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Sustainability of uranium extraction

Remarks on the taxonomy decision of the EU

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01: Summary

Nuclear power has been declared a green technology within the scope of the EU taxonomy. However, this decision did not take into account the mining of uranium and the final disposal of uranium products.

The different methods for mining uranium and their effects on the environment are discussed in this paper. In addition to the usual problematic issues related to mining, specific risks and future liabilities arise from mining of a hazardous substance. The processing of the ores and related products can be hazardous and represent liabilities for the environment and local population. There is a significant disparity between the rehabilitation costs of the contaminated sites that are often paid by the state, and the profits from uranium mining.

These facts are evaluated in the second chapter and demonstrate that environmental, social and governance concerns of uranium mining imply high to very high risks, mainly caused by the radioactivity and toxicity of the raw materials. In addition, there are political risks due to the close relationship between the use of uranium as an energy source and its use for nuclear armament.

02: Introduction

The EU taxonomy for sustainable financial products is of particular importance for the discussion on sustainability and the „green“ label. It is designed as a science-based classification system for sustainable economic activities, which should enable the financial sector to reliably offer sustainable financial products (European Commission). Natural gas and nuclear power were classified as green (transitional) technologies in the decision of the EU Parliament of 06.07.2022. This is criticized by many experts, including the German Environmental Agency (Umweltbundesamt 2022).

Primary nuclear fuel extraction, i.e. uranium mining, has been completely disregarded in the EU taxonomy classification, despite the serious environmental, social and governance risks. Likewise, the long-term economic consequences resulting from the continuous tasks of post-closure monitoring of uranium mining operations have been neglected. Significantly, uranium mining is either excluded or not considered in sustainability systems such as IRMA (Initiative for Responsible Mining Assurance) (Kielwasser 2022).

The aim of this position paper is to analyze and evaluate, from the geoscience and environmental science viewpoint, the sustainability risks that can arise prior to application in the energy cycle.

03: ”Green nuclear power“ is not feasible

This position paper of the working group „Green Nuclear Power?“ of the raw materials expert group of Scientists for Future (S4F) is based on the S4F discussion paper „Nuclear Energy and Climate“. We dive more deeply into the geological aspects of the issue that are outlined in section 1.3.1. of this discussion paper, and attempt to estimate the inevitable harm to people and environment that result from the exploitation of uranium deposits, as well as the associated closure, remediation, social, health and environmental costs. In addition to the environmental degradation caused by conventional mining, which has been known for a long time, radiotoxicity of the extracted material will persist for millions of years. The text is therefore of general interest, especially in countries that benefit from their uranium mines.

The claims of the proponents of nuclear power as a technology mitigating the climate crisis („green nuclear power“) are: nuclear power produces minimal greenhouse gas emissions, requires a low consumption of materials, impacts a small land area, has the highest energy density and an excellent health record; further arguments are given in Brunnengräber et al. (2023). Neither the interdisciplinary MIT study „The Future of Nuclear Energy in a Carbon-Constrained World“ nor the EU Commission‘s taxonomy take into account the emissions that occur at the sites where uranium ore is extracted and processed.

This is a contradiction because the EU Commission is currently developing a directive on supply chain responsibility, which concerns the upstream elements of the value chain, i.e. mining, processing and refining (Tarradellas Espuny 2022, Wolters 2023). The raw material supply of nuclear power plants (NPP), especially in France, is based on material exported from Niger, a country where the quality of (raw material) governance is considered to be highly problematic (World Bank 2020).

These problematic production conditions were excluded from the classification of nuclear power as a sustainable economic activity according to the EU taxonomy. Furthermore, the continuing negative effects of radioactive pollution in mining areas were not considered. This is as contradictory as it is irresponsible and dangerous.

03.1: Uranium mining

As already noted a description of the conditions in the uranium mining regions of the world has been largely excluded from the debate. Essential information about the initial stages in the whole value chain for uranium ore in the energy industry are provided in this paper (see also Engelbrecht 2017: 60-71; 87-89). The information base for the political debate will therefore be expanded and completed.

The scenarios discussed relate largely to the physical, chemical, and biological impacts of uranium mining on the environment. These include, in particular, the negative effects on the quality of soils, ground and surface waters, the atmosphere and ecosystems of the chemical substances in the industrial overburden dumps (waste rock piles, sludge ponds) and released during mining and processing. It concerns the mobilisation and subsequent accumulation of chemicals and radiotoxic hazardous substances in organic material as well as the subsequent deposition in sediment (Nassour 2014) and the damages and costs resulting from unavoidable dispersion of uranium in the environment during its further industrial processing.

Because the element uranium (U) is enriched in the earth‘s crust due to its chemical properties, and is also highly mobile as a U^{VI+} ion in oxygen-containing waters and fluids, uranium deposits were formed under a wide range of geological settings. Economically exploitable concentrations of uranium minerals are hosted by sandstone, granite, volcanics, as well as specific rock types such as black shale, phosphate, coal and 2.3 Ga quartz conglomerate, and occur as magmatic-hydrothermal gangue mineralization or on unconformities (Pohl 2020: 300-309).

Concentrations of uranium minerals present in the rock can be economically exploitable from 0.01 % U_3O_8 (Finch 1996). As a rule, rock with contents between 0.06 and 1.0 % U_3O_8 is mined (Pohl 2020: 296). Approximately 90% of uranium mining occurs in Australia, Canada, Kazakhstan, Namibia, Niger, Russia, the USA and Uzbekistan (Uran-Atlas 2019: 12, Bhutada 2021).

03.2: Uranium production and environmental aspects

Depending on the deposit type, associated metals such as gold, platinum, tin, tungsten, selenium, molybdenum, cadmium, cobalt, copper, silver, zircon, REE, etc. may be present and recoverable from the ore-bearing rock as well as the uranium and its decay products (Pohl 2020). Naturally occurring uranium consists of approx. 99.27% of the isotope ^{238}U; and almost the entire remainder (0.72%) of ^{235}U (Pohl 2020: 297).

It is not possible to distinguish between uranium mining for NPPs and that for nuclear weapons: they are the same deposits and production methods. The UO_2 (uranium dioxide) produced from the yellowcake is enriched in technically complex steps to 4% for use in NPPs and to over 90% ^{235}U for the explosive charge in the warheads of nuclear weapons. Note: Subsequent to disarmament negotiations, weapon-grade uranium was depleted to make it usable in NPPs (IAEA INIS 2000, IAEA 2007).

The extraction of the raw material is mainly done by two methods:

- Solution mining („in situ“ leaching): Here, solvents are injected via boreholes into uranium-bearing, porous sandstone layers that lie between impermeable rock. In a closed circuit, the leached solution is pumped out via extraction wells. About 70 to 80% of uranium is produced globally by this technically less expensive method (WISE 2020).

- The raw ore is extracted in open pit or underground mining. Ore heaps are produced and, in order to increase the reactive surfaces of the mineral grains in the rock, the rock is crushed and pulverized in ball mills. The uranium is then chemically extracted: sulphurous acid is used for quartz rock, sodium bicarbonate for carbonate rock. Admixtures of oxidising solutions convert insoluble U^{IV+} into soluble U^{VI+} (Pohl 2020: 296).

After application of the first method, the leached zones of a water-bearing succession remain with strongly altered chemical properties and permeability values: None of the subsequent remediation attempts in the USA after „in situ“ leaching could restore the original conditions of the water-bearing succession (Otton & Hall 2009). When the second method is used, large quantities of overburden and rock slurry are produced because of the generally low primary uranium grades. Both types of chemically treated residues are stored close to the mining areas and are surprisingly referred to as NORM (Naturally Occurring Radioactive Materials); there is no or rarely any further use for them (IAEA 2021b: 1).

In further technical processing steps, yellowcake (U_3O_8) is produced from the leached solutions. **Importantly, 75% of the original radioactive content of the ore-bearing rock remains in the overburden and slurry ponds when the second method is used** (Diehl 2011; IAEA 2021b: 74).

Using method 2, the production of 1 t of yellowcake requires the mining of an average of 913 t of uranium-bearing rock by blasting, processing and finally depositing approx. 912 t of rock sludge in the industrial tailings ponds. The amount of material to be provided annually to operate a 1 GW nuclear power plant - corresponding to 8.76 TWh of electrical energy - requires 27 t of enriched UO_2, which is produced from 230 t of yellowcake. The annual increment in the industrial tailings ponds next to the mines is thus 210,000 t, corresponding to 105,000 m^3 of milled and leached rock sludge containing the above chemicals and radioactive and toxic metal compounds (WNA 2015). For a better understanding of the size of this figure: this **volume corresponds to a cube enriched with pollutants with an edge length of just under 47.2 m - each year for each NPP with 1 GW output.**

From 1951 to 2017, 754 NPPs were built in 41 countries (Bulletin of the Atomic Scientists 2017). 450 nuclear reactors were in operation in 2019 and 55 were under construction (NEA/IAEA 2020: 76). In total, approximately 3,050,000 t U_3O_8 have been produced worldwide from 1949 to 2019 (NEA/IAEA 2020: 97). An estimate of the order of magnitude of the amount of residues including radiation produced in uranium mining areas since the beginning of the nuclear age shows: Between 1942 and 2004, about 1.8 billion m^3 of overburden dumps and rock slurry were produced; the radioactivity contained therein amounted to 3.3×10^{16} Bq (IAEA 2008: 23). Since an additional amount of 700,000 t U_3O_8 was produced from 2004 to 2018 (Uranium Atlas 2019: 13), the volumes of overburden and mud ponds increase to **2.12 billion m^3**. With this amount, an area of **310 km^2 (corresponding to the city of Berlin)** could be **covered with a 2.4 m thick layer of sludge.**

03.3: Damages and impacts due to uranium mining, processing and concentration

The mining, processing and concentration of uranium results in both the environmental impacts of mining, which have been generally known for a long time, and those that are specific to uranium. However, because the former are still a complex and expensive problem (Thisani et al. 2021), both are discussed below:

Chemical reactions occur in the tailings pond and overburden dumps: Rain and snowmelt water as well as oxygen, together with bacterial activity, cause the rapid onset of sulphide/pyrite weathering and the formation of sulphurous acid in this rock with its large reactive surfaces. Metal ions are mobilised in the acidic waters; such acidic, toxic seepage waters are known as AMD: acid mine drainage. These also mix with rising groundwater in abandoned underground galleries and opencast mines after the pumps have been switched off. The quality of surface and groundwater is impaired by AMD if there are no or inadequate/defective geotechnical barriers. This can be explained using the example of the 700,000 m^3 sludge pond of the former Schneckenstein mine (Erzgebirge, Saxony): from closure in 1957 until the start of remediation in 1990, 80 kg of uranium as well as increased amounts of As, Mo, Co, Zn, Cu were released annually from seepage water into the surface water network. The sludge pond metal inventory had a total mass of 45,000 t and consisted of 20 heavy metals (Merkel et al. 1998). The heavy metals are absorbed from the water by living organisms and enter the food chain (Le Guernic 2016, Committee on Uranium Mining in Virginia 2011). Such contaminated sites, which were created prior to the establishment of technical standards, are present in large numbers in all uranium-producing countries. They are a major challenge to clean up and rehabilitate; and usually the state addresses the costs related to these long-term liabilities.

In order to prevent contamination of ground and surface waters by such seepage, the spoil heaps and sludge ponds have been equipped with seals (geotechnical barriers, multi-barriers). However, because these may leak over time, their imperviousness must be constantly monitored. Covers on spoil heaps and sludge ponds prevent the drift of windborne radiotoxic dust; but these protective devices also require constant monitoring. Another problem is outgassing radon, which affects downwind air quality from such point sources (Mudd 2008, Sahu et al. 2014).

Repair, permanent maintenance and monitoring of the dams and barriers that stabilise, secure, cover and seal the spoil heaps and slurry ponds remain long-term liabilities and risks as long as this material cannot be put to any other use. Because heavy rainfall can occur more frequently due to climate change, there is an increasing risk of flooding of the dams and the question arises whether they therefore need to be retrofitted so that they remain stable in the case of such an event. The same applies to the dams of dump piles and mud ponds close to the sea, which may be affected in their stability by rising sea level and floods. It is unlikely that countries with weak governance will apply the standards of careful monitoring of mining contaminated sites and their reliable aftercare (ICMM 2020).

Although „in-situ“ leaching does not involve massive impairments like those caused by open-cast mining, this process is also highly problematic: 40 kg of solvent and up to 33 kWh of energy are needed to extract 1 kg of uranium compounds. Subsequent measures to remediate the exploited strata have had limited success: it turned out during remediation attempts that restoring the original chemical state (i.e. prior to the „in-situ“ leaching) in the uranium-bearing formation after the leaching process was neither technically nor economically feasible (Catchpole & Kirchner 1995, World Nuclear Association 2014). In addition, there is the problem of correctly disposing of expended leaching fluids. Furthermore, there is a qualitative impairment of the adjacent groundwater strata: Because impermeable rock formations must be intersected by several drill holes in the area of the uranium deposits, the risk of local leakage increases (Saunders et al. 2016).

In view of the extensive environmental impacts, remediation and post-mining measures described here for uranium mining and processing, it is difficult to understand that according to LCAs (Life Cycle Analyses) the greenhouse gas emissions of an NPP are only of minor importance: in LCAs concerning the production of uranium fuel, the greenhouse gas emission values range between 67–103 g CO_2eq / 1kWh (Nakagawa et al. 2022). However, Norgate et al. (2013) and Kadiyala et al. (2016), who have determined even lower values for this, think that with the expected declining ore grades in the mining areas and the increasing depth of mining, the greenhouse gas emissions will continue to rise.

03.4: Social Issues

Mining in general and uranium mining in particular have adversely affected local nature and people through their undesirable side effects. Typical adverse consequences include mining damage (subsidence, sinkholes, induced earthquakes due to large rock mass displacement), post-mining landscapes that are functionally impaired, unhappiness due to environmental degradation, poisoning due to surface and groundwater impairment, radiotoxic dust and radon exposure; resettlement, occupational diseases (e. g. silicosis, pneumoconiosis, lung cancer [historically: mine dust lung dysfunction, Schneeberg disease], bronchial cancer, leukaemia, kidney disease and genetic defects), (Bell & Donelly 2006, Marcak & Mutke 2013, Committee on Uranium Mining in Virginia 2011, Kreuzer et al. 2021, Richardson et al. 2020, Albrecht et al. 2007).

03.5: The enormous redevelopment costs and long-term liabilities

In the following, the total global closure, remediation, renaturation, social, health and environmental expenditures due to uranium mining since 1942 are estimated. The legacies caused by uranium mining in Saxony and Thuringia are among the largest in the world and are being remediated according to legal requirements. Thus, they can serve as comparative and reference objects (Lersow & Waggit 2020). The estimated remediation costs due to the uranium mining activities of Wismut SDAG, which produced approx. 216350 t of yellowcake from 1946 to 1989, are estimated at € 8.9 billion (1990 to 2050) (Wismut GmbH https://www.wismut.de/de/index.php); however, another estimate puts the total closure and remediation costs at approx. € 30 billion (Lersow & Waggit (2020: 102).

The costs of closure and rehabilitation of the uranium mining legacies in the 14 largest U-producing countries were estimated at $3.7 trillion in 1993 (WISE 2019). Closure and remediation costs for all uranium mines in the US were estimated at $2.3 trillion in 2007 (EPA 2007: 4-17). If the maximum market value achieved for yellowcake (2007: $136.22 / 1kg) is taken as a basis, then the costs just mentioned are more than one order of magnitude higher than the hypothetical profit from the sale of all yellowcake produced worldwide between 1949 and 2019.

The long-term effects of radiotoxic heavy metals and their concentrates exceed any human ability to envisage, to plan, to control, to take necessary precautions, and to be responsible.

04: Uranium mining is not sustainable

The mining of uranium ores and their processing for the purpose of electricity generation has a **very high environmental hazard potential** (including risks of pollutants, interference with the natural environment, risks of incidents and accidents, competitive water use and impacts on protected ecosystems), as derived by the ÖkoRess methodology developed on behalf of the German Environment Agency (Umweltbundesamt 2017 and 2020).

- Because of the **geological and geochemical conditions** under which uranium mining occurs, it is a source for acid mine drainage (AMD) and acid rock drainage (ARD).

  Furthermore, uranium deposits have high or considerably increased concentrations of heavy metals. Besides the highly toxic and radioactive uranium itself, rare earths, arsenic, vanadium, zirconium, thorium and others are to be mentioned here. Many of the uranium minerals are soluble in acidic and oxygen-containing waters, which mobilises the toxins from the rock and releases them into the environment (waters and soils). In addition, there is the high radioactivity and the outgassing of radon into the atmosphere.

- Further reasons for the high environmental hazard potential of uranium mining are to be found in the **technique of extraction and processing**: the raw material is predominantly extracted by in-situ leaching, in which uranium-bearing, water-permeable layers are drilled and the raw material is extracted by injecting chemicals (leaching) and pumping out the brines; in most cases, the water-permeable layer is damaged after uranium extraction. In addition, there is the classical method of hard rock mining, which implies large rock mass movements due to the low uranium ore contents. The considerable amounts of rock crushed during processing result in very large slurry dumps that are exposed to erosion by water (rain and flooding) and wind (drift of radioactive and toxic dust).

  Large amounts of water are used in the processing of the raw material, which causes an intensification of the water shortage, especially in the arid areas where a large number of these ore deposits are located. In addition, large quantities of toxic residues are produced which, together with the auxiliary materials used (acids, alkalis, solvents, etc.), are particularly problematic to dispose of.

- **The effects of uranium extraction on the climate** are also significant, because mining exclusively accounts for between 10 and 70% of the greenhouse gas emissions of the nuclear power cycle, depending on the extraction method and further use of the fuel. In addition, uranium mining encounters deposits with ever decreasing ore contents, which requires higher energy input and thus more greenhouse gas emissions (Nakagawa et al. 2022).

With regard to the **social aspects** of uranium extraction, there is also a **high risk potential** (and thus dangers for humans and health).

- **General human rights** - here Art. 25.1 of the Universal Declaration of Human Rights, the right to welfare - are restricted in the vicinity of extraction sites (pits and processing plants): there is increased exposure to radioactivity and windblown radioactive dust (IAEA 2021a, ecologic 2010)..

- **Working conditions**, especially in developing countries (Niger, Morocco, Kazakhstan, Namibia, Uzbekistan, Democratic Republic of Congo and others), do not meet the minimum standards of the International Labour Organization due to violations of international standards on occupational safety and health, fair pay and freedom of association (labournet Germany 2021, Hibakusha Weltweit 2021, ILO n.d.).

- With regard to **local livelihoods and concerns**, conflicts arise in the vicinity of uranium mining operations due to insufficient participation of local stakeholders in the licensing of the companies, competition for water resources, as well as insufficient accident and disaster prevention (Die nukleare Kette, greenpeace media 2010). In addition, the mining regions of origin do not benefit from the mining revenues. The unfair distribution of opportunities, risks, costs and benefits is, on the one hand, a major factor against sustainability and, on the other hand, a trigger for protests and low acceptance of the mining sector..

Issues of **commodity governance** are of great importance both at the level of the commodity-producing countries and in international commodity trade; the commodity uranium in particular involves a **high risk potential,** especially with regard to the implementation of valid legal norms and standards, as well as the protection of the rights of the population and nature:

- Particularly in the developing countries mentioned above, corruption and bribery, unfair political influence by companies and deficits in the execution of the legal framework are a distinct problem, as reflected in the World Governance Indicators (n.d.) of the World Bank and in the Corruption Perception Index (2023) of Transparency International. Considering that, for example, France sources its uranium from Niger, there is no guarantee that the upstream supply chain operates according to sustainable criteria and that responsible governance is enforced during the extraction of raw materials. The current war in Ukraine and international sanctions have, in the view of some experts, revealed an extremely high dependence of the USA on uranium from Russia (Bidder 2022, Platz 2022)..

Finally, uranium mining leads to **economic threats and risks because of the long-term liabilities**, that are difficult to calculate. For example, the radioactive legacy from disused opencast mines, dumps and sludge and tailings ponds. Just in Germany, the rehabilitation work for SDAG Wismut is valued at many billions of Euros paid from the public purse. Even if the efforts and costs of remediation in, for example, sparsely populated arid regions turn out to be less, the countries operating with uranium to generate electricity bear a large share of responsibility for these costs.

05: Conclusion and political considerations

The production of uranium dioxide for NPPs cannot – as our explanations show – be undertaken as a climate-neutral and sustainable technology. The figures demonstrate that the raw material and land use requirements in mining areas also have negative consequences for people and nature. A full life cycle assessment of nuclear energy must also take into account and include the first stages in the value chain, which are here the technological processes and engineering developments in the mining areas; they must not be neglected; this applies also to the expected costs for the final storage of „nuclear waste".

Historically, the so-called „peaceful use" of nuclear power is closely linked to its military use (Bundeszentrale für politische Bildung, bicc 2013). The main reason why France refuses to terminate the use of nuclear power is probably related to its status as a nuclear power. President Macron is quite open about that (Claußen 2022); and probably the situation is similar in the USA and the UK. Politically, a final phase-out of the use of this high-risk technology in the energy sector seems hardly possible without addressing nuclear deterrence. However, due to the current political situation, this has receded into a dimmer distance than before 24 February 2022.

In addition, the EU's taxonomy decision will probably effect that on the one hand funds so urgently needed for the energy transition flow back into the extraction of natural gas and uranium, thus delaying the replacement of these climate and environment impairing technologies by climate-neutral equivalents. On the other hand, this legitimises the export of environmental and social costs to the producer countries - and thus predominantly to the global South.

In this respect, it is a concern that the listing of nuclear power in the taxonomy will turn out to be a wrong decision with respect to environmental, climate, social, energy and developmental perspectives.

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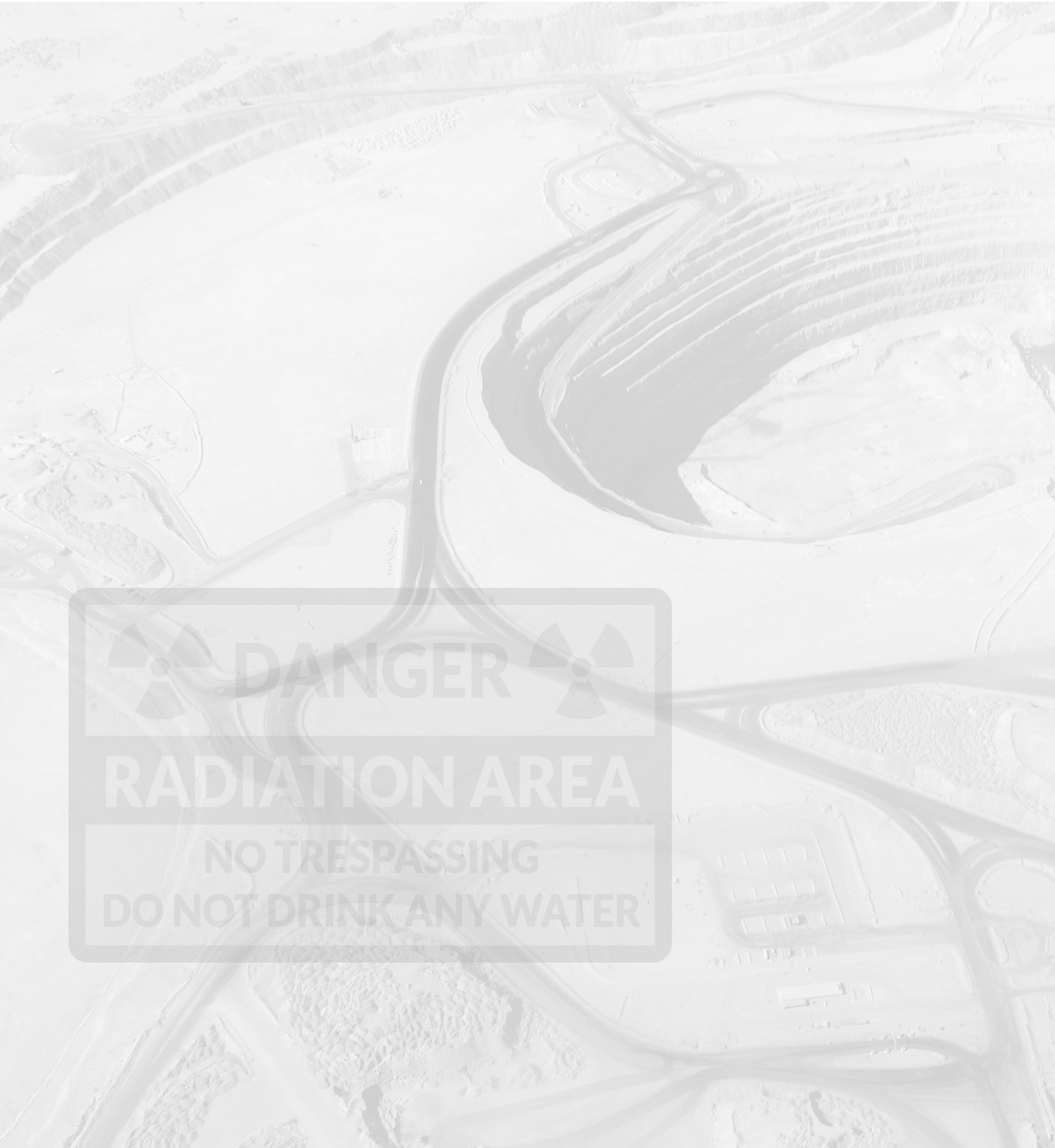
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