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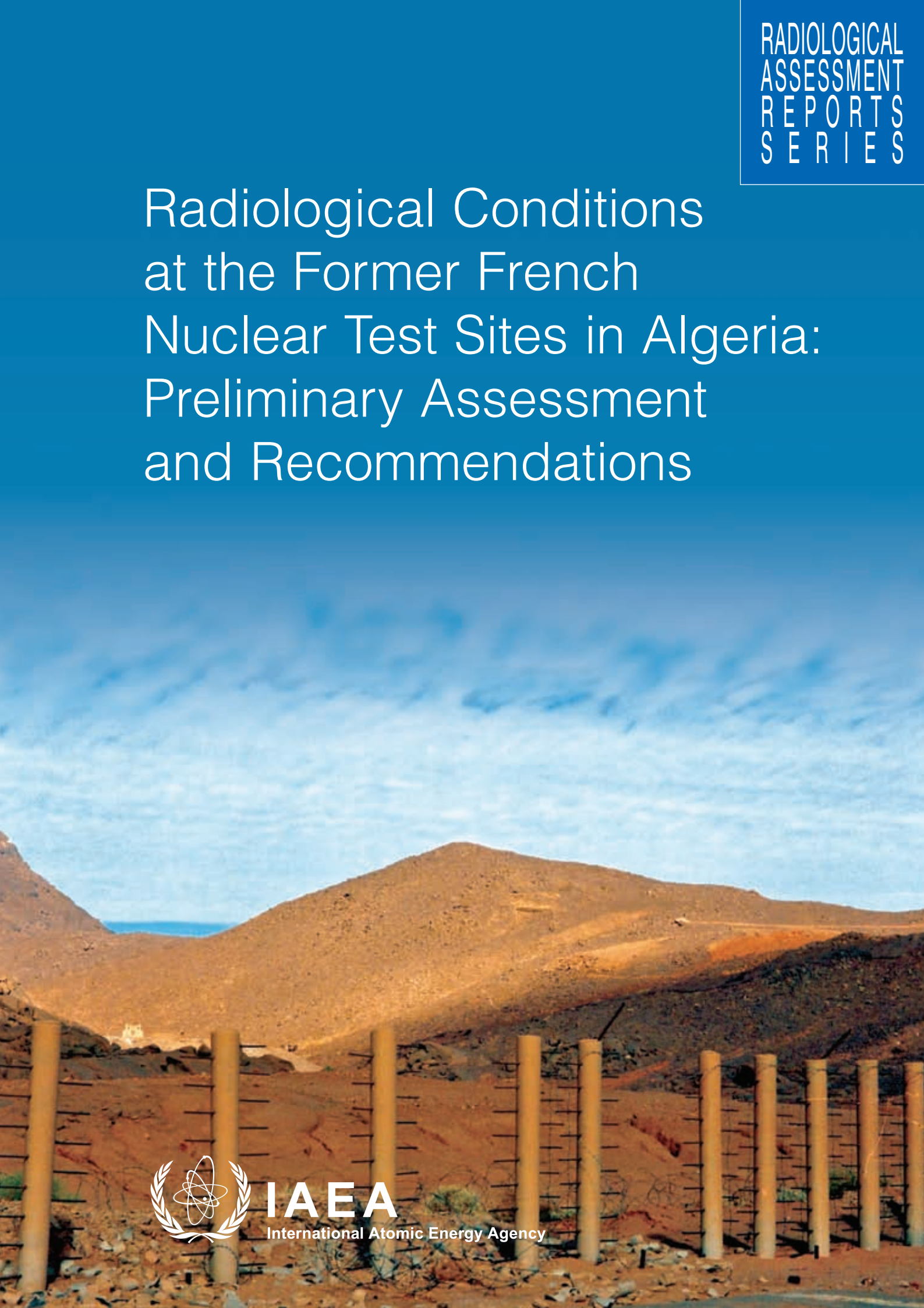
Radiological Conditions at the Former French Nuclear Test Sites in Algeria: Preliminary Assessment and Recommendations



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The cover photograph shows the area at Taourirt Tan Afella where nuclear explosions were performed from 1961 to 1966.

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RADIOLOGICAL CONDITIONS AT THE FORMER FRENCH NUCLEAR TEST SITES IN ALGERIA: PRELIMINARY ASSESSMENT AND RECOMMENDATIONS

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EDITORIAL NOTE

FOREWORD

There are various locations around the world that have been affected by radioactive residues. Some of these residues are the result of past peaceful activities, while others result from military activities, including residues from the testing of nuclear weapons. Stimulated by concern about the state of the environment, movement away from military nuclear activities and improved opportunities for international cooperation, attention in many countries has turned to assessing and, where necessary, remediating areas affected by radioactive residues.

Some of these residues are located in countries where there is a lack of the infrastructure or expertise necessary for evaluating the significance of the radiation risks posed by the residues and for making decisions on remediation. In such cases, governments have felt it necessary to obtain outside assistance. In other cases, it has been considered socially and politically necessary to have independent expert opinions on the radiological situation at the sites. As a result, the International Atomic Energy Agency (IAEA) has been requested by the governments of a number of Member States to provide assistance in relation to its statutory obligation "to establish…standards of safety for protection of health…and to provide for the application of these standards…at the request of a State".

On 22 September 1995, a resolution of the General Conference of the IAEA called on all States "to fulfil their responsibilities to ensure that sites where nuclear tests have been conducted are monitored scrupulously and to take appropriate steps to avoid adverse impacts on health, safety and the environment as a consequence of such nuclear testing".

Representatives of the Algerian Government requested the IAEA to carry out a study of the radiological situation at the former French nuclear test sites in Algeria. The findings of this assessment are summarized in this report.

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SUMMARY

Following a request by the Government of Algeria, the International Atomic Energy Agency (IAEA) conducted an expert mission in late 1999 to sites in Algeria that had been used by France in the early 1960s for the testing of nuclear weapons. The IAEA mission international team was made up of five experts in performing radiological assessments.

The terms of reference for the mission were:

- "make a preliminary assessment of the present radiological situation of the Reggane (atmospheric tests) and In-Ekker test sites (underground nuclear test site and radioactive waste sites) by performing radioactivity measurements at the sites and at selected inhabited locations, i.e., external dose rates, in-situ gamma spectroscopy.
- Selected environmental and food samples should be collected and subsequently analysed.
- The results of these measurements should be used to set up a plan to monitor the test sites more comprehensively, if justified, and to perform a preliminary dose assessment."

The team of experts, composed of members from France, New Zealand, Slovenia, the United States of America and the IAEA, was supported and assisted by a group of seven experts from the Algerian Commissariat à l'énergie atomique. During the course of an eight day mission, the sites of both above ground tests (Reggane site) and underground tests (In Ekker sites) were monitored for dose rates that resulted from residual radioactive material (fission and activation products). Samples of environmental media, i.e. sand, fused sand, solidified lava, vegetation and well water, were collected and analysed in the IAEA's Laboratories in Seibersdorf, Austria.

The mission was able to achieve more than expected as a consequence of the detailed information provided by France. The information was essential for understanding the kinds and degree of contamination.

All known locations of nuclear test sites in Algeria (Reggane and In Ekker — Taourirt Tan Afella and Adrar Tikertine) were included in the mission. The overall findings and conclusions from the fact finding mission were:

(a) Most of the areas at the test sites have little residual radioactive material except:
   - The ground zero localities of the Gerboise Blanche and Gerboise Bleue atmospheric tests at the Reggane test site;
   - At Taourirt Tan Afella in the vicinity of the E2 tunnel.

(b) External dose rate measurements were made at 76 locations. A total of 25 environmental samples were collected. While the number of dose rate measurements was considered adequate, the number of samples collected and analysed was somewhat small, in view of the size of the areas.

(c) According to the generally conservative scenarios assumed and the exposure pathways used, and on the basis of the results of dose rate measurements and analysis of a limited number of samples, there is no indication that for any of the sites (with the possible exception of the Gerboise Bleue, Gerboise Blanche and E2 tunnel sites) annual exposures might occur in excess of any accepted international guideline values for exposure of the public.

(d) A single location (the E2 gallery at Taourirt Tan Afella), at the opening of one of the partially confined underground tests where an accidental release of fission products mixed with molten rock took place and formed a large bed of hardened lava, has been protected from public intrusion by a security fence. Maintenance of that fence is advocated in the interest of keeping public exposures as low as reasonably achievable.

(e) A more detailed and comprehensive radiological survey does not appear necessary for any of the sites if there is no social or economic development in the region of interest.

(f) Corroboration and support of the general conclusions stated here could nevertheless be provided by an appropriate level of radiological surveillance activities, to be conducted by the Algerian authorities, e.g. monitoring air

concentrations in and around the populated villages closest to the above ground test sites.

(g) Despite the preliminary nature of the sampling and investigation programme, all conclusions indicate that present-day exposure rates do not justify a requirement for intervention, in view of the current state of development of the region. This would not preclude the Algerian authorities from carrying out remediation or preventing access to the sites for other reasons. However, if the economic conditions change in the area, the requirement for intervention at the Gerboise Bleue, Gerboise Blanche and E2 tunnel sites should be reconsidered.

(h) A more precise estimate of the doses to migrant and nomadic people of the Algerian desert could be developed by obtaining a more accurate and quantitative description of their lifestyles, habits, food collection methods, etc.

Appendix I provides details of the analytical procedures and results for the samples that were collected at the test sites. Appendix II provides an assessment of the radiation doses. Appendix III provides general radiological concepts in the context of nuclear weapon testing. Appendix IV provides general radiation criteria for intervention situations.

1. TEST SITES

In the early 1960s, France conducted a series of above ground and underground nuclear tests, at the Reggane and In Ekker sites, respectively, in the south of Algeria. Figure 1 shows the locations of the sites. These nuclear explosions resulted in releases of radioactive material to the environment.

The Reggane test sites are located in the desert (an area of only sand and rocks) about 50 km south of Reggane, which is an oasis village of a few thousand inhabitants situated about 150 km south of Adrar, a city with approximately 50 000 inhabitants. Access to the area of the test sites is restricted by military control. There are practically no roads leading to these sites. The old roads formerly used by the French military have now nearly disappeared. This is due to the demolition of the roads when the French forces left the area. This region is periodically affected by sandstorms.

In the In Ekker region there are two sites that were used for nuclear experiments. The first site is called Taourirt Tan Afella, from the name of the granite mountain (about 2000 m high) where the tunnels that were used for the nuclear weapon tests were excavated. The second site is Adrar Tikertine, named after a granite mountain about 1250 m high which is adjacent to the site.

The test site of Taourirt Tan Afella is located within the Hoggar mountains, about 140 km north of Tamanrasset, a city of about 30 000 inhabitants that lies at an altitude of 1000 m and is located about 2000 km south of Algiers and about 500 km north of the border with Niger. At this site, all nuclear tests were conducted in tunnels. One of the test site tunnels is surrounded by a fence that is in a state of deterioration, and therefore the area is easy to enter. The local authorities are now constructing a much larger fence that will encircle the Taourirt Tan Afella mountain.

The Adrar Tikertine site lies about 30 km west of the Taourirt Tan Afella mountain. At the Adrar Tikertine site, experiments on the dispersion of plutonium in air (the 'Pollen' experiments) were

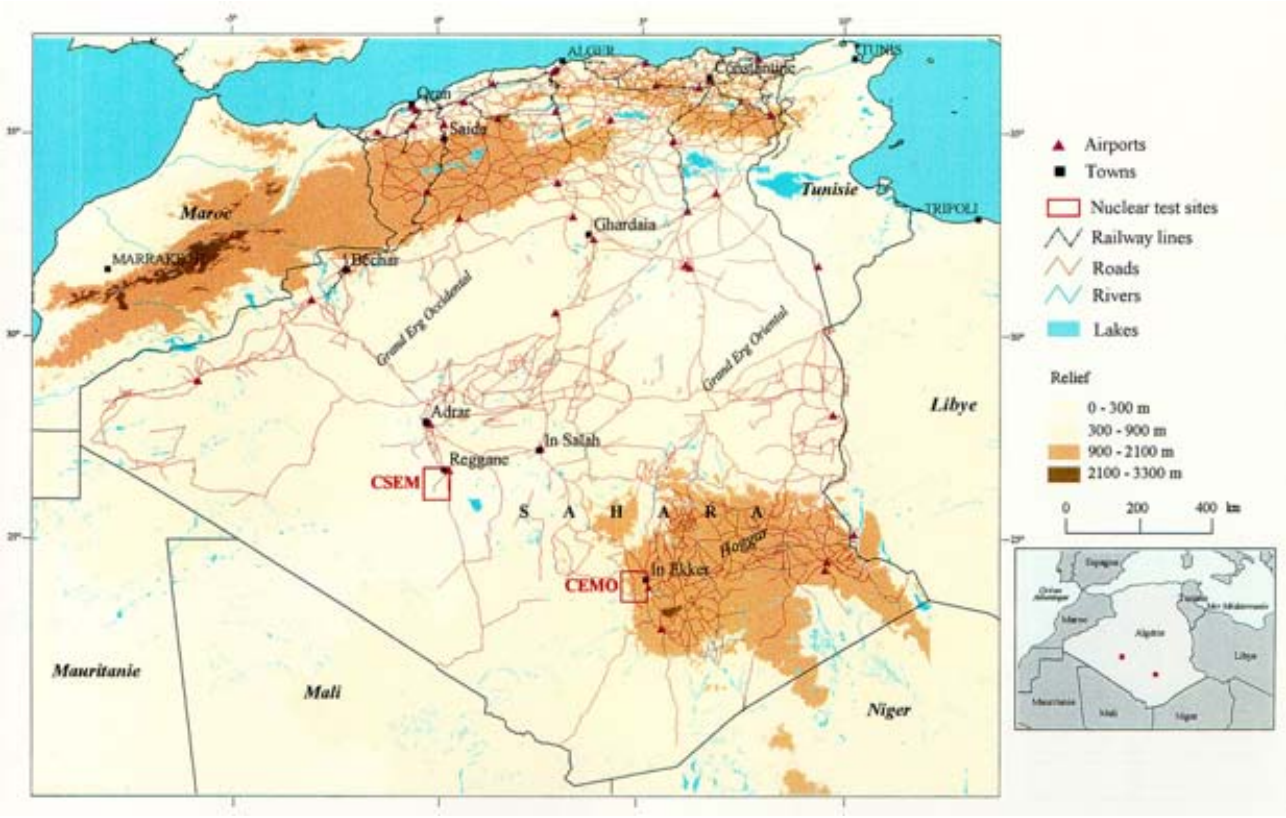

FIG. 1. Location of test sites. CEMO: Centre d'expérimentations militaires des oasis; CSEM: Centre saharien d'expérimentations militaires.

conducted. There are practically no roads leading to the area, and the terrain is rocky and traversed by dry stream beds. This makes for slow access and very difficult identification. On approaching the site, sparse vegetation is seen and there is a water well. Then the vegetation becomes scarcer, sand and rocks prevail, and the terrain is scarred by dry stream beds clearly indicating that from time to time there are torrential rains and the area becomes flooded (this was confirmed by local people). At the site of the Pollen experiments there is only sand and the granite mountain of Adrar Tikertine. There are many other granite hills in the nearby area.

2. BACKGROUND ON THE NUCLEAR TESTING PROGRAMME IN ALGERIA

The information set forth in this section was provided to the IAEA mission by the French authorities at the request of the IAEA. The information includes historical radiological data that were pertinent to the survey and estimates of the radiological conditions prevailing in 1999 prior to the IAEA mission. The estimates were extrapolated by the French authorities from data which are unpublished and not available to the public.

2.1. HISTORICAL INFORMATION

France performed 17 nuclear tests in the Sahara Desert between 1960 and 1966; the first four tests were atmospheric and the following 13 were underground.

The atmospheric tests named Gerboise (Bleue, Blanche, Rouge and Verte) were undertaken in 1960 and 1961 at the Centre saharien d'expérimentations militaires (CSEM), the Saharan Military Test Centre. This centre was set up around the Reggane Oasis (Fig. 2), situated in the heart of the southern Sahara to the south of the Western Grand Erg, 700 km south-east of Béchar.

Between 1961 and 1963, 35 experiments were performed on plutonium pellets at the CSEM, near ground zero of the Gerboise Rouge test (Fig. 2).

The underground tests, whose code names were those of precious stones (Agate, Béryl, Emeraude, Améthyste, Rubis, Opale, Topaze, Turquoise, Saphir, Jade, Corindon, Tourmaline and Grenat) were carried out between 1961 and 1966 at the Centre d'expérimentations militaires des oasis (CEMO), the Oasis Military Test Centre (Figs 3 and 4). The tests were performed at the ends of tunnels dug into the Taourirt Tan Afella massif, a granite mountain measuring 5000 m by 3700 m that is situated 140 km north-west of Tamanrasset.

Between 1964 and 1966 at the CEMO, five plutonium dispersal experiments code named Pollen were performed to the north-west of the Taourirt Tan Ataram massif near Adrar Tikertine (Fig. 3).

2.2. PRE-SURVEY ESTIMATION OF THE CURRENT RADIOLOGICAL SITUATION

Prior to the field mission of November 1999, data covering the period of activity of the two test centres from more than thirty years earlier were extrapolated to estimate the 'current' radiological situation (throughout this report, 'current', 'present' and 'now' refer to 1999). This estimation was conducted to guide the implementation of the field survey, in particular to indicate the level of exposure expected.

The hypotheses and results obtained from extrapolation of historical data must be considered with caution, taking into account that the activity measurement techniques used in the 1960s were not as precise as those used today. This is the case, for example, with gamma spectrometry that used NaI scintillation detectors whose performance levels (identification, detection and precision) were far lower than those of the present-day germanium semiconductor detectors.

To evaluate the residual activity due to the atmospheric nuclear tests and the partially confined underground tests performed on the Saharan sites, the measurements made at the time of the nuclear tests were extrapolated to the present day from the isodose rate curves at $H + 1$[1] .

2.2.1. Gerboise atmospheric tests

The Gerboise test zone is a desert area situated some 50 km south of Reggane, an oasis located to the south of the Western Grand Erg and 700 km from Béchar.

Three of the atmospheric tests (Gerboise Bleue, Gerboise Rouge and Gerboise Verte) were carried out on a tower, while the test at Gerboise Blanche was performed on the ground (Table 1).

[1] $H + 1$ represents time one hour after detonation. The isodose rate curves at $H + 1$ are synthetic curves which were based on aerial and terrestrial measurements carried out periodically after the fallout, and recalculated back to a reference time ($H + 1$ h).

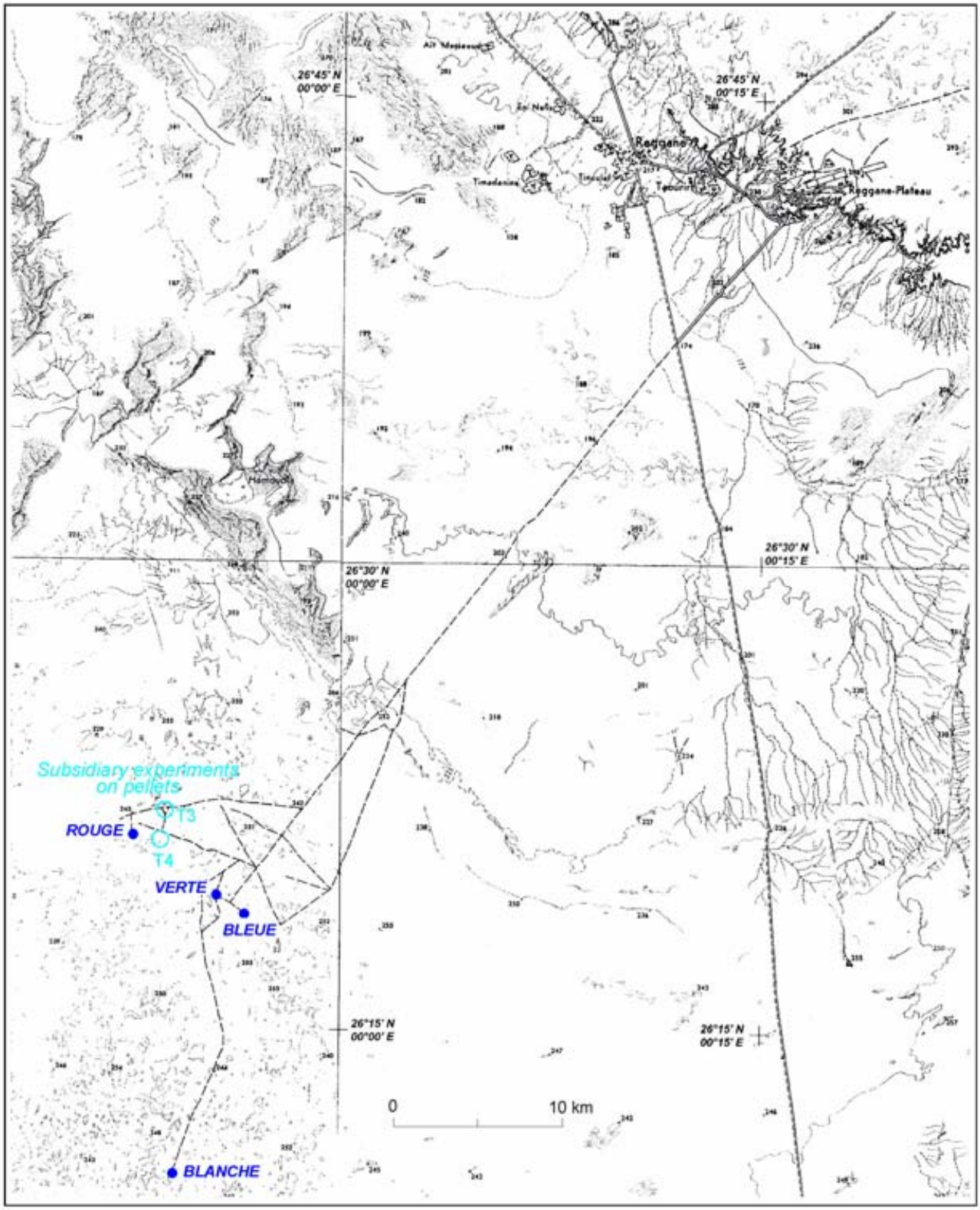

FIG. 2. Map showing Reggane, the location of the CSEM, and the locations of the four Gerboise atmospheric nuclear tests and the pellet experiments.

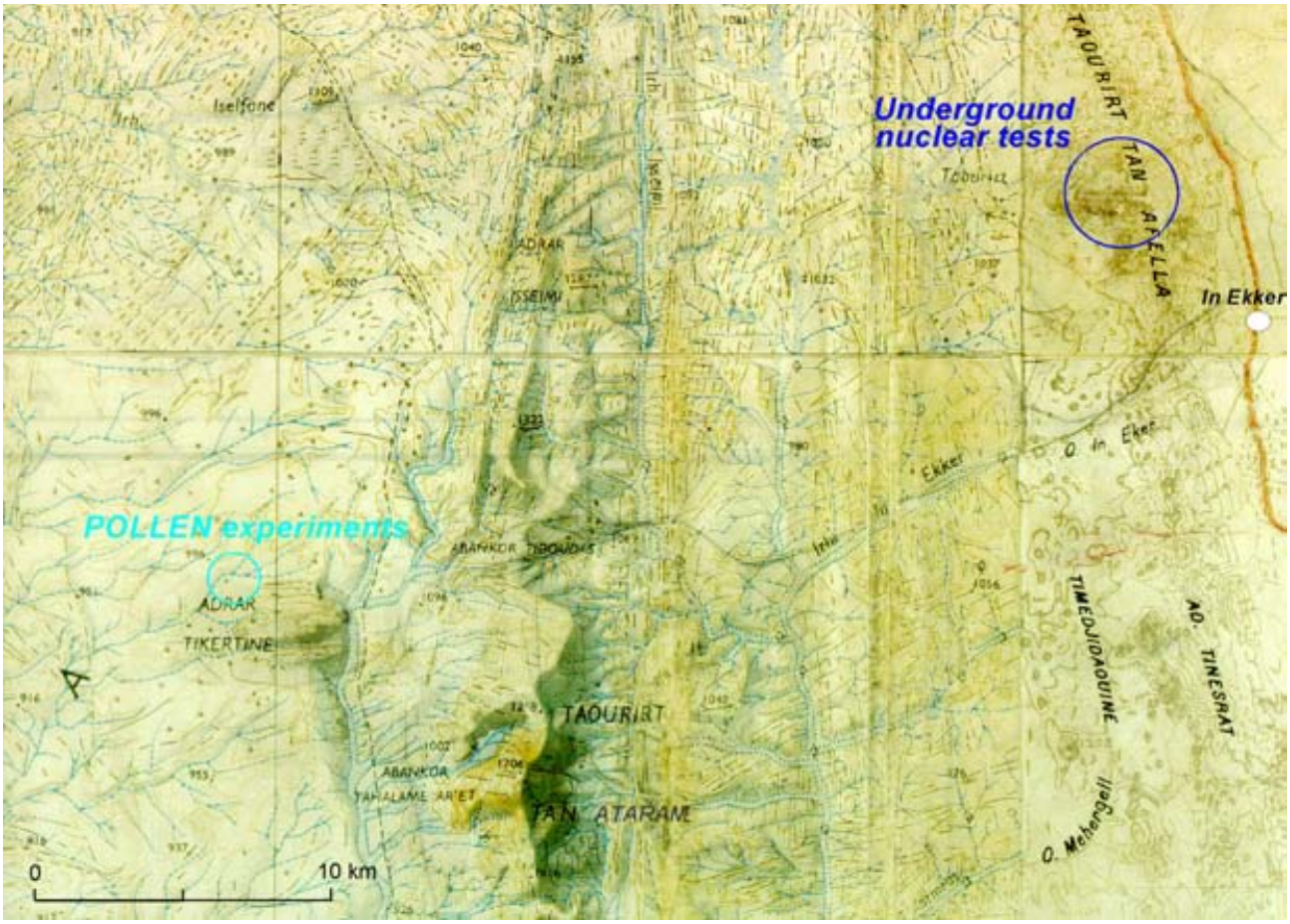

FIG. 3. Map showing the locations of the tests in the Taourirt Tan Afella massif and near the Taourirt Tan Ataram massif (CEMO).

The total explosive yield released in the four tests was between 40 and 110 kt TNT equivalent.

Estimates of the current radiological situation were developed from the isodose rate curves at $H + 1$ (Figs 5–8), applying to them a theoretical attenuation coefficient of the order of 2×10^7, defined as follows:

(a) The dose rate resulting from an unfractionated mixture of fission products decays by a factor of 0.8×10^7 between $H + 1$ and 38 years owing to radioactive decay.

(b) In the 38 years that have elapsed, the dose rate has decayed by an additional factor of the order of 2, owing to the dispersion of the finest contaminated particles by the wind.

(c) An additional attenuation factor of the order of 20% is used to take into account the presence of activation products in the initial dose rates measured at $H + 1$.

TABLE 1. ATMOSPHERIC NUCLEAR TESTS CONDUCTED AT REGGANE

Test	Date	Longitude	Latitude	Type	Yield, W (kt)
Gerboise Bleue	1960-02-13	0°03'26" W	26°18'42" N	Tower, 100 m	$40 < W < 80$
Gerboise Blanche	1960-04-01	0°06'09" W	26°09'58" N	Surface	$W < 10$
Gerboise Rouge	1960-12-27	0°07'25" W	26°21'13" N	Tower, 50 m	$W < 10$
Gerboise Verte	1961-04-25	0°04'24" W	26°19'18" N	Tower, 50 m	$W < 10$

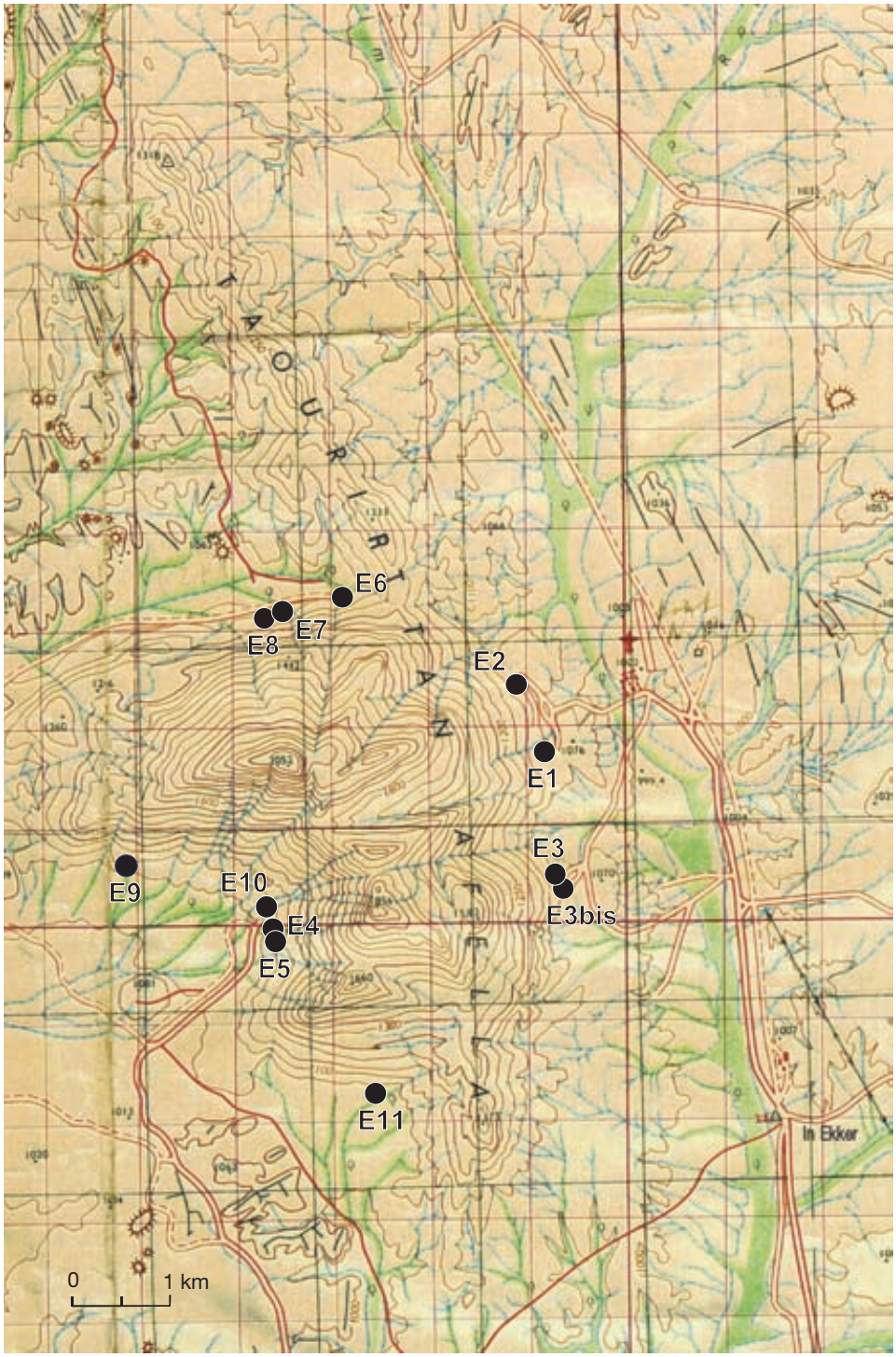

FIG. 4. Map showing the locations of the tunnel entrances for the underground tests in the Taourirt Tan Afella massif (CEMO).

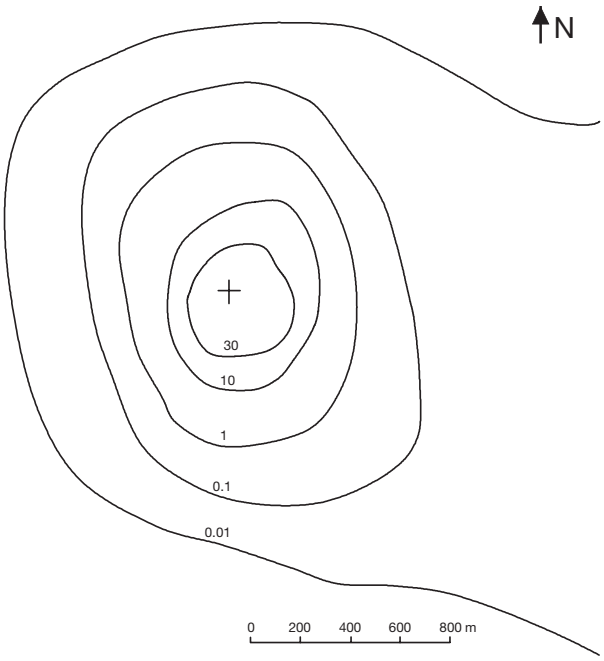

FIG. 5. Isodose rate curves at H + *1 for the Gerboise Bleue test (in Gy/h).*

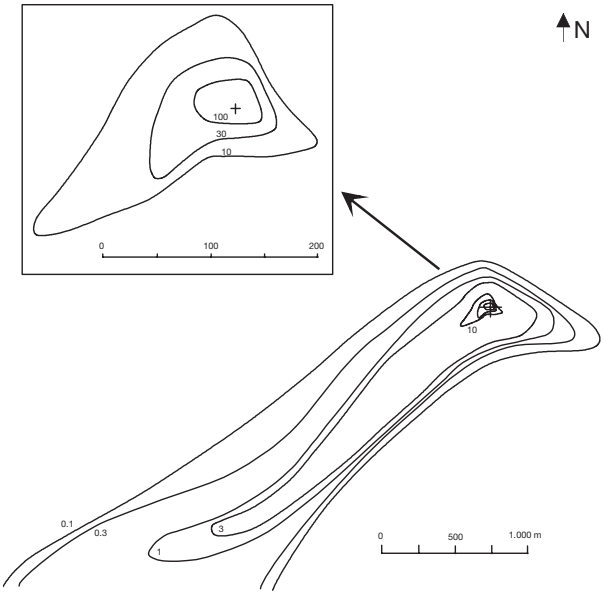

FIG. 6. Isodose rate curves at H + *1 for the Gerboise Blanche test (in Gy/h).*

The 1999 dose rate evaluations for the vicinity of the Gerboise ground zero points are given in Fig. 9, along with the surface areas of the fallout zones.

The current dose rates are essentially due to ^{137}Cs (in fact to its decay product ^{137m}Ba), with the other fission or activation products not contributing more than 5% to the present dose rate. The evaluated surface activity of ^{137}Cs in soil in 1999 is

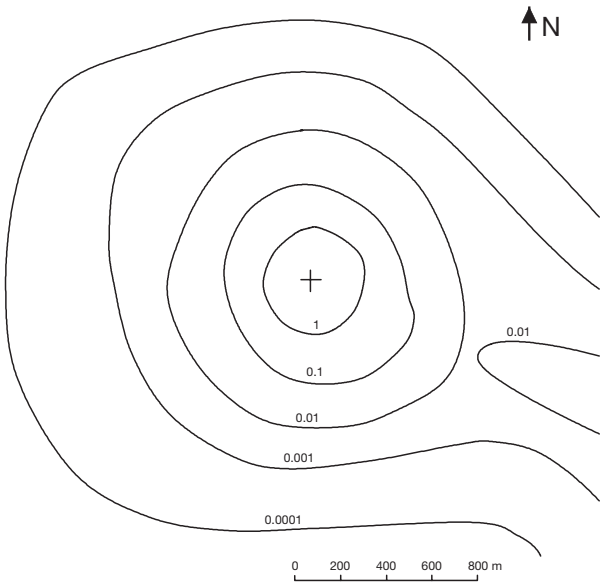

FIG. 7. Isodose rate curves at H + *1 for the Gerboise Rouge test (in Gy/h).*

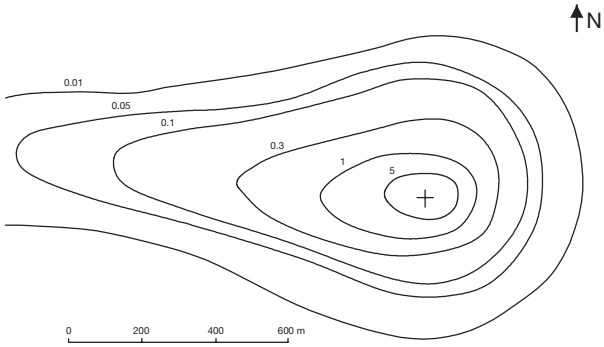

FIG. 8. Isodose rate curves at H + *1 for the Gerboise Verte test (in Gy/h).*

shown in Fig. 9, using the relation 2.5×10^{-12} Gy/h per Bq/m^2 of ^{137}Cs (i.e. 1 µGy/h per 0.4 MBq/m^2 of ^{137}Cs). The residual surface activities of ^{137}Cs should then be between:

- 0.02 and 2.0 MBq/m^2 over a surface area of about 1 km^2 for Gerboise Bleue;
- 0.02 and 3.0 MBq/m^2 over a surface area of about 1 km^2 for Gerboise Blanche;
- 0.02 and 0.2 MBq/m^2 over a surface area of about 0.2 km^2 for Gerboise Rouge;
- 0.02 and 0.2 MBq/m^2 over a surface area of about 0.2 km^2 for Gerboise Verte.

The areas of the Gerboise Bleue and Gerboise Blanche tests display the highest surface activities of ^{137}Cs. The Gerboise Blanche test performed on the ground produced a crater that was later filled in.

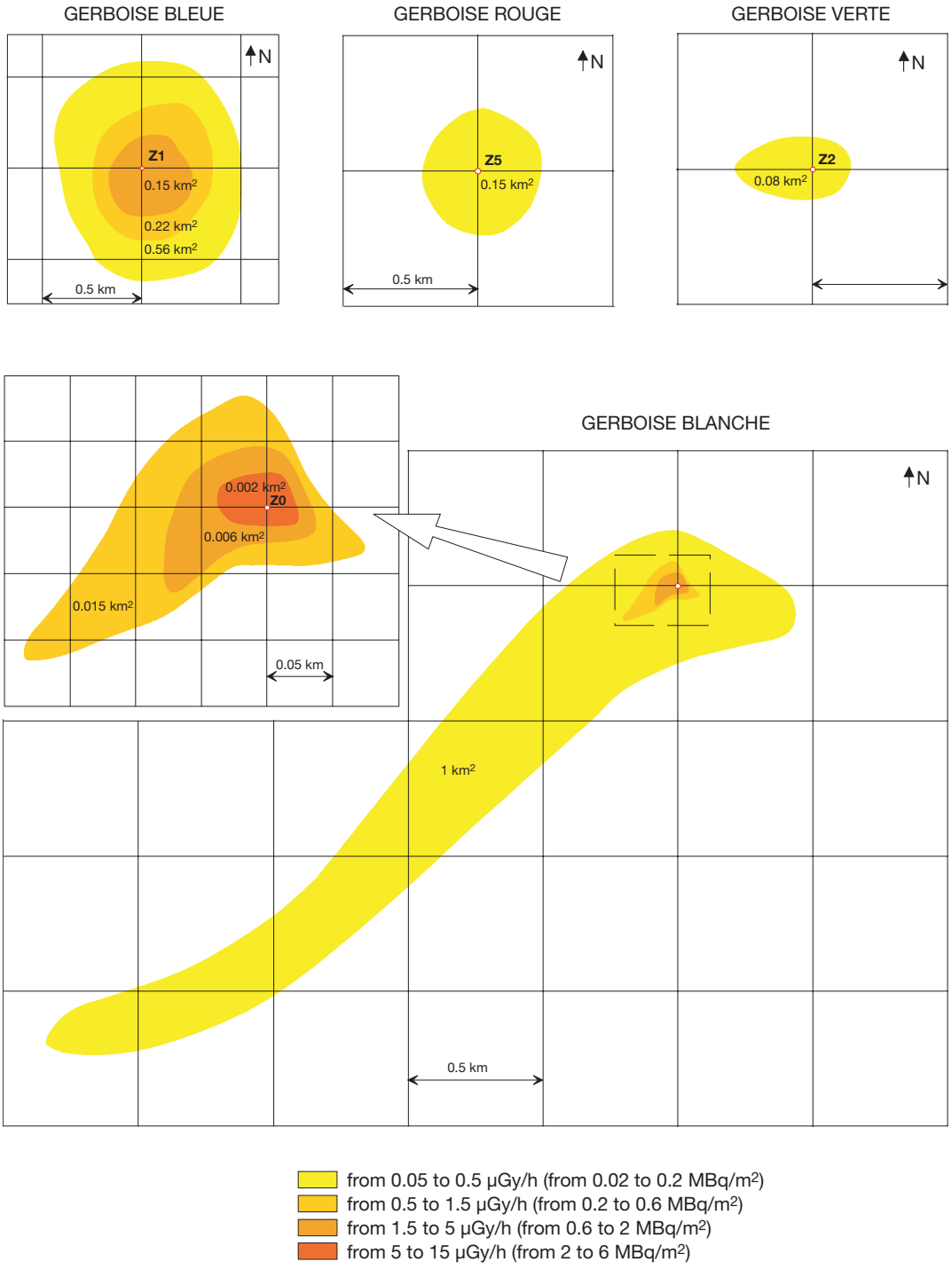

FIG. 9. Evaluation of dose rates and surface activity of ^{137}Cs in soil in 1999, and surface areas of fallout zones.

TABLE 2. MEAN RESIDUAL ACTIVITY IN 1999 IN THE VICINITY OF THE GERBOISE GROUND ZERO POINTS IN THE ABSENCE OF FRACTIONATION (NORMALIZED TO THAT OF ^{137}Cs)

Radionuclide	Bleue	Blanche	Rouge	Verte
^{90}Sr	0.3	0.3	0.3	0.3
^{137}Cs	1	1	1	1
^{155}Eu	0.003	0.003	0.003	0.003
^{60}Co	~0.005	~0.005	~0.005	~0.005
^{133}Ba	≤0.01	≤0.01	≤0.01	≤0.01
^{152}Eu	≤0.01	≤0.01	≤0.01	≤0.01
$^{239+240}$Pu	0.1	1	2	5

Consequently a large amount of the residual activity remains in material buried under several metres of sand.

At present the highest dose rates should be of the order of a few micrograys per hour in the immediate vicinity of the ground zero points of the Gerboise Bleue and Gerboise Blanche tests, and a few tenths of a microgray per hour for the other two Gerboise tests (marginally higher than the natural background).

The residual activity remaining after partial decay of the long lived fission products (^{90}Sr and ^{155}Eu) has been assessed from their relative fission yields, assuming there has been no fractionation of these radionuclides with respect to ^{137}Cs during the deposition process.[2] The activity ratios would then currently be:

$$^{90}\text{Sr}/^{137}\text{Cs} \approx 0.31$$
$$^{155}\text{Eu}/^{137}\text{Cs} \approx 0.003$$

The activity of activation products depends on the nature of the test device, the support components (tower, etc.) and the environment (soil type, etc.) and is therefore more difficult to predict. If we use the same hypotheses to estimate the production of ^{55}Fe and ^{60}Co as were used by the IAEA to determine the radiological situation at Mururoa and Fangataufa [1], i.e.:

— 1.5×10^{13} Bq of ^{55}Fe produced per kilotonne, and

— ^{55}Fe/^{60}Co activity ratio between 6 (underground tests) and 10 (tower tests),

then the residual activity of ^{60}Co (5.27 year half-life) after 38 years of decay would be between 1×10^4 MBq (test on tower) and 2×10^4 MBq (underground test) per kilotonne. The theoretical average ratio of ^{60}Co/^{137}Cs activity should at present lie between 0.003 and 0.006.

On the basis of their half-lives, three other activation products could still be present: ^{133}Ba (10.5 years), ^{152}Eu (13.53 years) and ^{154}Eu (8.59 years). The average activities should be of the same order of magnitude as that of ^{60}Co and undoubtedly should not exceed a few per cent of that of ^{137}Cs.

The related data for the activity of $^{239+240}$Pu were estimated from the mass of fissile material used and the radiochemical measurements made after the tests.

An evaluation of the mean residual activity in 1999, normalized to that of ^{137}Cs, in the vicinity of the Gerboise ground zero points is given in Table 2. This evaluation must be considered with caution, because it does not take into account the physicochemical characteristics or the mode of production of the various radionuclides, which can lead to substantial distortion (fractionation) between the ratios of products formed by the test and the ratios of products effectively deposited on the ground.

Based on Table 2, Table 3 shows an evaluation of the mean residual surface activity in 1999.

2.2.2. Underground tests

The underground tests were carried out in tunnels dug into the granite massif of Taourirt Tan Afella. This area and its immediate surroundings were virtually uninhabited at the time of the tests.

[2] The analytical results for the samples collected on the site during the IAEA mission of November 1999 show a significant fractionation of the products (see Section 4.4). The actual ratios standardized to the ^{137}Cs are significantly higher than indicated by this estimation, showing relatively low ^{137}Cs deposition, in good agreement with the known volatile behaviour of caesium.

TABLE 3. MEAN RESIDUAL SURFACE ACTIVITY (MBq/m^2) IN 1999 IN THE VICINITY OF THE GERBOISE GROUND ZERO POINTS IN THE ABSENCE OF FRACTIONATION

	Bleue	Blanche	Rouge	Verte
	~1 km^2	~1 km^2	~0.2 km^2	~0.1 km^2
^{90}Sr	0.01–0.6	0.01–0.9	0.01–0.1	0.01–0.1
^{137}Cs	0.02–2	0.02–3	0.02–0.2	0.02–0.2
^{155}Eu	≤0.01	≤0.01	≤0.001	≤0.001
^{60}Co	≤0.01	≤0.02	≤0.001	≤0.001
^{133}Ba	≤0.02	≤0.03	≤0.002	≤0.002
^{152}Eu	≤0.02	≤0.03	≤0.002	≤0.002
$^{239+240}Pu$	0.001–0.2	0.02–4	0.04–4	0.09–9

TABLE 4. UNDERGROUND NUCLEAR TESTS PERFORMED IN THE TAOURIRT TAN AFELLA MASSIF

Name[a]	Date	Type	Yield, W (kt)
Agate	1961-11-07	Tunnel	$W < 10$
Béryl	1962-05-01	Tunnel	$10 < W < 40$
Emeraude (*Georgette*)	1963-03-18	Tunnel	$10 < W < 40$
Améthyste	1963-03-30	Tunnel	$W < 10$
Rubis	1963-10-20	Tunnel	$40 < W < 80$
Opale (*Michèle*)	1964-02-14	Tunnel	$W < 10$
Topaze	1964-06-15	Tunnel	$W < 10$
Turquoise	1964-11-28	Tunnel	$W < 10$
Saphir (*Monique*)	1965-02-27	Tunnel	$W > 80$
Jade	1965-05-30	Tunnel	$W < 10$
Corindon	1965-10-01	Tunnel	$W < 10$
Tourmaline	1965-12-01	Tunnel	$10 < W < 40$
Grenat (*Carmen*)	1966-02-16	Tunnel	$10 < W < 40$

[a] Partial information relating to the phenomenology of some tests was declassified within the APEX programme (Application pacifique des expérimentations nucléaires — Peaceful Nuclear Test Programme); the corresponding APEX denominations are given in italics.

The rock overlying the firing points was sufficiently thick for test containment (several hundred metres on the average). The system was designed so that the radioactive products would be confined within the mountain at the ground zero point, in rock that became molten at the moment of firing. Containment was normally ensured by the design of the tunnel, which would be closed by the shock wave before any radioactive material could escape.

Table 4 lists the tests that were performed. The total energy released by the 13 tests was about 270 kt.

The estimated gross residual activities of the main radionuclides in the massif after 35 years of decay are given in Table 5.

Table 6 gives an estimate of the current specific activities of the lava buried in the mountain (total mass of about 3.5×10^5 t).

Of the 13 tests performed in the Taourirt Tan Afella massif:

(a) Nine tests (Agate, Emeraude, Opale, Topaze, Turquoise, Saphir, Corindon, Tourmaline and Grenat) were fully contained.

TABLE 5. GROSS RESIDUAL ACTIVITY (TBq) IN 1999 FROM THE UNDERGROUND TESTS

Radionuclide	$^{239+240}$Pu	^{238}Pu	^{90}Sr	^{137}Cs	^{155}Eu	^{60}Co
Remaining activity	240	15	250	800	1.5	<8

TABLE 6. MEAN RESIDUAL SPECIFIC ACTIVITY IN 1999 OF THE UNDERGROUND TEST LAVA (MBq/kg)

Radionuclide	$^{239+240}$Pu	^{238}Pu	^{90}Sr	^{137}Cs	^{155}Eu	^{60}Co
Concentration	0.7	0.045	0.72	2.3	0.004	<0.02

TABLE 7. GEOMETRICAL CHARACTERISTICS OF THE THREE LAVA STREAMS

Location of the lava stream	Volume (m^3)	Length (m)	Mean thickness (m)
On the side of Tan Afella	70	20	0.1
On the road below the bank	70	44	0.4
On the hill opposite the entrance	600	150	0.2

(b) Two tests (Rubis and Jade) were not fully contained in their respective galleries and gave rise to characteristic discharges (iodines and gases) from the tunnel openings. In the case of Jade, the activity detected outside the vicinity of the tunnel entrance was low. Only Rubis led to measurements of significant activity outside the test area at the time of the test. In view of the short half-lives of the radionuclides involved, no residual activity should be detectable at these locations now.

(c) Two tests (Béryl and Améthyste) were only partially contained and significant releases of radioactive products took place.

With the exception of the Béryl and Améthyste test areas, which are examined in the next two sections, the other areas of the Taourirt Tan Afella massif (used for the underground tests) should not display any significant radiological residues outside the galleries.

2.2.2.1. Béryl test

The Béryl test was carried out on 1 May 1962, on the north-east side of Taourirt Tan Afella, in tunnel E2 North. To contain the test, a spiral shaped tunnel opened into the firing chamber (Fig. 10). The spiral was designed to be closed off by the shock wave before the lava could reach the entrance of the tunnel. Blocking of the main tunnel did not take place as planned (probably because of a physics experiment situated in a tunnel parallel to the main tunnel which may have short-circuited the spiral).

A fraction of the test product's activity, of the order of 5–10%, escaped as lava, aerosols and gaseous products. The geometrical characteristics of the three lava streams (Figs 11–13) are given in Table 7.

To evaluate the residual activity outside the tunnel, the following conservative hypotheses were adopted:

— Discharge of 5–10% of the products formed, distributed in 10 000 t of contaminated soil (lava and scoria);
— No fractionation of the fission products[3].

[3] In practice, significant fractionation could be observed between the various radionuclides, especially for ^{137}Cs.

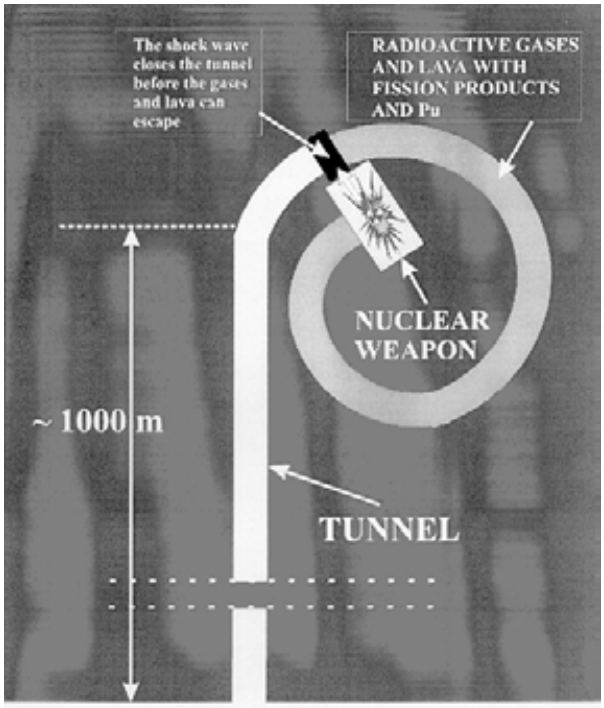

FIG. 10. Arrangement of a tunnel used for weapon testing.

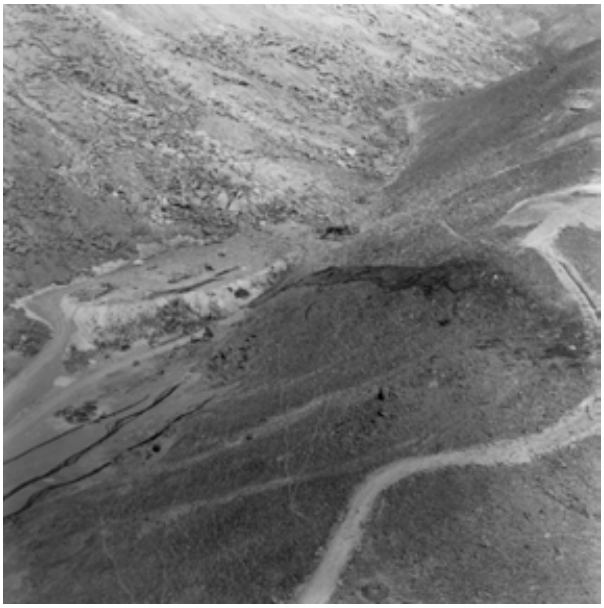

FIG. 11. General view (photograph taken in 1962) in a northerly direction of the area contaminated by the Béryl test. On the left is bank E2 at the foot of the eastern slope of the Taourirt Tan Afella massif. On the right is the south-western slope of the hill opposite the bank.

Estimates of activities and mean residual concentrations after 35 years of decay are shown in Table 8.

In the analyses performed between 1962 and 1965 on lava or scoria samples, the mean ratios for

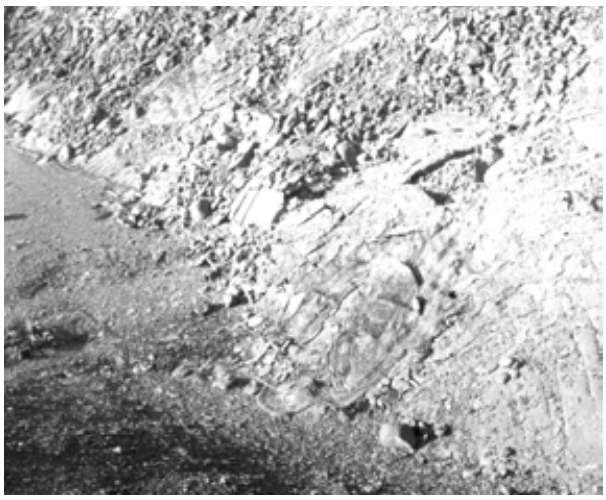

FIG. 12. Photograph taken in 1962 of the eastern slope of the Taourirt Tan Afella massif at the end of bank E2 and the lava stream caused by the Béryl test.

FIG. 13. Photograph taken in 1962 of the lava flow along the southwestern side of the hill and the lava flow at the foot of bank E2.

$^{239+240}Pu/^{137}Cs$ and $^{90}Sr/^{137}CS$ were of the order of 0.1 and 0.32, respectively, indicating that the concentrations of $^{239+240}Pu$ could reach 0.37 MBq/kg.

The most recent measurements available to the mission team date back to 1965, about three years after the test. At that time, the 1 m dose rates were between 2 and 10 mGy/h in an area covering about 0.03 km^2, and between 0.05 and 2 mGy/h in an area covering about 0.15 km^2. The present-day estimated dose rates in the area contaminated by this test are shown in Fig. 14.

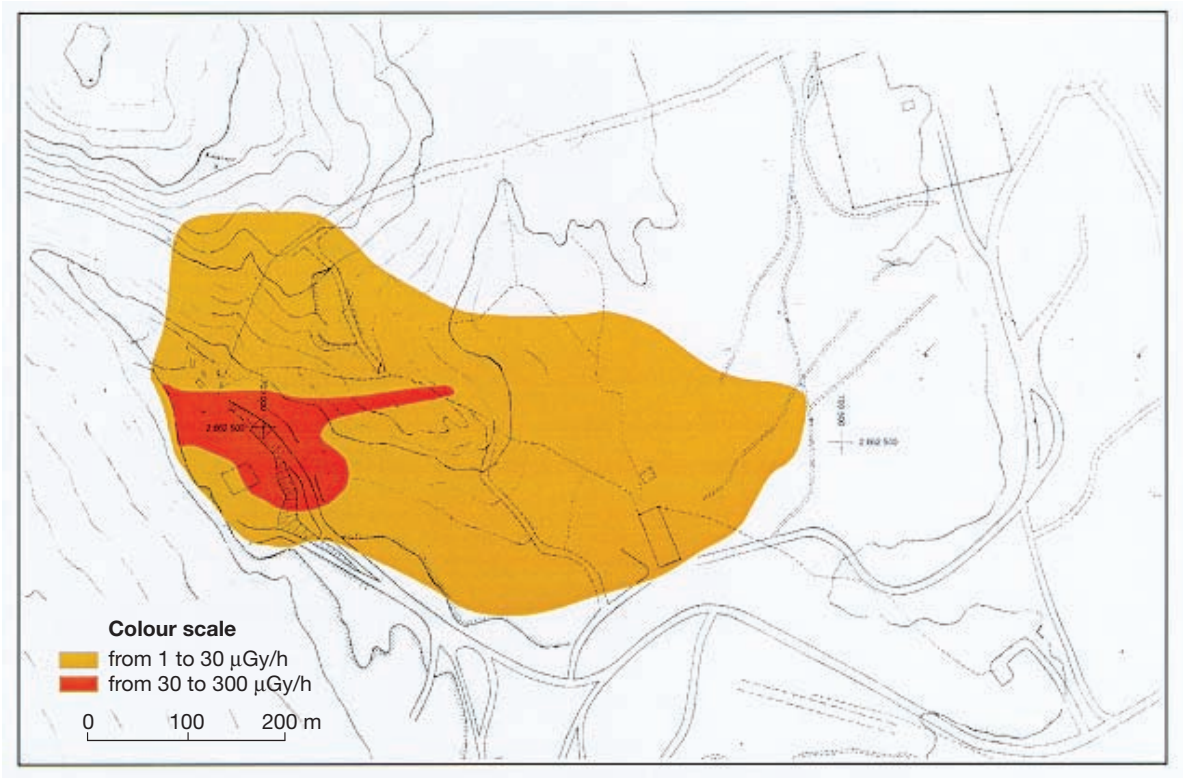

FIG. 14. Evaluation of dose rates in 1999 in the area contaminated by the Béryl test (extrapolated from measurements performed in 1965).

In the area displaying the highest dose rates, the contamination is fixed in the lava. Most of the area with dose rates currently estimated at more than 1 µGy/h is difficult to access owing to the very hilly topography: the side of the Taourirt Tan Afella, the entrance to the tunnel blocked by rocks, the west side of the hill facing the tunnel entrance (with a slope of about 40%), the thalweg (small valley) giving access to the bank, etc.

To prevent access, the area that was contaminated by this test was entirely fenced off and appropriate warning signs that forbid entry were affixed to the fence.

TABLE 8. ESTIMATION OF CURRENT MEAN RESIDUAL ACTIVITY IN THE AREA CONTAMINATED BY THE BÉRYL TEST

Radionuclide	Activity (TBq)	Concentration (MBq/kg)
^{137}Cs	5–10	0.5–1
^{90}Sr	1–3	0.1–0.3
$^{239+240}$Pu	1–2	0.1–0.2
^{238}Pu	0.1–0.2	0.01–0.02

2.2.2.2. Améthyste test

During the Améthyste test that was performed on 30 March 1963, on the eastern side of Taourirt Tan Afella in the E3 tunnel, a small quantity of molten rock and scoria escaped and was deposited near the entrance of the tunnel and in the immediate vicinity.

In 1965, the residual dose rates at 1 m above the surface could have exceeded 50 µGy/h in an area covering about 0.03 km^2. The area contaminated by this test that is estimated to have a present-day dose rate of >1 µGy/h is shown in Fig. 15.

2.2.3. Experiments with plutonium pellets

Subsidiary experiments were designed to measure the velocity of a shock wave in a pellet of plutonium. They were carried out near the area used for the Gerboise Rouge test.

A total of 35 experiments in three series were performed at Reggane in April–May 1961, April 1962 and March–May 1963 (T3 and T4 sites, Fig. 2). Each experiment involved a plutonium pellet weighing about 20 g.

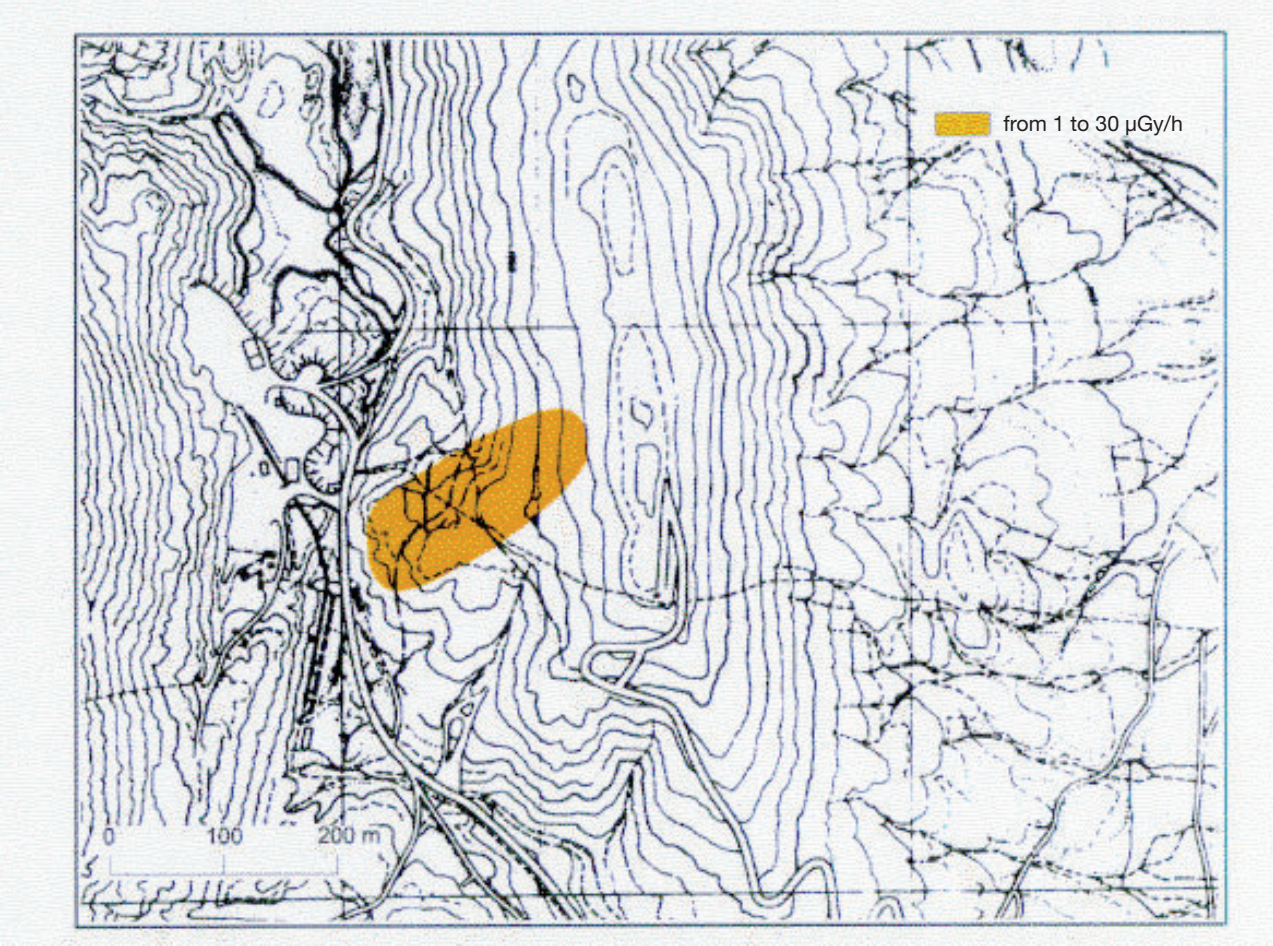

FIG. 15. Evaluation of dose rates in 1999 in the area contaminated by the Améthyste test (extrapolated from measurements performed in 1965).

The experiments were carried out in pits to limit dispersal. The majority of the plutonium remained in the pits. Low residual activity might still be detected near the test pits.

2.2.4. Pollen experiments

The Pollen experiments were designed to simulate an accident involving plutonium and to measure its consequences, including the degree of contamination that might arise in the vicinity. The method used consisted of measuring quantities of plutonium aerosols (spiked with ^{177}Lu) generated by pyrotechnic dispersal. The experiments were carried out in a desert-bound region of Adrar Tikertine (Fig. 3), some thirty kilometres south-west of Taourirt Tan Afella.

Five experiments involving 20 to 200 g of plutonium were carried out between May 1964 and March 1966, using the same firing area. The experiments were performed when winds were blowing across the sector planned for collection of the fallout.

For the five experiments, the plutonium deposit measured in the axis of the plume could have reached 3×10^3 kBq/m^2 up to 50 m from the ground zero point, and could then have fallen to below 40 kBq/m^2 beyond 1 km. After each experiment, the most contaminated area was covered with asphalt to limit resuspension.

On the basis of the experiments performed at this site, low residual activity might still be detected near the ground zero point.

3. IAEA MISSION

The Government of Algeria requested the IAEA to assess the levels of residual radioactive material at the sites where nuclear activities were conducted, to evaluate the potential radiological impact, and to advise on whether further monitoring of test sites was required and to what extent.

Accordingly, a fact finding field mission was sent to Algeria to make a preliminary assessment of the present radiological situation of the Reggane and In Ekker former nuclear test sites. The objective of this mission was to visit, jointly with the Algerian counterparts, the former French nuclear test sites, to perform in situ measurements and make a preliminary assessment of the current radiological conditions. A decision on the necessity to conduct more elaborate studies in the future would be possible on the basis of the findings of this mission.

In the absence of detailed information on the nuclear test programme, the contribution of the French expert on the team in providing briefings concerning each site was invaluable. This information is documented in Section 2 of this report.

The Algerian project counterpart personnel joined the IAEA mission and made all the necessary (logistical and other) arrangements for the implementation of the mission. The local authorities in Adrar (Reggane) and Tamanrasset (In Ekker) provided local logistical support, such as ground transportation and security arrangements. Internal travel by air (Algiers–Adrar–Tamanrasset–Algiers) was provided by the Algerian Government. This mission was sponsored by the IAEA Technical Cooperation Project ALG/9/014.

3.1. MISSION TEAM

The IAEA mission team was composed of the following international experts in the areas of radiological monitoring, laboratory analysis, radiation dosimetry and radiation protection: Andrew McEwan from New Zealand, Steven L. Simon from the United States of America, Jean-Francois Sornein from France, Peter Stegnar from Slovenia and Pier Roberto Danesi from the IAEA.

During the mission, the IAEA team was accompanied by the following national experts (Fig. 16) from the Algerian Commissariat à l'énergie atomique (COMENA): Y. Touil, A. Noureddine, A. Gheddou, M. Benkrid, M.S. Hamlat, R. Affoune, M. Chikouche and N.E. Rais.

3.2. MISSION ITINERARY

Thursday, 18 November 1999	Arrival of IAEA mission experts in Algiers.
Friday, 19 November 1999	Meeting with the Algerian team, departure for Adrar (the Reggane test site).
Saturday, 20 November 1999	Visit to the Reggane test site — four test locations where atmospheric (surface) tests were conducted. The team took external exposure dose rate measurements and air samples, and collected sand and other environmental samples. A preliminary assessment of the radiological conditions was made.
Sunday, 21 November 1999	Continuation of work at the Reggane test site. In addition, environmental samples were collected in Reggane, and a preliminary assessment of the radiological situation was made.
Monday, 22 November 1999	Travel to Tamanrasset (the In Ekker site).

FIG. 16. The mission team.

Tuesday, 23 November 1999	Visit to the Taourirt Tan Afella (In Ekker) underground test site. The team took external exposure dose rate measurements at the site contaminated with lava (from the Béryl test), collected environmental samples of lava, sand and vegetation (inside and outside the fence), and collected water samples from three wells in this area.
Wednesday, 24 November 1999	Visit to the Adrar Tikertine site (plutonium dispersion experiment). The team took dose rate measurements and air samples, and collected surface sand.
Thursday, 25 November 1999	Travel to Algiers, discussion with counterpart personnel on results of the mission, final discussion of the mission.
Friday, 26 November 1999	Departure from Algiers.

4. SAMPLING AND MEASUREMENT PROGRAMME

4.1. INTRODUCTION

4.1.1. Reggane

On 20 November 1999, the sites Gerboise Bleue and Gerboise Blanche were inspected for the purpose of determining sampling locations. On 21 November the sites Gerboise Rouge, Gerboise Verte, T3 and T4 were inspected for similar purposes. At the site of each test, the ground zero point was identified by visual inspection and global positioning system (GPS) measurements. Then, moving along the major axis of the areas (circular or elongated) where some residual contamination was expected, dose rate measurements were taken at locations about 100 to 200 m apart. Several dose rate meters were used for the purpose of comparing and verifying measurement data. At each point where the dose rate was measured, the geographical coordinates were recorded as determined by a handheld GPS unit. Several samples of sand mixed with black, fused sand (that had been solidified by the heat of the explosion) were collected at selected points. The measured dose rates were compared with those estimated by the French Commissariat à l'énergie atomique (CEA) from measurements following the conduct of the tests (see Section 2). Findings from these measurements are presented in Section 4.4.

4.1.2. In Ekker (Taourirt Tan Afella and Adrar Tikertine)

On 23 November 1999, the team inspected the Taourirt Tan Afella area and in particular the area immediately in front of the E2 tunnel (where a partially confined test occurred) and the adjacent area. Full protective clothing was worn in the area in front of the E2 tunnel. Starting from the fence built by the French authorities and moving in the direction of the entrance of the E2 tunnel, radiation dose rates were measured at close intervals using several dose rate meters, and the locations were recorded using the GPS. Some lava and soil samples were collected at selected points. A few samples of sand and vegetation were also collected along the path of dry water streams running from the site in the direction of the fence, on the assumption that if some contamination had been transported by rainwater, it would probably have accumulated in these locations. A water sample was also collected from a water well located at a distance of a few kilometres from the fence. The entrance to the E3 gallery was also inspected and external dose rate measurements were taken in the vicinity.

On 24 November 1999, the team inspected the Adrar Tikertine area. Masks were worn during this survey as a precaution against breathing fine particles suspended from the ground by high winds. The detonation site of the plutonium dispersion experiment (also known as the Pollen test) was identified with some difficulty because little in the way of visual clues remains today. Traces of asphalt were still visible in the proximity of the detonation site and also at distances of several hundred metres. Moving from the detonation site along the direction of the 213º axis, the team recorded the dose rates at regular intervals as well as the corresponding geographical coordinates obtained from the GPS for a few kilometres. Samples of sand were also collected at different depths. By using a portable NaI based spectrometry instrument, a few gamma spectra were recorded at this site, though monitoring equipment especially designed for monitoring the low energy gamma emissions from plutonium and americium was not available.

4.2. FIELD MEASUREMENTS

The absorbed dose rates in air at 1 m above ground were measured with field survey meters, such as GM counters (FAG and ESM models) and NaI scintillation detectors (GR 320 Exploranium and GR 130 Minispec models). The dose rates were taken at 76 different locations at the Reggane and In Ekker test sites with five different survey meters and three scintillation detectors, with an overall difference between instrument readings of about 30%. The differences between instruments were not considered important for radiation protection or assessment purposes.

4.3. FIELD SAMPLING

The field sampling, although an important aspect of the fact finding mission, was not intended to be as comprehensive as a full scale radiological monitoring programme might generally be. In this case, only a limited number of samples were obtained to provide preliminary data on the

radiological conditions, on the basis of which recommendations for further work could be made. The environmental media that normally include most of the local inventory of radioactive residues are soil, water and vegetation. In general, the relative frequency of sampling for each medium within the context of a well planned survey depends in part upon the availability of the samples and their importance to the assessment. In the case of the former French nuclear test sites in Algeria, the soil is low in organic material and coarse sand particles that are readily accessible for sampling. With respect to vegetation, none was available at the Reggane test site as the area is entirely a desert. Similarly, there were no water wells available at that site. The In Ekker region, though also desert-like, has sparse vegetation surrounding the Taourirt Tan Afella mountain and in some stream beds which are dry most of the year. These stream beds originate in the sites. In this area, there are a few scattered and remote water wells which local travellers occasionally use.

4.3.1. Soil

Soil was sampled primarily in the interest of evaluating the resuspendable fraction that might expose intermittent visitors and travellers as a consequence of high winds leading to dusty atmospheric conditions. For that purpose, soil was sampled at both the Reggane and In Ekker locations by collecting the top layer, to a depth of typically between 2 and 4 mm, over an area of about 0.5–1.0 m^2 (see Fig. 17). In addition, fused sand remaining from the above ground tests at the Reggane site was also collected. Samples were bagged for transport and marked with identification, and exposure rate measurements were taken as corroborative information.

FIG. 17. Sand sampling at the Adrar Tikertine site.

4.3.2. Water

Water from three different wells in the area near In Ekker on the route towards Adrar Tikertine was sampled by collecting water directly from the bucket used by travellers, which is dropped into a deep hole and drawn out on a rope.

4.3.3. Vegetation

Because of the scarcity of vegetation, only two plant samples were collected, both on the slopes of the Taourirt Tan Afella mountain beneath the E2 tunnel where the large release occurred. The plant types collected are known to be used by camels as food, though the particular plants sampled would be unavailable to them as they were located within a security fence. The plant types sampled were *Aerva persica* (Tomaberzist) and *Atriplex halimus* (araña).

4.4. RESULTS OF SAMPLING AND MEASUREMENTS

This section summarizes the field measurements and laboratory analyses of the samples that were collected during the mission. A complete set of measurement data is provided in Appendix I.

4.4.1. Field measurements

4.4.1.1. Reggane

At the site of the Gerboise Bleue test, dose rate measurements were made by the IAEA team from the ground zero point along two transections roughly perpendicular to one another. One transection was in the northwesterly direction, and the measured dose rates varied from 2.7 μSv/h near the ground zero point to about 0.1 μSv/h (background) at a distance of about 500 m from ground zero. The other transection was in the northeasterly direction, and the dose rates varied from around 1.5 μSv/h near the ground zero point to about 0.1 μSv/h (background) at a distance of 700 m from ground zero. Figure 18 shows the locations and values of the measurements relative to the original isodose contours produced by the French authorities. Figure 19 shows a three dimensional plot of the values, which can be seen to decrease approximately exponentially with increasing distance from

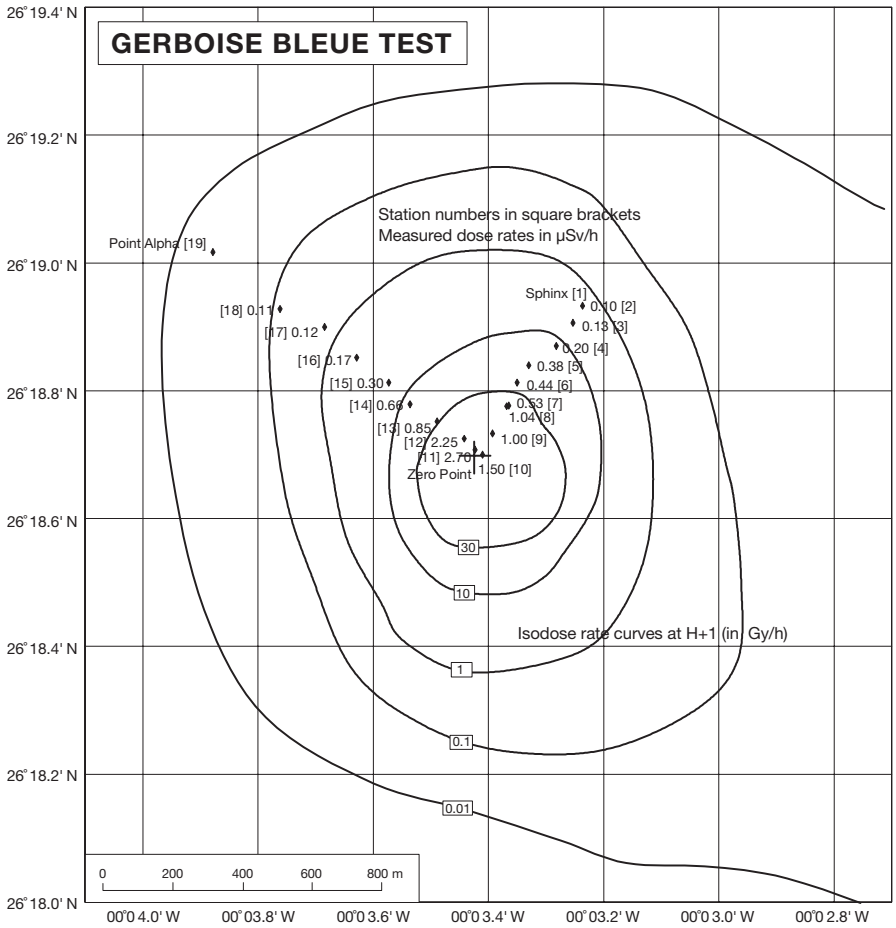

FIG. 18. Dose rate data obtained during the IAEA field mission to the Reggane test site near ground zero of the Gerboise Bleue test, compared with H + *1 values (see also Fig. 5).*

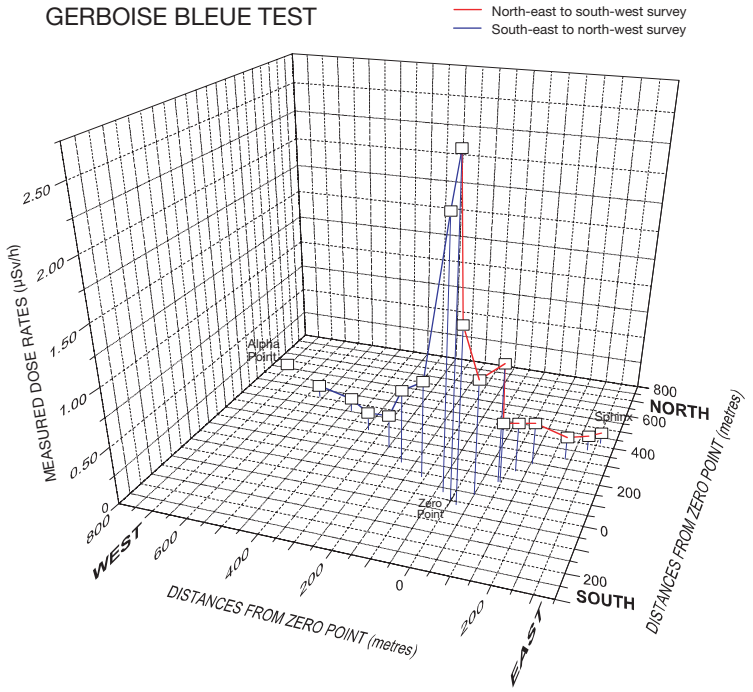

FIG. 19. Dose rate data obtained during the IAEA field mission to the Reggane test site near ground zero of the Gerboise Bleue test, showing a rapid decrease to background levels at distances of about 500 m.

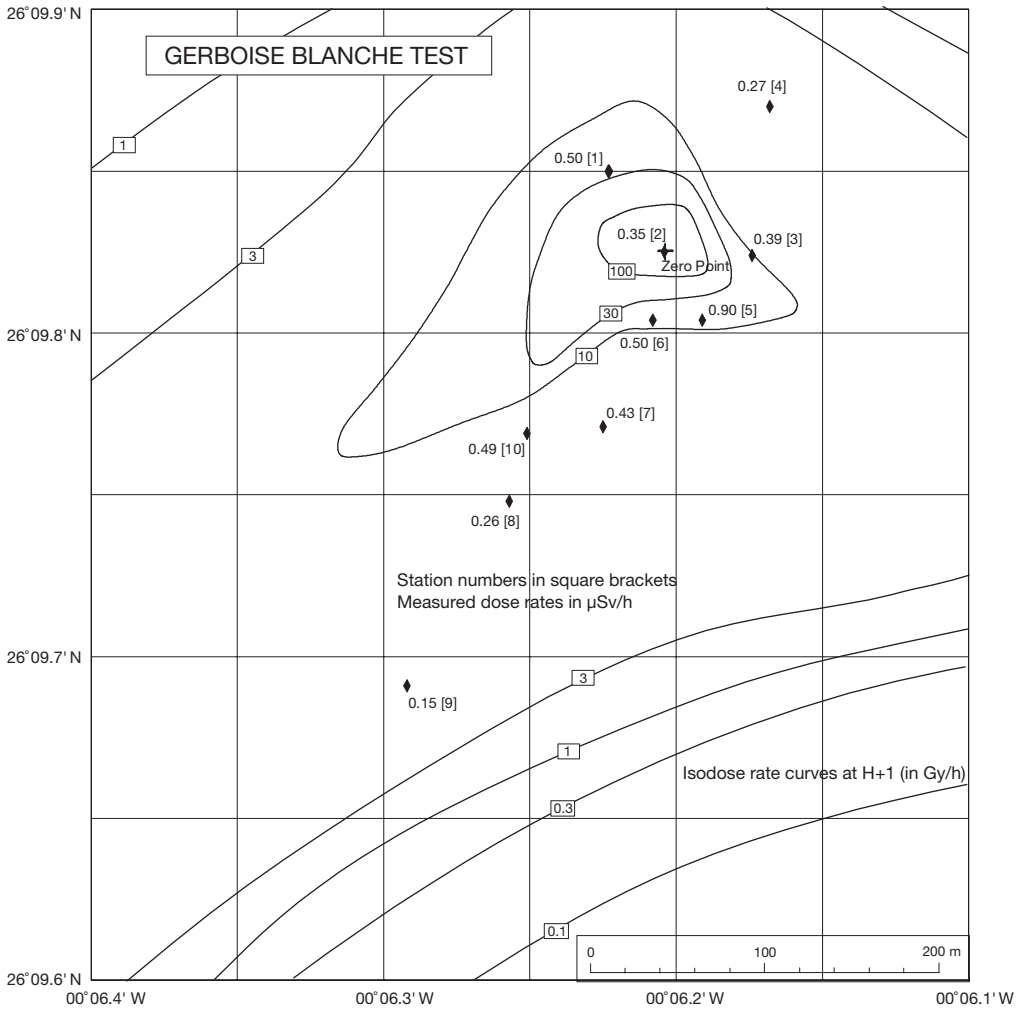

FIG. 20. Dose rate data obtained during the IAEA field mission to the Reggane test site near ground zero of the Gerboise Blanche test, compared with H + *1 values (see also Fig. 6).*

ground zero and which reach close to background levels at 500 to 600 m from the ground zero point.

At the site of the Gerboise Blanche test, dose rate measurements were made by the IAEA team along a north-east to south-west transection that crossed near the ground zero point. Dose rates varied from about 0.15 µSv/h at 300 m (south-westerly direction) to about 0.35 µSv/h near the ground zero point and decreased to about 0.27 µSv/h at a distance of about 100 m (north-easterly direction). Figure 20 shows these data plotted over the original isodose contours developed by the French authorities following the test.

At the site of the Gerboise Rouge test, the IAEA team performed dose rate measurements along two perpendicular transections, one running north to south and a second running east to west. Dose rates varied from about 0.06 µSv/h at 400 m (easterly direction) to about 0.2–0.35 µSv/h near the ground zero point, decreased to about 0.04 µSv/h at a distance of about 400 m (westerly direction). The measurements along the north–south transection varied similarly. Figure 21 shows the collected data overlaid on the original isodose contours developed by the French authorities, while Fig. 22 shows a three dimensional representation of these data.

At the site of the Gerboise Verte test, the IAEA team made dose rate measurements along a single transection running from north-east to south-west and passing near the ground zero point; a few additional measurements were made in the near vicinity. Dose rates varied from about 0.01 µSv/h at about 400 m (southwesterly direction) to about 0.2 µSv/h near the ground zero point and decreased to about 0.14 µSv/h at a distance of about 200 m (northeasterly direction). Figure 23 shows these

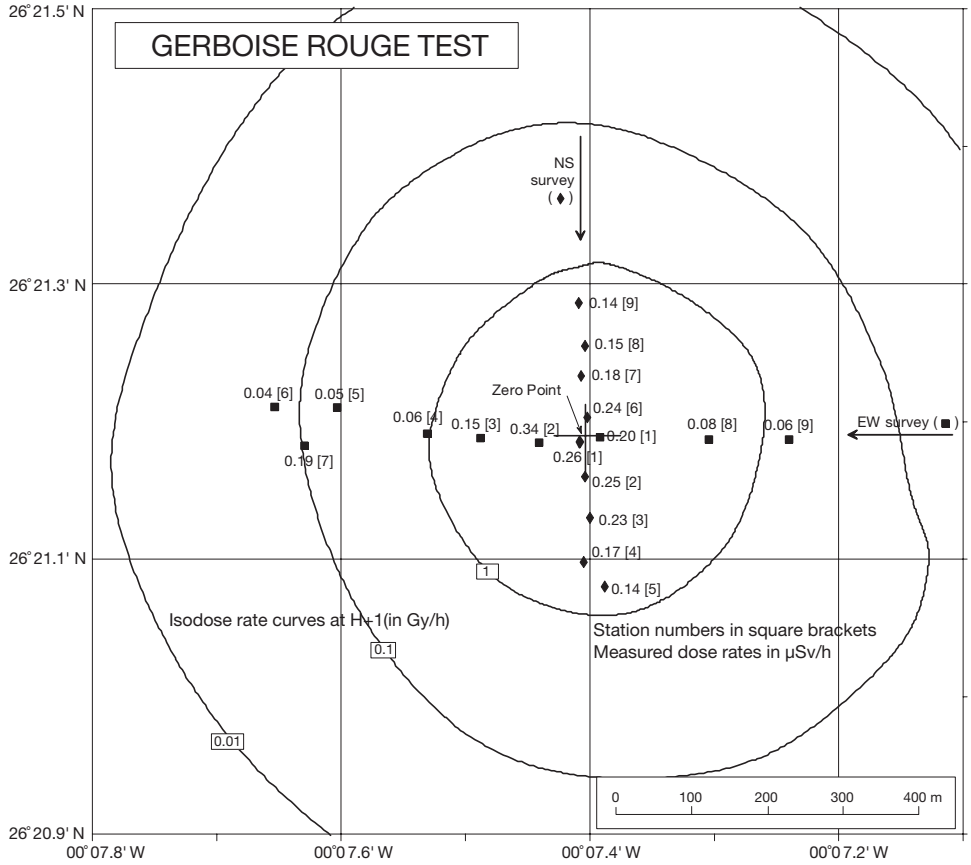

FIG. 21. Dose rate data obtained during the IAEA field mission to the Reggane test site near ground zero of the Gerboise Rouge test, compared with H + *1 values (see also Fig. 7).*

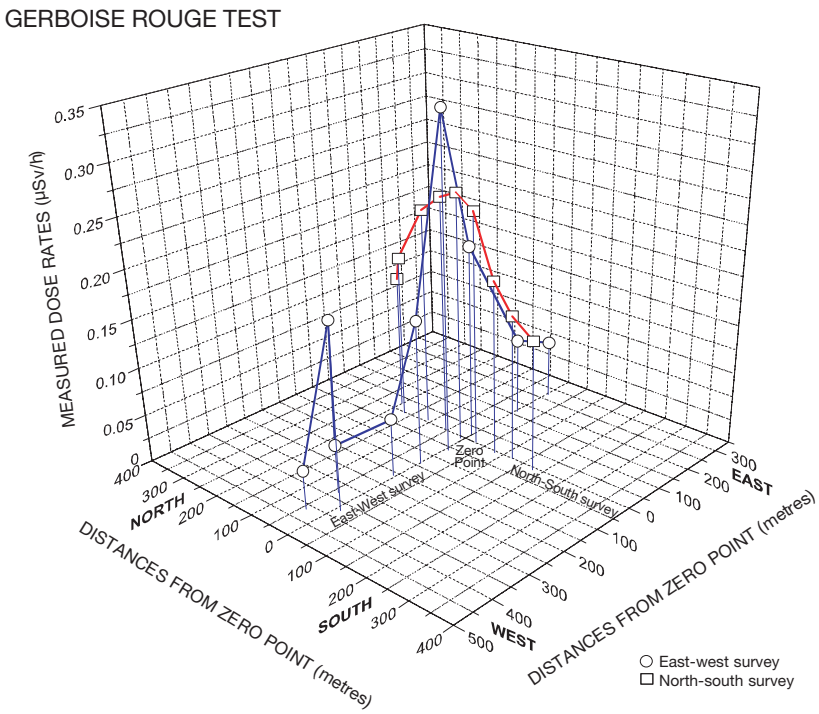

FIG. 22. Dose rate data obtained during the IAEA field mission to the Reggane test site near ground zero of the Gerboise Rouge test, showing a rapid decrease to background at distances of about 400 m.

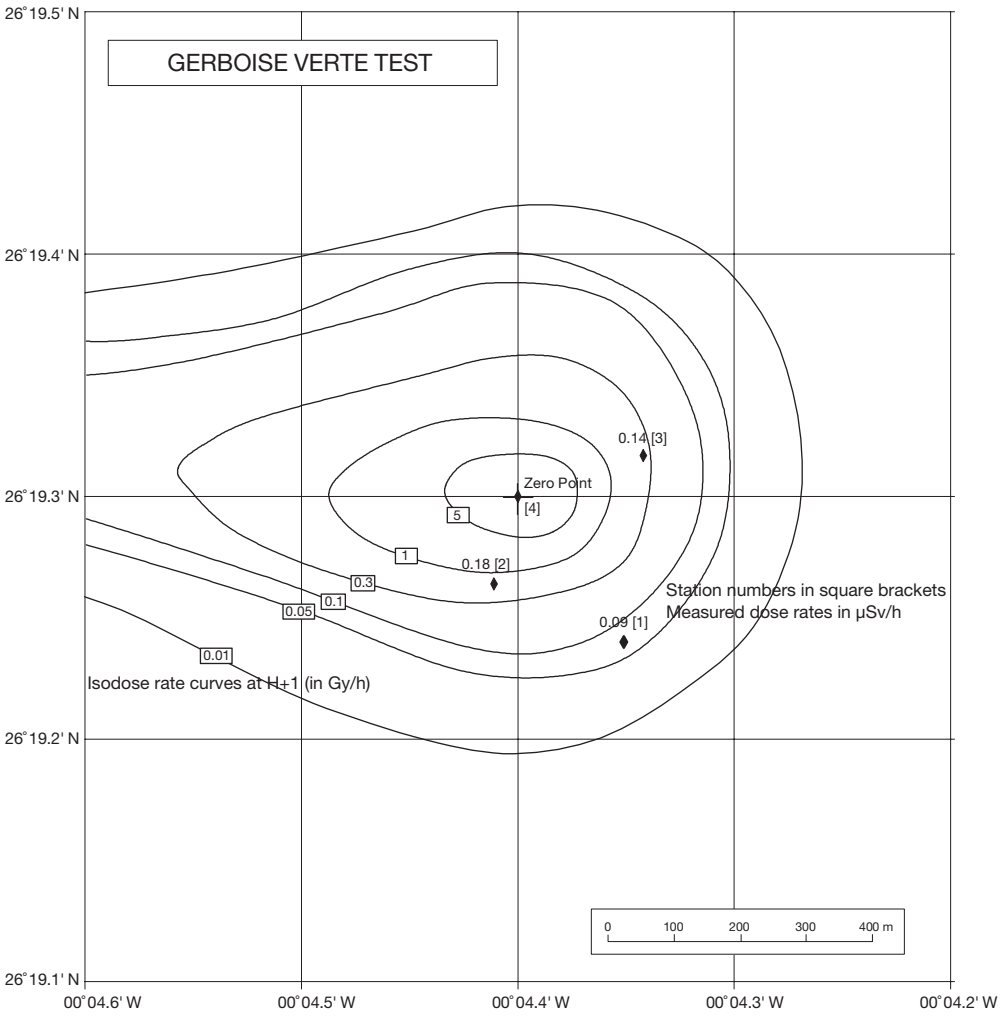

FIG. 23. Dose rate data obtained during the IAEA field mission to the Reggane test site near ground zero of the Gerboise Verte test, compared with H + *1 values (see also Fig. 8).*

data plotted over the original isodose contours developed by the French authorities following the test.

4.4.1.2. In Ekker — Taourirt Tan Afella

The dose rates in the vicinity of the Taourirt Tan Afella mountain varied widely, primarily as a function of proximity to the solidified lava in front of the E2 tunnel. Outside the original fence built by the French authorities, the most distant point of which is about 800 m from the E2 tunnel opening, the dose rates were about 0.1–0.2 µSv/h above background. Inside the fence, and progressing up the sloped hillside towards the E2 tunnel, dose rates rose two- to fourfold, to as high as 0.45 µSv/h and 0.7 µSv/h at some locations. Directly in front of the E2 tunnel opening and on top of the solidified lava, dose rates were measured at up to 200 µSv/h. Figure 24 shows a topographical map of the Taourirt Tan Afella mountain (Béryl test zone), giving the isodose rates extrapolated to 1999 and the dose rates measured by the IAEA team.

The maximum external exposure rate measured near the entrance to the E3 gallery was about 0.32 µSv/h, and the exposure rates were elevated above background (about 0.1 µSv/h) out to a distance of a few hundred metres.

4.4.1.3. In Ekker — Adrar Tikertine

The dose rates in the vicinity of Adrar Tikertine were at background levels. The collected gamma spectra nominally showed the presence of ^{241}Am (a product of ingrowth from ^{241}Pu), indicating that ^{239}Pu should also be present, though these spectra could not be evaluated quantitatively, nor was the detector of a type that optimized the

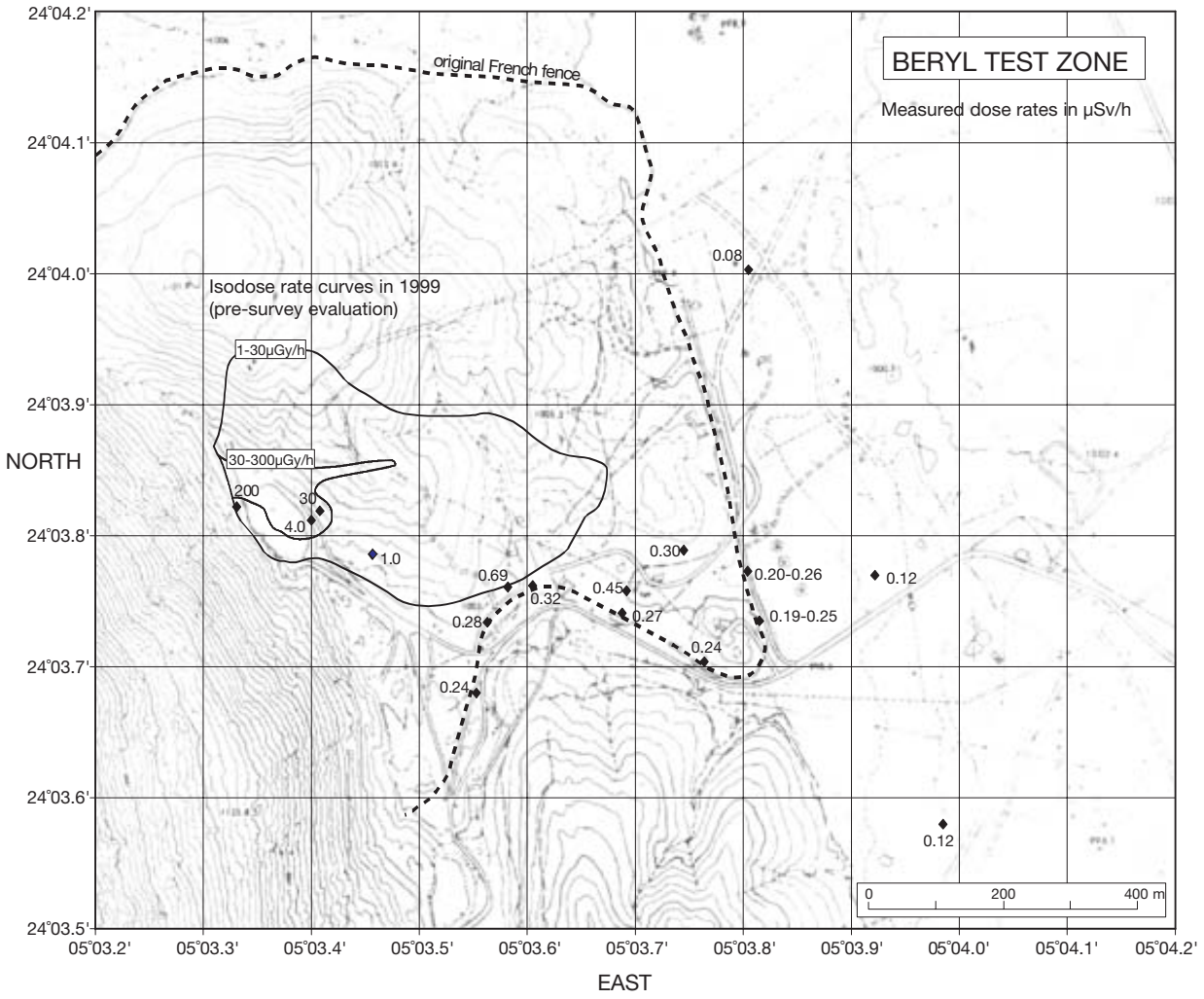

FIG. 24. Topographic map of the Béryl test zone (Taourirt Tan Afella mountain), showing the measured dose rate values and sampling locations.

detection efficiency of the low energy (60 keV) gamma emissions. Figure 25 shows the survey locations.

4.4.2. Laboratory measurements

The samples collected and the coordinates of the collection points are reported in Tables 11–14 in Appendix I. Selected samples were analysed by high resolution gamma spectrometry and by alpha and beta spectrometry after radiochemical separations at the IAEA's Laboratories in Seibersdorf. The concentrations of the following radionuclides have been determined: ^{133}Ba, ^{60}Co, ^{137}Cs, ^{152}Eu, ^{154}Eu, ^{155}Eu, ^{40}K, ^{228}Ra, ^{228}Th (gamma emitters); ^{90}Sr (beta emitter); and ^{238}Pu, $^{239+240}$Pu (alpha emitters). Americium-241 and ^{239}Pu were also determined by high resolution gamma spectrometry. The samples analysed consisted of sand, black fragments of fused sand, lava and water from a water well. In some sand samples, the fraction composed of particles with diameters of <50 µm was isolated by sieving, and the concentration of the gamma emitting radionuclides was measured by high resolution gamma spectrometry. One sample consisting of black fused sand (from the Gerboise Blanche test at Reggane) and one sample consisting of lava (collected in front of the E2 tunnel in Taourirt Tan Afella) were also subjected to a preliminary leaching experiment. The vegetation samples, two well water samples and air filters remain with COMENA in Algeria and have not yet been analysed.

The results of all the analyses performed and a description of the procedures used in the

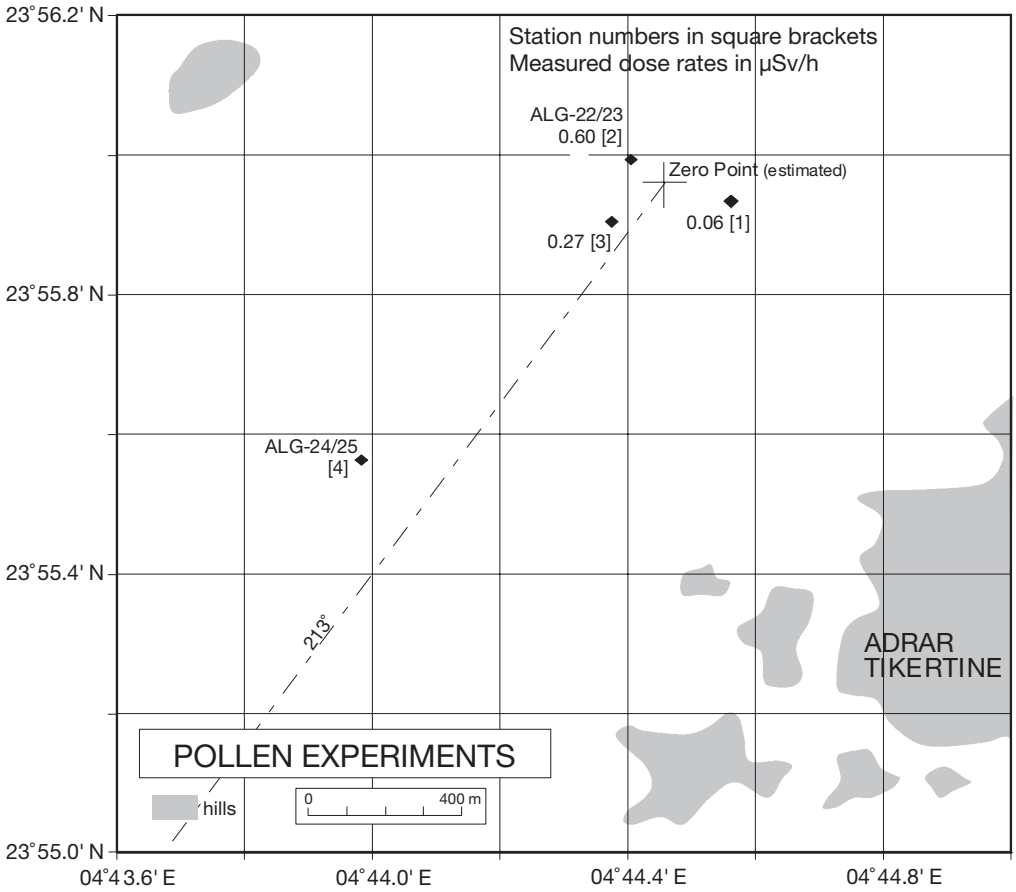

FIG. 25. Dose rate data obtained during the IAEA field mission to the Pollen experiment test area.

laboratory measurements are given in detail in Appendix I.

4.4.3. Major conclusions based on the laboratory measurements

The number of samples collected and analysed is somewhat small when viewed against the size of the sites visited during the field mission. This low ratio of number of samples to total area, particularly for Adrar Tikertine, restricts the general validity of conclusions that can be drawn by extrapolating the laboratory measurements to the entire areas potentially affected by the nuclear tests. Keeping this limitation in mind, the following conclusions can be drawn.

4.4.3.1. Samples from Reggane

All sites in Reggane are contaminated. Gerboise Blanche and Gerboise Bleue are locally highly contaminated, with most of the contamination residing in the black, vitreous and porous material (sand melted at the time of the explosion and then solidified, see Fig. 26). The unvitrified sand is much less active (100–1000 times less). A typical sample, such as ALG-3 (sand with many black fragments of fused sand), had the following activity concentrations:

FIG. 26. Black fragments of fused sand.

$^{239+240}$Pu = 1.2×10^6 Bq/kg;
^{137}Cs = 2.9×10^4 Bq/kg;
^{90}Sr = 1.8×10^5 Bq/kg.

The activity concentrations of the anthropogenic radionuclides in the sand fraction containing particles with a diameter of <50 μm were in general equal to or less than the level of detection (a few tens of becquerels per kilogram). The only measurable radionuclides were ^{137}Cs and the natural isotopes ^{40}K, ^{228}Ra and ^{228}Th. The activity concentration of ^{137}Cs was about 200 Bq/kg. The activity concentrations of ^{40}K, ^{228}Ra and ^{228}Th were about 300 Bq/kg. These data indicate that the activity concentrations of the radionuclides generated by the nuclear tests in the sand fraction that can be transported some distance (<50 μm) and that is respirable (<10 μm) should be negligible.

One sample consisting of 5 g of black fused sand (from sample ALG-3 of the Gerboise Blanche site at Reggane) was also leached by water at 40°C. After washing of the sample with distilled water to remove particles and dust, the activity concentrations of ^{137}Cs, ^{90}Sr, ^{241}Am and $^{239+240}$Pu in the leachate were measured after a leaching period of 30 days. The radionuclides in the leachate were always below or at the minimum detectable activity, i.e. less than approximately 1 Bq/L for ^{137}Cs, less than approximately 3×10^{-2} Bq/L for ^{90}Sr, less than approximately 1×10^{-3} Bq/L for ^{241}Am and less than approximately 2×10^{-2} Bq/L for $^{239+240}$Pu. The low radionuclide activity in the leachates generally indicates that the radionuclides are immobilized in the matrix of the vitreous fused sand. However, further and more representative experiments should be conducted before confirming this conclusion.

4.4.3.2. Samples from In Ekker — Taourirt Tan Afella

The Taourirt Tan Afella location is where several tunnel tests were conducted. The only location from which samples were taken was the area in front of the E2 tunnel where the partially confined test occurred (with ejection of radioactive lava) and its proximity. The activity concentrations of the more volatile radionuclides (caesium and strontium) were greater in the lava than in the vitrified sand at the atmospheric test site, though the concentration of plutonium was somewhat less. Activity concentrations in a typical lava sample (e.g. ALG-11) were:

$^{239+240}$Pu = 4.2×10^4 Bq/kg;
^{137}Cs = 2.1×10^6 Bq/kg;
^{90}Sr = 1.1×10^6 Bq/kg.

One sample (ALG-8, consisting of 148 g of ejected radioactive lava taken from the area in front of the E2 tunnel) was also leached following the procedure mentioned previously. Also in this case, 30 days of leaching resulted in concentrations of the radionuclides in the leachate below or at the minimum detectable activity.

The activity in the water taken from a well located about 6 km away from the E2 tunnel (sample ALG-21) was negligible, i.e.:

^{137}Cs < level of detection (7.5×10^{-2} Bq/kg);
^{90}Sr < level of detection (2×10^{-2} Bq/kg).

The soil and sand in the dry stream beds coming from the radioactive lava (ALG-18) had the following activity concentrations:

$^{239+240}$Pu = 50 Bq/kg;
^{137}Cs = 3.5×10^3 Bq/kg;
^{90}Sr = 1.2×10^4 Bq/kg.

4.4.3.3. Samples from In Ekker — Adrar Tikertine

The activity concentrations of $^{239+240}$Pu, ^{137}Cs and ^{90}Sr in the coarse sand samples from Adrar Tikertine were low. They fell in the range between 2 and 15 Bq/kg, i.e. at the lower level of detection. The activity concentrations of plutonium in the sand fraction containing particles with a diameter of <50 μm were also equal to or less than the level of detection. The activity concentrations of ^{137}Cs were somewhat higher (about 23–28 Bq/kg) but still relatively close to the level of detection (about 12–23 Bq/kg); however, sieving was conducted on only three sand samples. This limited analysis gave no indication that significant quantities of $^{239+240}$Pu (or other anthropogenic radionuclides) released during the Pollen tests should be present in the sand fraction (<50 μm) and respirable. The Pollen experiments would have been expected to disperse some active particles ('hot particles') in the area, with the larger and heavier ones settling closest to the site of dispersion in the area of the bitumen overlay. Small particles in the respirable range have probably been widely dispersed in the intervening years by the wind.

5. ESTIMATES OF PRESENT AND FUTURE DOSES TO PERSONS ARISING FROM RESIDUAL RADIOACTIVE MATERIAL AT THE SITES

5.1. GENERAL METHODOLOGY FOR CALCULATING DOSES

Generally, people may receive radiation doses in several ways. Radionuclides emitting penetrating radiations, most commonly gamma radiation, can give rise to a radiation dose even while they remain outside the body (external dose). However, radionuclides in the air, in foods or on the ground may also be taken into the body by inhalation or ingestion, or through cuts and wounds. Once radionuclides are within the body, emitted radiation is absorbed by the cells of organs where the radionuclides are stored and those of neighboring organs, resulting in a dose (internal dose).

Assessing possible and likely future doses is a three stage process. The first stage is to gather information about the environment, specifically the concentrations of radionuclides in environmental materials. For external doses, either the concentrations in soil or water or direct dose rate measurements in air are needed. For internal doses, it is necessary to know the concentrations in foods or aerosols that may be taken into the body. Environmental conditions at the nuclear test sites have been discussed in the previous sections of this report. The second stage of the process is to combine concentrations with exposure scenarios, including lifestyle factors and dietary information, to obtain the total likely intake of activity. For external doses, information on the amount of time spent in different radiation fields is needed, while for internal exposures, information on the amount of food eaten or air breathed is required. The final stage is to use standard coefficients which either relate concentrations in soil to external dose rates, or which convert a unit of intake into internal dose. These coefficients are estimated using mathematical models of radionuclide behaviour and radiation absorption in the body. Internationally agreed values of the committed effective dose per unit activity intake for a large number of radionuclides have been derived by the International Commission on Radiological Protection (ICRP) [2] and are published in the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (BSS) [3]. These values have been used in the assessments carried out in the framework of the survey of the test sites in Reggane and In Ekker.

5.2. SOURCES AND PATHWAYS OF EXPOSURE

Southern Algeria is in the Saharan zone. The region includes towns and villages with cultivation activities, though there is no soil cultivation or plant production in the immediate area of the test sites. It is an area of transit used by travellers, nomads and transporters.

5.2.1. Atmospheric test site at Reggane

At the present time, as was also the case when the tests were run, the area of Reggane is an entirely arid desert. For the purposes of dose estimation, and taking account of possible open access in future years, a scenario was assumed in which a person might stay in the test area, for example through overnight camping or other short term stay, for a period amounting to three days per year. This assumption excludes any future activity which could imply greater occupation of the area by people. If this assumption is not valid, a more detailed and comprehensive radiological assessment of the sites may be required.

The principal exposure pathways from residual radionuclides from the atmospheric tests to occasional transient visitors are:

- External exposure from radionuclides on the ground;
- Inhalation of resuspended material;
- Ingestion of soil adhering to hands and deposited on foodstuffs, particularly in windy conditions.

The town of Reggane is the closest inhabited location and is some 50 km distant from the nuclear test site. The doses that might arise to Reggane residents through dust transport have also been estimated.

5.2.2. Underground test site at In Ekker — Taourirt Tan Afella

The immediate area surrounding the Taourirt Tan Afella mountain is nominally restricted, particularly the area adjoining the entrance to the E2 tunnel, which was fenced off in 1965, although intermittent grazing by animals such as camels, goats and donkeys occurs throughout the region. Vegetation is very sparse. Runoff water from the area seeps into underground aquifers used for both stock water and, in In Ekker some 5 km distant, for drinking water. There is evidence of scavenging of materials such as iron rails within the fence surrounding the E2 tunnel lava flow area. For the purposes of dose assessment, it is assumed that nomadic camel and goat herders spend ten days per year in the immediate vicinity of the site outside the original fence, and that some persons and animals occasionally venture inside the fence in the vicinity of the E2 tunnel entrance.

The principal exposure pathways from residual radionuclides from the tests are:

— External radiation, particularly in the vicinity of ejected lava;
— Inhalation of dust;
— Ingestion of dust;
— Ingestion of water containing leached material;
— Ingestion of products (primarily milk and meat) from livestock that intermittently graze in the area.

5.2.3. Adrar Tikertine experimentation site

The Pollen experiments caused dispersion of plutonium in fine particulate form over a wide area in a southwesterly direction from the tower position of the Adrar Tikertine experimentation site. Vegetation in the area is extremely sparse but is grazed intermittently by stock herded by nomadic owners as at In Ekker. It is assumed that herders might be in the area for the equivalent of three days per year. The original surface soil deposition of fine particulates has been disturbed by both wind and water transport of surface material. The areal deposition of ^{241}Am accompanying the plutonium is not sufficiently high to give rise to a significant increase in the terrestrial gamma ray background in the area. The principal exposure pathways are therefore inhalation and ingestion of contaminated dust.

Another potential route of exposure is incorporation of radioactive particles in cuts and wounds. This may occur when wounds become contaminated with dust and soil, or if larger radioactive particles are retained at wound sites. The significance of this pathway will depend upon several factors, particularly the prevalence and the activity and physical size distributions of active particles, their physico-chemical form, the length of occupancy of the area, the frequency of incidents leading to cuts and wounds, and the treatment applied to wounds. Conclusions drawn from other studies [4, 5] are that exposure from contaminated wounds is likely to be very small compared with that from ingestion, and that the probability of long term incorporation of a very active particle is sufficiently low to not require further consideration.

5.3. RADIATION DOSES DUE TO RESIDUES FROM NUCLEAR TESTING

The radiation doses that might arise to adult persons present for short periods at the Reggane desert site, itinerant or resident in the In Ekker region, or itinerant in the Adrar Tikertine area, have been estimated from the radiological data presented in Section 4. Figure 27 shows dose rate measurements being made. The details of the calculations are given in Appendix II. Doses arising from each of the exposure pathways identified above, and for all significantly contributing radionuclides, have been estimated.

FIG. 27. Dose rate measurements being made at the Reggane test site.

TABLE 9. DOSES FOR A THREE DAY TRANSIENT OCCUPATION PERIOD AT THE REGGANE TEST SITE

Source	Nuclide	Maximum probable dose (μSv)	Upper bound dose (μSv)
External radiation		<2[a]	12
Inhalation of dust	All	<1	<1
Ingestion of dust	^{90}Sr		6
	^{137}Cs		1.2
	$^{239+240}$Pu		32
	^{241}Am		36
	All	<9	75
Total		<10	87

[a] Assumes occupation in the vicinity of the ground zero points but excludes the exceptional situation of full time occupancy at Gerboise Bleue ground zero. This would lead to a dose of about 120 μSv over three days.

5.3.1. Reggane atmospheric test site

At the site where the atmospheric tests were performed, the areas that have elevated external dose rates are only a very small part of the tracts surveyed and are confined to distances of a few hundred metres from the four individual ground zero points. Therefore, for occasional visitors to the site, exposures to external radiation from residual radionuclides from the tests are likely to be low. In terms of temporary occupancy, the location where an individual might be within the test site will also strongly influence possible doses that might be incurred from inhalation or ingestion of dust that is blown by the wind. Doses for both the most probable occupation time at the test site and for upper bounds of exposure for the assumed total days of occupancy are shown in Table 9. Probable doses are less than one tenth of the upper bound values.

Activation products, principally ^{60}Co in steel fragments in the immediate vicinity of the ground zero points, are still detectable, but the external exposure rates from such material are currently too low to constitute a radiological risk, even if some pieces are removed from the sites. Exposure rates from fragments containing ^{60}Co will decrease by half approximately every five years.

Most of the residual plutonium activity near the ground zero points is incorporated in the fused sand. This material has activity concentrations of up to about 1 MBq per kilogram of sand for plutonium and up to 0.1 MBq per kilogram of sand for ^{137}Cs. Individual pieces of this sand, if removed from the site, would not give rise to an external radiation hazard. They could only give rise to an inhalation radiological risk if the removed material were ground into respirable dust without respiratory protection.

To complete the assessment of the Reggane test site, possible doses to the inhabitants of the village of Reggane arising from inhalation and ingestion of wind-borne dust transported from the site have been estimated. Because of the highly conservative assumptions in the dose calculations, the present doses are likely to be much less than 1 μSv/a.

5.3.2. In Ekker — Taourirt Tan Afella underground test site

Over a small area at the Taourirt Tan Afella E3 tunnel site, and outside the original fence which was constructed in the 1960s at the E2 site, dose rates range up to about 240 nGy/h above background. The upper bound to the effective dose above background (about 80 nGy/h) from external radiation received by a nomadic herder remaining outside the original fence for ten days would then be about 40 μSv/a. This assumes a factor of 0.7 to relate dose to air to effective dose for 0.66 MeV radiation.

The exposure scenario of persons deliberately scavenging or exploring on or in the immediate vicinity of the lava flows from the E2 tunnel is the one which leads to the highest doses estimated for the former French nuclear test sites. If a person spent one day (eight hours) in an area immediately adjacent to or on the lava masses where the dose rates averaged 100 μGy/h, the effective doses received from such an exposure scenario would be about 0.5 mSv. Because the present external dose

rate is dominated by ^{137}Cs, possible doses will decline over time according to the half-life of ^{137}Cs, decreasing by one half every 30 years.

Measured soil concentrations of plutonium are very much lower than at the Reggane site, and for similar occupancy scenarios, inhalation doses are expected to be negligible (<1 μSv/a).

Ingestion of soil on foodstuffs handled in dusty conditions might contribute small doses to nomadic people in the area. As noted, measured surface soil activities of plutonium are very much lower than the peak levels at the Reggane test site, and ^{137}Cs and ^{90}Sr concentrations are comparable to the mean values in the areas of elevated concentrations. If a daily intake of 10 g is assumed, a value which may be extreme for this location, then for the equivalent of ten days spent in the area, annual doses (committed effective doses) of about 10 μSv are estimated. Concentrations of radionuclides in well water are below detection limits. The measured soil concentrations in the dry watercourse soils are sufficiently low to preclude the possibility of significant concentrations arising in downstream wells in future years.

The vegetation is sufficiently sparse for animals led to graze by nomadic herders to be almost constantly on the move, with at most a few days in one area. Livestock movements are also dictated by distances to available water sources, and animals would not normally be able to stay in the E2–E3 area for more than a day or two. Grazing animals could ingest residual radionuclides incorporated in plants through root uptake or deposited on plants as dust. Visual inspection suggested that deposited dust would dominate intakes and the concentrations in the dust would reflect the surrounding surface soil concentrations. Radionuclides ingested by grazing animals and transferred to meat or milk could contribute to radiation exposures of herders and their families. However, doses arising from this pathway are small. For the particular case of infants whose diet includes milk from animals that had been grazing in the area for a full ten day period, the upper bound doses are about 12 μSv.

Table 10 summarizes estimates of annual upper bound doses to nomadic herders who are grazing animals in the vicinity of the E2 and E3 tunnels.

5.3.3. Adrar Tikertine experimentation site

The concentrations originally estimated for the Adrar Tikertine site appear to have been substantially reduced by wind and water transport. However, even if the historically estimated concentrations were applicable, doses arising from ingestion and inhalation of dust would be about two orders of magnitude lower than those derived for the Reggane desert, so that for both intake routes, doses of less than 1 μSv/a are estimated.

TABLE 10. DOSES TO NOMADIC HERDERS IN THE VICINITY OF THE E2 AND E3 TUNNELS

Source	Upper bound effective dose (μSv/a)
External radiation	40[a]
Inhalation of dust	<1
Ingestion of dust	10
Ingestion of well water	<1
Consumption of products from grazed animals	<2[b]
All	50

[a] Excludes situation of scavengers working in the immediate vicinity of the lava.

[b] Infants drinking milk from grazing livestock might receive doses of a few microsieverts per year.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. GENERAL DISCUSSION

This report describes the findings of an expert mission to Algeria and follow-up activities whose purposes were to collect preliminary radiological data about the former French nuclear test sites, to collect a limited number of environmental samples for radiological analysis and to make a preliminary evaluation of the current radiological conditions. This assessment was intended to provide guidance on the need for a more detailed radiological monitoring and assessment programme.

Nevertheless it is considered that the assessment has allowed an adequate evaluation of the radiological situation to be made, in spite of the relatively limited sampling and measurements performed. However, the supporting measurement database could be broadened and enhanced if further samples were collected and analysed.

It was found that most of the areas at the test sites have little residual activity, but that there are two exceptions to this. The two sites that have high residual activity are:

- The Reggane test site at the ground zero localities of the Gerboise Blanche and Gerboise Bleue atmospheric tests;
- Taourirt Tan Afella in the vicinity of the E2 tunnel, where highly radioactive lava was ejected during an underground test.

Two additional areas had lower residual activity: at Taourirt Tan Afella in the vicinity of the E3 tunnel and at the Adrar Tikertine site where the Pollen tests were conducted.

All measurements led to doses which, on the basis of the assumed scenarios, were not in excess of safety standards, so that further sampling was generally not viewed as necessary. Despite the robustness of the present conclusions, it is recognized that all findings were developed from what would normally be considered a limited and minimal level of sampling. If the objectives of future monitoring were other than to establish compliance with safety standards, for example to document environmental concentrations, carry out a radioecological study, or assess inventory or special patterns, then the measurement data provided here would be inadequate and would require supplementation.

Considering the assumed exposure scenarios and pathways, the sites do not give rise to radiation doses that approach the generic reference level of 10 mSv/a above which intervention might be indicated. However, it is worth noting that the lifestyles of nomadic people that might visit this area are not thoroughly documented, and hence the estimates of likely dose, as opposed to the upper bound dose, are highly uncertain and should be interpreted with these caveats in mind.

This assessment finds that environmental remediation of any of the test areas is not required in order to reduce doses below established safety standards, and possible exposures can be controlled as in the case of Taourirt Tan Afella. However, future decisions by the Algerian authorities to conduct remediation or to further limit public access might be made if economic conditions change in the area and a more permanent presence of people is indicated.

6.2. SPECIFIC CONCLUSIONS

6.2.1. Reggane

Probable doses to visitors to the remote desert test site area at Reggane are estimated to be less than a few microsieverts per day. Residual steel fragments and fused sand, if removed from the site, do not present any significant radiological risk. However, if fused sand were ground to respirable dust and people were exposed without respiratory protection, this could present an inhalation hazard.

Calculated doses to residents of the town of Reggane from the airborne transport of dust from the test areas are predicted to be very low, much less than 1 μSv/a.

6.2.2. Taourirt Tan Afella

Nomadic camel and goat herders grazing their livestock on the sparse vegetation in the area of the E2 and E3 galleries might receive small doses, principally from external radiation, of less than an estimated 50 μSv/a. Persons scavenging metals in the immediate vicinity of the lava from the E2 tunnel might receive doses of up to about 0.5 mSv in 8 hours. Current external exposure rates are less than one tenth those existing in 1966. These potential doses are now decreasing annually due to

the decay of ^{137}Cs (currently at concentrations up to 2 MBq/kg). The assumed exposure scenarios and current doses arising are below the generic intervention criterion of 10 mSv/a. The alpha activity concentration in the lava is in the range between 0.04 and 0.4 MBq/kg, which is roughly similar to that of natural rock with a 0.2% uranium content, and below that of an ore body that would be commercially mined for uranium ore.

6.2.3. Adrar Tikertine

The concentration of plutonium was determined in a small number of sand samples that were not sufficient to be representative of the area and therefore could not be used for a detailed or precise evaluation of the inventory or special distribution of activity in the Adrar Tikertine area. Nevertheless, the activity concentration of anthropogenic radionuclides in those samples that were measured was generally below laboratory detection limits. Thus it is expected that the residual surface contamination from the plutonium dispersion experiments is unlikely to give rise to doses to nomadic herders or their families exceeding 1 μSv/a.

6.3. RECOMMENDATIONS

(a) The integrity of the fence constructed in the 1960s at Taourirt Tan Afella, now being restored by the Algerian local authorities, should be maintained to avoid exposures arising from human and animal intrusion in the region around the E2 tunnel entrance or through removal of samples of lava from the site.

(b) The upper bound evaluation of the radiological conditions assessed in this preliminary study is considered robust, and further extended sampling for radiological assessment is not considered to be necessary. Corroboration of the predicted low inhalation doses arising from the Reggane site could be readily achievable through an appropriate air sampling programme, and it is recommended that this be carried out.

(c) Similarly, corroboration of the finding that there is no dose impact to the local herders in the In Ekker area should be obtained by an appropriate environmental monitoring programme. In particular, water from wells adjacent to the Tan Afella test site could be analysed.

(d) Better descriptions of the lifestyles of the people that frequent these areas would add credibility to these findings. Such descriptions should be developed primarily by Algerian experts who are specialists in the appropriate fields but could be supplemented with assistance by IAEA experts familiar with dose assessment methodologies.

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Appendix I

DETERMINATION OF ^{90}Sr, ^{241}Am, Pu AND GAMMA EMITTING RADIONUCLIDES IN THE SAMPLES COLLECTED IN ALGERIA

All radioanalytical measurements and related experimental procedures were conducted at the IAEA's Laboratories in Seibersdorf, Austria.

I.1. RADIOISOTOPES ANALYSED

The beta emitting radionuclide ^{90}Sr, the alpha emitting ^{241}Am and Pu isotopes, and the gamma emitting radionuclides (^{241}Am, ^{239}Pu, ^{133}Ba, ^{60}Co, ^{137}Cs, ^{152}Eu, ^{154}Eu, ^{155}Eu, ^{40}K, ^{228}Ra, ^{228}Th) were analysed in selected solid and water samples. The results of the radiochemical analyses (beta and alpha emitters) and of the gamma spectrometry (gamma emitters) are shown in Tables 11 and 12, respectively.

I.2. SAMPLE DESCRIPTION

All samples collected and their codes are reported in Tables 13–16. The tables indicate those samples that were analysed for ^{90}Sr, ^{241}Am, Pu isotopes and the gamma emitters, and those that were analysed only for the gamma emitters. Different types of sample were analysed: coarse sand, fine sand (<50 μm), mixtures of sand and black vitreous fragments of fused sand, black vitreous fragments of fused sand, and lava. In addition, water samples from a well and from a leaching experiment on two solid samples were analysed.

I.3. GENERAL PROCEDURE

The general procedure carried out for the analysis was the following:

(1) The external gamma doses from the samples were measured by the laboratory's radiation protection personnel.
(2) A preliminary screening by gamma spectrometry was carried out on all samples to provide the approximate activity levels needed for the selection of samples for follow-up analysis. For this screening step, the entire amount of each sample was used 'as received', without any processing.
(3) A number of samples were selected for the radioanalytical determination of actinides (Pu isotopes and ^{241}Am) and ^{90}Sr by destructive radiochemical analysis, and of gamma emitting radionuclides using gamma spectrometry, on the basis of the external radiation dose rates measured at the sampling sites, the preliminary screening of the samples by gamma spectrometry and information provided by the French authorities on the history of the nuclear tests.
(4) The samples were physically homogenized, carefully avoiding cross-contamination.
(5) The activity of Pu, ^{241}Am, and fission and activation products was measured by gamma spectrometry.
(6) The activity of $^{239+240}$Pu, ^{238}Pu, ^{241}Am and ^{90}Sr, after sample dissolution and radiochemical separation, was measured by alpha spectrometry and liquid scintillation counting.
(7) Leaching experiments were conducted on lava and black nodule samples.

I.4. ANALYTICAL PROCEDURES

I.4.1. Gamma spectrometric procedures

For the determination of the activity concentration of gamma emitting radionuclides, two gamma spectrometric systems were used.

The first system consisted of a high efficiency (70%) coaxial HPGe gamma spectrometer, housed in a low background Pb shield (see Section I.4.10 for details). This system was used for the measurement of the large volume samples that had not undergone any processing and were expected to be heterogeneous. Samples were measured twice to evaluate the reproducibility of the measurements. The samples were placed in standard 240 mL cylindrical polyacrylic containers, and measurements were carried out under conditions where the detector had already been calibrated for photopeak efficiency response as a function of gamma ray energy.

The second system consisted of a well type HPGe gamma spectrometer that was used for

TABLE 11. ACTIVITY CONCENTRATIONS (Bq/kg) OF ALPHA AND BETA EMITTING RADIONUCLIDES

Sample code	N[a]	^{90}Sr	^{241}Am	^{238}Pu	$^{239+240}$Pu
ALG-1 (sand)	3				
Average		4[b]	35	2.0E+02	9.1E+03
Range		—	10–57	60–4.4E+02	4.1E+02–3.4E+04
ALG-1 (black material)	3				
Average		3.2E+05[b]	5.9E+04[c]	6.9E+04	3.2E+06
Range		—	—	2.2E+04–1.2E+05	1.1E+06–5.3E+06
ALG-3	5				
Average		1.8E+05	1.2E+04	2.2E+04	1.2E+06
Range		3.4E+04–7.1E+05	1.5E+03–2.4E+04	1.2E+04–3.2E+04	1.1E+06–1.4E+06
ALG-4	5				
Average		6.1E+04	1.8E+03	5.6E+03	5.4E+04
Range		4.2E+04–1.0E+05	1.3E+03–2.8E+03	2.4E+03–8.4E+03	4.9E+04–5.7E+04
ALG-8	6				
Average		7.8E+05	1.9E+04	2.2E+04	3.3E+05
Range		5.2E+05–1.2E+06	8.0E+03–4.4E+04	1.6E+04–3.7E+04	3.2E+05–3.4E+05
ALG-11	5				
Average		1.1E+06	1.2E+03	3.1E+03	4.2E+04
Range		2.0E+04–1.5E+06	1.0E+02–2.5E+03	2.6E+03–4.0E+03	3.9E+04–4.4E+04
ALG-18	4				
Average		1.2E+04	2.3	9.6	50.4
Range		2.0E+03–3.2E+04	0.4—3.3	3.1—20.2	22.9—85.6
ALG-21	1				
Average		<0.02	<0.002	<0.0002	<0.0003
Range		—	—	—	—
ALG-22	4				
Average		10	7.2	0.5	14
Range		<7—10	0.19—14.3	0.1—0.8	4.8—25
ALG-23	4				
Average		11	0.8	1.5	7.4
Range		<6—19	0.35—1.42	0.1—3.3	4.3—8.8

[a] N: number of subsamples analysed.
[b] Only one measurement of ^{90}Sr was performed.
[c] Only one measurement of ^{241}Am was performed.

TABLE 12. ACTIVITY CONCENTRATIONS (Bq/kg) OF GAMMA EMITTING RADIONUCLIDES

Sample code	N[a]	^{241}Am	^{239}Pu	^{133}Ba	^{60}Co	^{137}Cs	^{152}Eu	^{154}Eu	^{155}Eu	^{40}K	^{228}Ra	^{228}Th
ALG-1	2											
Average		1 110	80 000	407	50	2 880	152	<3.9	81	190	10	12
Range		462–1 754	<25 000–140 000	320–493	45–54	1 807–3 957	120–185	<3.9	33–128	186–194	9–12	10–13
ALG-3	2											
Average		9 000	650 000	4 446	658	29 026	1 210	419	695			<17
Range		8 400–9 500	550 000–740 000	5 800–6 522	619–696	27 563–30 489	1 037–1 382	399–439	639–750			<17
ALG-4	1	2 300	<230 000	3 727	1 029	31 711	7 108	1 261	824			<40
ALG-11	1	1 400	<1 600 000	<1 400	1 050	2 120 000	<1 100	<400	320			
ALG-12	1	13 000	<1 100 000	4 696	3 610	672 989	6 651	1 606	2 956			270
ALG-13	1	3 000	<1 000 000	749	1 707	1 544 390	1 158	315	617			310
ALG-14	1	940	<434 000	268	640	1 030 156	386	101	244			141
ALG-15	1	1 700	<1 870 000	<1 600	1 159	2 521 046	<1 300	<470	226			<366
ALG-18	2											
Average		<22	<39 000	<6	2.8	3 457	<7	<5	28.4	1 140	169.2	166.0
Range		<22	<39 000	<6	2.8	3 457	<7	<5	27.8–28.9	1 140	153.7–184.7	148.5–183.4
ALG-21	1	<0.3	<600	<0.1	<0.072	<0.075	<0.13	<0.1	<0.16	<0.8	<0.27	<0.12
ALG-22	2											
Average		<8	<14 000	<2	<1	2.0	<3	<2	<4	532	16.2	17.1
Range		<8	<14 000	<2	<1	1.37–2.68	<3	<2	<4	507–558	14.0–18.4	16.0–18.4
ALG-23	2											
Average		23.6	<12 000	<1.9	<1.1	4.4	<2.7	<1.9	<4.1	557	26.8	26.6
Range		23.2–24.1	<12 000	<1.9	<1.1	3.43–5.46	<2.7	<1.9	<4.1	557	23.0–30.7	23.9–31.3

[a] N: number of subsamples analysed.

TABLE 13. REGGANE — SAMPLES OF SAND AND BLACK VITREOUS FRAGMENTS OF FUSED SAND

Code	Sample type	Coordinates	Dose rate (nSv/h)	Location, comments
ALG-1[a]	Sand with black fragments of fused sand, 1526 g	26°09'763" N 00°06'255" W	~500	Gerboise Blanche, surface test, <10 kt
ALG-2	Sand with black fragments of fused sand, 1260 g	26°09'804" N 00°06'191" W	~950	Gerboise Blanche, surface test, <10 kt
ALG-3[a]	Sand with black fragments of fused sand, 502 g	26°09'804" N 00°06'208" W	~600	Gerboise Blanche, surface test, <10 kt
ALG-4[a]	Black fragments of fused sand, 468 g	26°18'704" N 00°03'421" W	~4000	Gerboise Bleue, ground zero, 100 m tower test, ~60 kt
ALG-5	Sand, 1574 g	26°18'704" N 00°03'421" W	~4000	Gerboise Bleue, ground zero, 100 m tower test, ~60 kt
ALG-6	Corroded metal, 374 g	26°18'704" N 00°03'421" W	Not known	Gerboise Bleue, 100 m tower test, ~60 kt
ALG-7	Sand, 780 g	26°21'098" N 00°07'405" W	~200	Gerboise Rouge, 50 m tower test, <10 kt

[a] Samples analysed for ^{90}Sr, ^{241}Am, Pu isotopes and gamma emitters.

TABLE 14. TAOURIRT TAN AFELLA — LAVA SAMPLES COLLECTED WHERE THE PARTIALLY CONFINED TEST OCCURRED

Code	Sample type	Coordinates	Dose rate (μSv/h)	Location
ALG-8[a]	Lava, crystalline, 148 g	24°03'819" N 05°03'408" E	30	In front of the E2 tunnel from which radioactive lava was ejected
ALG-9	Lava, porous, red, 120 g	24°03'812" N 05°03'400" E	4	Same
ALG-10	Lava, porous, red, 98 g	24°03'822" N 05°03'331" E	200	Same
ALG-11[a]	Lava, porous, yellow/ white, 81 g	24°03'512" N 05°03'220" E	10	Same
ALG-12[b]	Lava, crystalline, 176 g	24°03'819" N 05°03'408" E	30	Same
ALG-13[b]	Lava, porous, red, 158 g	24°03'812" N 05°03'400" E	4	Same
ALG-14[b]	Lava, porous, red, 111 g	24°03'822" N 05°03'331" E	200	Same
ALG-15[b]	Lava, porous, yellow/ white, 42 g	24°03'512" N 05°03'220" E	10	Same

[a] Samples analysed for ^{90}Sr, ^{241}Am, Pu isotopes and gamma emitters.
[b] Samples analysed only for gamma emitters.

measurement of small volume (<5 mL) samples that had been homogenized and contained elevated levels of Pu and ^{241}Am. In this case, a standard counting vial was filled with approximately 1 mL of sample material. The gamma ray spectrometer had been calibrated for photopeak efficiency response as a function of gamma ray energy for this sample geometry before the measurements were made. The

TABLE 15. TAOURIRT TAN AFELLA — SEDIMENT, SAND, VEGETATION AND WATER SAMPLES COLLECTED NEAR THE TUNNEL WHERE THE PARTIALLY CONFINED TEST OCCURRED

Code	Sample type	Coordinates	Dose rate (nSv/h)	Location, comments
ALG-16	Soil sediments from a dry stream bed, 316 g	24°03'770" N 05°03'992" E	~800	In the proximity of the old French fence, 0.8 km from the E2 tunnel. Collected to evaluate possible radionuclide transport
ALG-17	Soil sediments from a dry stream bed, 439 g	24°03'580" N 05°03'985" E	~800	Same as above but 400 m from sample ALG-16
ALG-18[a]	Sand, 914 g	24°03'736" N 05°03'542" E	~800	Same
ALG-19	Vegetation	24°03'736" N 05°03'542" E	~800	Same
ALG-20	Water used for washing sample ALG-19	24°03'736" N 05°03'542" E	~800	Same
ALG-21[a]	1.5 L of well water (divided between two containers)	24°00'959" N 05°04'805" E	Background	6 km NW of well 1 (24°04'003" N 05°03'805" E)

[a] Samples analysed for ^{90}Sr, ^{241}Am, Pu isotopes and gamma emitters.

TABLE 16. ADRAR TIKERTINE — SAND SAMPLES COLLECTED AT THE SITE OF THE POLLEN EXPERIMENTS

Code	Sample type	Coordinates	Dose rate	Comments
ALG-22[a]	Sand, first layer, ~3 mm, 270 g	23°55'958" N 04°43'343" E	Not available	Sand presumably containing Pu and Am
ALG-23[a]	Sand, second layer, ~3 mm, 743 g	23°55'958" N 04°43'343" E	Not available	Same
ALG-24	Sand, first layer, ~3 mm, 534 g	23°55'569" N 04°43'983" E	Not available	Same
ALG-25	Sand, second layer, ~3 mm, 1163 g	23°55'569" N 04°43'983" E	Not available	Same

[a] Samples analysed for ^{90}Sr, ^{241}Am, Pu isotopes and gamma emitters.

resultant gamma ray spectra were processed using commercial peak search and nuclide identification software.

The measurements from both systems were corrected for background radiation, and also for attenuation due to differences between the mass density and atomic composition of the sample matrix and the standard. In the case of the well type detector, the results were further corrected for true coincidence summing (cascade summing). For this latter correction, several single-photon energy sources were prepared, and the total counting efficiency of the well detector was determined at several energies that spanned the energy region of the gamma rays of the radionuclides of interest. The correction factors for true coincidence summing were calculated with the KORSUM software (PTB Braunschweig, Germany).

In addition to the solid samples, a series of water samples from two leaching experiments were measured. The leaching experiments were performed on two samples: ALG-8 and ALG-3. The leaching experiments were carried out at 40°C according to a standard American Society for Testing and Materials (ASTM) procedure for the leaching of nuclear waste forms with volumes of

240 mL and 90 mL, respectively. The measuring time for these samples ranged from 20 to 70 hours. No gamma emitting radionuclides were detected above the background.

The minimum detectable activity concentration for the radionuclides of interest was calculated according to Ref. [6], and typically was ~3 Bq/kg for ^{241}Am and ~0.5 Bq/kg for ^{137}Cs.

I.4.2. Radiochemical procedures

Two sample dissolution methods were applied: conventional wet digestion and fusion with lithium metaborate, as discussed in section 1.2 of Ref. [7].

Most of the analyses were carried out applying a sequential procedure for the determination of ^{241}Am, ^{90}Sr and Pu radionuclides. A few analyses carried out on small aliquots taken from high activity samples after dissolution and dilution of the sample did not involve any radiochemical separation for Pu other than the microcoprecipitation of Pu(IV) with NdF_3. Also, for ^{90}Sr additional analyses were performed without applying a sequential procedure. Plutonium radioisotopes and ^{241}Am were analysed by using the principle of isotope dilution alpha spectrometry. Strontium-90 was measured by liquid scintillation counting using the double energy window method.

I.4.3. Sample crushing

Owing to the very heterogeneous nature of some of the samples collected, selected samples had to be partially or fully homogenized by crushing prior to analysis. Because of the limitations and restrictions on working with high activity dust, the reduction of particle size was carried out only for selected samples. Samples ALG-3, ALG-4, ALG-12, ALG-13, ALG-14 and ALG-15 were totally or partially crushed before measurement. All crushed samples had 'P1' added to the sample number. To perform the crushing, the samples were carefully transferred into a steel container (10 cm in diameter and 15 cm in height). The container and the crushing pestle were wrapped with plastic fixed with adhesive tape to avoid release of any dust. Each sample was mechanically crushed using a large hammer and the pestle. The sample was then transferred back to the storage container. To avoid cross-contamination, the samples were crushed in three different containers. Samples ALG-13, ALG-14 and ALG-15 were crushed in container 1 in the order ALG-14, ALG-13, ALG-15, i.e. in order of increasing activity concentration (preliminary gamma measurements). The container and pestle were cleaned with paper and with a vacuum cleaner between samples. Sample ALG-4 was crushed in container 2 and ALG-12 in container 3. Container 2 was also used for sample ALG-3 after it had been cleaned with a decontamination liquid and dried. Samples ALG-4 and ALG-12 were only partially crushed.

To avoid contamination, the samples were prepared in a separate room suitable for work with higher activity. The tables were appropriately protected and the work was performed under an exhaust system with a high exhaust rate. Appropriate procedures were followed and the analysts used protective clothing consisting of filter masks, gloves, disposable coats and overshoes. A health physicist was present at all times.

The handling of the higher activity samples (ALG-1, ALG-8 and ALG-11) was done using sealed plastic boxes inside a fume hood. Subsamples from ALG-8 were taken using an electric hand drill with a 5 mm diameter carbide drill bit.

All other samples were measured as collected.

I.4.4. Sample dissolution

Samples to be analysed for beta and gamma emitters were dissolved. Two sample dissolution methods were applied: conventional wet acid dissolution for low activity samples and lithium metaborate fusion for both high and low activity samples.

The conventional wet acid dissolution method was used for one run of analyses (Set 3) of the low activity samples (ALG-22, ALG-23 and ALG-18). This is described in section 2.1 of Ref. [7].

A total dissolution method based on fusion with $LiBO_2$ was applied for the decomposition of most of the samples. The samples were fused with lithium metaborate using a sample/flux ratio of 4:1. Any insoluble residue that remained after fusion and dissolution in 1 mol/L HNO_3 was separated by filtration. The residues were dissolved with a mixture of concentrated HNO_3/HF acids. After evaporation with concentrated HNO_3, the residues were dissolved in 10–20 mL of 1 mol/L HNO_3. The resultant solution was combined with the main 1 mol/L HNO_3 solution and diluted to either 200 or 250 mL with 1 mol/L HNO_3. The dilution factor (ratio of mass of solution after dilution to the original mass of sample that was fused) was recorded.

I.4.5. Sample size and tracer activities

Small aliquots of the diluted solutions were used to measure by liquid scintillation counting the gross alpha plus beta activities. This information was needed to evaluate the tracer activities to be added and the sample size necessary for the radiochemical analysis.

I.4.6. Separation of particle fraction <50 μm

The sand fraction having a diameter of <50 μm was isolated in samples ALG-1, ALG-22 and ALG-24 using a 50 μm sieve (DIN standard). In each case the volume of the fine material was ≲ 1 mL. The material was then measured for approximately 20 hours using a well type detector (Canberra model GCW2022-7500SL) using a standard counting vial. The results, corrected for the contribution of natural background activity and spectral interference and for true coincidence summing, are reported in Table 16.

I.4.7. Radiochemical separation procedures

A combined sequential procedure for the determination of ^{90}Sr, ^{241}Am and Pu radionuclides was generally applied [7–9]. In some cases thin sources of Pu were prepared by micro-coprecipitation without performing any radiochemical separation other than the micro-coprecipitation with NdF_3. In a few cases, in order to improve precision, ^{90}Sr was analysed separately [10].

I.4.7.1. Combined radiochemical separation procedure using extraction chromatography and anion exchange

The radiochemical procedure involved the separation of Pu from Am and Sr by extraction chromatography after the preconcentration of Am and Sr by coprecipitation with Ca/Ba/Mg oxalates. Plutonium had to be reduced before performing the oxalate precipitation. The reduction was carried out by reducing any Fe(III) to Fe(II) with 1 mL of concentrated hydrazinium hydroxide in 1 mol/L HNO_3. The mixed oxalates containing Pu, Am and Sr were destroyed with concentrated nitric acid. Then the residues were dissolved in 1 mol/L HNO_3. Before the radiochemical separation was performed, the oxidation state of Pu was adjusted to the tetravalent state. The procedures for the oxidation state adjustment of Pu are indicated in Ref. [7]. When no Fe(III) was observed in the samples, 0.1 g of Mohr's salt was added to the 1 mol/L HNO_3. To ensure the complete reduction of Pu, 1 mL of concentrated hydrazinium hydroxide was added by stirring to the hot 1 mol/L HNO_3 solution. The adjustment to the tetravalent oxidation state of Pu was carried out by adding between 0.65 and 1.0 g of $NaNO_2$ to the 4 mol/L HNO_3 solution. After boiling for approximately 1 min, the solution was cooled and the nitric acid concentration was adjusted to approximately 8 mol/L HNO_3. The total volume of this solution was approximately 40 mL at this stage. The solution was then passed through columns of TEVA Resin (EIChroM Industries, Inc.) with approximately 2 mL bed volume. The columns were washed with 20 mL of 8 mol/L HNO_3 to remove non-retained ions (Sr and other alkaline earth metals, Am and rare earth elements, K and other alkaline metals, etc.). From each column, Th was separated with 12 mL of 10 mol/L HCl. Plutonium was finally separated by passing through the columns 25 mL of 0.1 mol/L NH_4I/9 mol/L HCl. The Pu fractions were converted to nitrate form by evaporating to a thick paste three times with 2 mL HNO_3. The residues were dissolved in 20 mL of 1 mol/L HNO_3. The procedure described in section 2.1 of Ref. [7] was followed to ensure a higher decontamination from U. Thin sources for alpha spectrometric measurements of Pu and Am were prepared by micro-coprecipitation with NdF_3. Americium was separated from Sr by extraction chromatography using TRU Resin (EIChroM Industries, Inc.). The final Sr separation and purification were performed by extraction chromatography using Sr Resin (EIChroM Industries, Inc.). The detailed radiochemical procedure for Am and Sr can be found in sections 2.2–2.5 of Ref. [7]. Americium was not separated from rare earth elements.

I.4.7.2. Separation of Pu by ion exchange

The process of Pu separation by ion exchange is described in detail in section 2.1 of Ref. [7].

I.4.7.3. Direct micro-coprecipitation with NdF_3

For high activity samples (ALG-3, ALG-4, ALG-8 and ALG-11), a direct micro-coprecipitation of Pu with NdF_3 was carried out from small aliquots taken from the diluted solutions. The procedure for Pu source preparation is described in section 2.1 of Ref. [7].

I.4.7.4. Determination of ^{90}Sr

In addition to the combined sequential procedure, ^{90}Sr was also determined separately, in aliquots taken from diluted solutions of high activity samples. In this case, ^{90}Sr was coprecipitated as Ca/Mg/Ba oxalate as described in section 2.2 of Ref. [7]. The purification of Sr from alkaline earth metals was carried out by extraction chromatography using Sr Resin as indicated in section 2.5 of Ref. [7].

I.4.8. Analysis of ^{137}Cs, Pu isotopes, ^{241}Am and ^{90}Sr in well water

Well water (1.5 L) was filtered through a membrane 0.2 μm filter. The filtrate was used for the radiochemical analysis of ^{137}Cs, Pu isotopes, ^{241}Am and ^{90}Sr. The residue was measured for gross alpha/beta activities using a proportional counter and for gamma activities using a high resolution Ge (Li) semiconductor detector [7]. Caesium was preconcentrated from the filtrate by using the method based on the selective adsorption on insoluble ammonium molybdatephosphate [10]. The yellow precipitate was separated by filtration through a membrane polypropylene filter. The solution was evaporated to approximately 200 mL after the addition of Pu and Am radiotracers and 20 mg of Sr carrier. The previously described sequential determination of Pu isotopes, ^{241}Am and ^{90}Sr was followed.

I.4.9. Leaching experiments

The leaching experiments were carried out at 40ºC using deionized water as leachant. The two specimens, ALG-3 and ALG-8, were first washed four times with 90 mL of deionized water to remove dust and fragments. They were then transferred to a container filled with 90 mL of the leachant. After 30 days the leachant was filtered through a 0.2 μm polypropylene membrane (45 mm diameter) and the pH was adjusted to 1 with HNO_3. After determination of the gamma emitting radionuclides, the solution was analysed for $^{239+240}Pu$, ^{241}Am and ^{90}Sr.

I.4.10. Instrumentation

I.4.10.1. Gamma spectrometry

The low level counting system used consisted of:

(a) Detector: HPGe model GEM-XX185-S (EGG Ortec) with 70% efficiency relative to 3 in × 3 in[4] of NaI crystal, resolution of 2.5 keV at 1.3 MeV with a low level cryostat (selected materials of low radioactivity were used for construction), mounted in a 10 cm thick low level Pb shield;
(b) Automatic sample changer supplied by EGG Ortec;
(c) Nuclear spectroscopy electronics: Ortec model 660 HV power supply, Canberra model 2025 amplifier, Canberra model 8075 ADC, Canberra S-100 Microchannel MCA board.

The counting system, based on a well type detector, consisted of:

(1) Detector: well type HPGe model Canberra GCW2022-7500SL with 18% efficiency relative to 3 in × 3 in of NaI crystal, resolution of 1.9 keV at 1.3 MeV, mounted in a 10 cm thick Pb shield;
(2) Nuclear spectroscopy electronics: Ortec model 459 HV power supply, Canberra model 2025 amplifier, Canberra model 8075 ADC, Canberra AIM 556 acquisition interface module.

Details of the settings of each of the systems are documented in the detector dedicated files. The software used was Genie-2000 version 1.4 by Canberra.

I.4.10.2. Alpha spectrometry and liquid scintillation counting

Alpha spectrometry and liquid scintillation counting are described in detail in the chapters on 'Apparatus' and 'Calculation and calibration' in Ref. [7].

I.4.11. Metrological parameters

The minimum detectable activities of the alpha spectrometry system and the liquid scintillation counter were calculated on the basis of Currie's method [6]. The combined uncertainty in the activity concentration was calculated algebraically and/or using the spreadsheet method of Kragten [11].

[4] 1 inch = 2.54 cm.

I.4.12. Quality control

In order to assess reproducibility in the measurements, different radiochemical procedures were applied to the analysis of relevant radionuclides in the selected samples. The reproducibility of the results obtained in most of the samples (lava and black fragments of fused sand) was good, taking into consideration that not all samples were mechanically homogenized. Recoveries for Pu, Am and Sr were generally higher than 65%, which indicates that the radiochemical procedures performed well in the analysis of this type of sample. Two IAEA reference materials (IAEA-135 and Soil-6) were analysed in parallel with the samples. Results for Pu, ^{241}Am and ^{90}Sr were within the confidence intervals of the reference values after corrections for ingrowth (^{241}Am/^{241}Pu), decay (^{241}Pu, ^{90}Sr), etc.

I.5. RESULTS AND DISCUSSION

The results of the radiochemical analyses (beta and alpha emitters) and of the gamma spectrometry (gamma emitters) are shown in Tables 11 and 12, respectively.

I.5.1. Reggane samples

In sample ALG-1 from Reggane (composite of sand and black fragments of fused sand), most of the activity was found in the black fused sand. The analysis carried out on subsamples that contained only the black fused sand showed activity concentrations for $^{239+240}$Pu of the order of 1×10^6 Bq/kg. The activity in the sand was three to four orders of magnitude lower. Sample ALG-3 was also a composite with black fragments of fused sand and sand. In this case the results for all subsamples taken for the black fragments were very reproducible, showing that Pu is homogeneously distributed throughout this material. The activity concentrations of all measured anthropogenic radionuclides in the sand fraction containing particles with a diameter of <50 μm were in general equal to or less than the level of detection (a few tens of becquerels per kilogram). The only measurable radionuclides were ^{137}Cs and the natural isotopes ^{40}K, ^{228}Ra and ^{228}Th. The activity concentration was 196 Bq/kg for ^{137}Cs and was about 300 Bq/kg for ^{40}K, ^{228}Ra and ^{228}Th.

One sample consisting of 5 g of black fused sand (from sample ALG-3 from Reggane, Gerboise Blanche) was also leached by water at 40°C. After the sample was washed with distilled water to remove particles and dust, the activity concentrations of ^{137}Cs, ^{90}Sr, ^{241}Am and $^{239+240}$Pu in the leachate were measured after a period of 30 days. The radionuclides in the leachate were always below or at the minimum detectable activity, i.e. less than approximately 1 Bq/L for ^{137}Cs, less than approximately 0.03 Bq/L for ^{90}Sr, less than approximately 1×10^{-3} Bq/L for ^{241}Am and less than approximately 0.02 Bq/L for $^{239+240}$Pu. The low radionuclide activity in the leachates in the time interval of the experiment could indicate that the radionuclides are immobilized in the matrix of the vitreous fused sand. However, further and more representative experiments should be conducted before confirming this conclusion.

I.5.2. In Ekker — Taourirt Tan Afella samples

As expected, the lava samples ALG-8 and ALG-11 from Taourirt Tan Afella, collected in front of the tunnel where the partially confined test occurred, were highly radioactive. The activities of $^{239+240}$Pu, ^{241}Am and ^{90}Sr seem to be very homogeneously distributed in this type of sample. The activity concentration of $^{239+240}$Pu ranges between 1×10^4 and 1×10^5 Bq/kg. For ^{241}Am the activity concentration ranges between 1×10^3 and 1×10^4 Bq/kg. For ^{90}Sr the activity concentration ranged between 1×10^4 and 1×10^6 Bq/kg. Sample ALG-8, consisting of 148 g of lava, was also leached following the same procedure as mentioned above. Also in this case, after 30 days of leaching the radionuclides in the leachate were always below or at the minimum detectable activity.

The activity concentrations of all gamma emitters and of $^{239+240}$Pu, ^{241}Am and ^{90}Sr in the water sample (ALG-21) taken from a well about 6 km beyond the perimeter of the old fence that had been erected by the French authorities and that surrounds the area affected by the partially confined test were below the minimum detectable activity.

In sample ALG-18, which was collected in the proximity of the old fence, slightly higher activities for Pu, Am and Sr were observed.

I.5.3. In Ekker — Adrar Tikertine samples

Samples ALG-22 and ALG-23 from Adrar Tikertine consisted of sand collected at the site where the Pollen experiments were conducted. The

activity concentrations for Pu radioisotopes, ^{241}Am and ^{90}Sr in ALG-22 and ALG-23 were below 25 Bq/kg. The two sand samples (ALG-22 and ALG-24, see Table 17) were sieved and the sand fraction containing particles with a diameter of <50 μm was measured by high resolution gamma spectrometry. As in the case of the sample from Reggane (Gerboise Blanche), the activity concentrations of all anthropogenic radionuclides were in general equal to or less than the level of detection (a few tens of becquerels per kilogram). The only measurable radionuclides were ^{137}Cs and the natural isotopes ^{40}K, ^{228}Ra and ^{228}Th. The activity concentration was about 25 Bq/kg for ^{137}Cs and was about 300 Bq/kg for ^{40}K, ^{228}Ra and ^{228}Th.

I.6. CONCLUSIONS

Selected samples have been analysed by high resolution gamma spectrometry and alpha and beta spectrometry after radiochemical separation. The concentrations of the following radionuclides have been determined:

^{133}Ba, ^{60}Co, ^{137}Cs, ^{152}Eu, ^{154}Eu, ^{155}Eu, ^{40}K, ^{228}Ra, ^{228}Th (gamma emitters);
^{90}Sr (beta emitter);
^{241}Am, ^{238}Pu, $^{239+240}$Pu (alpha emitters).

The number of samples collected and analysed is somewhat small when viewed against the size of the sites visited during the field mission. This restricts to some extent the validity of conclusions based on extrapolating the laboratory measurements to the entire areas potentially affected by the nuclear tests. Nevertheless, keeping in mind this limitation, some general conclusions can still be drawn.

I.6.1. Samples from Reggane

The only site at Reggane from which samples were taken and where significantly elevated radionuclide concentrations were detected is Gerboise Blanche. This is the site of the only test conducted on the surface (<10 kt). Most of the contamination is in the black, vitreous and porous material (sand melted at the time of the explosion and then solidified). The sand is much less active (100–1000 times less). A typical sample is ALG-3 (sand with many black fragments of fused sand), which has the following activity concentrations:

$^{239+240}$Pu = 1.2×10^6 Bq/kg;
^{137}Cs = 2.9×10^4 Bq/kg;
^{90}Sr = 1.8×10^5 Bq/kg.

The activity concentrations of the anthropogenic radionuclides in the sand fraction containing particles with diameters of <50 μm were equal to or less than the level of detection (a few tens of becquerels per kilogram). The only activity concentration that was measurable was ^{137}Cs at 196 Bq/kg. This indicates that the activity concentrations of the radionuclides generated by the nuclear tests in the sand fraction that is respirable (<10 μm) should be negligible.

I.6.2. Samples from In Ekker — Taourirt Tan Afella

Taourirt Tan Afella is the location where several tunnel tests were conducted. The only site from which samples were taken was the area in front of the E2 tunnel where the partially confined test occurred (ejection of radioactive lava) and its proximity. As expected, the activity of the lava was high. Activity concentrations in a typical lava sample (ALG-11) were:

$^{239+240}$Pu = 4.2×10^4 Bq/kg;
^{137}Cs = 2.1×10^6 Bq/kg;
^{90}Sr = 1.1×10^6 Bq/kg.

The activity in the water taken from a well in the proximity (about 6 km) of this site (sample ALG-21) was negligible, i.e.:

^{137}Cs < level of detection (0.075 Bq/kg);
^{90}Sr < level of detection (0.02 Bq/kg).

This result indicates that at present there is no evidence that drinking the well water involves any radiological risk.

The soil and sand in the dry stream beds coming from the radioactive lava (ALG-18) had the following activity concentrations:

$^{239+240}$Pu = 50 Bq/kg;
^{137}Cs = 3.5×10^3 Bq/kg;
^{90}Sr = 1.2×10^4 Bq/kg.

I.6.3. Samples from In Ekker — Adrar Tikertine

The activity concentrations of $^{239+240}$Pu, ^{137}Cs and ^{90}Sr in the coarse sand samples were low. They

TABLE 17. ACTIVITY CONCENTRATION OF GAMMA EMITTING NUCLIDES IN THE SAND FRACTION WITH A DIAMETER OF <50 μm IN SAMPLES ALG-22, ALG-24 AND ALG-1

Nuclide	Activity concentration (Bq/kg)	Standard uncertainty (Bq/kg)	LOD[a] (Bq/kg)	Status
ALG-22				
^{241}Am	36.5	3.3	17	
^{133}Ba			138	<LOD
^{60}Co			56	<LOD
^{134}Cs			80	<LOD
^{137}Cs	28.5	8.6	27	
^{152}Eu			114	<LOD
^{154}Eu			43	<LOD
^{155}Eu	48.6	5.2	27	
^{40}K			618	<LOD
^{239}Pu			171 000	<LOD
^{228}Ra	224	36	167	
^{228}Th	214	22	39	
ALG-24				
^{241}Am			7.6	<LOD
^{133}Ba			60	<LOD
^{60}Co			22	<LOD
^{134}Cs			33	<LOD
^{137}Cs	23.0	3.9	12	
^{152}Eu			42	<LOD
^{154}Eu			15	<LOD
^{155}Eu	43.0	2.8	11	
^{40}K	484	73	217	
^{239}Pu			41 300	<LOD
^{228}Ra	262	16	59	
^{228}Th	285	23	12	
ALG-1				
^{241}Am	27.3	1.3	7.1	
^{133}Ba			55	<LOD
^{60}Co			19	<LOD
^{137}Cs	196.5	7.6	13	
^{152}Eu	69.9	8.6	28	
^{154}Eu			15	<LOD
^{155}Eu	47.7	2.9	8.4	
^{40}K	306	78	249	
^{239}Pu			32 600	<LOD
^{228}Ra	300	18	72	
^{228}Th	309	23	12	

[a] LOD: limit of detection.

fell in the range 2–15 Bq/kg. The activity concentration of plutonium in the sand fraction containing particles with a diameter of <50 μm was also equal to or less than the level of detection. This indicates that significant quantities of $^{239+240}$Pu (or other anthropogenic radionuclides) released during the Pollen tests should not be present in the sand fraction that is respirable (<10 μm).

I.7. PERSONNEL

The work was carried out at the IAEA's Laboratories in Seibersdorf under the direction and scientific responsibility of P.R. Danesi. The following staff members were involved in the work: E. Zeiller (sample preparation), M. Makarewicz (sample preparation, gamma measurements), G. Kis Benedek (sample preparation, radiochemical analysis of ^{90}Sr, analysis of well water sample, leaching of lava and black nodules), L. Benedik (sample preparation; radiochemical analysis of Pu radioisotopes, ^{241}Am and ^{90}Sr; calculations), J. Moreno (sample preparation; radiochemical analysis of Pu radioisotopes, ^{241}Am and ^{90}Sr; calculations; evaluation of results; drafting of the report), K. Burns (coordination, evaluation of results, revision of the report).

Appendix II

ASSESSMENT OF RADIATION DOSES

II.1. REGGANE

The principal exposure pathways at the Reggane test site are:

— External radiation;
— Inhalation of dust;
— Ingestion of dust.

A short term stay or a series of short stays at the Reggane desert test site amounting to up to three days per year was postulated as the upper bound on likely occupancy for the foreseeable future.

II.1.1. External exposure

The background dose rate to air in the region was about 80 nGy/h. The maximum dose rate recorded at 1 m height (at about the ground zero of the Gerboise Bleue test) was about 2.5 μGy/h, which, since ^{137}Cs is the dominant contributor, implies a peak activity concentration of the order of 5 MBq/m^2 of ^{137}Cs (or about 50 kBq/kg, assuming uniform deposition to a depth of 5 cm). The peak measured activity concentration of 30 kBq/kg is concordant with these values although some loss through transport of the surface soil by the wind has occurred. For Gerboise Blanche the peak external dose rate was about 1 μGy/h, and for Gerboise Verte and Rouge the maximum rates were only of the order of 2–3 times above background. The tests were conducted within a total area of about 10 km × 20 km, or about 200 km^2. Even for the Gerboise Bleue site the dose rates were near background at a distance of 800 m from ground zero, so that the total area with elevated exposure rates within the 200 km^2 test zone was only about 2 km^2, or 1%. A person camping in the area and choosing a campsite randomly would with high probability be at a site where exposure rates are at the background level. In the extremely unlikely scenario that the Gerboise Bleue ground zero point were selected, the effective dose accumulated from external exposure over the assumed maximum of three days would be about 0.1 mSv/a. For the assumed exposure scenario (camping occasionally in the general test area) the most probable annual dose from nuclear test residues would be negligible.

Some pieces of scrap steel exist in the test zones that still exhibit detectable ^{60}Co activation. The exposure rate from these pieces is too low to represent a radiological hazard even if material were taken as souvenirs and kept in fairly close proximity to people.

II.1.2. Inhalation of dust

In windy conditions the dust loadings in the air near ground level can be very high. Information on the frequency of such conditions is lacking. It is likely that in extremely dusty conditions, e.g. dust storms, protective measures are taken (such as respiratory protection, sheltering in tents or indoors) against inhalation and ingestion of dust. For the extremely dusty living conditions of aborigines studied in the Maralinga assessment [12], a mean airborne dust loading of 1 mg/m^3 was assumed, with a 90 percentile value of 3 mg/m^3. These values will be adopted here because site specific data are not available.

For persons who might be in the area immediately downwind of an area with elevated concentrations of residual activity, the inhalation activity intake rate is dependent on wind velocity and therefore dust loading and aversion measures. Assuming dusty conditions with 1 mg/m^3 of soil in air and an adult inhalation rate of 23 m^3/d, the inhaled mass intake is 23 mg/d, or for constant extremely dusty conditions about 3 to 5 times this quantity. It is evident that much of the dust transported by wind in the desert has been moved to and fro over long periods, and much of the inhaled dust in the proximity of the test sites will have originated elsewhere.

Plutonium is the major contributor to inhalation dose because of its higher committed effective dose per unit intake factor, and higher surface soil concentration at the test sites. The data provided by the French authorities indicate that peak $^{239+240}$Pu concentrations are about 4 MBq/m^2 at the Gerboise Blanche, Rouge and Verte sites, and rather lower at the Bleue site. Assuming a uniform deposition to a depth of 0.5 cm and a soil density of

2000 kg/m^3, this implies a concentration of about 0.4 MBq/kg. The peak concentration measured at Blanche was about 1 MBq/kg, which is within about a factor of 2 of the implied value. Assuming an exponential fall-off (to 2% of the peak) with radius out to a distance of 800 m from ground zero in the case of the Blanche site, an area of about 2 km^2 has residual plutonium activity at a mean concentration of about 0.1 MBq/kg, with smaller areas having this concentration at the Rouge and Verte sites and a lower mean concentration at the Bleue site. The airborne source generating area can then for calculational purposes be approximated by a mean concentration of about 0.1 MBq/kg over an area of 2.5 km^2 (Table 18).

For the equivalent of three days in a year spent in a downwind direction from the test sites, the activity intake upper bound for $^{239+240}$Pu is therefore less than 9 Bq. The upper bound to the annual dose for this scenario is then derivable from the respirable fraction of airborne dust, modified by any enhancement factor. In view of the constant movements of desert dust, the enhancement factor is likely to be less than 1. For a respirable fraction of r%, the upper bound to inhalation dose (committed effective dose) from $^{239+240}$Pu is then less than 1.4r μSv (assuming slow clearance for the oxide form and a dose coefficient of 1.6×10^{-5}), or in constant extremely dusty conditions a few times greater than this. Again, on the basis of randomly selected camping locations within the test area and variable wind directions, the annual dose to persons behaving as in the assumed scenario would be much smaller. Further, the peak concentrations of plutonium measured were in fused sand, which generally contributes little to respirable particulates unless it is finely broken up by natural forces and processes or human activities. The activity concentrations in surface layers of sand are 2–3 orders of magnitude lower. In reality, for the Gerboise Blanche sand sample, ALG-3, the measured activity concentrations of anthropogenic radionuclides in the sand fraction of particle size below 50 μm were equal to or below the limits of detection. The postulated maximum inhalation doses arising from this exposure scenario are therefore negligible.

The committed effective dose per unit activity intake factors have been taken from the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources [3] and are shown in Table 19.

II.1.3. Ingestion of dust

Dust may settle on clothing, skin and foodstuffs, and so be transferred to the mouth and ingested. For the extremely dusty and high dust to food transfer processes associated with aborigine life styles [12], an ingestion rate of 10 g/d was assumed. If this value is applied, the upper bounds for ingested activities of contributing radionuclides arising from three days of camping in a contaminated area are the mean soil activities (Table 18) times 30 g. Camping in the 98% of the test site area with little residual activity would lead to much smaller doses.

Plutonium pellet experiments

In the future some contaminated soil from the plutonium pellet experiments could potentially be unearthed and give rise to an inhalation risk. The specific sites of the experiments are moderately raised above the surrounding soil but can only be identified after diligent searching. A few of the experiments that were not totally contained may have given rise to some very localized soil contamination.

TABLE 18. CONCENTRATIONS (Bq/kg) USED TO ESTIMATE DOSES

Nuclide	Measured peak concentration (ALG-3)	Estimated mean concentration over 2.5 km^2 area for estimating airborne source term and ingestion intakes
^{90}Sr	7.1×10^5	1.2×10^5
^{137}Cs	3×10^4	3.5×10^3
$^{239+240}$Pu	1.4×10^6	7×10^3
^{241}Am	2.4×10^4	6×10^3

TABLE 19. DOSE COEFFICIENTS FOR INHALATION AND INGESTION

Nuclide	Lung retention type[a]	f_1 [b]	Committed effective dose per unit intake (Sv/Bq)
Inhalation			
^{90}Sr	F	0.3	2.4×10^{-8}
^{137}Cs	F	1.0	4.8×10^{-9}
$^{239+240}$Pu	S	1.0×10^{-5}	1.5×10^{-5}
^{241}Am	M	5.0×10^{-4}	3.9×10^{-5}
Ingestion			
^{90}Sr		0.3	2.8×10^{-8}
^{137}Cs		1.0	1.3×10^{-8}
$^{239+240}$Pu		1.0×10^{-5}	9.0×10^{-9}
^{241}Am		5.0×10^{-4}	2.0×10^{-7}

[a] F: fast; M: medium; S: slow.
[b] f_1: gut transfer factor.

II.1.4. Inhalation doses in the town of Reggane

The town of Reggane is approximately 50 km north-east of the test site. If, taking account of the distance to Reggane, the nominal 2.5 km^2 contaminated area is considered as a point source giving rise to a ground level release, the air concentration at the distance of Reggane for a wind with a bearing in the direction of the town would be less than three orders of magnitude below that at a distance of 1 km from the nominal site, ignoring deposition (see fig. 3 in Ref. [13]). During windy conditions the dust loading in the lower atmosphere is in equilibrium, with resuspension and deposition rates roughly equal, so that in higher winds deposition rates are also higher. The inhalation rate in Reggane of material from the active zone is then less than 0.023 mg/d, neglecting deposition and with wind direction fixed. Taking account of deposition in high dust conditions will lead to airborne concentrations at the distance of Reggane being reduced by at least a further order of magnitude. If the wind is in the direction of Reggane for 25% of the time, an upper bound to annual $^{239+240}$Pu inhalation intake is then of the order of 2.3×10^{-6} (g/d) × 0.25 × 120 (Bq/g) × 365 (d) = 0.02 Bq. The derivation of the annual dose arising from inhalation needs to take account of the respirable fraction of the inhaled activity. This is likely to differ from that near the test site because of differential settling, but on the basis of the very small measured respirable activity fraction at the Gerboise Blanche site, the resulting doses are clearly negligible (far below 1 μSv/a).

II.2. IN EKKER — TAOURIRT TAN AFELLA

The principal exposure pathways at Taourirt Tan Afella are:

- External radiation, particularly in the vicinity of ejected lava;
- Inhalation of dust;
- Ingestion of dust;
- Ingestion of water containing leached material;
- Ingestion of products (milk, meat) from animals that intermittently graze in the area.

II.2.1. External exposure

External exposure rates are elevated from deposition following airborne releases at the time of the tests (and from lava ejecta in the case of the E2 site) in the vicinity of both the E2 and the E3 galleries. The deposition from the E2 site is the more widespread. Some smaller ejected pieces were dispersed for several hundred metres at the time of the detonation, and others have been subsequently transported by water in occasional rainstorms. Both over a small area at the E3 site and outside the

TABLE 20. ANNUAL DOSES FROM INGESTION OF DUST IN THE VICINITY OF THE E2 TUNNEL

Nuclide	Soil concentration (Bq/kg)	Committed effective dose equivalent (μSv/a)
^{90}Sr	2×10^3	5.6
^{137}Cs	3.5×10^3	4.6
$^{239+240}$Pu	5×10^1	<1
All		10

original fence constructed by the French authorities at the E2 site, dose rates range up to about 240 nGy/h above background. The upper bound to the effective dose above background (about 80 nGy/h) from external radiation received by a nomadic herder remaining outside the original fence would then be about 40 μSv/a. (This assumes a factor of 0.7 to relate dose to air or ambient dose equivalent to effective dose for 0.66 MeV radiation.)

Occasional visits within the original fence could give rise to higher exposures, particularly if the bulk lava areas were walked on. It may be noted, however, that these lava areas are generally quite steeply sloping and support no vegetation, so that the only reason for people to venture into the area (which has a warning monument) is curiosity or the desire to scavenge materials. In an extreme case, if some persons spent as much as two working days (of eight hours each) in an area immediately adjacent to or on the lava masses where the dose rates were 100 μGy/h, an upper bound to effective doses received from such an exposure scenario would be about 1.1 mSv/a.

II.2.2. Inhalation of dust

Measured soil concentrations of plutonium are very much lower than at the Reggane site (by a factor of 10^3 less, comparing the ALG-18 results with Table 18), and for similar occupancy scenarios, inhalation doses are expected to be negligible (<1 μSv/a). Further, the presence of the mountain may affect wind directions such that high winds allowing direct transport from the site do not occur.

II.2.3. Ingestion of soil

Ingestion of soil on foodstuffs handled in dusty conditions might contribute small doses to nomadic people in the area. As noted, measured surface soil activities of plutonium are very much lower than the peak levels at the Reggane test site, and ^{137}Cs and ^{90}Sr concentrations are comparable to the mean values in the areas of elevated concentrations at Reggane. If again a daily intake of 10 g is assumed, which may be extreme for this location, then for the equivalent of ten days spent in the area, annual doses of about 10 μSv are estimated (Table 20).

II.2.4. Ingestion of water

Doses arising from consumption of well water at In Ekker were anticipated to be small, with ^{90}Sr expected to have the greatest mobility of the potentially contributing radionuclides. For a person consuming 1000 litres of water per year from the well the doses incurred are:

$$1000(C_{Cs} \times 1.3 \times 10^{-8} + C_{Sr} \times 2.8 \times 10^{-8}) \times 10^3 \text{ mSv/a}$$

where C_{Cs} and C_{Sr} are the ^{137}Cs and ^{90}Sr concentrations in Bq/L. The mobility of strontium in soils is generally greater than that of caesium. For an annual dose of 1 mSv, a ^{90}Sr concentration of about 35 Bq/L would be required. The measured concentrations are below the limits of detection (for ^{90}Sr < 0.02 Bq/L), indicating that the current doses arising from ingestion of anthropogenic radionuclides in water are negligible.

In the longer term, the water concentrations could increase through continued leaching. If concentrations in water had been readily measurable, it would have been useful to extract water samples at different distances along the watercourse to assess the variation in concentration with distance, and in conjunction with these

TABLE 21. TRANSFER FACTORS FROM ANIMAL INTAKE TO ANIMAL PRODUCTS [14]

Nuclide	Concentration in food on the basis of animal intake	
	Meat (Bq/kg)/(Bq/d)	Milk (Bq/L)/(Bq/d)
^{90}Sr	3×10^{-3}	2×10^{-3}
^{137}Cs	5×10^{-1}	5×10^{-3}

measurements also to determine the distribution coefficient for strontium and caesium in the soils. These values would have aided in the prediction of possible future trends in water concentrations. However, taking account of common values for distribution coefficients in soils for the nuclides of interest and the probable very low rate of leaching from the lava, the measured concentrations in the dry watercourse soils are sufficiently low to preclude the possibility of significant concentrations arising in downstream wells.

II.2.5. Ingestion of animal products

The sparse vegetation in the region is grazed by camels and other domestic species (goats, donkeys). The vegetation is sufficiently sparse for the animals to be almost constantly on the move, spending at most a few days in one area. Distances to available water sources also dictate animal movements, and animals would not normally be able to stay in the E2 and E3 areas for more than a day or two. Grazing livestock could ingest residual radionuclides incorporated in plants through root uptake, and deposited on plants in dust. Visual inspection suggested that deposited dust may dominate intakes and the concentrations in this dust would reflect the surrounding surface soil concentrations. Dietary intake of livestock is related to body mass. For the dusty vegetation conditions observed, it is postulated that an animal might ingest 1–2 kg per day of soil per 500 kg of body mass (which can be compared with a value of 0.5 kg/d for cattle used in a modelling program [14]).

The ^{137}Cs soil concentration corresponding to 240 nGy/h, taking account of background, is about 0.4 MBq/m^2. If this activity is distributed over a soil depth of 5 cm (say 100 g/cm^2), the soil concentration is about 4 kBq/kg, in good agreement with measured values. An upper bound to livestock intake for ten days of grazing in the area is then 40 kBq per 500 kg body mass. Using an ingestion to meat transfer factor of 0.5 for ^{137}Cs [15], the concentration in animal muscle would be similar to that arising from natural ^{40}K in the body at about 120 Bq/kg. This is well below the Codex Alimentarius value of 1000 Bq/kg for food moving in international trade [16], so that the upper bound for dose to persons eating meat from animals slaughtered immediately after grazing in the area is unlikely to be more than a few microsieverts. (A butchered animal is likely to be eaten by a large number of people, so that particular individuals are not likely to have more than a few meals from any specific animal. Five meals of 200 g servings would result in a maximum likely intake of about 120 Bq of ^{137}Cs, giving rise to an effective dose of <2 μSv.) A smaller contribution to dose would arise from ^{90}Sr ingestion, but the concentration in soil is lower and the transfer factor to muscle is almost two orders of magnitude lower than for caesium. The soil to meat transfer factors shown in Table 21 are based on values derived from sheep, which are more restrictive (i.e. are larger values) than those for cattle. They are derived for continuous intake and equilibrium conditions rather than for short term ingestion over a few days. The transient concentration in meat is therefore likely to be overestimated.

Consumption of milk from grazing livestock is also not likely to be a significant contributor to dose. If an infant 1–2 years old consumed 0.5 L/d of milk from an animal that had ingested 80 kBq of ^{137}Cs, on the basis of the transfer factor in Table 17 in Appendix I the cumulated activity intake from the milk would be 200 Bq, and applying an effective dose per unit intake factor from the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (BSS) [3] for members of the public who are 1–2 years old, this results in a dose of about 2 μSv. Adding the contribution from ^{90}Sr implies a total dose of about 6 μSv for this hypothetical milk consumption. These values could be doubled if the

solids content of the milk of desert livestock were notably greater than that of cows.

II.3. IN EKKER — ADRAR TIKERTINE

The principal exposure pathways at Adrar Tikertine are inhalation and ingestion (of soil).

The data supplied by the French authorities suggest that plutonium concentrations at 200 m from the tower position in the downwind direction are about 37 kBq/m^2, corresponding to about 4 kBq/kg in surface (0.5 cm depth) soil, and decreasing with increasing distance. There has been both wind and water transport of surface soils and particles during the intervening years since the tests were performed. It is assumed that nomads who graze livestock spend a total of three days per year in the area, which is in general much more remote than In Ekker. The measurement results indicate much lower current concentrations of $^{239+240}Pu$ than those that have been estimated from historic data.

II.3.1. Inhalation and ingestion of dust

Historic concentrations appear to have been substantially reduced by wind and water transport. However, even if the historical concentrations were applicable, doses arising from ingestion and inhalation of dust would be about two orders of magnitude lower than those derived for the Reggane desert, so that for both intake routes, doses of less than 1 μSv/a would apply. The measurements also demonstrate that the activity concentrations of anthropogenic radionuclides in respirable particles were at or below detection limits.

Appendix III

RADIOLOGICAL CONCEPTS IN THE CONTEXT OF NUCLEAR WEAPON TESTING

This appendix provides the context for the assessment of the radiological conditions at the Algerian nuclear test sites by introducing the most important radiological concepts, quantities and units used in the report. It briefly describes the health effects that can be caused by exposure to ionizing radiation.[5]

III.1. RADIOLOGICAL QUANTITIES AND UNITS

Radiation is the transport of energy through space. In traversing material, radiated energy is absorbed. In the case of ionizing radiation, the absorption process consists in the removal of electrons from the atoms, producing ions. Ionizing radiation (hereafter referred to as radiation) is immanent in the universe. It originates from the cosmos. It is also produced in manufactured devices such as X ray tubes, and it results ubiquitously from the disintegration of radioactive atoms of matter (or radionuclides) — the phenomenon that is called radioactivity. Radionuclides occur naturally or they may be produced artificially, for instance in nuclear explosions such as those with which this publication is concerned. As the radionuclides disintegrate, they often transform into other radionuclides, but they finally transform into stable elements. The time required for the transformation of one half of the atoms of the radionuclide concerned is a constant value and is termed the half-life of the radionuclide.

The BSS [3] have adopted the international system of radiation quantities and units recommended by the International Commission on Radiation Units and Measurements (ICRU). The main physical quantities of the system are the activity, or rate of nuclear transformation of radionuclides emitting radiation, and the absorbed dose, or energy absorbed per unit mass of matter from the radiation to which it is exposed. Thus:

(a) The activity of a radioactive material is the number of nuclear disintegrations of radionuclides within that material per unit time, the unit of activity being the reciprocal second, termed the becquerel (Bq)[6];
(b) The absorbed dose of radiation is the energy imparted per unit mass of material, the unit of absorbed dose being the joule per kilogram, termed the gray (Gy).

Although the absorbed dose is the basic physical dosimetric quantity, it is not entirely satisfactory for radiation protection purposes since the effectiveness of radiation in damaging human tissue differs for different types of ionizing radiation. Consequently the absorbed dose averaged over a tissue or organ can be multiplied by a radiation weighting factor to take account of the effectiveness of the given type of radiation in inducing health effects. The resulting quantity is termed the equivalent dose.

The quantity equivalent dose is used when individual organs or tissues are irradiated. However, the likelihood of injurious late effects owing to a given equivalent dose differs for different organs and tissues. Consequently, when part of the body or the whole body is irradiated, the equivalent dose to each organ and tissue can be multiplied by a tissue weighting factor to take account of the differing radiosensitivities of different organs of the body. The sum total of such weighted equivalent doses for all exposed tissues in an individual is termed the effective dose. The effective dose was derived to provide a metric of radiation exposure that would be better correlated with the risk of developing all cancer types.

The unit of equivalent dose and that of effective dose are the same as that of absorbed dose, namely the joule per kilogram (or gray), but the

[5] This information has been derived from the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (commonly known as the Basic Safety Standards (BSS)) [3] and the latest UNSCEAR reports [4, 5].

[6] Since the becquerel is a unit expressing a very small activity, the following multiples are commonly used: 1000 Bq or kilobecquerel (kBq); 1 million Bq or megabecquerel (MBq); 1×10^9 Bq or gigabecquerel (GBq); 1×10^{12} Bq or terabecquerel (TBq); 1×10^{15} Bq or petabecquerel (PBq); 1×10^{18} Bq or exabecquerel (Ebq).

term sievert (Sv) is the special name applied to the equivalent and effective dose. This report commonly uses the millisievert (mSv), a subdivision of the sievert that is equal to a thousandth of a sievert. (For the purpose of comparison, the average annual individual effective dose that the world's population incurs as a result of exposure to cosmic rays and radiation arising from naturally radioactive materials in the biosphere is about 2.4 mSv.)

In general, unless otherwise stated, the term dose is used in this report to mean effective dose when it refers to the whole body or equivalent dose when it refers to body organs.

When radionuclides are taken into organs of the human body, the resulting dose is received by the exposed individual throughout the period of time during which their activity continues in the body. The committed dose is the total dose delivered during this period of time, but is assigned to the year of intake. Dose assessments in this report are based on the committed dose from intake.

III.2. RADIOLOGICAL RELEASES DUE TO TESTING OF NUCLEAR WEAPONS

III.2.1. Above ground testing and the generation of radioactive fallout

The radioactive debris from an above ground (either surface or atmospheric) nuclear test is partitioned between the local ground or water surface and the tropospheric and stratospheric regions of the atmosphere, depending on the type of test, location and yield. In general, the higher the explosive yield of the test, the higher the altitude to which the debris is ejected. The subsequent precipitation or falling out of the debris is termed local fallout when the debris is locally dispersed, and tropospheric fallout and stratospheric fallout when it is regionally or globally dispersed.

Local fallout can include as much as 50% of the total activity produced and/or released from surface tests and usually includes a large fraction of the activity in the form of relatively large particles which are deposited within about 100 km of the test site.

Tropospheric fallout consists of smaller aerosols which are not carried across the tropopause after the explosion and which deposit with a mean residence time of up to 30 days. During this period the debris becomes dispersed, although not well mixed, in the latitude band of the test site and follows trajectory directions governed by wind patterns. From the viewpoint of human exposures, tropospheric fallout is important for nuclides with a half-life of a few days to two months, such as ^{131}I, ^{140}Ba and ^{89}Sr.

Stratospheric fallout, which comprises a large part of the total worldwide fallout, is due to those particles that are carried to the stratosphere and later give rise to global fallout, the major part of which is deposited within the hemisphere of the test site. Stratospheric fallout accounts for most of the worldwide deposited residues consisting of long lived fission products. Exposure of humans to fallout activity results from internal irradiation (as a result of inhalation of activity in surface air and ingestion of contaminated foodstuffs) and from external irradiation from activity present in surface air or deposited on the ground.

III.2.2. Underground testing and releases of radioactive material to the environment

Underground nuclear tests have been conducted at various locations worldwide, primarily by the United States of America and the former Soviet Union but also by France in Algeria. The placement of the nuclear devices within the earth defines the specific type of underground test [17]:

- Tunnel: exploded at the end of a long horizontal hole mined into a mountain or mesa (plateau) in a way that places the burst point deep within the earth;
- Shaft: exploded at the end of a drilled or mined vertical hole;
- Crater: placed shallow enough underground to produce a throw-out of the earth when exploded.

When a nuclear device is exploded underground, a sphere of extremely hot, high pressure gases (a temperature of about a million degrees and a pressure of several million atmospheres are reached with a few microseconds), including vaporized weapon residues and rock, is formed [18]. The rapid expansion of the gas initiates a shock wave that travels in all directions away from the burst point. The shock (or compression) wave is typically reflected back from the ground surface towards the detonation, and depending on the depth of the explosion, the returning shock wave may intersect with the expanding gas bubble while it is still growing. In that case, the upper ground layers,

having already experienced the transmission and destruction of the shock wave, provide less resistance to the expanding gas bubble so that there is a relative degree of acceleration of the expanding gas towards the surface.

While many underground tests are intended to contain the generated radioactive material, releases to the environment do occur from shallow underground bursts as well as from more deeply placed devices when the ground surface is breached by cracks or when accidental circumstances, such as in the case of one of the tests at the Taourirt Tan Afella mountain, result in a tunnel not properly closing before the gas bubble reaches the exit.

Unlike the case of above ground or atmospheric explosions where bomb debris and vaporized soil are ejected high into the atmosphere, releases from underground tests typically either are contained underground or vent to the atmosphere and are accompanied by massive amounts of soil and rock (not vaporized) that are ejected only to a few hundreds of metres. If the release is directly above the explosion, much of the ejected material is hurled upwards and normally falls back into a crater. In rare circumstances, such as at the Taourirt Tan Afella mountain, molten rock and hot gases are ejected horizontally from the tunnel entrance and the ejected material that is deposited appears as a long stream of solidified lava.

III.3. HEALTH EFFECTS OF RADIATION EXPOSURE

It has been recognized since the time of the first studies of X rays and radioactive minerals that exposure to radiation at high levels can cause acute damage to the tissues of the human body. If this damage is extremely severe, it can lead to death. In addition, long term epidemiological studies of both human and animal populations exposed to radiation, particularly the survivors of the atomic bombing of Hiroshima and Nagasaki in Japan in 1945, have demonstrated that exposure to radiation also has a potential for the delayed (or late) induction of malignancies and, plausibly, for hereditary effects.

III.3.1. Early effects

Exposure to very high radiation doses can cause effects such as nausea, reddening of the skin or, in severe cases, more acute syndromes that are clinically expressed in exposed individuals within a short period of time after the exposure. Such effects are called deterministic effects because they are certain (predetermined) to occur if the dose exceeds a threshold level. Deterministic effects are the result of various processes, mainly cell death and impaired cell division, caused by exposure to radiation. If these processes are extensive enough, they can impair the function of the exposed tissue. The higher the dose is above the threshold for the occurrence of a particular deterministic effect in an exposed individual, the more severe is the effect. The threshold dose levels depend on the type of effect, the organ affected and the duration of exposure. For doses delivered in a short period of time, deterministic effects are generally not observed below equivalent doses of 1000 mSv. Death due to acute radiation syndrome may occur at an effective dose of several tens of thousands of millisieverts.

III.3.2. Late effects

Radiation exposure can also induce effects such as malignancies, which are expressed after a long latency period of about four to five years in the shortest instances or of many decades in other cases. A complete understanding of the processes which lead to cancer development following radiation exposure is not available, yet there is a significant body of knowledge which relates the likelihood of cancers arising in different organs to various levels of exposure. In the case of cancer, it is the likelihood, rather than the severity of the disease, that is increased by radiation exposure. For most organs, the likelihood or risk increases linearly with increasing radiation dose and is often assumed not to have a threshold. In addition, experimental studies in animals and plants have shown hereditary effects from radiation. Although hereditary effects have not been observed in humans, it is considered prudent for the purposes of setting standards to assume that they do occur. These radiation induced malignancies and hereditary effects are termed stochastic effects because of their probabilistic nature. The induction of stochastic effects is assumed to take place over the entire range of doses, without a threshold level. Under certain conditions, primarily of relatively high doses and/or large numbers of people exposed, stochastic effects may be epidemiologically detectable in the exposed population as an increase in their incidence.

Appendix IV

RADIATION PROTECTION CRITERIA

IV.1. GENERAL CONSIDERATIONS

The International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (BSS) [3] are radiation safety standards developed by consensus through international cooperation and participation by the Food and Agriculture Organization of the United Nations (FAO), the International Atomic Energy Agency (IAEA), the International Labour Organization (ILO), the OECD Nuclear Energy Agency, the Pan American Health Organization (PAHO) and the World Health Organization (WHO). The development of these standards relied on scientific information on radiation levels worldwide and on related health effects compiled globally by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), a body set up by the United Nations General Assembly in 1955. The latest report of UNSCEAR to the United Nations General Assembly was issued in 1993 [4] and a revised report was published in 2000 [5]. The safety criteria in the BSS are based primarily on the recommendations of the International Commission on Radiological Protection (ICRP), a non-governmental scientific organization founded in 1928 to establish basic principles and recommendations for radiation protection. The most recent recommendations of the ICRP were issued in 2000 [19].

International radiation safety standards such as the BSS [3] are intended to provide requirements on safety for the national regulation of the peaceful, beneficial uses of radiation and nuclear energy only. The practice of nuclear weapon testing was therefore not considered during their establishment. However, the BSS do consider chronic exposure situations.

The BSS apply to two classes of societal activities involving radiation exposure. These are practices and interventions. Practices are any human activity that introduces additional sources of exposure or exposure pathways so as to increase the exposure or the likelihood of exposure of people or the number of people exposed. Interventions are activities intended to reduce or avert exposure or the likelihood of exposure to sources which are not part of a controlled practice or which are out of control as a consequence of an accident. In the latter case it is feasible and reasonable to take remedial measures to reduce the doses to some extent.

In general, practices are not authorized unless the practice produces sufficient benefit to the exposed individuals or to society to offset the radiation harm that it might cause. The BSS require that additional doses above background levels that are expected to be delivered by the introduction or proposed continuation of a practice be restricted. The restriction is intended to be applied prospectively to constrain the forecast extra doses.

With respect to interventions, the BSS state that such actions are justified only if they are expected to achieve more good than harm, with due regard to health, social and economic factors. If the dose levels approach or are expected to approach specified levels, protective actions or remedial actions will be justified under almost any circumstances.

Two types of intervention situation are recognized in the BSS. The first relates to emergency exposure situations, such as in the immediate aftermath of a radiological accident, requiring protective actions to reduce or avert the temporary (short term) doses caused by the situation. The second relates to chronic exposure situations where long term environmental radiation levels exist that lead to continuing exposure of a resident population, usually at a relatively low dose rate, requiring remedial actions to reduce the exposure rate.

IV.2. GENERIC INTERVENTION LEVELS

The underlying policy of intervention as set out in the BSS [3] is that the decision on whether or not intervention should be contemplated and how much the existing dose levels should be reduced depends on the circumstances of each individual case. In order to determine whether and when an intervention should be undertaken, intervention levels are established. These levels should be determined in terms of the doses expected to be averted by a specific remedial action intended to protect people from exposure. The intervention

levels are usually expressed in quantities derived from the avertable dose. In the case of chronic exposure situations these derived levels are usually referred to as action levels.

Intervention action levels are expected to be established ad hoc, i.e. on a case by case basis, and tailored to the specific circumstance of the intervention situation. However, there has been a recognized need for simple and internationally agreed guidance on generic levels applicable to any intervention situation, particularly in cases of chronic exposure.

The BSS establish that if doses approach levels at which the likelihood of deleterious health effects is very high, intervention would be expected to be undertaken under almost any circumstances. These quasi-mandatory levels, which are set up in the BSS, depend on the organ exposed, and for chronic exposure situations vary from a level of equivalent dose of 100 mSv/a for the lens of the eye to 400 mSv/a for the bone marrow (Table 22).

From the established levels of equivalent doses and on the basis of recommended weighting factors to take account of the radiosensitivity of the relevant organs, it could be construed that intervention would not be expected to be undertaken under any circumstances unless the annual effective dose exceeds several tens of millisieverts. At lower doses, proposed interventions need to be justified on a case by case basis.

IV.3. GUIDELINES THAT MAY BE APPLICABLE TO CHRONIC EXPOSURE SITUATIONS

Temporary relocation and permanent resettlement are among the more extreme protective measures available to control exposures to the public in the event of a radiological emergency. Table 23 shows the generic levels established in the BSS for temporary relocation and permanent resettlement.

TABLE 22. LEVELS OF EQUIVALENT DOSE RATE AT WHICH INTERVENTION IS EXPECTED TO BE UNDERTAKEN UNDER ANY CIRCUMSTANCES

Organ or tissue	Equivalent dose rate (mSv/a)
Gonads	200
Lens of the eye	100
Bone marrow	400

TABLE 23. GENERIC LEVELS FOR TEMPORARY RELOCATION AND PERMANENT RESETTLEMENT

Intervention	Initiate	Terminate
Temporary relocation	30 mSv/month	10 mSv/month
Permanent resettlement	Lifetime dose > 1 Sv	

Temporary relocation is used to mean the organized and deliberate removal of people from the area affected during an extended, but limited, period of time. As the situation is temporary, the generic guidelines to initiate and terminate relocation refer to relatively high levels of dose: 30 and 10 mSv per month, respectively.

Permanent resettlement is the term used for the deliberate removal of people from the area with no expectation of return. Permanent resettlement should, according to the BSS, be considered if the lifetime dose over 70 years cannot be reduced by other means and is projected to exceed 1 Sv. When doses are below this level, permanent resettlement is unlikely to be necessary.

The BSS establish that if there is no shortage of food and there are no other compelling social or economic factors, action levels for the withdrawal and substitution of specific supplies of food and drinking water which have been contaminated with radioactive substances should be based on the guidelines for foodstuffs in international trade established by the Codex Alimentarius Commission (CAC) [16]. These are included in the BSS [3] as recommended generic action levels for activity in foodstuffs. The levels are limited to radionuclides usually considered relevant to emergency exposure situations. All the relevant radionuclides for the prevailing situation at the nuclear test sites in Algeria are included (Table 24).

Depending on the annual 'food basket' [16] of the population, the doses resulting from the CAC levels will vary, but using the FAO figure for total food consumption of 550 kg per year (not including drinking water), the consumption of food of which every component has activity concentrations at the CAC action levels would result in a maximum annual committed effective dose of up to about 10 mSv. This figure assumes that the food basket is contaminated to the full CAC values for the whole year.

IV.4. REFERENCE FOR COMPARISON: DOSES DUE TO NATURAL BACKGROUND RADIATION

The worldwide individual average annual dose incurred among the global population owing to radiation from natural sources is estimated to be 2.4 mSv [5, 19], of which about half is mainly due to cosmic and terrestrial background radiation and half is due to exposure to ^{222}Rn. There is, however, a large variability in the annual effective doses resulting from natural sources. It is common to find large regions with exposures elevated by up to an order of magnitude and smaller regions with even higher levels. Table 25 indicates average typical and elevated values of annual effective doses to adults from natural sources. The elevated values are representative of large regions, but much higher atypical values may occur locally.

The effective dose rate due to cosmic radiation depends on the height above sea level and the latitude. The annual effective doses in areas of high exposure (locations at higher elevations) are about five times the average. The terrestrial effective dose rate depends on the local geology, with a high level typically being about ten times the average; the effective dose to communities living near some types of mineral sand may be up to about 100 times the average. The effective dose from radon decay products depends on the local geology and on housing construction and use, with the dose in some regions being about ten times the average. Local geology and the type and ventilation of some houses may combine to give effective dose rates from radon decay products of several hundred times the average.

The range of the worldwide annual effective dose from natural sources would be 1–20 mSv, with values in some regions of the order of 30–50 mSv and high levels of above 100 mSv, although the global average annual effective dose due to natural background radiation is of the order of a few millisieverts.

TABLE 24. GENERIC ACTION LEVELS (kBq/kg) FOR FOODSTUFFS

Radionuclide	Foods destined for general consumption	Milk, infant food and drinking water
^{134}Cs, ^{137}Cs, ^{103}Ru, ^{106}Ru, ^{89}Sr	1	1
^{131}I		0.1
^{90}Sr	0.1	
^{241}Am, ^{238}Pu, ^{239}Pu	0.01	0.001

TABLE 25. ANNUAL EFFECTIVE DOSES (mSv) TO ADULTS FROM NATURAL SOURCES

	Worldwide average annual effective dose	Typical range
External dose		
Cosmic rays	0.4	0.3–1.0
Terrestrial gamma rays	0.5	0.3–0.6
Internal dose		
Inhalation	1.2	0.2–10
Ingestion	0.3	0.2–0.8
Total	2.4	1–10

IV.5. GENERIC GUIDANCE FOR REHABILITATION OF AREAS OF CHRONIC EXPOSURE

From the earlier discussion, it appears that an annual effective dose of up to about 10 mSv can be used as a generic guideline for action levels for considering protective remedial actions to rehabilitate areas subject to chronic exposure, such as the areas with residual radionuclides from nuclear weapon testing in Algeria. For doses below the guidance action levels, the situation could, after due consideration, generally be taken as not being hazardous above accepted norms.

It is emphasized, however, that this generically acceptable action level of annual dose does not imply that below such a level it is never worth while reducing the radiation exposure. If it is justified on radiological grounds, intervention for purposes of radiological protection should always be undertaken, and the form, scale and duration of the intervention would be determined by a process of optimization of protection.

One point of confusion is whether it is the doses due to the residual radionuclides or the total dose (including doses due to the natural background radiation) that should be compared with the action level. In this report both dose values are presented.

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