz. Chemical composition of the original clay (wt.%): 69.4 – SiO_2, 21.4 – Al_2O_3, 3.2 – Fe_2O_3, 1.8 – CaO, 0.8 – MgO, 0.6 – Na_2O, 0.7 – K_2O, 1.2 – TiO_2 [28]. To separate alumina from this aluminosilicate, the clay is treated with sulfuric acid at a temperature of 280°C for 90 min. Next, it is treated with water at 90°C for 30 minutes and the resulting pulp is filtered. The filtrate is treated with lime, the precipitated aluminum hydroxide is separated and heated to 1100°C. The hydroxide decomposes into aluminum oxide with a purity of up to 98.5%.

Ash and slag waste from coal combustion at thermal power plants contains (wt.%) [29]: 2.54 – Ca, 27.16 – Si, 14.12 – Al, 5.34 – Fe, 0.52 – Mg, 0,67 – Ti, and others. The technological procedure for extracting of silicon and alumina is as follows: grinding, magnetic separation to obtain hematite concentrate with a purity of 50%, the non-magnetic charge is dried, fired, treated with hydrochloric acid, filtered to obtain silica in the sediment, which is washed and dried (commercial SiO_2 has ultimately 99% of purety), and the solution with $AlCl_3$ is crystallized, thermally decomposed and metallurgical alumina grade G-0 is obtained (suitable for producing Al).

Slags from the processing of copper-nickel raw materials contain (wt.%) [30]: 37.5 – SiO_2, 38.5 – FeO, 7.94 – MgO and 0,4 – sums of copper, nickel and cobalt. To extract silica and iron, the slag is crushed to a size of less than 80 microns, treated with 10% sulfuric acid at 20°C for 1 hour, dried at 50°C and then in drying cabinets at 250°C, the resulting gel is washed with water and ferrous sulfate is separated from SiO_2. The silica is further washed with 20% hydrochloric acid at 60°C for 15 min, obtaining silica with a purity of 93%.

Theoretically, these technologies can be transferred to the processing of RW, taking into account that all operations must take place indoors to prevent leaks of radioactive dust generated during the grinding of RW into the environment. Since only part of the RW encapsulated in the original matrix will be transferred into the compounds, discussed above, extracted from mixture RW and cement, the remainder is planned to be mixed in small portions with non-radioactive charge used for the production of structural elements and parts of automatic spacecraft. That is, it is necessary to consider the residue of RW as a modifier for metal alloys or composites used in the space industry. Since the residue will contain a wide range of chemical elements, the amount of radioactive waste added to a non-radioactive charge, to a metal melt, etc. is selected in each specific case.

It should be especially noted that the production of radioactive powders of varying degrees of dispersion with the subsequent study of their properties is in itself a new scientific and technical problem, which has not been considered anywhere before.

Let us consider a 200-liter barrel for storing cemented LLW or ILW. The mass of such an empty steel barrel is 47 kg [31]. Let us take the density of concrete for encapsulating RW equal to 3500 kg/m^3 [32], not taking into account the difference between the density of radioactive waste and the density of cement, the mass of cemented waste is then m_w = 700 kg (or m_{brl} = 747 kg together with the barrel). Let the specific activity of the compound (a mixture of cement with radioactive waste): A_{rw} = 10^8 kBq/kg. Because the mass of radioactive waste encapsulated in cement does not exceed 30% of the mass of cement, then the mass of radioactive waste in the barrel: m_{rw} ≈ 210 kg, weight of cement: m_{cem} ≈ 490 кг. Let us assume that we have been able to extract the main components of radioactive cement:

- silica SiO_2 weighing 23% of m_{cem}: m_{SiO2} ≈ 113 kg. Let the purity of the extracted silica be 98%, then 2% of its mass is radioactive waste: m_{rw_SiO2} ≈ 2.26 kg.
- alumina Al_2O_3 weighing 8% of m_{cem}: m_{AlO} = 39.2 kg. Let the degree of extraction of the isolated alumina be 98%, then the mass of radioactive waste in it is: m_{rw_AlO} = 0.8 kg.
- hematite Fe_2O_3 weighing 4% of m_{cem}: m_{FeO} = 19.6 kg. Let the degree of hematite extraction be 86%, which we take from the possibilities of processing tailings dumps of an iron processing plant for the extraction of iron from ferruginous quartzites [33]. Then the mass of radioactive waste in hematite is: m_{rw_FeO} = 2.75 kg.
- quicklime CaO weighing 65% of m_{cem}: m_{CaO} ≈ 319 kg. Most likely, when processing radioactive waste, they will immediately obtain calcium, but let us assume that the yield of CaO is

approximately equal to the yield of calcium - 90% when it is obtained by the aluminothermic method [34]. Then the mass of radioactive waste in calcium oxide is: $m_{rw\_CaO} \approx 31.9$ kg.

As a result, the remainder we get: $m_{res} = m_{rw} - (m_{rw\_SiO2} + m_{rw\_AlO} + m_{rw\_FeO} + m_{rw\_CaO}) \approx 172$ kg of radioactive residue. A steel radioactive barrel, into which radionuclides diffused during the storage of radioactive waste and its own activity was also induced, melts and mixes with metal alloys used in space industry. It is also possible to obtain iron radioactive powders of various dispersion from this steel.

Let us assume that isolated radioactive chemical compounds and elements are mixed with non-radioactive analogues to reduce the specific activity to the level of waste removed from regulatory control or to the level of very low-level waste VLLW according to classification abroad. That is, for example, radioactive silica with inclusions of radioactive waste is mixed with non-radioactive silica and the resulting mixture is then used in the production of materials for space equipment. The radioactive residue inevitably must be mixed with a non-radioactive charge as a modifier, which will either improve the properties of future materials or at least not worsen their properties.

Today, composites and alloys for space applications have been obtained that are resistant to radiation and even improve their properties when irradiated. Thus, a composite of a polypropylene matrix and a filler of Fe_2O_3 powder (7% by weight of the matrix) is resistant to radiation (its electrical conductivity does not change at large absorbed doses) and is used in electronics [35]. Radiation strengthening of SiO_2 quartz glasses up to absorbed doses of 1 MGy and an increase in the strength of a composite with a quartz glass filler after irradiation with a dose of 10^5 Gy were observed in [36]. In [37], strengthening of aluminum-magnesium alloys under low-intensity electron irradiation was observed. In [38], it was found that gamma irradiation with doses up to 10^4 Gy has no effect on the thermoelectric properties of the SiGe alloy, and damage from neutron irradiation with doses up to 10^{15} n/cm^2 is neutralized by heating the material. And so on. The creation of radioactive analogues of radiation-resistant materials will be a new scientific and technical result and direction. Since work with radioactive materials is robotic, it is of interest to create radioactive structural materials for robots working with RW.

Let us calculate how much non-radioactive charge is needed in order to obtain, after mixing the radioactive waste with it, a material with an activity corresponding to waste removed from regulatory control or corresponding to the activity of VLLW abroad. Let the total mass of RW $m_{rw} \approx$ 750 kg, its specific activity $A_{rw} = 10^8$ kBq/kg (LLW), the final activity should be $A = 10^6$ kBq/kg (corresponds to the activity of VLLW). We also take into account that a steel barrel of RW, with the same specific activity A_{rw}, is melted down and added to the non-radioactive alloy in the form of a melt. Let us denote the mass of non-radioactive material (charge) as m_0. Because the total activity before and after mixing should be the same, then from the formula:

$$A \cdot (m_{rw} + m_0) = m_{rw} \cdot A_{rw}$$

we find m_0: $m_0 = m_{rw} \cdot ((A_{rw}/A) - 1) \approx 74$ tons. Let us assume that the entire automatic space installation that will need to be launched into space can be made from this very low-level radioactive material. Then this mass m_0 is less than the payload of the future Starship carrier, which is 100 ÷ 150 tons [39]. That is, one Starship launch can dispose of two containers with LLW. Since 2010 there have been 334 Falcon9 launches with a 23 tons payload, 46 Dragon launches with a 6 tons payload, since 2018 year 9 Falcon Heavy launches with a 64 tons payload [40]. Assuming that the cheap Starship will be no less in demand, we can assume that 11 recycled LLW containers will be sent into space as a payload within 15 years. We assume that with the development of technology, the volume of recycled LLW launched into space will grow exponentially.

We can apply the same calculation for ILW ($A_{rw} = 10^{11}$ kBq/kg) assuming a decrease in specific activity by two orders of magnitude and find the same mass of non-radioactive material of 74 tons for mixing with ILW.

Before applying any technology to RW recycling, it is necessary to test this technology with non-radioactive material mixed with RW simulators - non-radioactive atoms of cesium, cobalt, manganese, etc. Having received information about the distribution of simulators in the final products, the rates of chemical reactions, side processes, etc., it is possible to estimate the final specific activity, the volumes of the initial non-radioactive charge, etc.

3. Quantitative Cost Estimates

Let us estimate the cost of processing one container of LLW (mass is around 750 kg, volume is 0.2 m^3), provided that the cost of sending the Starship payload is expected to be 200 $/kg [6]. The cost of disposal (capital and operating costs) of long-lived LLW (and ILW) in Belgium is 235 thousand $/$m^3$ in 2009 prices [41] or $47000 for one 200-liter barrel, or 63 $/kg. Taking into account inflation, this cost already exceeds $100/kg. The cost of disposal of non-heat-emitting LLW and ILW in Germany at 2016 prices is $12320/$m^3$ [41] or $2460 for one 200-liter barrel, or $3.3/kg. That is, the average in Europe is $33/kg, or taking into account inflation is about $50/kg. Considering that the burial time of LLW and ILW is 300 - 500 years and more than a thousand years for long living LLW and ILW, and the cost of sending a payload decreases by 4 - 5 times over 50 years [6,42], we assume that by the end of this century the cost of disposal of 1 kg of LLW and ILW and the cost of launching the same mass into space will be equal.

The cost of HLW disposal in Belgium in 2009 prices is $3.03 million/$m^3$ [41] or $607 thousand for one 200-liter barrel. Let us take the density of the vitrified HLW equal to 2500 kg/m^3 [43], then the mass of a 200-liter barrel is 500 kg. As a result, the cost of HLW disposal in Belgium is $1200/kg. The cost of HLW disposal in France in 2012 prices is 470 thousand $/$m^3$ [41] or 94 thousand $ for one 200-liter barrel, or 190 $/kg. On average in Europe, we will get $1350/kg. That is, already now the cost of burying 1 kg of HLW and launching into space the same mass of cargo is approximately equal [42]. But in this case, the HLW will be passive ballast.

For prices for disposal of spent nuclear fuel we have [41]: Canada – 170 $/kg (2015 prices), Spain – 340 $/kg (2009 prices), Czech Republic – 270 $/kg (2009 prices), Sweden – 350$/kg (2009 prices), Finland – 770$/kg (2017 prices). The world average is $380/kg. It turns out that the cost of burying 1 kg of spent nuclear fuel is comparable to the cost of launching 1 kg into space on a Starship carrier [6]. But again, spent nuclear fuel will be passive ballast.

Since in the production of structural materials is now widely switching to additive technologies, where the initial raw material is powder, we will estimate the cost of recycling of cemented LLW and ILW based on the cost of the final product: micro- and nanopowders of CaO, SiO_2, Al_2O_3, Fe_2O_3. Prices from [44] for nanopowders ($/kg): 2500 – CaO, 140 – SiO_2, 320 – Al_2O_3, 330 – Fe_2O_3; for micropowders: 14300 – CaO, 360 – SiO_2, 470 – Al_2O_3, 300 – Fe_2O_3. Averaging, taking into account the percentage composition of each chemical compound in the cement mixture, we get $1390/kg. That is, the cost of producing 1 kg of powders from LLW and ILW is comparable to the cost of sending 1 kg of payload into space on modern carriers [42].

For the prices of powders that could be obtained from the vitrified HLW, we obtain from [44] for nanopowders ($/kg): 140 – SiO_2, 4740 – B_2O_3, 2500 – CaO, 320 – Al_2O_3, 460 – TiO_2; for micropowders: 360 – SiO_2, 14300 – CaO, 470 – Al_2O_3, 254 – TiO_2. Averaging, taking into account the percentage composition of chemical compounds in glass, we get $1270/kg. The same result as for LLW and ILW, but we must understand that processing HLW will cost significantly higher than for LLW and ILW.

4. Conclusion

In this work, we came to the conclusion that with the launch of Starship, sending 1 kg of HLW or spent nuclear fuel into space as passive ballast will be cheaper than storage them at disposal points. The cost of disposing of LHW and spent nuclear fuel has already become equal to the cost of sending 1 kg of cargo into space on modern carriers (Falcon9), which has not been indicated anywhere before. Reprocessing of the LLW and LLW, and with the development of technology in the future, spent nuclear fuels and HLW, in order to obtain radioactive powders and composites based on them, is advisable now for several reasons. Firstly, we get a new material with unknown properties. Secondly, we ensure the safety of future generations for hundreds and thousands of years to come from man-made disasters and terrorist attacks by creating radioactive equipment for working in space. Also, this will reduce the amount of RW that needs to be stored at disposal points and reduce the number of created radioactive waste disposal points and ultimately reduce them to zero.

References

1. Лобач Д.В., Смирнова Е.А. Терроризм и наркотрафик в условиях перманентного вооруженного конфликта в современной Колумбии. *Азиатско-Тихоокеанский регион: экономика, политика, право*, 3, 2016, 135-148. URL: https://cyberleninka.ru/article/n/terrorizm-i-narkotrafik-v-usloviyah-permanentnogo-vooruzhennogo-konflikta-v-sovremennoy-kolumbii
2. Тенгизова Ж.А. Международный терроризм и оружие массового поражения. *Юридический журнал*, 4, 2014, 223-234. URL: https://cyberleninka.ru/article/n/mezhdunarodnyy-terrorizm-i-oruzhie-massovogo-porazheniya
3. Ливанова Л.О., Чикишева В.А. Психология современного терроризма. *Colloquium-journal*, 11(63), 2020, 174-175. DOI: 10.24411/2520-6990-2020-11762
4. Мусаева С.Д., Магдиева Н.Т. К вопросу об актуальных проблемах сохранения здоровья подрастающего поколения. *Вестник науки и образования*, 22(76), 2019, 44-46. DOI: 10.24411/2312-8089-2019-12201
5. Буткалюк В.А. Проблема социально-экономического неравенства в глобальном и национальном измерении. *Наука. Культура. Общество*, 27(4), 2021, 66-75. DOI: 10.19181/nko.2021.27.4.6
6. Bruno Venditti, Carmen Ang, Sam Parker "The Cost of Space Flight Before and After SpaceX" 2022 *Visual Capitalist online publisher*: https://www.visualcapitalist.com/the-cost-of-space-flight/
7. Kizka V.A. Nanocomposites and Semiconductor Devices Based on Recycled Radioactive Waste. *Preprints 2023*, https://doi.org/10.20944/preprints202207.0188.v1
8. Гафарова В.В., Кулагина Т.А. Безопасные методы утилизации радиоактивных отходов. *Журнал Сибирского федерального университета. Техника и технологии*, 2016, 9(4), 585-597. DOI: 10.17516/1999-494X-2016-9-4-585-597
9. Lebedev A. S., Eremyashev V. E., Rassomahin M. A., Korinevskaya G. G. Влияние защитного покрытия на процессы коррозии металлических контейнеров для иммобилизации высокоактивных радиоактивных отходов. *Радиоактивные отходы*, 2024, no.1 (26), pp. 47—56. DOI:10.25283/258-9707-2024-1-47-56.
10. Шубабко О.Э. и др. Преимущества использования керамических матриц для иммобилизации радиоактивных отходов. *Труды Кольского научного центра*, 2-2(9), 2018, DOI: 10.25702/KSC.2307-5252.2018.9.1.911-913
11. Guangxin Shen et al. Effect of nano-CaO particle on the microstructure, mechanical properties and corrosion behavior of lean Mg-1Zn alloy. *Journal of Magnesium and Alloys*, V. 12(2), 2024, 794-814. DOI: https://doi.org/10.1016/j.jma.2022.12.009
12. Jingying Bai et al. Applications of magnesium alloys for aerospace: A review. *J. Magnes. Alloy*, 11(10), 2023, 3609-3619. DOI: https://doi.org/10.1016/j.jma.2023.09.015
13. Hanieh Yeganeh et al. Enhanced oxidation and overheating resistance of the extruded Mg–Zn–Al–Mn magnesium alloy by Calcium addition. *J. Magnes. Alloy*, 11(4), 2023, 1276-1291. DOI: https://doi.org/10.1016/j.jma.2023.03.004
14. Elchin Huseynova,, Adil Garibova, Ravan Mehdiyeva. TEM and SEM study of nano SiO2 particles exposed to influence of neutron flux. *J. Mater. Res. Technol.* 5(3), 2016, 213-218. DOI: http://dx.doi.org/10.1016/j.jmrt.2015.11.001
15. Павленко В.И., Черкашина Н.И., Манаев В.А., Сидельников Р.В. Изменение морфологии и термооптических характеристик композита с кристаллическим диоксидом кремния при вакуумно-тепловом воздействии. *Вестник БГТУ*, 11, 2018, 83-90. URL: https://cyberleninka.ru/article/n/izmenenie-morfologii-i-termoopticheskih-harakteristik-kompozita-s-kristallicheskim-dioksidom-kremniya-pri-vakuumno-teplovom
16. Мустафаев Г.А. и др. Влияние технологических факторов на дефектность структур кремний на сапфире. *Электроника и электротехника*, 1, 2017, 7-15. DOI:10.7256/2453-8884.2017.1.22388
17. Ахмедов Ф.И., Кулиев А.Д. Изучение электропроводности полимерных композитов на основе полипропилена с различным содержанием наполнителей α-Al_2O_3 и α-Fe_2O_3. *Электронная обработка материалов*, 49(5), 2013, 98–101. URL: https://eom.ifa.md/en/journal/shortview/938
18. Батиенков Р.В., Бурковская Н.П., Большакова А.Н., Худнев А.А. Высокотемпературные композиционные материалы с металлической матрицей (обзор). *Труды ВИАМ*, 6-7(89), 2020, 45-61. URL: https://cyberleninka.ru/article/n/vysokotemperaturnye-kompozitsionnye-materialy-s-metallicheskoy-matritsey-obzor
19. Долгополов В.Г. и др. Способы влияния на структуру и свойства алюминиевых сплавов, используемых в авиакосмической отрасли. *Вестник ПНИПУ*, 18(2), 2016, 50-63. URL:

https://cyberleninka.ru/article/n/strukturnye-osobennosti-gomogenizirovannogo-silumina-ispolzuemogo-v-aviakosmicheskoy-otrasli-s-modifitsirovaniem-i-bez-nego
20. Антипов В.В. Перспективы развития алюминиевых, магниевых и титановых сплавов для изделий авиационно-космической техники. *Авиационные материалы и технологии*, S, 2017, 186-194. URL: https://cyberleninka.ru/article/n/perspektivy-razvitiya-alyuminievyh-magnievyh-i-titanovyh-splavov-dlya-izdeliy-aviatsionno-kosmicheskoy-tehniki
21. R. Chaitra et al. Investigation of gamma shielding parameters of VMQ/W/TiO2 polymer composites. *Nuclear and Particle Physics Proceedings*, 339–340, 2023, 139-141. DOI: https://doi.org/10.1016/j.nuclphysbps.2023.08.011
22. Garner J.C., Baker W.E., Braun W., Kim J. Sodium sulfur battery cell space flight experiment. 1995, *U.S. Department of Energy, Office of Scientific and Technical Information, official web-site:* https://www.osti.gov/biblio/187010
23. Geoffrey A. Landis, Rachel Harrison. Batteries for Venus Surface Operation. *Journal of Propulsion and Power*, 26, 2010. DOI: https://doi.org/10.2514/1.41886
24. Yingying Zhou et al. Preparation of boron nitride fiber by organic precursor method. *Results in Physics*, 7, 2017, 705-708. DOI: https://doi.org/10.1016/j.rinp.2016.12.004
25. Бєліков С.Б., Волчок І.П., Мітяєв О.А., Плескач В.М., Савченко В.О. Композиційні матеріали в авіабудуванні (огляд). *Нові матеріали і технології в металургії та машинобудуванні*, 2, 2017, 32-39. URL: http://nmt.zntu.edu.ua/article/view/131033/126779
26. Zübeyde Özkan, Uğur Gökmen, Sema Bilge Ocak. Analyses of Gamma and Neutron Attenuation Properties of the AA6082 composite material doped with boron carbide (B_4C). *Radiation Physics and Chemistry*, 206, 2023, 110810. DOI: https://doi.org/10.1016/j.radphyschem.2023.110810
27. Kizka, V. Recycled Radioactive Waste in the Space Industry. *Preprints 2022*, 2022050198. DOI: https://doi.org/10.20944/preprints202205.0198.v1
28. Наимов Н.А. и др. Комплексная переработка каолиновых глин месторождения "Зидды". *Доклады Академии наук Республики Таджикистан*, 61(3), 2018, 286-292. URL: https://cyberleninka.ru/article/n/kompleksnaya-pererabotka-kaolinovyh-glin-mestorozhdeniya-ziddy
29. Досмухамедов Н.К. и др. Технология комплексной переработки золы: технологические расчеты по переработке золы. *Наука и техника Казахстана*, 3, 2023, 133-144. DOI: https://doi.org/10.48081/RTBP8301
30. Тимощик О.А. Комбинированный способ комплексной переработки отвального шлака комбината «Печенганикель». *Вестник Кольского научного центра*, 4(11), 2019, 69–74. DOI: 10.25702/KSC.2307-5228.2019.11.4.69-74
31. Report of Dnipro National University named after Oles Honchar "Containers and materials for low and intermediate level radioactive waste management". URL: https://knute.edu.ua/file/MjA=/a482fa000fd437de8ee25d63ab1d88c6.pdf
32. Павленко В.И. и др. Контейнерная технология утилизации твердых радиоактивных отходов АЭС. *Вестник БГТУ*, 5, 2013, 165-169. URL: https://cyberleninka.ru/article/n/konteynernaya-tehnologiya-utilizatsii-tverdyh-radioaktivnyh-othodov-aes
33. Шелепов Э.В., Игнатова Т.В. Выбор технологии получения гематитового концентрата из хвостов мокрой магнитной сепарации обогатительной фабрики ОАО «Михайловский ГОК» по результатам лабораторных исследований и пилотных испытаний. *Горный информационно-аналитический бюллетень*, 10, 2013, 139-144. URL: https://cyberleninka.ru/article/n/vybor-tehnologii-polucheniya-gematitovogo-kontsentrata-iz-hvostov-mokroy-magnitnoy-separatsii-obogatitelnoy-fabriki-oao-mihaylovskiy
34. Фалин В.В., Сухарев А.В. Термические методы получения металлического кальция. *Технические науки – от теории к практике*, 26, 2013. URL: https://cyberleninka.ru/article/n/termicheskie-metody-polucheniya-metallicheskogo-kaltsiya
35. Ахмедов Ф.И. и др. Влияние гамма-облучения на электропроводность полимерных композитов полипропилена с оксидами алюминия и железа. *Электронная обработка материалов*, 49, 2013, 94-97. URL: https://eom.ifa.md/ru/journal/shortview/992
36. Никулина О.В., Степанов В.А. Радиационные изменения оптических и механических свойств материалов на основе SiO_2. *Рос. Хим. Ж.*, 65(3), 2021, 51-56. URL: https://cyberleninka.ru/article/n/radiatsionnye-izmeneniya-opticheskih-i-mehanicheskih-svoystv-materialov-na-osnove-sio2
37. Дмитриевский А.А., Ефремова Н.Ю., Гусева Д.Г. Микротвердость алюминий-магниевых сплавов в условиях действия низкоинтенсивного бета-облучения. *Вестник ТГУ*, 7(5), 2012, 9-10. URL: https://cyberleninka.ru/article/n/mikrotverdost-alyuminiy-magnievyh-splavov-v-usloviyah-deystviya-nizkointensivnogo-beta-oblucheniya
38. Yixiao Li et al. Influence of fast neutron and gamma irradiation on the thermoelectric properties of n-type and p-type SiGe alloy. *Journal of Nuclear Materials*, 528, 2020, 151856. DOI: https://doi.org/10.1016/j.jnucmat.2019.151856

 doi:10.20944/preprints202409.1466.v1

39. SpaceX official site: https://www.spacex.com/vehicles/starship/
40. SpaceX official site: https://www.spacex.com/
41. Сорокин В.Т., Павлов Д.И. Стоимость захоронения РАО: зарубежные оценки. *Радиоактивные отходы*, 1(6), 2019, 46—55. URL: https://radwaste-journal.ru/docs/journals/6/6ithe_cost_of_radwaste_disposal_a_foreign_assessment.pdf
42. Thomas G. Roberts "Space Launch to Low Earth Orbit: How Much Does It Cost?" Aerospace Security website: https://aerospace.csis.org/data/space-launch-to-low-earth-orbit-how-much-does-it-cost/
43. Сорокин В. Т., Павлов Д. И., Кащеев В. А., Мусатов Н. Д., Баринов А. С. Научные и проектные аспекты остекловывания жидких радиоактивных отходов АЭС с ВВЭР-1200. *Радиоактивные отходы*, 2020, no. 2 (11), pp. 56—65. URL: https://radwaste-journal.ru/docs/journals/22/scientifi_c_and_design_aspects_of_liquid_radioactive_waste_vitrification.pdf
44. https://nanografi.com/