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Reassessing Radiological Contamination and Hazards in the French Nuclear Test Site in Algeria

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Abstract

In 1999, at the request of Algeria, the International Atomic Energy Agency (IAEA) conducted a preliminary assessment of the residual radiological contamination resulting from 17 nuclear weapon tests by France that took place in the Algerian Sahara from 1960 to 1966. Here, we review the subsequent IAEA preliminary report with the goal of identifying additional studies necessary to develop a more comprehensive analysis on the radiological conditions of Algeria's Sahara, in the context of addressing environmental damage and humanitarian concerns resulting from the nuclear weapon tests. Recognizing that no study is entirely comprehensive within its own scope and merit, we recommend specific areas for expanding the scope of the study with particular consideration given to the obligations related to victim assistance and environmental remediation laid out in the Treaty on the Prohibition of Nuclear Weapons, which Algeria has signed but has not yet ratified.

To better understand the current status of the radiological contamination of the Algerian Sahara, we consider the possible utility of Unmanned Aerial Vehicles (UAV's) equipped with radiation sensors as an option for baseline monitoring of the former French test sites. We also explore what further studies and disclosures may be needed to ensure completeness and accuracy of data regarding the initial contamination by the French nuclear testing program and related activities. Finally, we consider whether and how scientists from African countries with relevant capabilities can assist Algeria under Article 7 of the Treaty on the Prohibition of Nuclear Weapons in reassessing and monitoring hazards from the former nuclear weapon test sites to support local communities at possible risk.

1. Introduction

The end of World War II marked the beginning of the nuclear arms race, where states developing nuclear weapons conducted nuclear test explosions, often in secret and on colonized lands and territories, exposing the public, the military, and test personnel to ionizing radiation. The rationales for where nuclear weapon States chose to test nuclear weapons included the need to reduce political opposition and prevent radiological impact in their core regions and of their national populations[1]. Since colonies and overseas territories had little to no say in the administration of their land and country, they were susceptible to exploitation without due consideration for the potential environmental and human impacts of residual radioactivity. Information regarding nuclear weapon development, testing, and manufacturing programs remains largely classified in most nuclear weapon states. This lack of transparency can add further

[1] Lacovsky, "Opposing Nuclear Weapons Testing in the Global South: A Comparative Perspective."

psychological burden and trauma to impacted communities that are left with uncertainties about environmental damage and potential consequences to their health[2].

The first nuclear weapon test on African soil was detonated by France in Reggane, Algeria on February 13, 1960. France conducted a total of seventeen nuclear tests, including 13 underground tests, eleven of which were after Algeria gained independence from France. These tests were carried out without the public knowledge on how ionizing radiation can negatively impact their health and some in secrete[3]. Following the tests, the French military asserted that all tests were safe, and procedures and safety measures were in place to monitor radioactive fallout and ensure safety of personnel and communities. The official summary of the report stated that, out of the 24,000 people engaged in the test experiments, 75% did not receive any external radiation dose, and the remaining 25% were exposed to varying levels of external dose of up to 600 mSv. The likelihood of community exposure was considered to be minimal for both nearby and distant fallout[4].

In the years following France's abandonment of the site, there has been no systematic monitoring of radiological contamination. Apprehensions regarding the legacy of radiological contamination in the Sahara desert, coupled with the perceived lack of transparency from French authorities, prompted Algeria's government to seek assistance from the International Atomic Energy Agency (IAEA) to assess its radiological conditions in 1999. The IAEA sent a team of experts to visit Algeria in 1999 and made a preliminary assessment in Reggane situated 50 km South of the village Oasis of Reggane and In-Ekker located within the Hoggar mountains, situated about 140 km North of Tamanrasset (fig. 1)[5].

The IAEA findings revealed that all sites were still contaminated with radionuclides of plutonium, cesium, and strontium and identified several pathways that could lead to radiation exposure. The report published by the IAEA was preliminary in nature, yet it provided valuable insights into the prevailing radiological conditions of the sites and its potential consequences.

Despite the longstanding and documented concerns that emerged during the IAEA preliminary evaluation, the response toward a comprehensive analysis of the impact on nuclear testing in the Algerian Sahara has been inadequate. Similarly to other territories where nuclear testing was conducted by occupying administrations or colonizers, the humanitarian and environmental consequences have persistently

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[2] Garb, "Victims of 'Friendly Fire' at Russia's Nuclear Weapons Sites."

[3] Cooper, "Saharan Fallout: French Explosions In Algeria And The Politics Of Nuclear Risk During African Decolonization (1960–66)."

[4] Bataille and Revol, "The Environmental and Health Impacts of Nuclear Tests Carried out by France between 1960 and 1996 and Elements of Comparison with the Tests of Other Nuclear Powers."

[5] IAEA(a), Radiological Conditions at the Former French Nuclear Test Sites in Algeria: Preliminary Assessment and Recommendations.

burdened national governments and communities. These nation-states have had to contend with the aftereffects often without technical and financial resources to assist victims and address the toxic environment left behind once testing is completed. A 2020 study by Colin and Bouveret documented how France had buried nuclear and other wastes from its nuclear testing activities in the desert when it departed Algeria[6]. Following these revelations, Algerian authorities asked the French government for the maps and the locations of the waste burial sites. As of 2024, this information has not been shared by the French government [7].

Algeria is not the only place where France tested nuclear weapons. From 1966 to 1996, France conducted 193 nuclear tests in French Polynesia in the South Pacific. A recent book, *Toxique*, by Philippe and Statius, based on the analysis of hundreds of declassified documents and the reconstruction of radioactive fallout from multiple tests across Polynesia, has shown how nearly all the French Polynesian population at the time of the tests (more than 110,000 people) could have received doses of radiation higher than current legal compensation threshold under French law[8]. Following these revelations, French President Emmanuel Macron promised to improve access to compensation for victims of nuclear tests, to open all related government archives, and to begin the clean-up of several sites[9]. Algeria was unfortunately left out from these major advances in the Polynesian case. Scholars and French members of parliament have questioned this difference of treatment between the two sites. The compensation record for members of the public in Algeria is abysmal. In 2021, only one member of the public had obtained compensation from the French government in more than 10 years of the application of the Law. The law and documents explaining how to file a claim were translated to Arabic for the first time in 2023[10].

Up to now, there has been no universal policy to adequately address environmental concerns and assist victims who suffered as a result of nuclear testing. The Treaty on the Prohibition of Nuclear Weapons (TPNW) which came into effect for its parties in 2021, is the only recent universal treaty that seeks to address the consequences that emanate from the use or testing of nuclear weapons. The treaty is unique in that it makes provisions that obligate State Parties to aid victims of nuclear tests and for affected countries to take steps towards remediation of their environments.

Algeria is a signatory to the treaty but is yet to ratify it. However, it has expressed its commitment to universal adherence[11]. The benefit of the TPNW is that it provides a strategic framework for Algeria to implement

[6] Collin and Bouveret, "Radioactivity Under the Sand – Analysis with Regard to the Treaty on the Prohibition of Nuclear Weapons."
[7] rfi, "Essais nucléaires au Sahara: «Alger tente de faire pression auprès de la France» sur la dépollution des sites."
[8] Philippe and Statius, Toxique: Enquête Sur Les Essais Nucléaires Français En Polynésie.
[9] ÉLYSÉE, "Discours Du Président Emmanuel Macron Depuis Papeete."
[10] rfi(a), "Algérie: La Loi d'indemnisation Des Victimes Des Essais Nucléaires Français Disponible En Arabe."
[11] ICAN, "Universalising the Treaty on the Prohibitions of Nuclear Weapons in Africa."

policy measures that effectively mitigate the consequences of nuclear testing in its region. It also provides an opportunity for instituting technical cooperation among African States with relevant capacities to assist Algeria in obtaining complete and accurate data and establish a foundation for trust among local communities at risk from the hazards of these former test sites. It is also worth noting that Algeria set up a National Agency for the rehabilitation of former French nuclear test and explosion sites in 2021[12].

In this work, we first review the preliminary report on the radiological condition of the former French nuclear test site in Algeria published by the IAEA in 2005. We then make recommendations on what additional data could enhance the comprehensiveness of the study to draw definitive conclusions regarding the radiological conditions and to facilitate the understanding of the ongoing impact of residual contamination in the region. Given the vast expanse of the Algerian Sahara and areas that are challenging to access due to elevated radiation levels from residual contamination, we propose the use of Unmanned Aerial Vehicles (UAVs) such as drones equipped with radiation sensors to perform a new baseline survey of the Algerian test site. We explore the advantages of using UAV-based measurements in place of ground-based approaches as well as their technical requirements.

Lastly, we consider the role of the TPNW and the benefit it provides in addressing the challenges of victim assistance and environmental remediation. We also consider the aspect of technical cooperation through engaging African States and organizations to provide technical expertise and collaborate with Algeria in resolving the radiological situation in the Algerian Sahara. We note how the declassification of French government archives, similar to France's new transparency commitment to French Polynesia, would facilitate both victim assistance and environmental remediation.

2. Background of the French Nuclear Tests in Algeria

The nuclear weapons testing period in the Algerian Sahara desert can be categorized into two eras: the first period, from 1960 to 1961, involved four above-ground (atmospheric) tests. The second period, from 1961 to 1966 involved underground tests. See appendix I for the list of tests conducted.

[12] rfi(b), "L'Algérie Crée Une Agence Pour Réhabiliter Les Anciens Sites d'essais Nucléaires Français."

Figure 1: Map showing the Southern part of Algeria where the four atmospheric tests (Reggane) and thirteen underground tests (In Ekker-Taourirt Tan Affela) were conducted by France.

The first atmospheric test detonation took place just 50 km from the Oasis town of Reggane. The test was code-named Gerboise Bleue (after the desert rodent found in the area) and had a yield of almost 70 kt (several times the yields of the Hiroshima and Nagasaki bombs). After this test, three more above-ground tests followed: Gerboise Blanche in April 1960 (3 kt), Gerboise Rouge in December 1960(2 kt), and Gerboise Verte in April 1961 (0.7 kt)[13, 14]. This latter test took place amid a military coup in Algeria[15]. The radioactive fallout from these four tests left a lasting contamination caused by fragments of radioactive black vitrified sand mixed with desert sand[16]

In response to the 1963 Partial Test Ban Treaty (PTBT), which ended atmospheric testing for its parties as a result of a study carried out in the United States on deleterious health effects of radioactive fallout, France's military temporarily suspended its atmospheric nuclear testing program, in order to suppress criticism from its Atlantic allies and prevent independence conflict from escalating in response to

[13] Collin and Bouveret, "Radioactivity Under the Sand – Analysis with Regard to the Treaty on the Prohibition of Nuclear Weapons."

[14] Johnston, "Database of Nuclear Tests, France."

[15] Bruno, Tertrais, "A 'NUCLEAR COUP'? France, The Algerian War, and the April 1961 Nuclear Test."

[16] IAEA(a), Radiological Conditions at the Former French Nuclear Test Sites in Algeria: Preliminary Assessment and Recommendations, 2005.

atmospheric testing [17,18]. The tests were moved underground to a site located 600 km South of Reggane, at In Ekker-Taourirt Tan Affela, within the Hoggar mountains. Thirteen devices were detonated underground from October 1961 until February 1966, with a combined yield of 285 kt, all using weapon grade plutonium (France only began production of highly enriched uranium for weapons in 1967)[19].

The purpose of conducting nuclear tests underground is to contain radioactive fission products and unfissioned material within the rock. This is ensured by digging testing tunnels designed to be closed off by the mechanical effect of the shockwave from the explosion before radioactive fission products have a chance to escape. However, in the case of the French tests, only nine of the thirteen tests conducted were reported as being fully contained while four tests (Béryl, Améthyste, Rubis, and Jade) experienced containment failure giving rise to radioactive discharges from the tunnels' entrances E2 and E3[20].

In addition to the nuclear weapon tests, France performed subcritical experiments involving the dispersion of plutonium using chemical explosives, presumable to understand the velocity of the shockwave in a plutonium pellet, test weapon safety, and simulate consequences of accidental detonation of the chemical explosives around the plutonium in a bomb. These tests were codenamed Augias and Pollen. Augias experiment was conducted in steel containment vessels on the site of Gerboise Rouge and the Pollen experiments were conducted in holes dug up on the ground at Ekker-Adrar Tikertine close to In Ekker test site[21, 22].

Radioactive Fallout, Exposure and Environmental Contamination

In 1960, the French government was aware of the effects of ionizing radiation on humans resulting from radioactive fallout, particularly in light of the 1954 Castle Bravo incident, which faced global condemnation. Before commencing nuclear testing in Reggane, French officials visited the U.S. Nevada Test Site (now the Nevada National Security Site) to witness the effects of the fallout in preparation for its tests[23]. People who would be subjected to the effects of radioactivity were classified into two categories: personnel working on the tests and population living in the vicinity of the test sites[24].

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[17] Cooper, "Saharan Fallout: French Explosions In Algeria And The Politics Of Nuclear Risk During African Decolonization (1960–66)."

[18] Park and Ewing, "Environmental Impacts of Underground Nuclear Weapons Testing."

[19] Philippe and Glaser, "Nuclear Archaeology for Gaseous Diffusion Enrichment Plants."

[20] IAEA(a), Radiological Conditions at the Former French Nuclear Test Sites in Algeria: Preliminary Assessment and Recommendations, 2005.

[21] IAEA(a).

[22] Collin and Bouveret, "Radioactivity Under the Sand – Analysis with Regard to the Treaty on the Prohibition of Nuclear Weapons."

[23] Henni, "Toxic Imprints of Bleu, Blanch, Rouge: France's Nuclear Bombs in the Algerian Sahara."

[24] Bataille and Revol, "The Environmental and Health Impacts of Nuclear Tests Carried out by France between 1960 and 1996 and Elements of Comparison with the Tests of Other Nuclear Powers."

A total number of 24,000 individuals were assigned to the test experiments, comprising military personnel, test personnel, and general workers (which included members of settled local and nomadic communities)[25]. The sedentary population during the period of the tests was located in the North of the Reggane test site and further South (In Amguel) and East (Mertoutek) near In Ekker 150 km North of Tamanrasset. The sedentary population living in the Sahara within a 100 km radius around In Ekker was estimated to not exceed 2000 people[26]

A French parliamentary report published in 2001 confirmed that environmental contamination and exposure occurred during the atmospheric and underground test experiments[27]. All four atmospheric tests exposed personnel to external radiation but no external radiation was detected in nearby communities. According to the report, the tests were considered clean, and nearby and distant fallout was monitored using temporary monitoring networks installed across Algeria and in other neighboring countries. Monitoring results showed that after the Gerboise Bleue explosion, the highest levels of radioactivity were recorded within Algeria at posts in Arak, Amguid, and Ouallen. Radiation in Arak reached levels three times higher than the safe drinking water standard, with water samples measuring 10^7 Bq/m^3 on the day of the test. However, radiation levels were reported to have decreased rapidly, soon falling below safety thresholds. Distant fallout was also detected at monitoring stations in Ouagadougou (Haute Volta, now Burkina Faso) and Zinder in Niger[28].

In 2007, a declassified map from the Ministry of Defense showed the radioactive fallout for all four atmospheric tests series (appendix II- figure 5). Following the first atmospheric test on the February 13, 1960, France maintained that the test was relatively clean, and that radioactive fallout cloud safely remained in the dessert and only drifted in one direction of the East-Southeast at a high altitude[29]. The fallout curve is shown to be falling in one direction releasing a dose of 5 mSv covering an inhabited area situated East from ground zero, while the other tests are localized within the desert area[30].

However, in 2014, a new map of the first test was declassified (appendix II-figure 6) following the establishment of the Loi Morin law in 2010—which set official criteria for the recognition and compensation of victims of France's nuclear weapons program. This map revealed the true extent of radioactive fallout days after detonation. The newly declassified map revealed that radioactive fallout was not confined within

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[25] Bataille and Revol.

[26] Bataille and Revol.

[27] Bataille and Revol.

[28] Bataille and Revol.

[29] Cooper, “Saharan Fallout: French Explosions In Algeria And The Politics Of Nuclear Risk During African Decolonization (1960–66).”

[30] Barrillot Bruno, “French Nuclear Tests: When Will There Be Real Transparency?”

the desert boundaries as previously claimed but had, in fact, spread across the entire Sahara and reached neighboring states in West Africa (see appendix II for further discussion)[31,32].

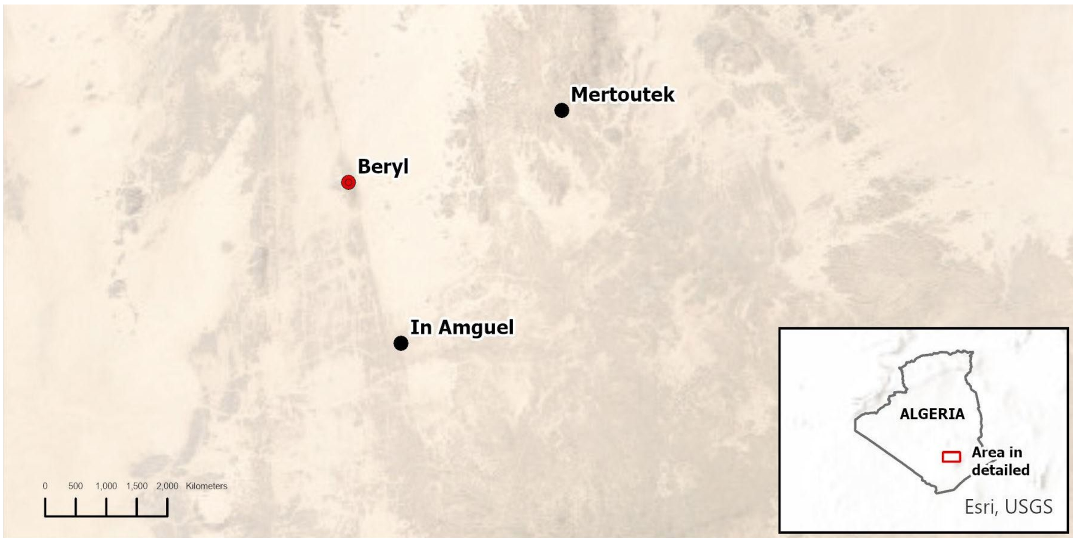

Figure 2: Map indicating communities affected by the radioactive releases of uncontained Béryl underground test.

The most consequential exposure of the French tests occurred during the underground test explosion of Béryl (yield 40kt). About 5-10% fraction of the fission products (and some unfissioned material) escaped from the galleries in particles of molten rock lava and slag[33]. The escaping radioactive particles and gas formed a plume reaching a height of 2.6 km[34]. The plume moved in the eastern direction up to a distance of 150 km where there were no sedentary communities. However, a community of 240 persons living in the Northern fringes of the fallout located in Mertoutek (~60km from ground zero) were exposed to an estimated radiation dose of 2.5 mSv (Fig. 2)[35]. The fallout also reached Oasis 2 (In Amguel) which was located 10 km South of In Ekker. Locally, approximately 2000 personnel which included two French ministers received doses of ionizing radiation ranging from 0.5 to 600 mSv (Fig. 3).

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[31] Jarvis, "Mapping the Afterlives of French Nuclear Imperialism in the Sahara."

[32] Le Parisien, "The Shocking Document on the A-Bomb in Algeria."

[33] IAEA(a), Radiological Conditions at the Former French Nuclear Test Sites in Algeria: Preliminary Assessment and Recommendations, 2005.

[34] Bataille and Revol, "The Environmental and Health Impacts of Nuclear Tests Carried out by France between 1960 and 1996 and Elements of Comparison with the Tests of Other Nuclear Powers."

[35] Bataille and Revol.

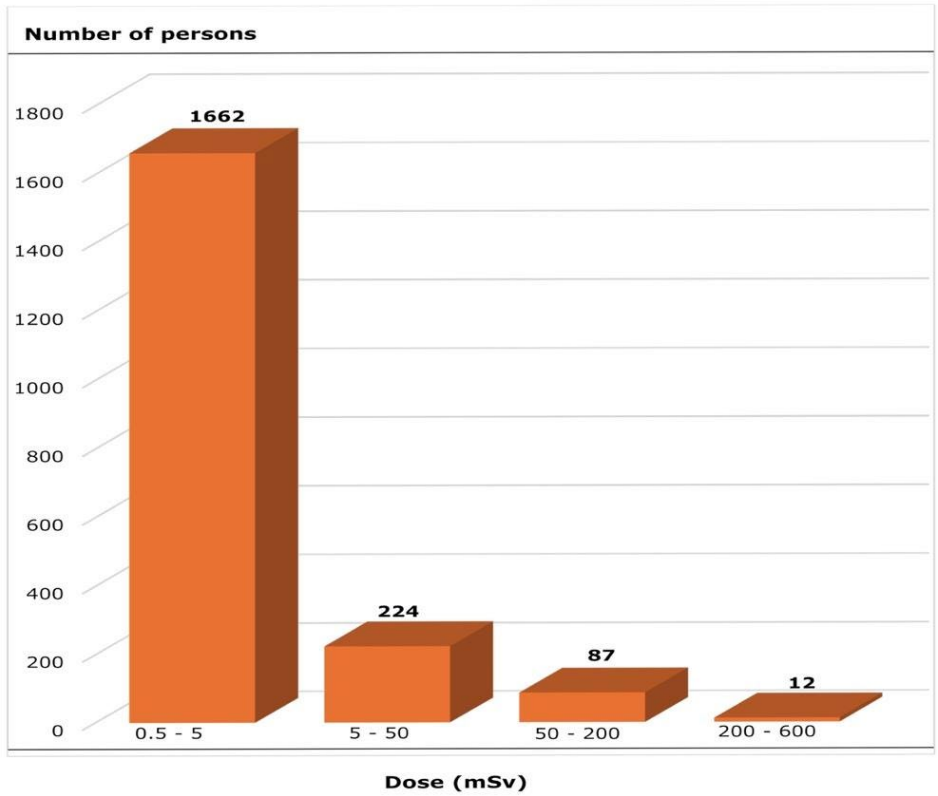

Figure 3: Distribution of external dose (mSv) from the partially contained Béryl test and the number of personnel affected[36].

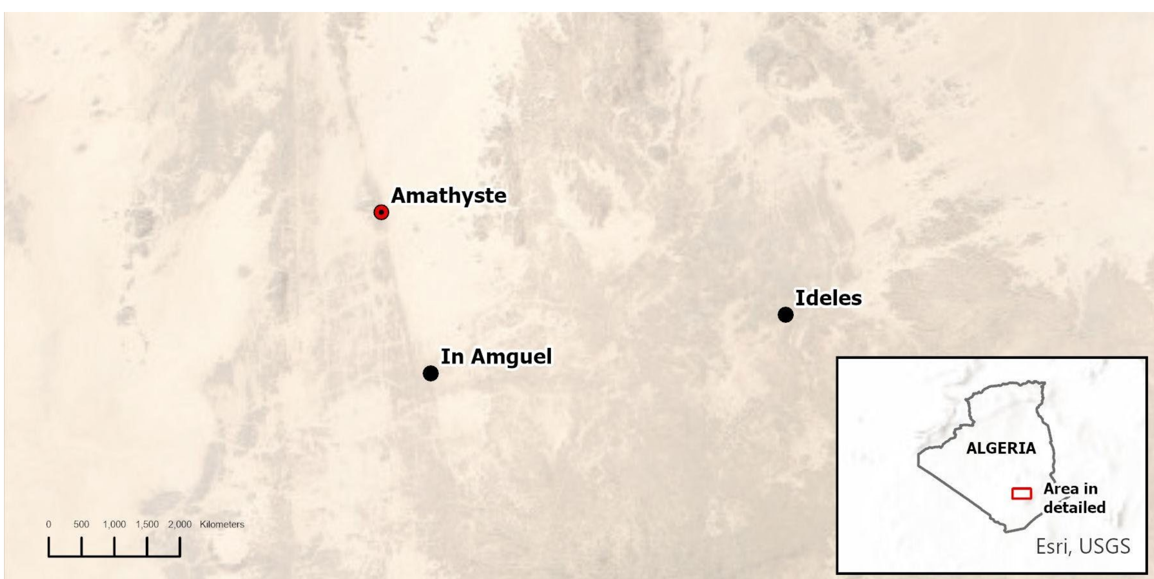

Figure 4: Two villages affected by the venting of the Améthyste test which again contaminated Amguel and the Ideles community. The estimated external dose exposure to communities was less than 1 mSv on the day of the test.

[36] Bataille and Revol.

Similarly, the containment failure of Améthyste test (yield 2.5kt) resulted in the escape of small quantities of molten rock and scoria through the galley that was deposited at the entrance tunnel E3 and in the vicinity[37]. About 9 personnel who intervened during the accident received around 10 mSv dose of ionizing radiation[38]. High external irradiation of the fallout plume was measured at Oasis 2 towards the South (In Amguel) from ground zero. The radioactive plume that formed due to venting traveled a distance of up to 100 km toward the village of the Ideles which at the time had a population of 280 people who were estimated to have received a dose of less than 1 mSv (Fig. 4).

During the Rubis test (yield 52kt), which was detonated on October 20, 1963, venting occurred during the first hour after the test, prompting the evacuation and radiation monitoring of 500 military personnel[39]. Radiation from this test was detected as far as the South Tamanrasset located 150 km from ground zero.

Given that information on hematological studies conducted during the tests is not disclosed in the report, it is important to note that dose estimates provided are based on external radiation exposure, which only accounts for part of the effective dose that can be received by individuals exposed to radioactive fallout. It is possible that personnel and populations received additional doses due to inhalation and ingestion. Furthermore, based on the safety guidelines for the maximum admissible doses, which were set at 15 mSv/a in 1960 and then 5 mSv/a in 1961, most exposures that were deemed safe by French officials are subject to review as the standard limit per annum has now been revised to 1 mSv/a[40,41].

3. Review of the IAEA Findings

In November 1999, the IAEA conducted a 5-day mission visit to the Algerian test sites to assess its radiological conditions. A preliminary report was published six years later in 2005. In-situ measurements were performed to provide a preliminary assessment and guide the development of a detailed radiological study program. The assessment covered the atmospheric test sites in Reggane, underground tests, and Pollen experiment sites, in Ekker-Taourirt Tan Afella and Adrar Tikertine respectively. Dose-rate measurements were conducted at 76 locations, and 25 environmental samples were collected followed by laboratory analysis at the IAEA Seibersdorf laboratory, Austria[42].

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[37] IAEA(a), Radiological Conditions at the Former French Nuclear Test Sites in Algeria: Preliminary Assessment and Recommendations, 2005.

[38] Bataille and Revol, “The Environmental and Health Impacts of Nuclear Tests Carried out by France between 1960 and 1996 and Elements of Comparison with the Tests of Other Nuclear Powers.”

[39] Bataille and Revol.

[40] Bataille and Revol.

[41] Clarke and Valentin, “The History of ICRP and the Evolution of Its Policies.”

[42] IAEA(a), Radiological Conditions at the Former French Nuclear Test Sites in Algeria: Preliminary Assessment and Recommendations, 2005.

3.1 Overview of the IAEA Preliminary Assessment in the Algerian Test Sites

The investigation by the IAEA team found that both test sites (Reggane and In Ekker) were still measurably contaminated 40 years after the initial tests. For Reggane, all four atmospheric test sites were contaminated with low residual radioactivity with the exception of Gerboise Bleue and Blanche which presented elevated residual activity at ground zero[43]. At these sites, residual radioactivity was largely contributed by radionuclides of cesium, strontium, and plutonium (^{137}Cs, ^{90}Sr, $^{239+240}$Pu, ^{238}Pu) embedded in a black, vitreous (glassy) porous material. The activity levels were the highest for long-lived plutonium radionuclides. Most of the radioactivity from ^{137}Cs, and ^{90}Sr had already decayed due to the half-life of ^{137}Cs and ^{90}Sr decreasing by one-half every 30 years. Small particles (diameter of less than 50 μm) which are considered respirable when resuspended from the ground and transported during high winds were found to have radioactivity "equal to or less than the level of detection"[44].

For the underground nuclear tests site (In Ekker-Taourirt Tan Afella), specimens were collected and included lava deposited at the entrance of tunnel E2 (Bérly test site), water from a well located 6km away, and soil from dry stream waterbeds. These samples were analyzed for radioactivity concentrations. The IAEA found elevated residual activity of ^{137}Cs, ^{90}Sr, and $^{239+240}$Pu in the lava samples. The sand from the dry stream water beds was also contaminated. No significant residual radioactivity was detected in the water from the well.

On the site where Pollen experiments were conducted (In Ekker- Adrar Tikertine), residual radionuclide (^{137}Cs, ^{90}Sr, $^{239+240}$Pu) was at a low level of detection. For resuspendable radioactive sand of less than 50 μm in diameter, concentration of ^{137}Cs was found to be slightly elevated. No indication of the presence of $^{239+240}$Pu released during the Pollen experiments was found. This was attributed to dispersion of particles in the intervening years[35].

Exposure pathways were identified for all three sites and dose estimates were obtained from radionuclide activity concentrations. Reggane, recognized as an area of transit for nomads, travelers, and transporters was identified to have principal pathways of exposure in the form of "external exposure to radionuclides in the ground, inhalation of resuspended material, ingestion of soil adhering to hand and deposited on foodstuff"[45]. The maximum doses were estimated to be 0.1 mSv for all the different pathways if an individual were to visit the sites for a duration of three days. This would translate to a dose of 1 mSv in 30 days which is above the threshold an individual should accumulate per annum.

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[43] IAEA(a), p.g 32.

[44] IAEA(a), p.g 27.

[45] IAEA(a), p.g 47.

In In-Ekker, additional exposure pathways included "external radiation, particularly in the vicinity of ejected lava, ingestion of water containing leached material; and ingestion of products (milk, meat) from animals that intermittently graze in the area"[46]. A person visiting the vicinity where the lava was deposited during the venting of Béryl test near tunnel E2 for 8 hours would receive an effective dose of 0.5 mSv, this will translate to 1mSv in two days[34]. Furthermore, this site was found to have sparse vegetation which nomadic livestock can graze resulting in the ingestion of residual radionuclides that have been incorporated into plant matter. This could in turn be transferred into animal products such as meat and milk which could contribute to radiation exposure to communities[47].

4. Discussions

The Evian accords of 1962, which marked Algeria's independence from France, did not obligate France to dismantle and monitor the test sites upon completing its nuclear weapon experiments (Bataille and Revol 2001). In 1967, the French military handed over the sites to the newly independent Algerian government after all the technical installations had been dismantled and the galleries partially cleaned and sealed (Bataille and Revol 2001). No guidelines were provided on how to monitor the sites, and no environmental monitoring program was instituted in the intervening years (Collin and Bouveret 2020). Forty-five years after the tests were conducted, the IAEA evaluated the radiological conditions of the sites and found that the contamination was still in situ though much of it had decayed and, in some instances, fine plutonium radioactive particles had dispersed (IAEA(a) 2005).

To address environmental contamination and its toxic impact in the Sahara requires a comprehensive environmental monitoring program to characterize radioactive particles and understand their interaction and long-term behavior in the environment. A monitoring program could assist in tracking the distribution and concentration of radionuclides in the air and soil over time and ensure public and environmental safety. Regular and systematic environmental monitoring programs have been used in former nuclear testing sites where residual radioactivity has been a major concern(Artemev et al. 2000), (NNSS 2018). Monitoring activities would also allow for identification of abnormal radiation levels, enabling prompt intervention and facilitating informed decision-making related to land use, remediation, and risk mitigation. In the following section, we make recommendations on interventions that can be implemented in addressing environmental contamination and humanitarian concerns.

The IAEA report marked a significant advancement in offering a preliminary assessment of the radiological conditions of the Algerian Sahara. However, the assessment can be expanded upon to corroborate and

[46] IAEA(a), p.g 49.

[47] IAEA(a), p.g 32.

strengthen its conclusions. This section will discuss and propose recommendations regarding the additional information required to facilitate a more comprehensive assessment.

4.1 Sampling Campaign

External dose assessments were conducted at 76 locations and only 25 environmental samples were collected. The samples collected in Reggane comprised soil, air, and black vitreous porous material formed during atmospheric explosion when fission products, un-fissioned material, and neutron activation products are entrained in the nuclear fireball and re-solidify to form a glassy material[48]. In Ekker, collected samples included lava samples deposited at tunnel entrance E2, water samples from the well to assess the potential leaching of radionuclides, sparse vegetation suitable for grazing by nomadic livestock, and the soil from the dry stream waterbeds.

The number of samples collected during the investigation was deemed small by the IAEA in view of the large area of the test sites[49]. A too small sample can impede ability to draw accurate conclusions on inventory and distribution of residual radionuclides. Accuracy and reliability in assessing radiological conditions depend on representativeness and comprehensiveness of collected samples. Insufficient sample sizes therefore may fall short of achieving statistical significance thus compromising the validity of results that are based on extrapolated laboratory measurements and thus impeding the ability to draw conclusions[50].

To obtain the optimal number of samples, a sampling campaign requires good knowledge of the spatial distribution of residual radionuclides in the area. Former nuclear test sites are characterized by radionuclides which vary widely when deposited in the environment[51]. The spatial distribution pattern of radionuclides then becomes an important criterion when selecting a sampling plan[52].

Given that the IAEA study was a preliminary exercise, the scope of the sampling campaign was limited, and the spatial distribution of sampling locations was primarily focused on areas that were easily accessible and deemed to have higher contamination[53]. Terrains that were difficult to access by foot were not samples

48 Wallace et al., "A Multi-Method Approach for Determination of Radionuclide Distribution in Trinitite."

49 IAEA(a), Radiological Conditions at the Former French Nuclear Test Sites in Algeria: Preliminary Assessment and Recommendations, 2005.

50 IAEA(b), Environmental and Source Monitoring for Purposes of Radiation Protection.

51 Prăvălie, "Nuclear Weapons Tests and Environmental Consequences: A Global Perspective."

52 Gilbert, Statistical Methods for Environmental Pollution Monitoring.

53 IAEA(a), Radiological Conditions at the Former French Nuclear Test Sites in Algeria: Preliminary Assessment and Recommendations, 2005.

due to their rock or hilly topography[54]. To conduct a comprehensive sampling campaign, sample collection and measurements should be prioritized at all relevant sites, with a focus on identifying all potential hotspot areas. This may necessitate a long-term environmental program to monitor the evolving distribution of radioactive particles in the environment.

4.2 Analytical Techniques

Alpha, beta, and gamma spectrometry were employed to determine radionuclide composition and concentrations [55]. The challenge with bulk analytical techniques is their reliance on average bulk mass or surface activity concentration (e.g. Bq/kg or Bq/L), presuming a uniform distribution of residual radioactivity[56]. This assumption of homogeneous distribution has been shown to result in analytical inconsistencies, irreproducible findings, and inconclusive interpretations of radiological conditions[57]. Therefore, bulk analytical techniques may not offer a good representation of the radiological conditions as inventories may be underestimated[58].

Literature studies show that in the aftermath following nuclear weapon test or safety test (e.g. plutonium dispersion experiments), fission products together with unburned weapon-grade uranium or plutonium are dispersed in the environment in a form of discrete radioactive particles[59,60,61,62]. The IAEA defines radioactive particles as localized aggregations of radioactive atoms, leading to an inhomogeneous distribution of radionuclides[63]. These particles are deposited as uneven point sources and contain a substantial amount of refractory transuranic, fission products, and activation products that hold valuable information pertaining to their radiological and chemical characteristics and potential impact[64]. Radioactive particles also undergo transformation processes, weathering, and interactions that influence their mobilization, distribution, and biological uptake[65]. Therefore, the behavior and transportation of radioactive particles in the environment become important when assessing long-term impacts of anthropogenic radionuclides.

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[54] IAEA(a), p.g 15.

[55] IAEA(a), p.g 25.

[56] IAEA(c), Radioactive Particles in the Environment: Sources, Particle Characterization and Analytical Techniques.

[57] Salbu, Fesenko, and Ulanowski, "Radioactive Particle Characteristics, Environmental Behaviour and Potential Biological Impact."

[58] Salbu, "Source-Related Characteristics of Radioactive Particles: A Review."

[59] Salbu.

[60] Lind et al., "Characterization of U/Pu Particles Originating from the Nuclear Weapon Accidents at Palomares, Spain, 1966 and Thule, Greenland, 1968."

[61] Rolph, Ngan, and Draxler, "Modeling the Fallout from Stabilized Nuclear Clouds Using the HYSPLIT Atmospheric Dispersion Model."

[62] Philippe, Schoenberger Sonya, and Ahmed Nabil, "Radiation Exposures and Compensation of Victims of French Atmospheric Nuclear Tests in Polynesia."

[63] IAEA(c), Radioactive Particles in the Environment: Sources, Particle Characterization and Analytical Techniques.

[64] Salbu, Fesenko, and Ulanowski, "Radioactive Particle Characteristics, Environmental Behaviour and Potential Biological Impact."

[65] Salbu et al., "Challenges Associated with the Behaviour of Radioactive Particles in the Environment."

To better understand the scope of radionuclide behavior at the Algerian test site, advanced characterization techniques need to be deployed. Information on size, shape, structure, and oxidation states of radioactive particles obtained using advanced techniques such as Scanning Electron Microscopy (SEM) for example is crucial in obtaining comprehensive data about the radiological conditions of former nuclear test sites. Since the 1999 IAEA study, there have been significant advances in analytical techniques used in environmental analysis[66]. According to the IAEA, detailed information on radioactive particle characteristics and behavior have been studied for most former test sites except for Algeria and Lop Nor, China[67]. Therefore, to fully understand the radiological conditions, the scope of the study on the Algerian test site should be expanded to include the characterization of radioactive particles.

4.3 Radiological Survey: Use of Unmanned Aerial Vehicles (AUV's)

Traditionally, scientific interventions for monitoring radiological sites require an extensive ground-based survey involving personnel moving on foot or in vehicles carrying handheld or vehicle-mounted radiation detectors. The major drawback with ground-based surveys is that they can expose operators to risks of receiving high levels of radiation doses. Additionally, because individuals or vehicles carrying detectors move slowly, these surveys tend to be time-consuming especially when surveying large areas and areas with restricted access may be missed during the assessment resulting in inconsistent findings.

UAV-based radiation surveys has been moving away from developmental stages and becoming more applicable to routine application and gaining recognition in the radiological monitoring toolbox[68]. In recent years, UAV-based surveys have increasingly been used in radiological mapping and in identifying radiological hotspots even during radiological emergencies, aiding first responders in their efforts[69,70,71,72]. The emergence of this technology supplements piloted and ground-based radiation monitoring and provides an opportunity to characterize radionuclides and capture large-size areas in a short space of time[73]. Because UAVs are unmanned, they can also survey terrains that are difficult to reach by foot and they can be controlled remotely eliminating the risk of radiation exposure to surveyors[74].

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[66] Salbu Brit and Lind Ole Christian, "Analytical Techniques for Charactering Radioactive Particles Deposited in the Environment."

[67] IAEA(c), Radioactive Particles in the Environment: Sources, Particle Characterization and Analytical Techniques.

[68] van der Veeke et al., "Optimizing Gamma-Ray Spectrometers for UAV-Borne Surveys with Geophysical Applications."

[69] Limburg, "Towards Drone-Borne Gamma Ray Mapping of Soils."

[70] Geelen et al., "Drone-Borne Dosimetry in a Radiological or Nuclear Scenario."

[71] Bunn et al., "Drones for Decommissioning."

[72] Martin et al., "Radiological Assessment on Interest Areas on the Sellafield Nuclear Site via Unmanned Aerial Vehicle."

[73] Borbinha et al., "Performance Analysis of Geiger–Müller and Cadmium Zinc Telluride Sensors Envisaging Airborne Radiological Monitoring in NORM Sites."

[74] Luff, Stöhlker, and Bossew, "Unmanned Aerial Vehicles ('drones') as Tools for Small Scale Radiometric Surveys."

UAVs such as drones are flown at low altitudes while moving at low speeds collecting spectroscopic data with a resolution that is comparable to that of ground-based measurements[75]. Drone surveys can accurately map radiation distribution with high spatial and spectral accuracy, making it possible to fingerprint radionuclides over areas with high and low activity concentrations[76]. Drones are also cost-effective, enabling the deployment of a fleet to reduce survey time of large areas.

Detector and Drone Selection

Radionuclides that have been deposited into the ground following a nuclear weapon explosion create a constant flux of radiation that can be measured using radiation detectors. Gamma-ray systems have been the most selected due to their capability to identify and quantify numerous radionuclides and isotopes.

A good detector that has the capability of measuring individual radionuclide concentrations without compromising the quality of data collected is essential. For UAV-based surveys, the goal is to select a detector with a small weight, to reduce the drone payload whilst not compromising on the precision and accuracy of data collection. Considerations of gamma energy resolution also become important due to the need to resolve radionuclide signals that are present in the environment. A gamma-spectrometer detector resolution of at least 8% (FWHM at 662 keV) is considered adequate, along with other factors relating to detector performance such as temperature stability, durability, hygroscopicity, and volume[77].

Various types of gamma detectors are commonly employed in UAV-based surveys, including Geiger–Muller (GM) tubes, Compton cameras, Sodium Iodide (NaI), Cesium Iodide (CsI), and Cadmium Zinc Telluride (CzT) detectors[78,79]. Scintillation detectors such as NaI, and CsI have been the preferred choice for drone-based surveys in areas with elevated radiation concentrations[80,81,82,83]. This is largely because they are cheaper and more accessible. “However, due to their low spectral resolution and poor peak shaping,

[75] van der Veeke, “UAV-Borne Radioelement Mapping.”

[76] Borbinha et al., “Performance Analysis of Geiger–Müller and Cadmium Zinc Telluride Sensors Envisaging Airborne Radiological Monitoring in NORM Sites.”

[77] Parshin et al., “Advantages of Gamma-Radiometric and Spectrometric Low-Altitude Geophysical Surveys by Unmanned Aerial Systems with Small Scintillation Detectors.”

[78] Šálek, Matolín, and Gryc, “Mapping of Radiation Anomalies Using UAV Mini-Airborne Gamma-Ray Spectrometry.”

[79] Mochizuki et al., “First Demonstration of Aerial Gamma-Ray Imaging Using Drone for Prompt Radiation Survey in Fukushima.”

[80] Lee and Kim, “Optimizing UAV-Based Radiation Sensor Systems for Aerial Surveys.”

[81] Borbinha et al., “Performance Analysis of Geiger–Müller and Cadmium Zinc Telluride Sensors Envisaging Airborne Radiological Monitoring in NORM Sites.”

[82] Martin et al., “Radiological Assessment on Interest Areas on the Sellafield Nuclear Site via Unmanned Aerial Vehicle.”

[83] Ardiny, Beigzadeh, and Mahani, “Applications of Unmanned Aerial Vehicles in Radiological Monitoring: A Review.”

scintillator detectors are not recommended for detecting low-level radiation"[84]. Semiconductor detectors such as CzT provide high energy resolution (2.5% FWHM at 662 keV) and counting efficiency making it possible to perform accurate and precise radiation measurements[85]. They are also portable and do not require a cooling system. Given that CzT detectors are compact ($1cm^3$), a detector array to improve efficiency may be desired[86].

Concerning drone selection, there are numerous categories of drone technologies available in the market that can be deployed for UAV-based surveys[87]. In radiation monitoring, fixed wings, multi-rotor, hybrid and ornithopter UAV's have been exploited[88]. Commercially available drones with the capacity to carry a payload consisting of detectors and other auxiliary sensors such as Laser altimeter (LiDAR) for obtaining an elevation model of the test site prior to surveying and Global Positioning System (GPS) for locating hotspots as the survey is being carried out are desirable[89]. In this work, drone selection is not elaborated as the technology is rapidly developing. For the Algerian test site, the integration of ground penetrating radar (GPR) coupled with radiation detectors should also be considered as a complementary approach for a comprehensive assessment. GPR allow for detection of subsurface anomalies and can be instrumental in locating the buried nuclear waste while the radiation detectors can identify directly and quantify the radioactive contamination[90].

Surveying radiological site

Due to the vastness of the Algerian test sites, radioecological surveys have to be carried out on tens or hundreds of square kilometers. The four atmospheric tests in Reggane were conducted over a total area of 200 km^2, with each test site exposing an area of 1-2 square kilometers[91]. To optimize data collection and improve accuracy, the type of detector system suitable for the mission and parameters such as flight

[84] Borbinha et al., "Performance Analysis of Geiger–Müller and Cadmium Zinc Telluride Sensors Envisaging Airborne Radiological Monitoring in NORM Sites."

[85] Kromek Group PLC, "Kromek GR1 User Guide Sheet."

[86] Luke et al., "A CdZnTe Coplanar-Grid Detector Array for Environmental Remediation."

[87] Pinto et al., "Radiological Scouting, Monitoring and Inspection Using Drones."

[88] Ardiny, Beigzadeh, and Mahani, "Applications of Unmanned Aerial Vehicles in Radiological Monitoring: A Review."

[89] Pinto et al., "Radiological Scouting, Monitoring and Inspection Using Drones."

[90] Ukaegbu, Gamage, and Aspinall, "Nonintrusive Depth Estimation of Buried Radioactive Wastes Using Ground Penetrating Radar and a Gamma Ray Detector."

[91] IAEA(a), Radiological Conditions at the Former French Nuclear Test Sites in Algeria: Preliminary Assessment and Recommendations, 2005.

altitude, speed profile, and minimum detectable activity (MDA) and their mutual effects on data collection need to be analyzed[92,93].

The flight altitude of the drone affects the intensity of the gamma radiation that reaches the sensor of the detector because radiation is attenuated as it passes through the air. The speed with which the drone flies affects the MDA, due to its relationship with counting time for any surface area. Therefore, as the UAV's flight velocity increases, the counting time will decrease, which will in turn reduce the MDA since there is less time to detect radiation. Conversely, a slower flight velocity increases the counting time, potentially improving the MDA by allowing more time for detection[94].

	Sand mixed with black vitreous material (Gerboise Blance)		*Lava (In Ekker-Béryl site)*		*Dry stream soil (In Ekker)*	
Nuclide	**Measured** (Bq/kg)	**Decay-corrected** (Bq/kg)	**Measured** (Bq/kg)	**Decay-corrected** (Bq/kg)	**Measured** (Bq/kg)	**Decay-corrected** (Bq/kg)
Cs-137	2.9×10^4	1.63×10^4	2.1×10^6	1.18×10^6	3.5×10^3	1.97×10^3
Sr-90	1.8×10^5	9.9×10^4	1.1×10^6	6.05×10^5	1.2×10^4	6.6×10^3

Table 1: Activity concentrations (Bq/kg) measured during the IAEA visit in 1999 decay corrected to 2024 which is 25 years later since the measurements were taken. Both ^{137}Cs and ^{90}Sr have a half-life of ~30 years[95].

Given the large areas requiring monitoring in Algeria, faster flight speeds and higher altitudes are ideal, but this comes at the expense of lower MDA especially when using compact radiation sensors and UAVs with a smaller payload capacity[96]. In order to optimize MDA, a larger and more efficient radiation sensor to enhance detection is needed. The choice over which system is more suitable for the prevailing conditions of the Algerian Sahara will be decided upon by researchers following a careful consideration of all other factors that may influence the survey mission. Overall, the selected approach should be determined based on the MDA thresholds within the environmental matrix. Detectable values measured by the IAEA and decay-corrected to 2024 for sites reported to have elevated radiation levels are provided in Table 1 above.

[92] Lee and Kim, "Optimizing UAV-Based Radiation Sensor Systems for Aerial Surveys."

[93] Kunze et al., "Development of a UAV-Based Gamma Spectrometry System for Natural Radionuclides and Field Tests at Central Asian Uranium Legacy Sites."

[94] Lee and Kim, "Optimizing UAV-Based Radiation Sensor Systems for Aerial Surveys."

[95] IAEA(a), Radiological Conditions at the Former French Nuclear Test Sites in Algeria: Preliminary Assessment and Recommendations.

[96] Lee and Kim, "Optimizing UAV-Based Radiation Sensor Systems for Aerial Surveys."

Study Region	Area Size	Detector type	Altitude (Alt), Speed (S)	Time(min)	Reference
Namie-city, Fukushima	0.008 km^2	Compton Camera	Alt = 10 m	10 minutes	(Mochizuki, et al. 2017)
Fukushima, Japan	0.01 km^2	CzT	Alt = 1-10 m S = 1.0 m. s^{-1}	15 min	(Martin, et al. 2016)
Siberia, Russian Federation)	1.0 km^2	CsI (Tl)	Alt = 25 m S = 5.5 m. s^{-1}	180 min	(Parshin, et al. 2021)
Chernobyl Exclusion Zone	15 km^2	CsI	Alt=40-60m S=14-18 m.s^{-1}	540 min	(Connor et al. 2019)

Table 2: The table below shows some of the UAV-based surveys studies conducted using different parameters and different radiation sensors.

To estimate the duration required for surveying a site, we analyzed data from prior studies where UAV-based surveys had been conducted (Table 2). It is important to note that the majority of the available literature consists predominantly of proof-of-concept research. In these studies, the duration of the survey was not a primary consideration; instead, the focus was primarily on enhancement of radiation detection sensors driven by the objective of assessing the adaptability of radiation sensors for field application[97,98]. This focus on operational parameters and sensor improvement implies that time-related data on how long a survey would take under typical field conditions is not provided. Extrapolations based on these studies therefore should be approached with caution. Furthermore, empirical research is needed to establish more accurate estimates for survey durations, considering various environmental areas and operational factors. This will in future guide decision makers when making consideration to deploy UAV-based to missions that involve large size areas.

To provide an estimation of how much time is required for surveying the atmospheric test sites where Gerboise Bleue and Verte were detonated (in Reggane), we refer to a study conducted in a comparable large area (1 km^2) by researchers in the Baikal region (Siberia, Russian Federation). In this study, a drone equipped with a CsI (Tl) detector, traveling at a speed of 20 km/h (5.5 m. s^{-1}) and at a flight altitude of 25m was deployed. The survey duration was 3 hours (180 minutes)[99].

By applying the same parameters and operational tools (i.e. the identical UAV and detector) used in the aforementioned study and excluding other variables such as drone battery life and meteorological conditions, we can estimate the time it would take for a typical survey in Gerboise Bleue and Verte test sites which have a combined area of ~6 km^2. Given that it took 3 hours to survey a 1.0 km^2 area, it is

[97] Gong et al., “Locating Lost Radioactive Sources Using a UAV Radiation Monitoring System.”

[98] Borbinha et al., “Performance Analysis of Geiger–Müller and Cadmium Zinc Telluride Sensors Envisaging Airborne Radiological Monitoring in NORM Sites.”

[99] Parshin et al., “Advantages of Gamma-Radiometric and Spectrometric Low-Altitude Geophysical Surveys by Unmanned Aerial Systems with Small Scintillation Detectors.”

reasonable to project that it would require approximately 18 hours to survey an area of 6 km². This estimation is based on a direct proportional relationship between the surveyed area and the required survey duration, assuming consistent operational conditions. In another study conducted over the Chernobyl exclusion zone of 15 km^2, the survey using a fleet of two fixed-wing drones mounted with CsI radiation sensors, took 9 hours (540 min) of flight time to survey the area over a course of seven days[100]. Applying the same principles, from this study, it will take approximate 4 hours to survey a total area of 6 km².

4.4 Reconstructing the radioactive fallout to estimate the effective dose rate

During atmospheric nuclear test detonations, fission products, along with radioactive material, are released without containment, allowing them to disperse over significant distances before being deposited into the ground as fallout. Underground detonations, on the other hand, are intended to take place at sufficient depths to ensure that radioactivity is contained within the earth. However, containment methods have not proven reliable at all times, and radioactive material can vent into the atmosphere, expose persons to ionizing radiation, and contaminate the environment[101]. This release can be instantaneous and/or can occur over a period of time following the test.

The summary of the official results of external doses provided in the Senate report indicates that out of the 24,000 people involved in the test, 18, 000 did not receive any radiation dose, 6, 500 received doses up to 5 mSv, and 581, i.e. 2.5%, received cumulative doses of over 5 mSv[102]. The actual dose values received by members of the communities which were monitored during the atmospheric and underground test experiments are not publicly available and only estimates are provided in some instances. These estimates only account for external exposure and do not account for effective dose exposures. Effective doses are a result of the sum of doses received from four pathways: inhalation of radioactive aerosols, external irradiation by the plume (cloudshine), external irradiation by ground deposits (groundshine), and ingestion of contaminated food products[103]. Therefore, persons who may have been classified as unexposed because of absence of external test-related gamma radiation measurement may have received internal radiation exposure.

According to the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), the effects of radiation due to nuclear weapons related exposure can lead to immediate and long-term health

[100] Connor et al., "Radiological Mapping of Post-Disaster Nuclear Environments Using Fixed-Wing Unmanned Aerial Systems."

[101] Park and Ewing, "Environmental Impacts of Underground Nuclear Weapons Testing."

[102] Bataille and Revol, "The Environmental and Health Impacts of Nuclear Tests Carried out by France between 1960 and 1996 and Elements of Comparison with the Tests of Other Nuclear Powers."

[103] Philippe, Schoenberger, and Ahmed, "Radiation Exposures and Compensation of Victims of French Atmospheric Nuclear Tests in Polynesia."

effects[104]. Exposure to radioactive radionuclides such as ^{137}Cs, ^{90}Sr and ^{131}I increases the risks of cancers in particular thyroid cancer, leukemia, lung and breast cancer. Elevated radiation levels in individuals residing near nuclear test sites have also been associated with an increased risk of infertility, miscarriages, birth defects and developmental abnormalities in children[105]. In addition to this, radiation exposure has been linked to DNA damage potentially causing genetic mutations that may affect the offsprings of the exposed individual. Anthropogenic radionuclides that remain many years in the environment resulting in chronic exposure to low levels of radiation have been associated with increased risk of heart disease, respiratory problems, stroke due to the inhalation or ingestion of small radioactive particles[106].

In the case of Algeria, information on external and internal dose estimates (inhalation and ingestion) is not publicly available. An independent review of dose estimates from French tests in French Polynesia where France moved its testing after leaving Algeria indicated that the estimates made by France were generally higher than what was officially declared[107]. In the absence of historical data, modeling techniques such as NOAA's Hybrid Single-Particle Integrated Trajectory (HYSPLIT) can be utilized to reconstruct, investigate, and measure the trajectory and impact of radioactive fallout[108,109]. Reconstructing radioactive fallout will provide a baseline for assessing the fallout distribution and indicate if exposure to communities occurred.

4.5 Nomadic Lifestyle in the Algerian Sahara

To strengthen the examination on the impact of radioactive fallout and provide an accurate dose estimation requires a clear description of the lifestyle of nomadic communities. The Southern Algerian Sahara where France tested its nuclear weapons is home to many Algerian nomads. Nomadic communities spent many centuries traveling the expanse of the Sahara desert and during the nuclear testing period, nomadic communities still habituated the area although most were reported to be settling into a more sedentary lifestyle[110]. The change of nomadic lifestyle was brought on by colonization, which resulted in loss of their land, and the emergence of newly independent African States, which affected their trade routes. This change disrupted their traditional norms for earning income which largely included farming, pastoralism, and commodity trading. As a consequence, nomadic communities had to find other ways of supplementing

[104] UNSCEAR, "Sources, Effects and Risks of Ionizing Radiation."

[105] Simon et al., "Radiation Doses and Cancer Risks in the Marshall Islands Associated with Exposure to Radioactive Fallout from Bikini and Enewetak Nuclear Weapons Tests."

[106] Kamiya et al., "Long-Term Effects of Radiation Exposure on Health."

[107] Philippe, Schoenberger, and Ahmed, "Radiation Exposures and Compensation of Victims of French Atmospheric Nuclear Tests in Polynesia."

[108] Philippe, Schoenberger, and Ahmed.

[109] Stein et al., "NOAA's HYSPLIT Atmospheric Transport and Dispersion Modeling System."

[110] Keenan, "The Last Nomads: Nomadism amongst the Tuareg of Ahaggar (Algerian Sahara)."

their income by taking up conventional employment at the French atomic base in In Ekker. It is estimated that many nomads who worked at the base were employed as manual laborers[111].

Traditional Algerian nomadic communities are known for traveling through the desert in camel caravans accompanied by livestock. They mainly live in tents made of skin from camels and goats. Their diet mostly consists of meat, cheese, and milk from camel or goats, and water is scarce resource meaning that they have to travel significant distances to reach water wells[112]. To evaluate the health effects on the Algerian communities resulting from the fallout of atmospheric and underground tests requires a study of the lifestyle of the communities in the affected areas. Information on the types of residence, material used in its construction, time spent indoors and outdoors, sources of drinking water as well as information of the various types of food consumed from infancy to adulthood and consumption rates needs to be gathered.

5. Technical Assistance under the TPNW

The Treaty on the Prohibition of Nuclear Weapons (TPNW) was adopted by United Nations in 2017 and entered into force for its parties in January 2021[113]. The TPNW prohibits the development, testing, and use of nuclear weapons and seeks to promote disarmament and prevent nuclear proliferation. Since its adoption, African countries including Algeria, have become signatories. Algeria signed the treaty in September 2017 and has yet to ratify it.

Among the advances of the TPNW are its positive obligations approach guided by the treaty's goal to address the human and environmental impact of nuclear weapon tests. Under Articles 6 and 7 of the treaty, States are obligated to provide a range of assistance to victims of the tests or use of nuclear weapons and to undertake necessary steps to remediate the environment through technical cooperation[114,115]. This ensures that States like Algeria are not left with the sole burden of implementing treaty provisions. By ratifying the treaty, Algeria would be entitled to support from other member states to address the harm caused by French nuclear testing in the Sahara region.

The implementation of the positive obligation of the TPNW will require Algeria to devise strategies and policies to ensure that environmental remediation and victim assistance measures are implemented. This can be done by identifying the extent of damage and danger caused by the legacy of nuclear testing in its region. The government of Algeria can also leverage its membership with regional organizations such as

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[111] Keenan, *The Tuareg: People of Ahagga*.

[112] Khaled Sekkoum et al., "Water in Algerian Sahara: Environmental and Health Impact."

[113] Docherty, "From Obligation to Action: Advancing Victim Assistance and Environmental Remediation at the First Meeting of States Parties to the Treaty on the Prohibition of Nuclear Weapons."

[114] Minor, "Progress and next Steps towards Addressing Nuclear Harm through the TPNW."

[115] United Nations, "Treaty on the Prohibition of Nuclear Weapons."

the African Commission on Nuclear Energy (AFCONE) and the African Regional Cooperative Agreement for Research, Development, and Training (AFRA). These organizations already serve as crucial platforms for promoting the safe and secure use of nuclear energy and technology, regional cooperation, disarmament and non-proliferation in the region.

The involvement of AFCONE and AFRA could expedite State engagement by fostering high-level talks, mobilizing resources, and assembling a network of technical experts. This network of experts can contribute technical expertise and collaborate with Algeria alongside international organizations like the IAEA and the Red Cross to coordinate efforts aimed at addressing the radiological situation in the Algerian Sahara. Several countries within the continent, including Egypt, Ghana, Libya, Morocco, Nigeria, and South Africa already possess sufficient technical infrastructure, atomic agencies, nuclear professionals, and academic programs to actively participate in conducting a comprehensive radiological study (see appendix III).

Understanding the long-term effects of residual contamination will also require collaboration across various research disciplines beyond nuclear science. Material scientists, geochemists, microbiologists, actinide chemists, historians, psychologists, and architects are essential members of forming a multidisciplinary team. Their combined expertise will enable a more efficient cooperative approach to finding solutions for remediating contaminated sites and ensuring the protection of local communities and ecosystems.

6. Conclusion

The IAEA preliminary study provided important but limited insight into radiological conditions of the former test sites in the Algerian Sahara. Additional research is required to broaden the scope of radiological studies and, in some cases, to independently confirm existing findings or data provided by the French government. Significant residual radioactivity remains measurable near nuclear test sites, posing a hazard to visitors and those passing through nearby areas. This raises questions about the necessity for environmental remediation and cleanup efforts. Furthermore, the declassification of France Algerian nuclear test archives is paramount in obtaining a complete understanding into the potential extent of damage caused by the French nuclear tests in the region. In 2021, the leaders of France and Algeria held discussions focused on advancing transparency and justice regarding the French nuclear tests conducted in the Sahara. A primary topic was the declassification of site maps, which would provide a clearer picture of the locations of radioactive waste and spread of radioactive fallout from these tests, allowing for a more accurate assessment of affected areas and communities in the Sahara[116]. Additionally, both parties aimed to expedite the process of compensating those impacted by the tests, acknowledging the long-standing health and environmental consequences experienced by residents. This meeting represented a significant step toward addressing historical grievances and fostering cooperation between the two nations.

[116] Nadjia Bouzeghrane and El Watan, “Essais Nucléaires et Autres Essais Français En Algérie: Ce Dossier «complexe» Serait-Il Enfin Débloqué ?”

Regional and international organization can assist Algeria by expediating high-level talks between Algeria and France in order to declassify this information and calling for a change in legislation in France that prohibits the publication or declassification of records. The TPNWs positive obligations on victim assistance, environmental remediation, and technical cooperation places humanitarian and ecological concerns at the core of policymaking. Most importantly, it offers an opportunity for Algeria to develop national policies that can address the ongoing impact of residual contamination. It also revives the need for renewed reassessment of radiological conditions of former test sites in Algeria as well as institution of programs for ongoing monitoring of potential hazards. This presents an opportunity to leverage advanced technologies, such as UAVs and analytical techniques discussed in this paper to be deployed during the assessment. The involvement of African scientists in driving this research is paramount in order to build confidence in data obtained and advance capacity building in the continent.

Appendix I: List of the 17 nuclear weapon tests France conducted in Algeria between 1960 – 1966[117].

Test	Type	Date & Time	Lat (deg)	Long (deg)	Yield (KT)
Gerboise Bleue	Atmospheric Tower:100m	Feb 13 1960 7:04	26.3117	-0.0572	70
Gerboise Blance	Atmospheric Ground: 0m	Apr 01 1960 6:17	26.1661	-0.1025	3
Gerboise Rouge	Atmospheric Tower: 50m	Dec 27 1960 7:30	26.3536	-0.1236	2
Gerboise Verte	Atmospheric Tower: 50 m	Apr 25 1961 6:00	26.3217	-0.0733	0.7
Agate	Underground	Nov 07 1961 11:29:00	24.0571	5.0521	10
Béryl	Underground	May 01 1962 10:00:00	24.063	5.0418	40
Emeraude	Underground	Mar 18 1963 10:02	24.0413	5.0521	10
Améthyste	Underground	Mar 30 1963 9:59:00	24.0433	5.057	2.5
Rubis	Underground	Oct 20 1963 13:00:00	24.0355	5.0386	52
Opale	Underground	Feb 14 1964 11:00	24.0536	5.0523	3
Topaze	Underground	Jun 15 1964 13:40	24.0666	5.0345	2.5
Turquoise	Underground	Nov 28 1964 10:30	24.0418	5.0416	10
Saphire	Underground	Feb 27 1965 11:30	24.0587	5.0311	127
Jade	Underground	May 30 1965 11:00	24.055	5.0508	2.5
Corindon	Underground	Oct 01 1965 10:00	24.0649	5.034	2.5
Tourmaline	Underground	Dec 01 1965 10:30	24.0437	5.0469	10
Grenat	Underground	Feb 16 1966 11:00	24.0441	5.0412	13

[117] Johnston, "Database of Nuclear Tests, France."

Appendix II: Declassified maps showing the radiological fallout of the atmospheric test conducted by France in Algeria.

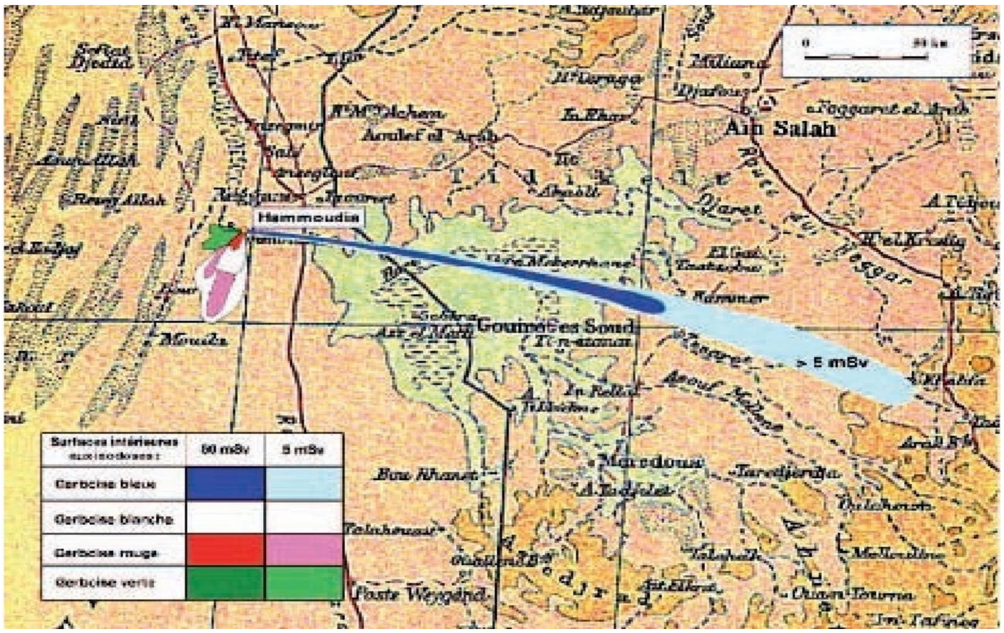

Figure 5: Map depicting the fallout from the four atmospheric tests France conducted in Reggane, Algeria. The map was declassified by France Ministry of Defense in 2007[118].

Gerboise Series Radioactive Fallout Measurements

The effects of ionizing radiation following a thermonuclear test in the Marshall Islands had raised serious doubts and concerns about the safety of communities living near the firing range of nuclear testing. These concerns prompted neighboring African States such as Nigeria, Ghana and Tunisia to seek assistance in independently monitoring radioactive fallout from the French blasts. Nigeria received assistance from the United Kingdom Atomic Energy Authority, Ghana worked with Canada and Tunisia sought assistance from the United States and IAEA[119]. These concerns on the radioactive fallout was substantiated as increased radioactivity levels were measured in Algeria a day after the first atomic blast in Reggane (Gerboise Bleue) and the fallout reached Ghana the following day[120]. However, the radioactivity measurement in Nigeria and Ghana was too low to warrant any significant health concerns to the population[121]. However, this indicated that the radioactive fallout from the France explosion did travel further than it was estimated by French nuclear experiment planners.

[118] Barrillot Bruno, “French Nuclear Tests: When Will There Be Real Transparency?”

[119] Cooper, “The Tunisian Request.”

[120] Cooper, “Saharan Fallout: French Explosions In Algeria And The Politics Of Nuclear Risk During African Decolonization (1960–66).”

[121] Agu, “Observation of Radioactive Fall-out in Nigeria up to 1961.”

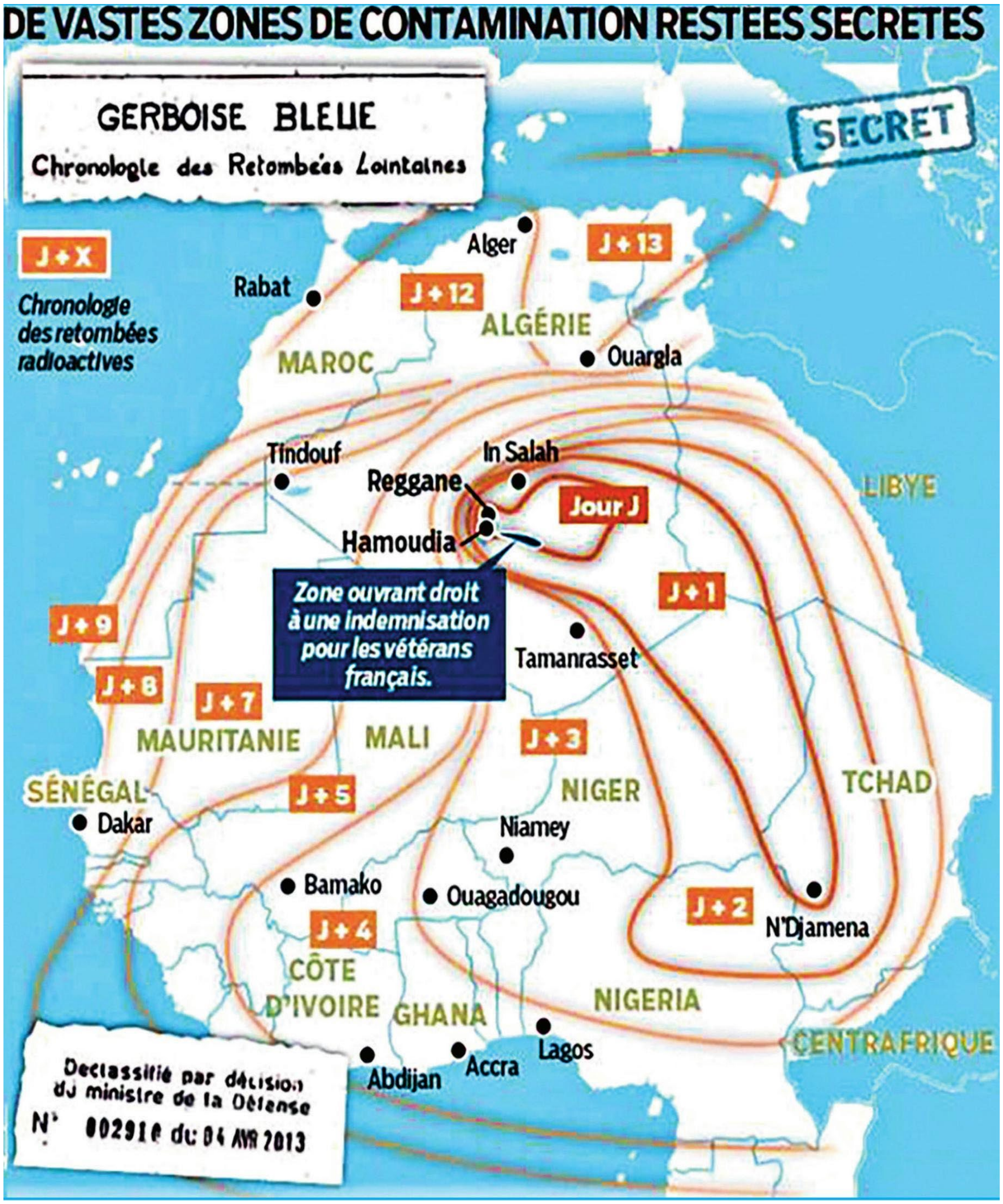

Figure 6: The ministry of defense declassified further documents in April 2013 which showed the true extent of fallout resulting from Gerboise Bleue[122, 123]. The fallout covered the Sahara and went beyond the Algerian borders, days after the test (J+13).

[122] Jarvis, "Mapping the Afterlives of French Nuclear Imperialism in the Sahara."

[123] Le Parisien, "The Shocking Document on the A-Bomb in Algeria."

Appendix III: Institutions with technical capacities for radiation science research.

Country	Organizations	University Programs
Algeria	• Commission of Atomic Energy (COMENA) • The Algiers Nuclear Research Center (CRNA), • The Birine Nuclear Research Center (CRNB), • The Draria Nuclear Research Center (CRND), • The Tamanrasset Nuclear Research Center (CRNT)	• University Of Science And Technology Houari Boumediene
Egypt	• Egypt's Atomic Energy Agency	• American University in Cairo • Tanta University • Mansoura University
Ghana	• Ghana Atomic Energy Commission • Nuclear Power Ghana	• University of Ghana
Libya	• Atomic Energy Establishment	• University of Tripoli • University in El-Beida
Morocco	• National Center of Energy, Sciences, and Nuclear Technology (CNESTEN)	• University of Mohammed
Nigeria	• Nigerian atomic energy commission	• Ahmadu Bello University, • Federal University of technology, Owerri, • Obafemi Awolowo University, University of Maiduguri, • University of Port Harcourt, University of Abuja
South Africa	• The South African Nuclear Energy Corporation (NECSA), • iThemba Labs	• University of Witwatersrand • University of Pretoria • North-West University • University of the Western Cape • University of Johannesburg • University of Cape Town

*This list is not exhaustive and can be expanded on upon availability of further information

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